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

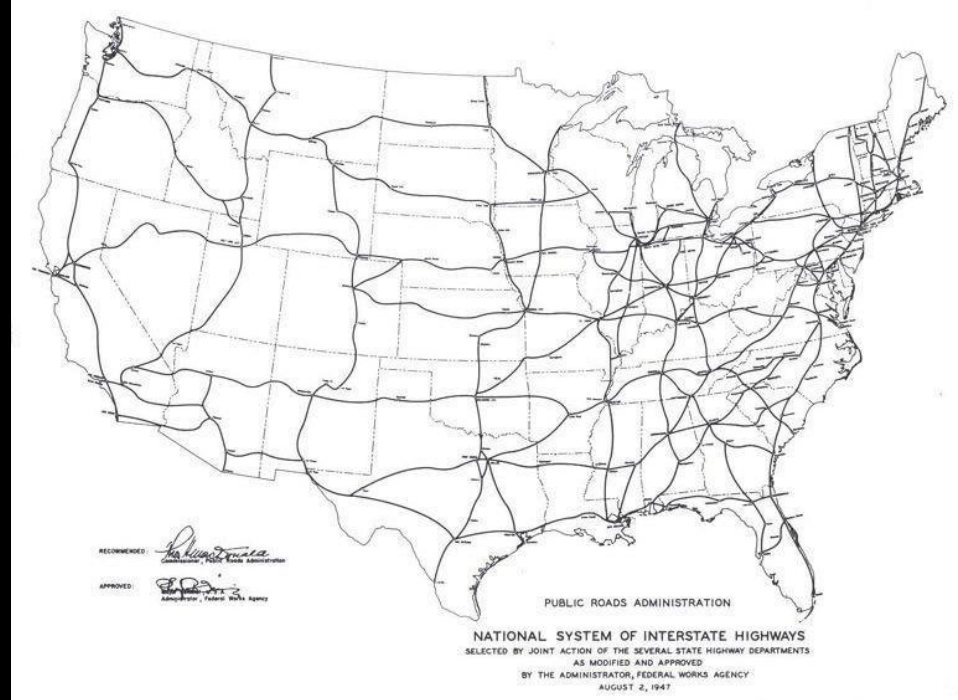
Communications
An open access market for global communications

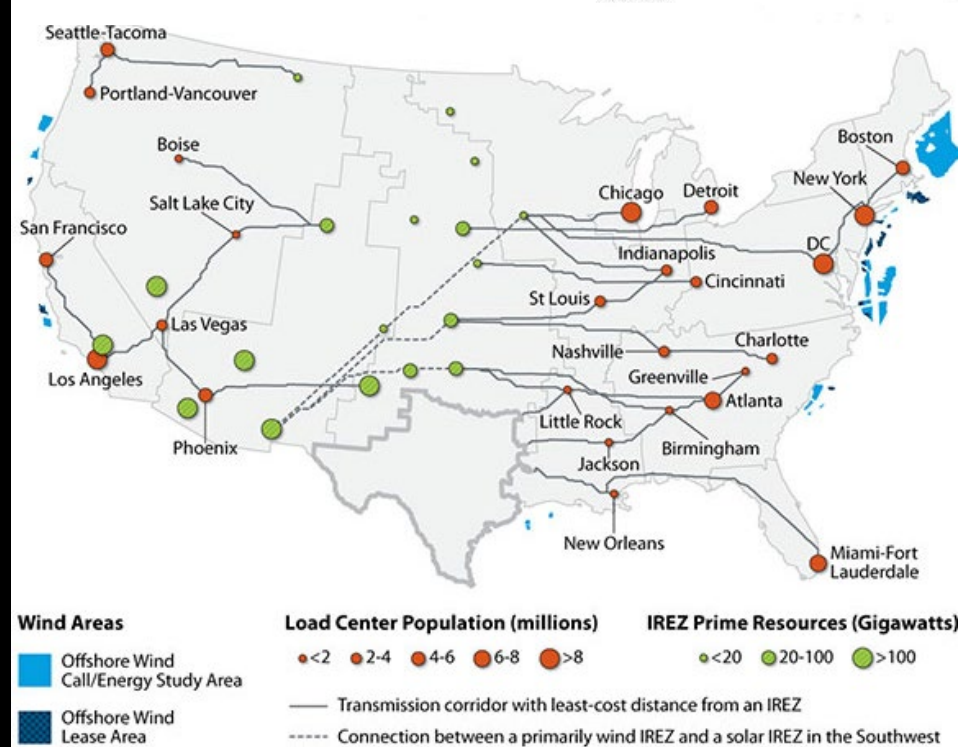
Transportation
A market for airport slots (and roads)

