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 and Max Planck Institute for Collective Goods*

16 October 2024

*In collaboration with Eric Budish, University of Chicago; Simon Brandkamp and Axel Ockenfels, University of Cologne and Max Planck Institute for Collective Goods; 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.
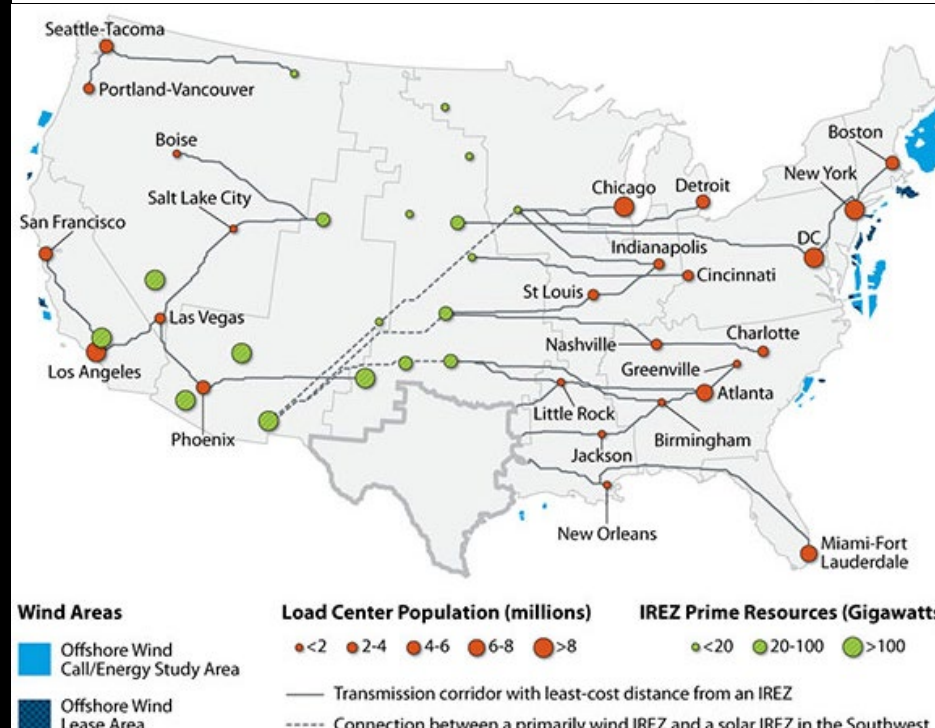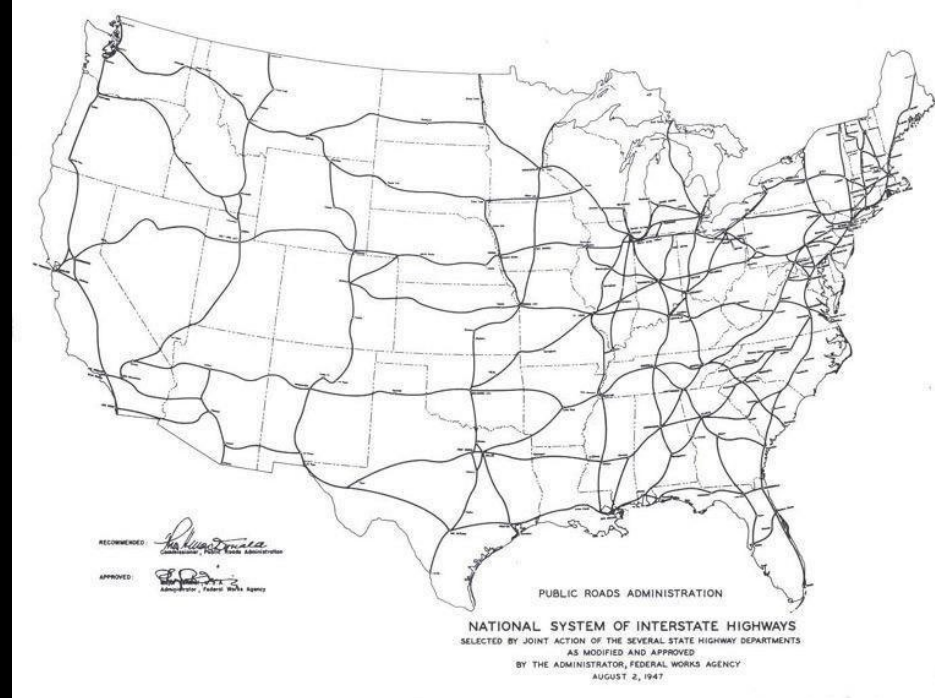
Market design

Goal: maximize social welfare subject to physical constraints

What potential market failures arise, and how to mitigate?

Prisoner's dilemma

Incomplete markets

Market power

Uncertainty

Adverse selection and moral hazard

An Open Access Market
for Global Communications

Peter Cramton

University of Maryland and Max Planck Institute for Collective Goods

20 September 2024 [Latest version] [Presentation] [Interactive Demo] [Sample Source Code]

Applications

Trading platform for forward and spot global communications

Merger remedy for mobile communications to foster wholesale competition (merged entity sells ≥ 10% in open access market)

Efficient and transparent forward and spot trade of spectrum input

Capacity of a satellite vs. terrestrial fiber cable

	Proposed Satellite Project			
	Amazon	Starlink	Rivada	Single
Altitude, km	610	570	1,052	Cable
Speed, Gbps	100	100	20	100,000
Capacity, GB	12.5	12.5	2.5	12,500

Capacity per second based on throughput of a single laser.

Satellite communications are limited by capacity of uplink and downlink to/from satellite
Terrestrial communications are limited by capacity of uplink and downlink to/from cell tower

Optical mesh network time savings in milliseconds between each of top-ten global financial centers

74%

	<0 ms	0-2 ms	2-4 ms	4-8 ms	8-16 ms	>16 ms
City pairs	11	1	5	5	17	6
Percent	24%	2%	11%	11%	38%	13%
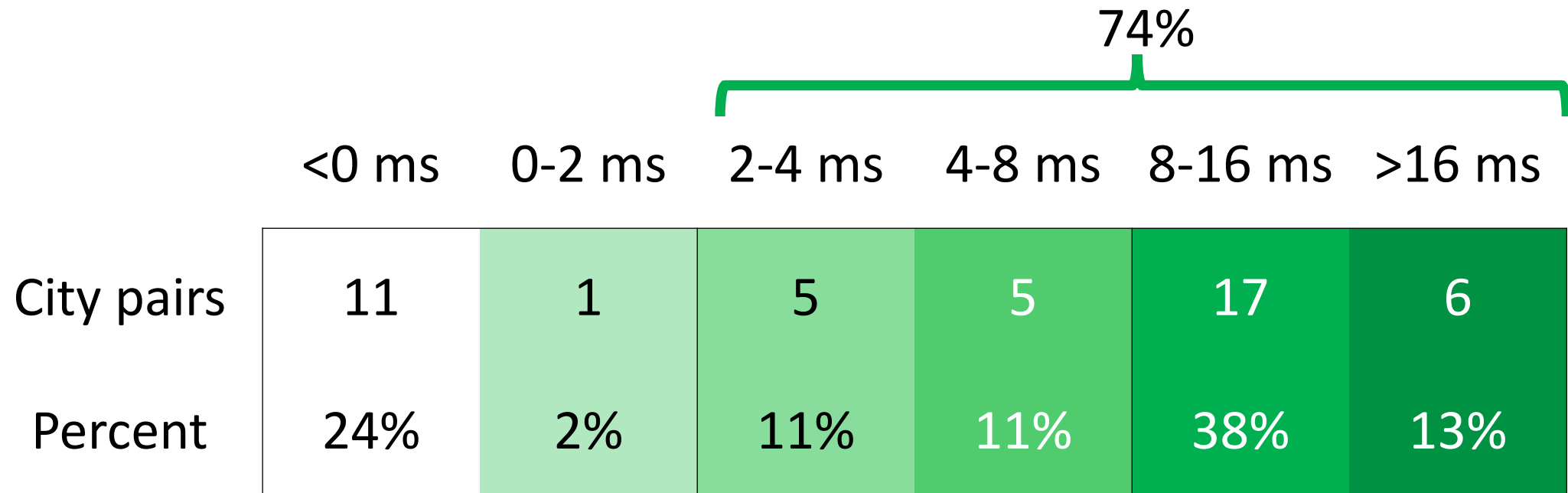
"One millisecond is an eternity for a high-frequency trader."