Peter Cramton, University of Maryland, Max Planck Institute*

21 May 2025

*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.

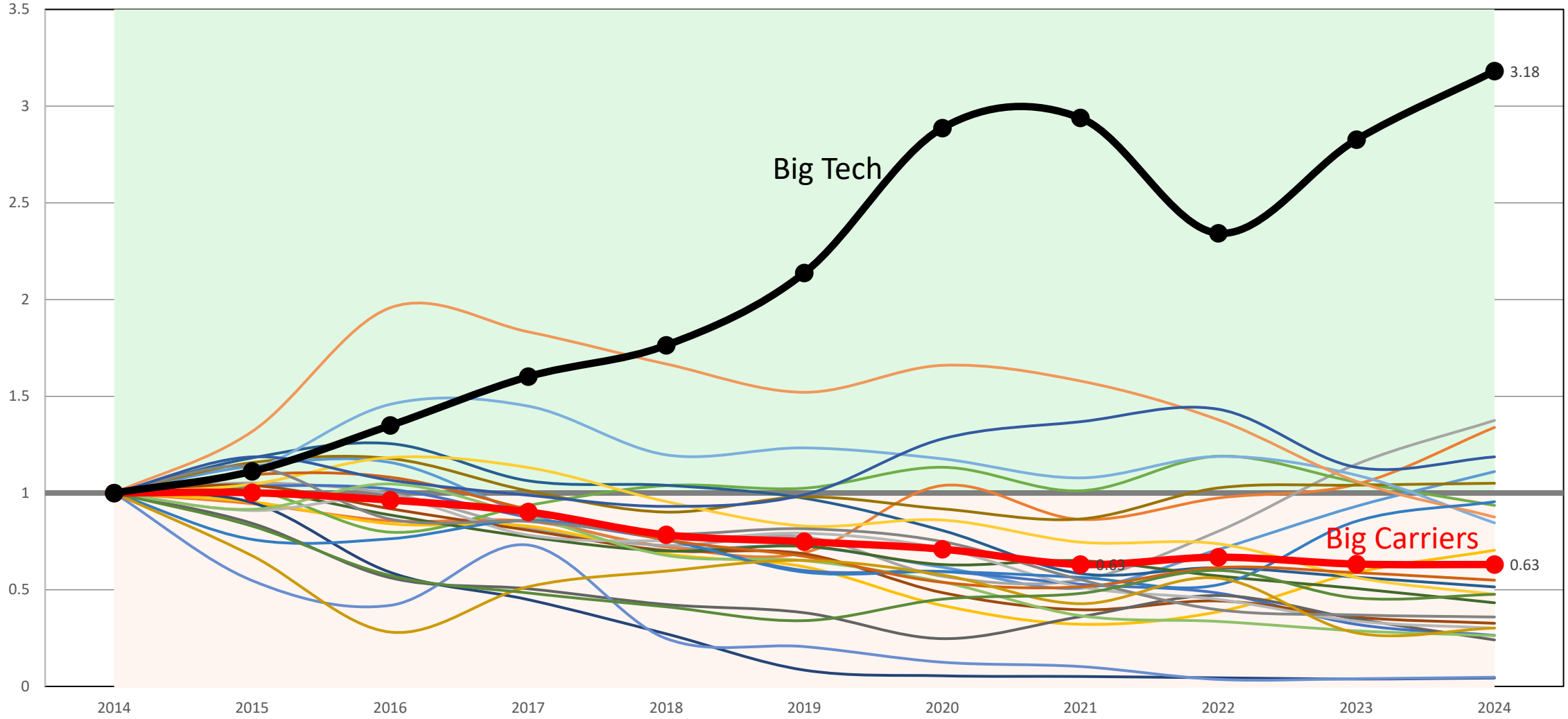




Evolution of communications
from monopoly to competition (commoditization)