Mexico City cell towers, September 2017

Vibrant forward trade

Forward prices

Efficient operation & investment

Foster innovation

Encourage resiliency
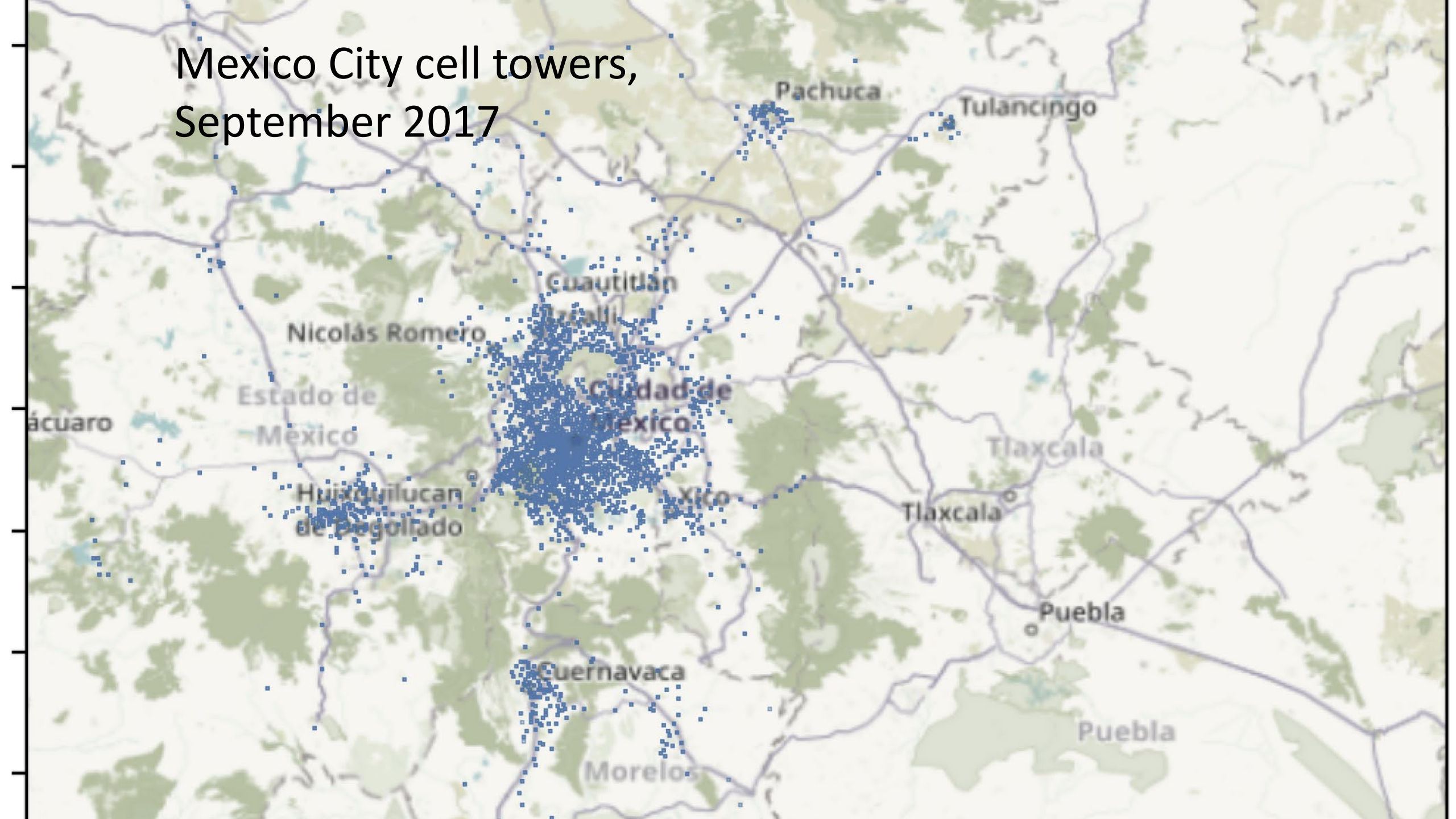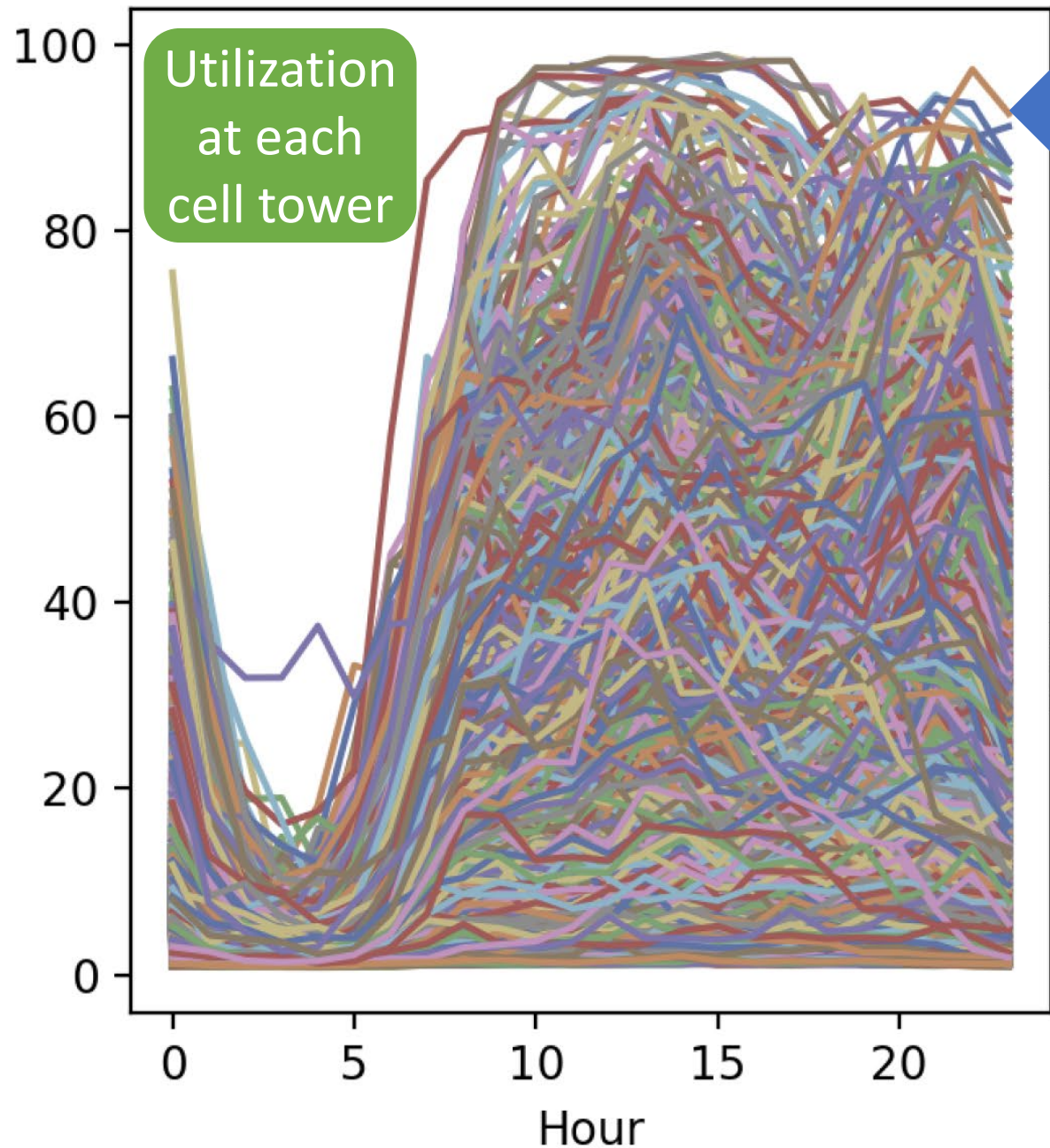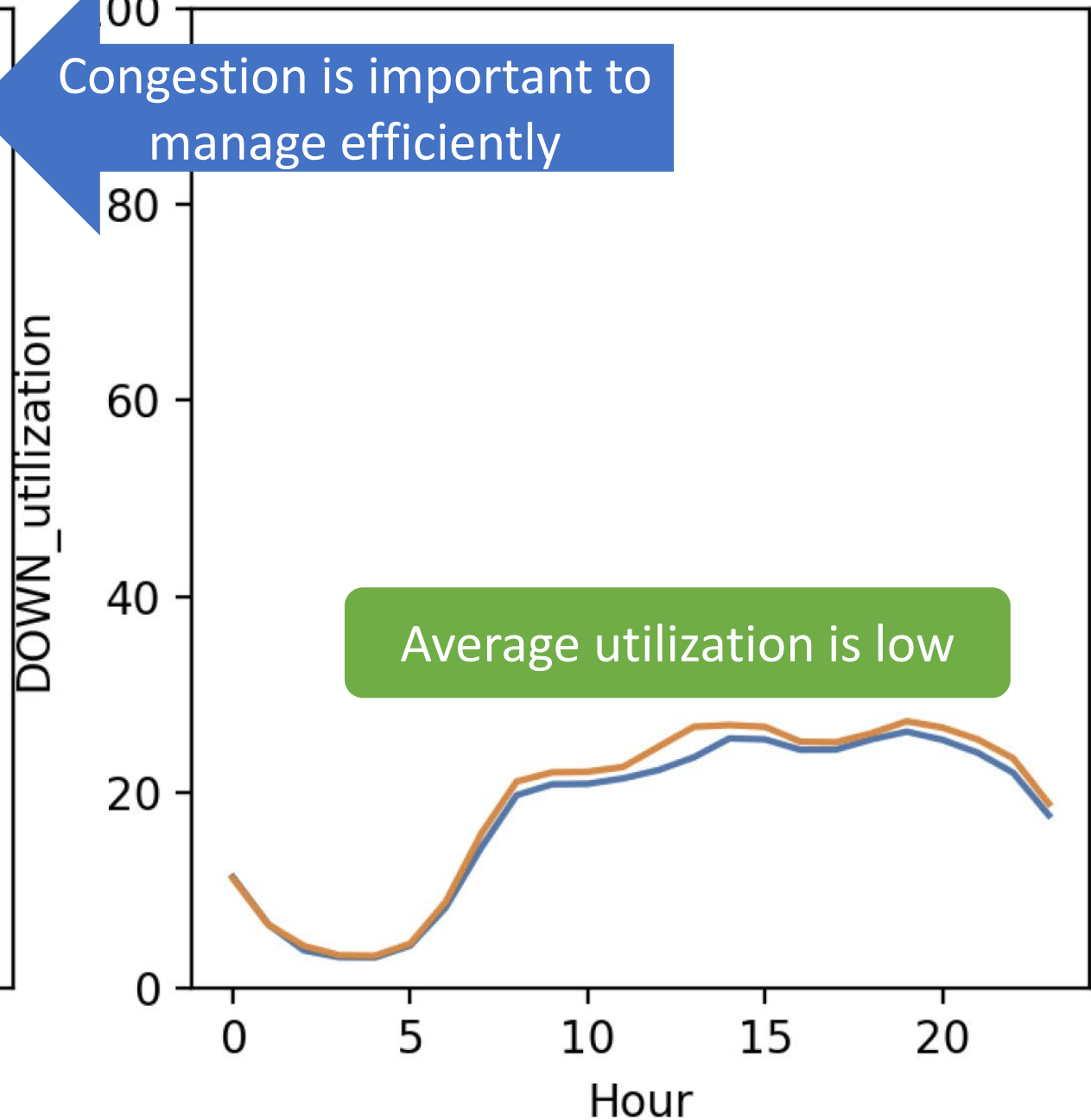
Factors to consider in market design

- 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

Key features

Fine granularity in time and location	Gradual coordinated trade	Persistent portfolio flow orders
• Flexibility to trade consistent with needs and capabilities	• Reduces risk and market power • Robust clearing prices	• Easy participation with effective trade-to-target strategies

Real-time market

- Three products with optimized routing
  - Fast: routing optimized for speed then reliability
  - Premium: nearly never rationed; routing optimized for reliability and speed
  - Regular: rationed as necessary; routing optimized for reliability and speed
- Physical market
  - Customers consume what they want of three products
- Real-time measured communications (hourly GB)
- Priced at intersection of supply and demand
  - Fast, premium, and regular, weekday and weekends, region, hour
- Conducted and settled by the market operator

Forward market

- Voluntary market
- Derivative of real-time communications (hourly GB)
- Yearly forward communications (10 to 1 year ahead)
  - Hourly, fast/premium/regular, weekday or weekend, regions
- Monthly forward communications (12 to 1 month ahead)
  - Hourly, fast/premium/regular, weekday or weekend, regions
- Hourly forward communications (30 to 1 day ahead)
  - Hourly, fast/premium/regular, regions
- Flow trading (Budish-Cramton-Kyle-Lee-Malec)
  - Persistent piecewise linear net demand for any product portfolio (rate of trade in GBps as a function of price)
  - Cleared hourly
  - Unique prices and quantities, trivial computation
- Conducted and settled by the market operator
- Transparent forward pricing and positions
- Flexible way to manage risk, operation, and investment
  - Participant moves smoothly from current position to target
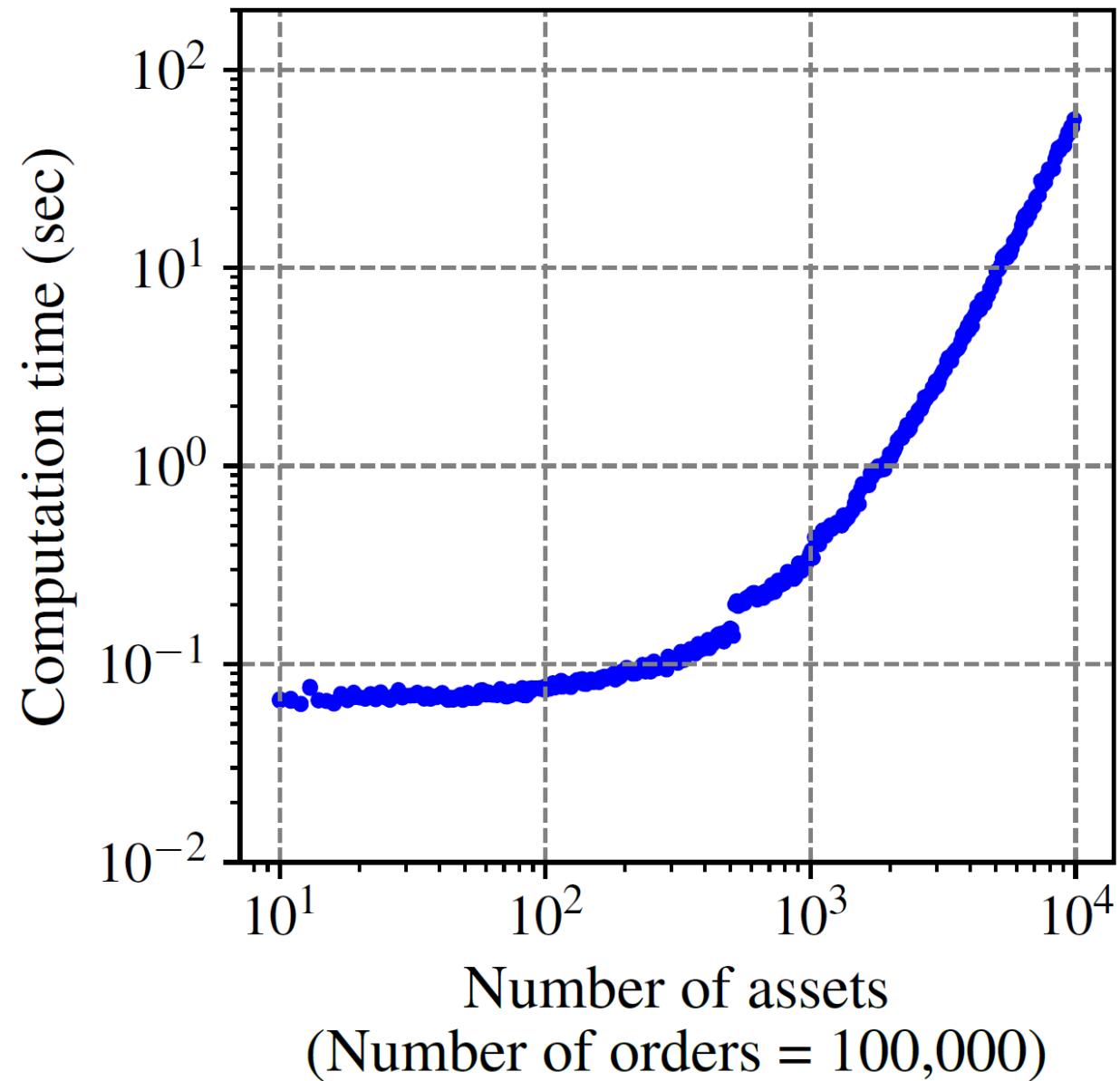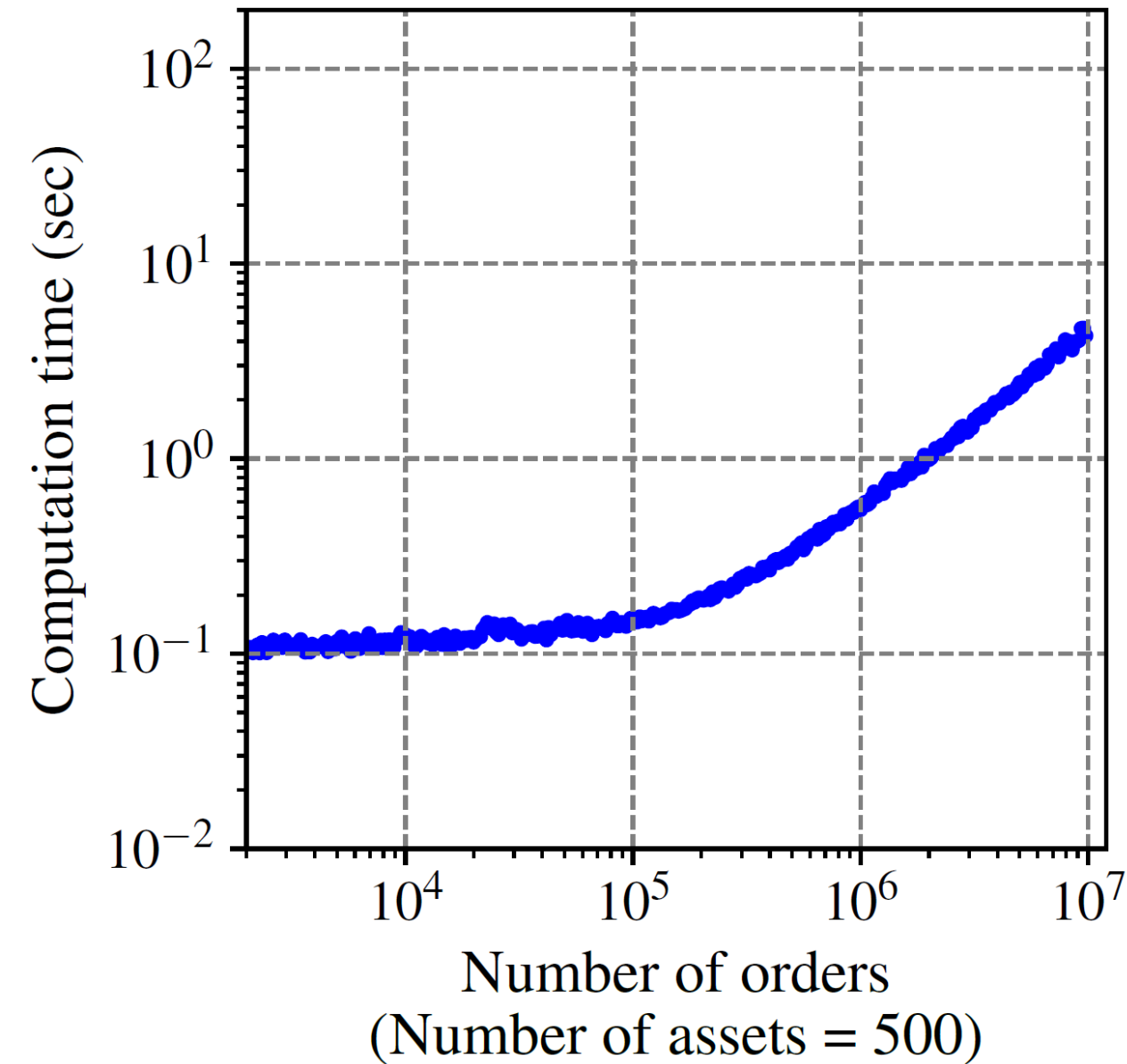
Participating in market is straightforward

- Inputs
  - Current position
  - Expected net demand by hour
  - Expected real-time price by hour
  - Risk attitude and cost of capital
- Trade-to-target strategy
  - Adjustment to reach target (GB)
  - Flow rate to reach target (GBps)
  - Slope of net demand curve: how much does flow rate increase with a $1/GB price decrease (GBps)?