Past	Current	Future
Competition from entry	Consolidation	Competition from open access
Few bands, little flexibility	Many bands, good flexibility	Efficient sharing and trading
Acquire sufficient quantities of essential bands	Balance portfolio of low-, mid-, & high-band	Efficient and transparent commodity market

Relative Performance of Big Tech and Big Carriers (Stock/Index)



Big Carriers = 24 largest publicly traded MNOs; Big Tech = Amazon, Google, Microsoft, Meta, and Apple

Spot and forward in commodity markets

- Commodity becomes physical in the spot market
  - Physical delivery occurs in the spot market
  - In many spot markets, buyer's consumption is not controlled (electricity, communications, transportation); clearing is approximate and determined ex post.
- Forward products are financial derivates of the spot product
- Deviations in spot performance are settled at the spot price, which is called efficient performance in contract law
  - Example: You buy 10 units for $40 in a forward market for 4 pm on 18 August 2027. At 4pm on 18 August 2027 you consume 8 units. The spot price is $30. The settlement is 10 × $40 - 2 × $30. You bought 10 units at $40 and sold 2 units at $30.
- Futures are forwards efficiently settled by a clearinghouse (exchange)
- Products settled by the system operators are called forwards to distinguish them from those settled in commercial exchanges like CME and ICE

Market design

Goal: maximize social welfare subject to physical constraints

What potential market failures arise, and how to mitigate?

Incomplete markets

Market power

Uncertainty

Adverse selection and moral hazard

An Open Access Market for Global Communications

Peter Cramton (Max Planck Institute) and Erik Bohlin (Ivey Business School)

August 2024

[Latest version] [Presentation] [Interactive Demo] [Sample Source Code]