Inputs

Risk preference

Cost of Capital

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

Anticipated prices

Mar/Apr 2022

US 5-Year Breakeven Inflation
US 10-Year Breakeven Inflation
WTI Crude

Distribution of hourly net demand

Trade-to-target strategy

Speed of trade

Price arbitrage

Arbitrage

[ˈär-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

Net demand

Price ($/GB)

Quantity (GB)

Outputs

Prices

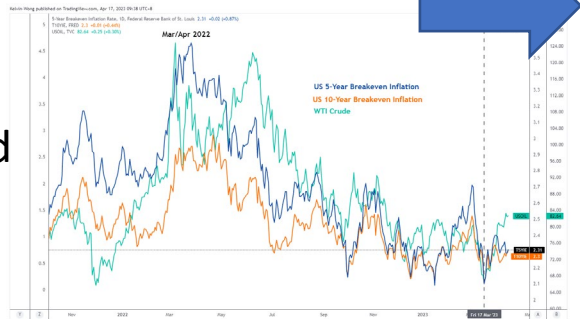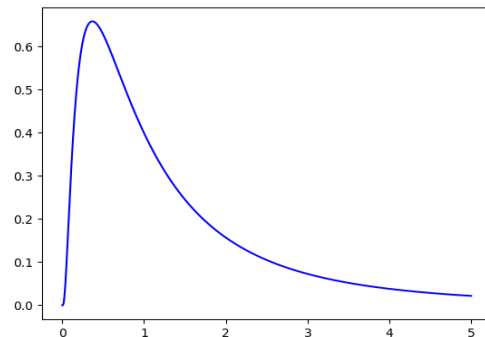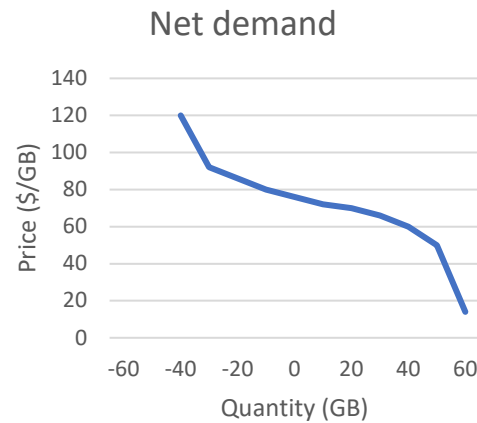| | | | | | Year / Years Ahead | | | | | |
Hour	2033 10	2032 9	2031 8	2030 7	2029 6	2028 5	2027 4	2026 3	2025 2	2024 1
0	8.57	8.52	8.57	8.60	8.64	8.76	9.12	8.90	8.69	8.97
1	8.56	8.52	8.56	8.61	8.61	8.69	8.97	8.60	8.23	8.47
2	8.55	8.53	8.55	8.61	8.58	8.63	8.85	8.52	8.15	8.38
3	8.63	8.59	8.63	8.69	8.62	8.70	8.82	8.37	7.91	8.06
4	8.71	8.70	8.77	8.80	8.79	8.89	9.00	8.57	8.18	8.29
5	8.96	8.95	9.01	9.03	9.02	9.08	9.18	8.66	8.19	8.29
6	9.24	9.24	9.30	9.34	9.34	9.34	9.50	9.15	8.82	8.99
7	9.67	9.65	9.68	9.72	9.70	9.64	9.79	9.43	9.07	9.20
8	10.17	10.15	10.19	10.26	10.27	10.18	10.36	9.98	9.56	9.71
9	10.63	10.58	10.60	10.67	10.66	10.57	10.75	10.46	10.13	10.27
10	10.96	10.91	10.96	11.02	11.01	10.92	11.14	10.71	10.28	10.46
11	10.97	10.90	10.95	11.00	11.00	10.96	11.13	10.66	10.19	10.28
12	11.07	11.00	11.04	11.09	11.10	11.06	11.29	10.84	10.38	10.53
13	11.08	11.02	11.05	11.10	11.07	11.03	11.33	11.06	10.77	11.03
14	11.23	11.19	11.21	11.25	11.23	11.19	11.51	11.27	11.02	11.31
15	11.33	11.31	11.33	11.36	11.36	11.35	11.62	11.25	10.89	11.13
16	11.43	11.36	11.38	11.41	11.46	11.45	11.75	11.32	10.88	11.06
17	11.30	11.24	11.25	11.32	11.37	11.40	11.74	11.17	10.55	10.77
18	11.12	11.07	11.05	11.07	11.13	11.16	11.50	11.12	10.68	10.91
19	10.88	10.81	10.80	10.82	10.85	10.89	11.29	10.87	10.42	10.74
20	10.63	10.55	10.57	10.58	10.62	10.62	11.02	10.61	10.20	10.50
21	10.29	10.24	10.28	10.31	10.33	10.33	10.59	10.08	9.57	9.77
22	9.93	9.91	9.99	10.02	10.05	10.05	10.19	9.56	8.98	9.07
23	9.67	9.67	9.75	9.79	9.84	9.84	9.87	8.97	8.11	8.09

Flow trade rate

| | | | | | | | | Days Ahead | | | | | | | |
Hour	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
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	0.010	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	0.005	-0.112	-0.027	-0.141	0.135	1.880	11.955
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	0.002	-0.008	0.032	-0.008	0.001	0.009	0.009	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	-0.001	-0.009	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	0.024	0.133	0.120	-0.148	-0.126	-0.156	0.060	1.311	9.754
15	0.016	-0.002	-0.010	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	-0.001	-0.010	0.017	-0.012	-0.009	-0.010	0.099	-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	-0.095	-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	0.008	-0.013	-0.016	-0.007	0.106	0.123	-0.113	-0.075	-0.101	-0.201	1.039	10.604
20	0.011	0.000	-0.013	0.022	-0.006	-0.013	0.006	0.099	0.114	-0.082	-0.126	-0.161	-0.167	0.486	6.688
21	0.013	-0.004	-0.017	0.023	0.000	-0.004	0.002	0.077	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

Architecture

Applications

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

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

Energy Market
- 100,000 products, MWh by time and location
- Houston, 4pm, weekday, July 2027

Transportation Market
- Million products, airport slots by time and location
- CDG, 16.50, 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**

Yearly forward prices, New York, premium, weekday ($/GB)
10 to 1 year ahead (10 × 24 = 240 yearly products per region)

Hour	2033 / 10	2032 / 9	2031 / 8	2030 / 7	2029 / 6	2028 / 5	2027 / 4	2026 / 3	2025 / 2	2024 / 1
0	8.57	8.52	8.57	8.60	8.64	8.76	9.12	8.90	8.69	8.97
1	8.56	8.52	8.56	8.61	8.61	8.69	8.97	8.60	8.23	8.47
2	8.55	8.53	8.55	8.61	8.58	8.63	8.85	8.52	8.15	8.38
3	8.63	8.59	8.63	8.69	8.62	8.70	8.82	8.37	7.91	8.06
4	8.71	8.70	8.77	8.80	8.79	8.89	9.00	8.57	8.18	8.29
5	8.96	8.95	9.01	9.03	9.02	9.08	9.18	8.66	8.19	8.29
6	9.24	9.24	9.30	9.34	9.34	9.34	9.50	9.15	8.82	8.99
7	9.67	9.65	9.68	9.72	9.70	9.64	9.79	9.43	9.07	9.20
8	10.17	10.15	10.19	10.26	10.27	10.18	10.36	9.98	9.56	9.71
9	10.63	10.58	10.60	10.67	10.66	10.57	10.75	10.46	10.13	10.27
10	10.96	10.91	10.96	11.02	11.01	10.92	11.14	10.71	10.28	10.46
11	10.97	10.90	10.95	11.00	11.00	10.96	11.13	10.66	10.19	10.28
12	11.07	11.00	11.04	11.09	11.10	11.06	11.29	10.84	10.38	10.53
13	11.08	11.02	11.05	11.10	11.07	11.03	11.33	11.06	10.77	11.03
14	11.23	11.19	11.21	11.25	11.23	11.19	11.51	11.27	11.02	11.31
15	11.33	11.31	11.33	11.36	11.36	11.35	11.62	11.25	10.89	11.13
16	11.43	11.36	11.38	11.41	11.46	11.45	11.75	11.32	10.88	11.06
17	11.30	11.24	11.25	11.32	11.37	11.40	11.74	11.17	10.55	10.77
18	11.12	11.07	11.05	11.07	11.13	11.16	11.50	11.12	10.68	10.91
19	10.88	10.81	10.80	10.82	10.85	10.89	11.29	10.87	10.42	10.74
20	10.63	10.55	10.57	10.58	10.62	10.62	11.02	10.61	10.20	10.50
21	10.29	10.24	10.28	10.31	10.33	10.33	10.59	10.08	9.57	9.77
22	9.93	9.91	9.99	10.02	10.05	10.05	10.19	9.56	8.98	9.07
23	9.67	9.67	9.75	9.79	9.84	9.84	9.87	8.97	8.11	8.09

Price $/GB: 7.91 — 11.75

18

Monthly forward prices, New York, premium, weekday ($/GB)
12 to 1 month ahead (12 × 24 = 288 monthly products per region)

Hour	Dec 12	Nov 11	Oct 10	Sep 9	Aug 8	Jul 7	Jun 6	May 5	Apr 4	Mar 3	Feb 2	Jan 1
0	8.53	8.49	8.51	8.45	8.36	8.15	8.20	8.06	7.63	7.99	8.41	7.90
1	8.51	8.47	8.51	8.44	8.40	8.22	8.32	8.14	7.74	8.30	8.93	8.40
2	8.56	8.49	8.56	8.50	8.42	8.29	8.40	8.24	7.82	8.35	8.90	8.37
3	8.69	8.60	8.64	8.57	8.47	8.37	8.49	8.34	7.95	8.38	8.76	8.24
4	8.92	8.82	8.87	8.81	8.69	8.63	8.73	8.62	8.24	8.62	8.90	8.43
5	9.12	9.04	9.09	9.05	8.93	8.84	8.90	8.80	8.48	9.06	9.57	9.21
6	9.36	9.30	9.38	9.35	9.25	9.15	9.15	9.09	8.84	9.65	10.42	10.16
7	9.73	9.70	9.74	9.68	9.58	9.47	9.46	9.32	9.09	9.93	10.75	10.48
8	10.21	10.21	10.25	10.20	10.10	9.95	9.92	9.78	9.57	10.41	11.24	11.01
9	10.60	10.60	10.67	10.65	10.57	10.45	10.44	10.28	10.04	10.97	11.83	11.59
10	10.91	10.92	10.97	10.97	10.87	10.78	10.76	10.80	10.51	11.63	12.63	12.34
11	10.93	10.94	10.97	10.99	10.90	10.86	10.84	10.86	10.58	11.44	12.14	11.88
12	11.07	11.07	11.10	11.09	10.98	10.92	10.86	10.97	10.72	11.57	12.29	12.07
13	11.11	11.08	11.12	11.08	10.98	10.91	10.85	10.89	10.78	11.58	12.30	12.20
14	11.27	11.23	11.32	11.26	11.16	11.04	10.98	10.99	10.82	11.71	12.56	12.40
15	11.39	11.35	11.43	11.40	11.29	11.16	11.05	10.98	10.85	11.75	12.64	12.60
16	11.43	11.41	11.45	11.47	11.33	11.21	11.07	10.94	10.66	11.48	12.25	12.13
17	11.29	11.29	11.32	11.34	11.19	11.08	10.99	10.86	10.53	11.51	12.42	12.21
18	11.09	11.08	11.10	11.08	10.94	10.86	10.81	10.67	10.33	11.43	12.43	12.12
19	10.89	10.89	10.93	10.89	10.79	10.70	10.65	10.59	10.23	11.23	12.18	11.84
20	10.64	10.61	10.68	10.65	10.55	10.43	10.34	10.26	10.03	10.91	11.75	11.58
21	10.27	10.26	10.34	10.34	10.24	10.14	10.05	10.07	9.88	10.65	11.38	11.28
22	9.88	9.89	9.96	9.97	9.85	9.71	9.62	9.63	9.45	10.20	10.92	10.81
23	9.60	9.62	9.71	9.73	9.60	9.47	9.43	9.47	9.29	10.16	10.96	10.80

Month / Months Ahead

Price $/GB
7.63 — 12.64

Hourly forward prices, New York, premium, weekday ($/GB), 30 to 0 days ahead (odd shown) (30 × 24 = 720 hourly products per region)