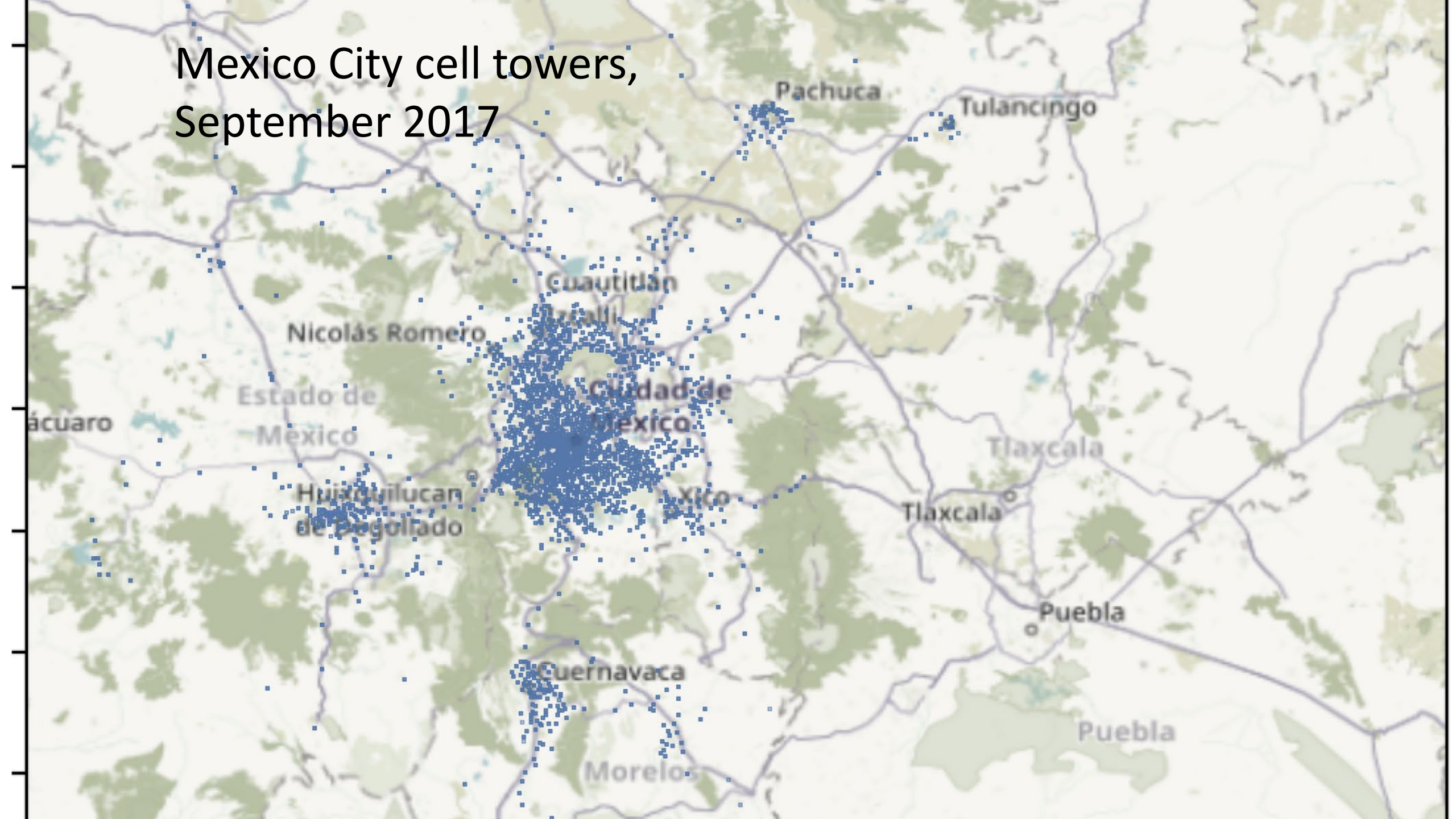
*In collaboration with Erik Bohlin at Ivey Business School, Simon Brandkamp and Axel Ockenfels at the University of Cologne and Max Planck Institute for Collective Goods, Albert S. Kyle and David Malec at the University of Maryland, and Jason Dark, Darrell Hoy, and Chris Wilkens at Cramton Associates. Support by Rivada Networks and the German Science Foundation through Germany's Excellence Strategy (EXC 2126/1 390838866) is gratefully acknowledged.