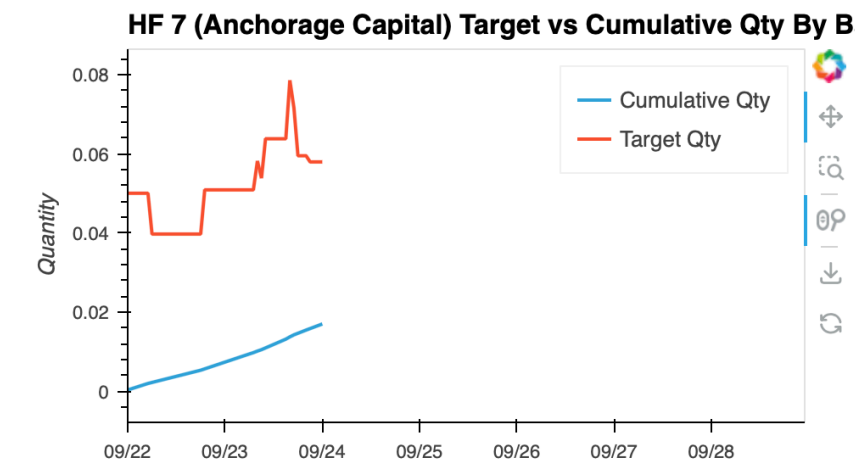| Hour	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
0	8.55	8.57	8.58	3.17	8.55	8.59	3.24	8.68	8.64	8.68	2.49	8.76	8.06	2.39	7.64
1	8.54	8.55	8.56	3.12	8.52	8.56	3.20	8.62	8.59	8.64	2.37	8.74	8.20	2.26	7.87
2	8.56	8.58	8.58	3.08	8.51	8.56	3.16	8.61	8.57	8.60	2.43	8.77	8.43	2.40	8.24
3	8.62	8.65	8.66	3.08	8.57	8.58	3.09	8.62	8.59	8.61	2.54	8.78	8.34	2.66	8.09
4	8.74	8.78	8.82	3.26	8.73	8.72	3.18	8.77	8.70	8.72	2.62	8.79	8.30	2.65	8.02
5	8.94	8.98	9.04	3.51	8.96	8.92	3.41	8.99	8.92	8.99	2.62	9.04	8.53	2.46	8.24
6	9.26	9.27	9.32	3.76	9.26	9.19	3.75	9.27	9.19	9.30	3.06	9.36	8.78	2.84	8.34
7	9.67	9.67	9.70	4.23	9.66	9.59	4.30	9.70	9.60	9.69	3.61	9.77	9.36	3.26	9.07
8	10.16	10.16	10.17	4.72	10.15	10.11	4.78	10.19	10.06	10.11	4.03	10.12	9.64	3.64	9.30
9	10.59	10.58	10.60	5.18	10.60	10.59	5.24	10.68	10.52	10.56	4.42	10.48	9.92	3.90	9.57
10	10.88	10.89	10.92	5.44	10.92	10.92	5.49	11.01	10.88	10.89	4.70	10.72	10.16	4.22	9.83
11	10.91	10.96	10.99	5.46	10.95	10.95	5.54	11.04	10.97	10.97	4.78	10.81	10.23	4.26	9.95
12	11.02	11.08	11.11	5.58	11.05	11.01	5.65	11.07	11.04	11.02	4.96	10.89	10.57	4.43	10.56
13	11.06	11.12	11.14	5.57	11.03	11.00	5.63	11.06	11.05	10.96	5.01	10.81	10.56	4.61	10.58
14	11.24	11.27	11.26	5.70	11.20	11.16	5.76	11.21	11.18	11.16	5.39	11.14	10.83	5.19	10.72
15	11.38	11.36	11.31	5.76	11.27	11.26	5.86	11.31	11.26	11.25	5.67	11.32	10.86	5.72	10.53
16	11.41	11.38	11.33	5.79	11.34	11.32	5.86	11.38	11.33	11.40	5.64	11.53	11.01	5.69	10.65
17	11.25	11.27	11.23	5.66	11.21	11.18	5.70	11.26	11.22	11.32	5.56	11.38	10.81	5.60	10.40
18	11.04	11.09	11.08	5.49	11.07	11.01	5.48	11.07	11.00	11.14	5.06	11.20	10.47	4.94	9.91
19	10.83	10.89	10.92	5.39	10.88	10.78	5.40	10.84	10.77	10.85	4.66	10.88	10.08	4.31	9.53
20	10.58	10.62	10.64	5.18	10.59	10.50	5.20	10.57	10.50	10.58	4.36	10.60	10.01	4.00	9.68
21	10.28	10.29	10.28	4.81	10.25	10.16	4.86	10.27	10.20	10.28	4.26	10.24	9.72	3.98	9.49
22	9.94	9.91	9.87	4.35	9.84	9.79	4.38	9.93	9.87	9.90	4.15	9.81	9.35	3.94	9.04
23	9.67	9.64	9.59	4.05	9.58	9.55	4.06	9.68	9.64	9.63	4.10	9.60	8.99	4.06	8.47

Days Ahead

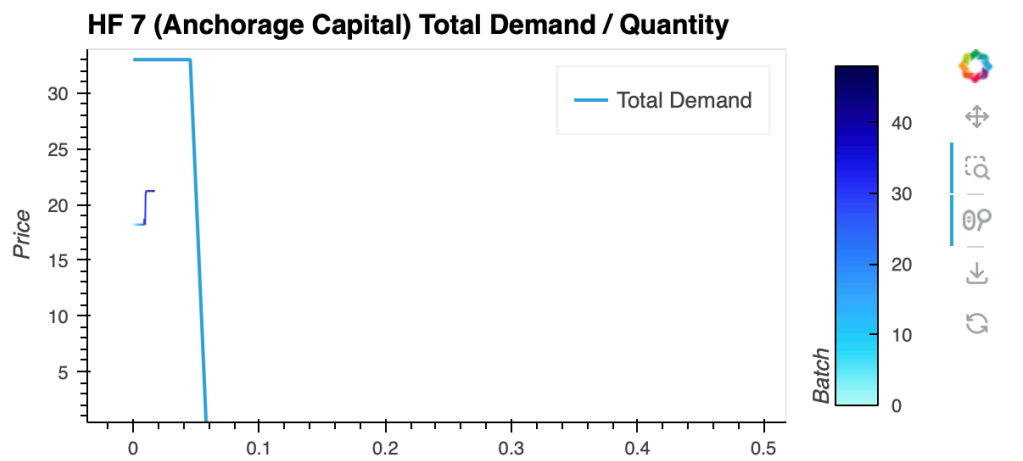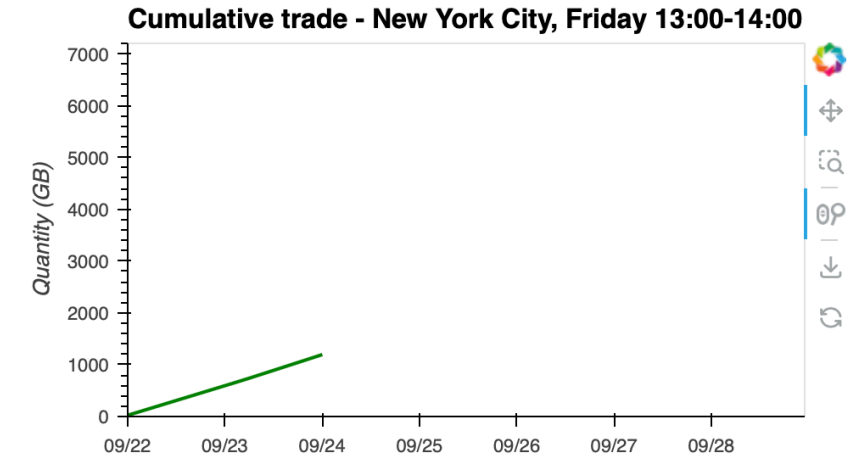Price $/GB: 2.26 — 11.53

Hourly and weekend effects dominate

Region
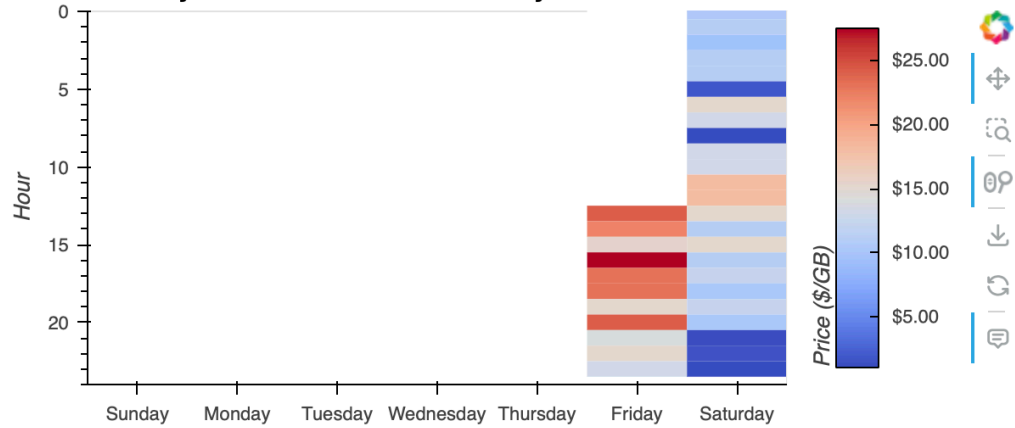
New York City

Batch
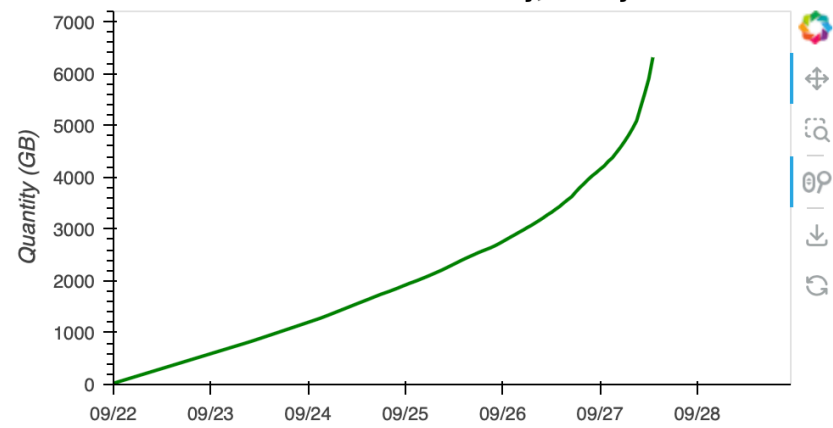
48

Product

D05H13

Run

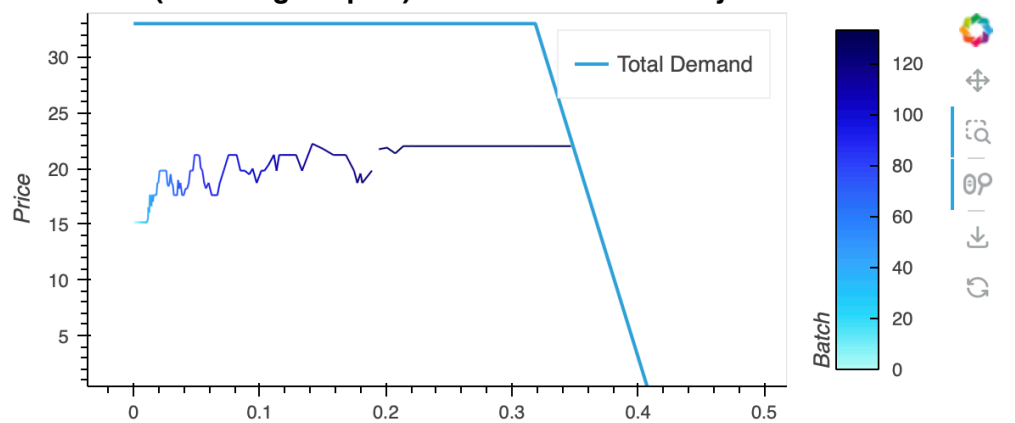### Price - New York City, Friday 13:00-14:00

Price by time of use - New York City

Cumulative trade - New York City, Friday 13:00-14:00

HF 7 (Anchorage Capital) Total Demand / Quantity

HF 7 (Anchorage Capital) Target vs Cumulative Qty By B
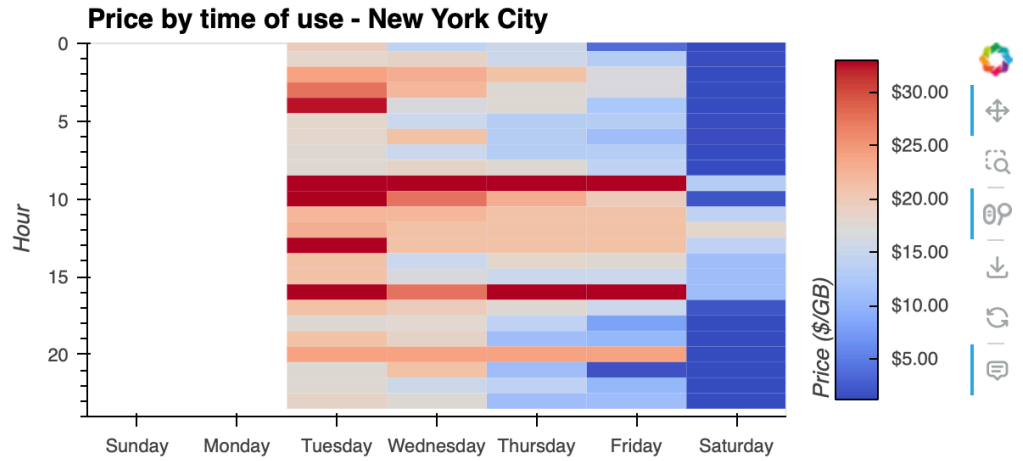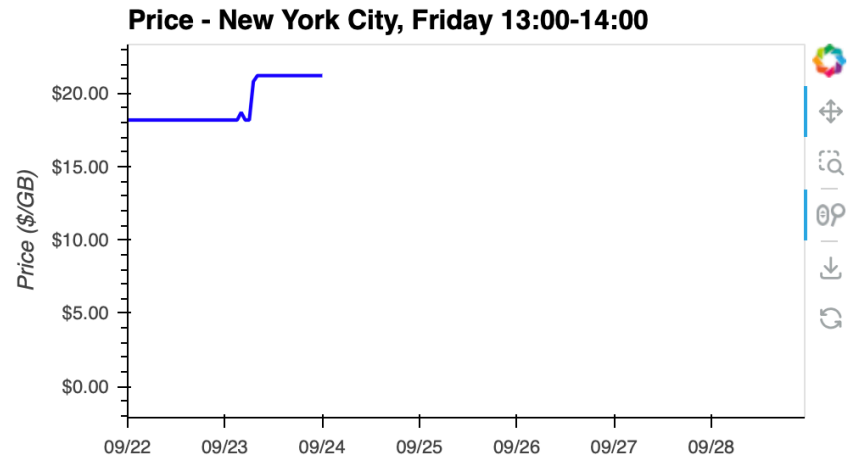
Region

New York City ▾

Batch

133 ▾

Product

D05H14 ▾

Run

Price - New York City, Friday 14:00-15:00
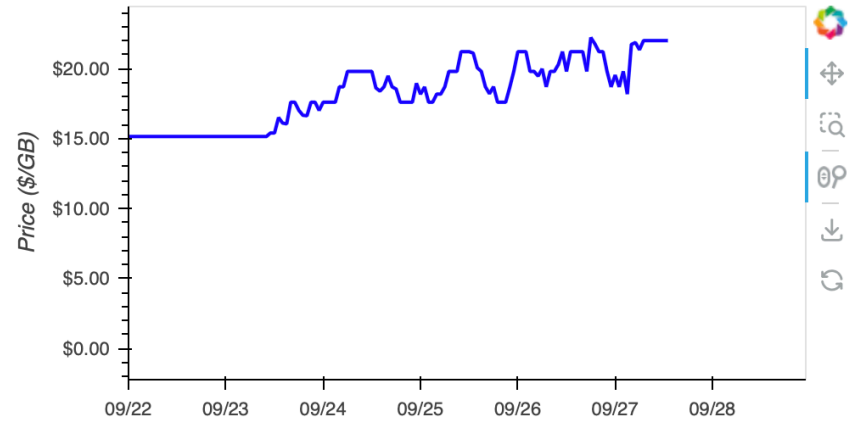
Price by time of use - New York City

Cumulative trade - New York City, Friday 14:00-15:00

HF 7 (Anchorage Capital) Total Demand / Quantity

Total Demand

HF 7 (Anchorage Capital) Target vs Cumulative Qty By B

Cumulative Qty
Target Qty