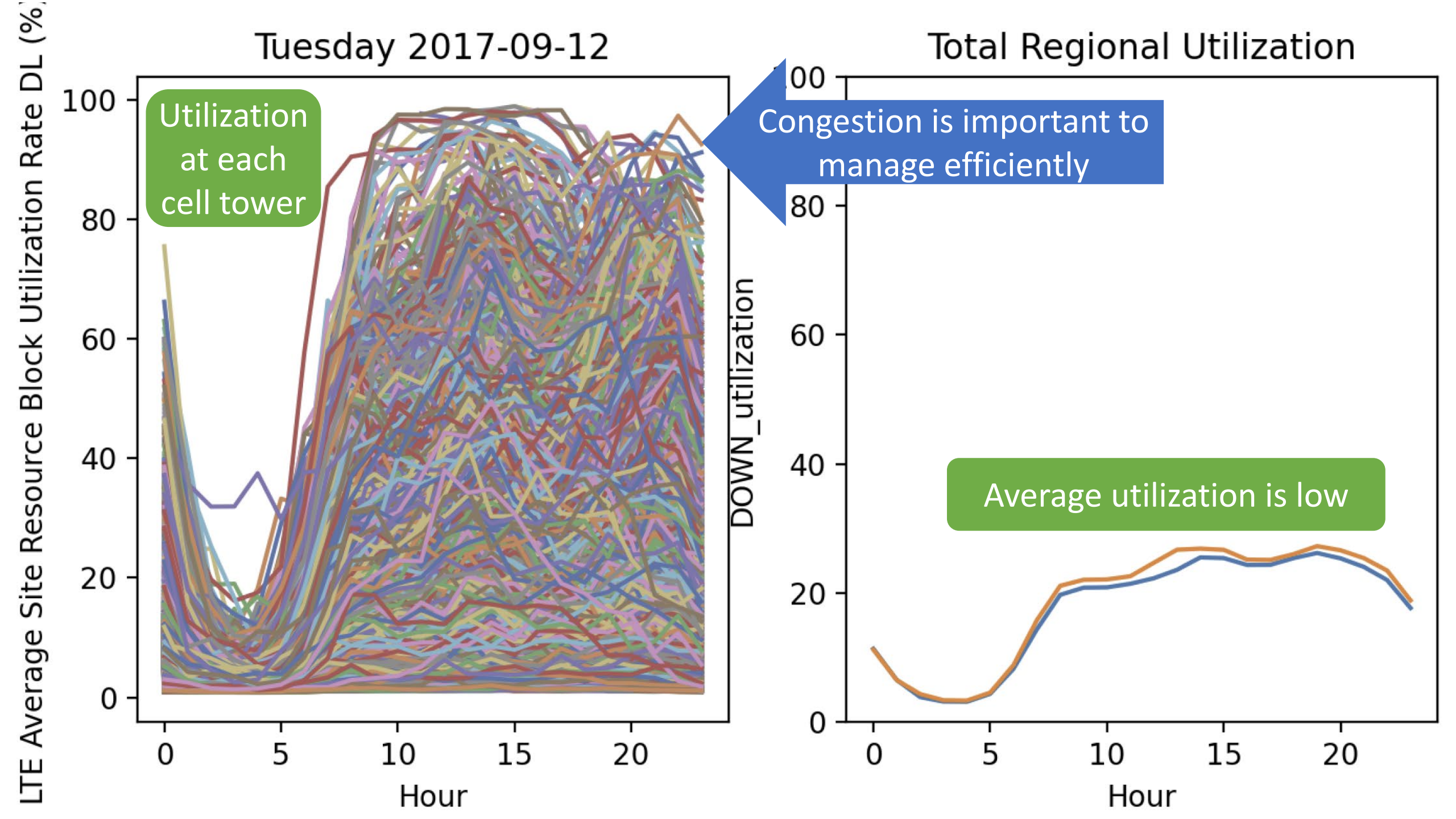
Applications

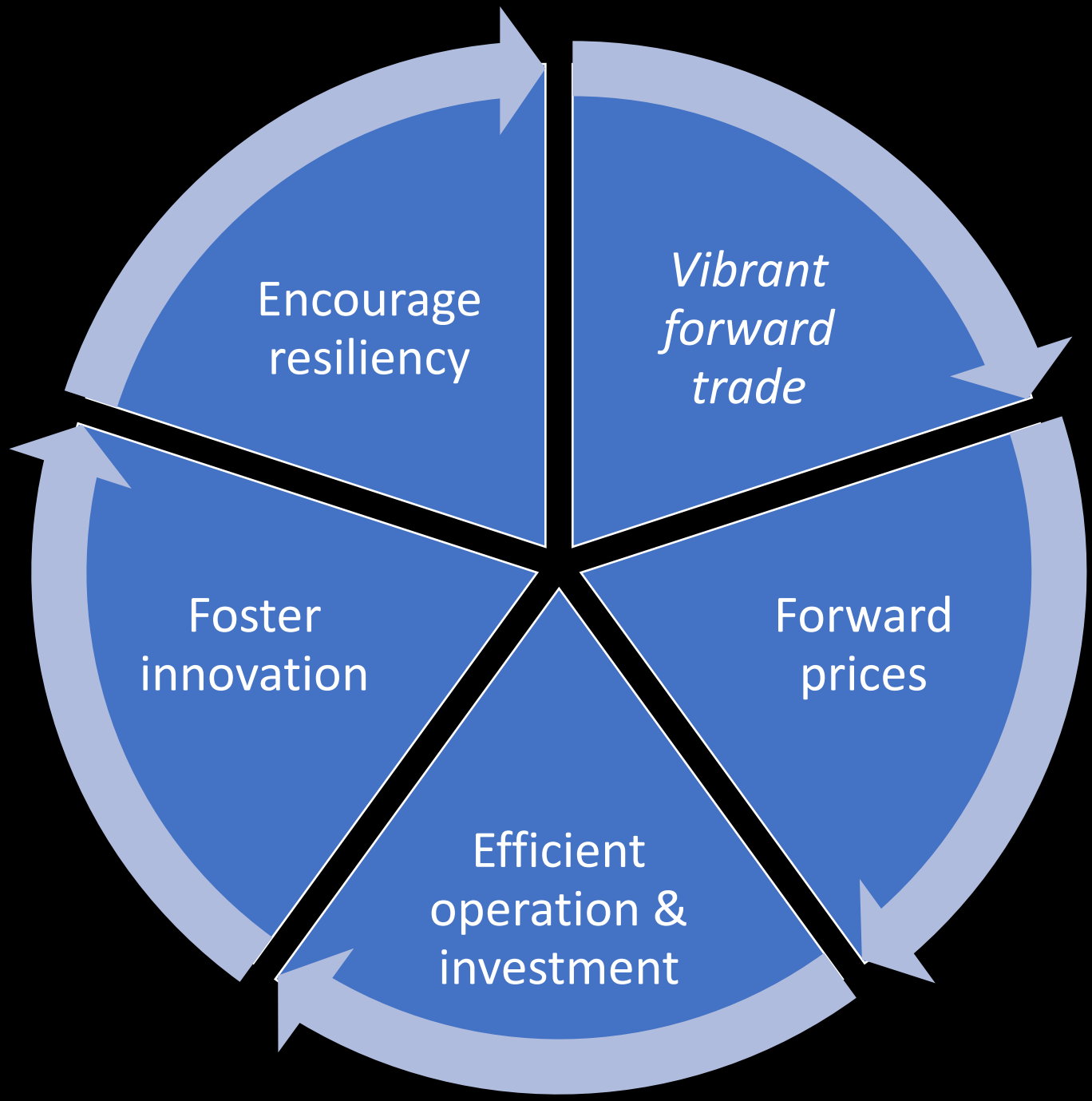
Trading platform for forward and spot global communications

Merger remedy or license condition for mobile communications to foster wholesale competition (merged entity sells ≥ 15% in open access market)

Efficient and transparent forward and spot trade of spectrum input


Mexico City cell towers,
September 2017
Pachuca
Tulancingo
Cuautitlán
Nicolás Romero
Estado de
México
Ciudad de
México
Tlaxcala
Tlaxcala
Puebla
Cuernavaca
Puebla
Morelos


Tuesday 2017-09-12
LTE Average Site Resource Block Utilization Rate DL (%)
Utilization at each cell tower
Hour
Congestion is important to manage efficiently
Total Regional Utilization
DOWN_utilization
Average utilization is low
Hour


Encourage resiliency
Vibrant forward trade
Forward prices
Efficient operation & investment
Foster innovation

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

- Flexibility to trade consistent with needs and capabilities

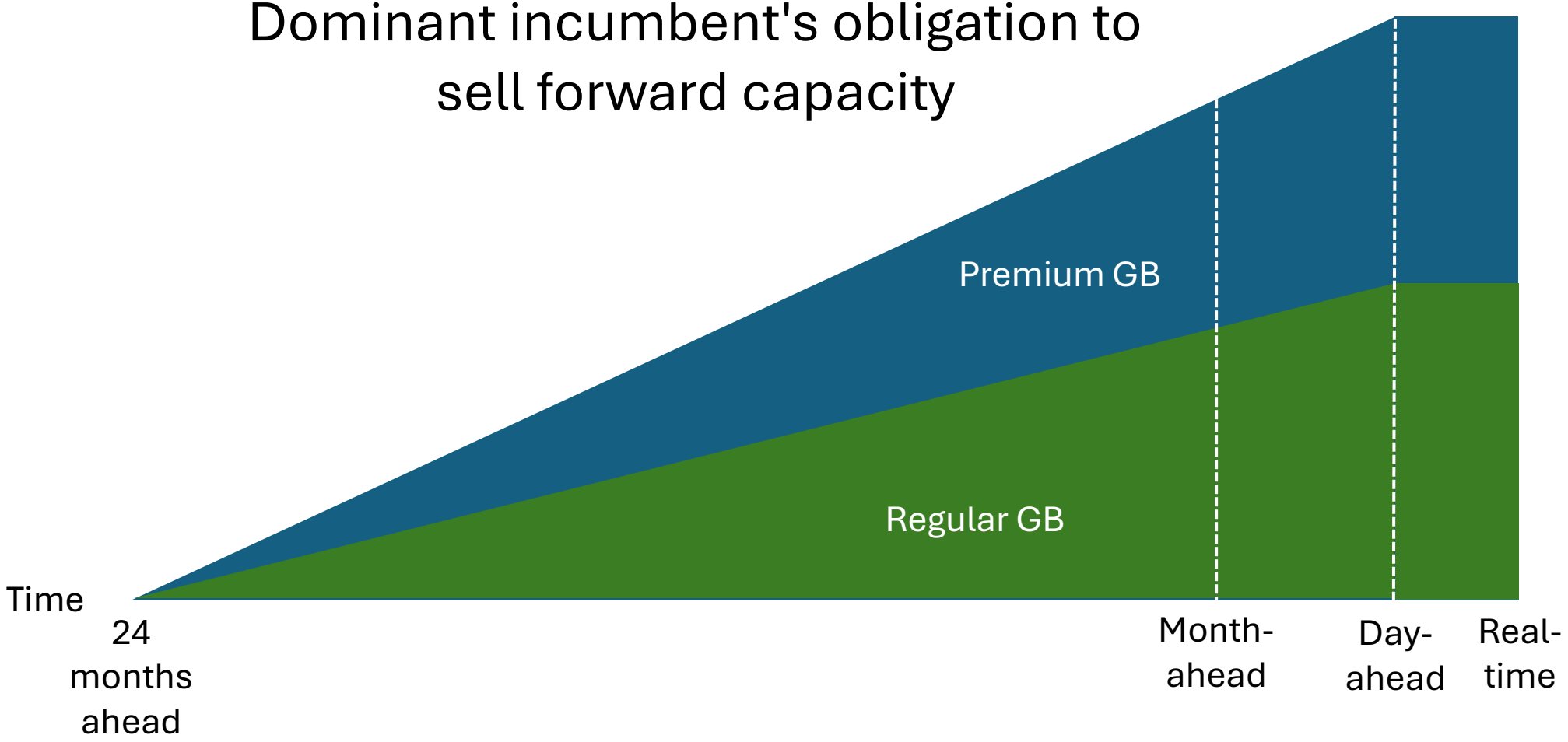
Gradual coordinated trade

- Reduces risk and market power
- Robust clearing prices

Persistent portfolio flow orders

- Easy participation with effective trade-to-target strategies

Dominant incumbent's obligation to sell forward capacity



Real-time market

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

Forward market

- Voluntary market except for modest obligation on large MNOs
- Derivative of real-time communications (hourly GB)
- Yearly forward communications (2 to 1 year ahead)
  - Hourly, premium/regular, weekday or weekend, regions
- Monthly forward communications (12 to 1 month ahead)
  - Hourly, premium/regular, weekday or weekend, regions
- Hourly forward communications (30 to 1 day ahead)
  - Hourly, 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

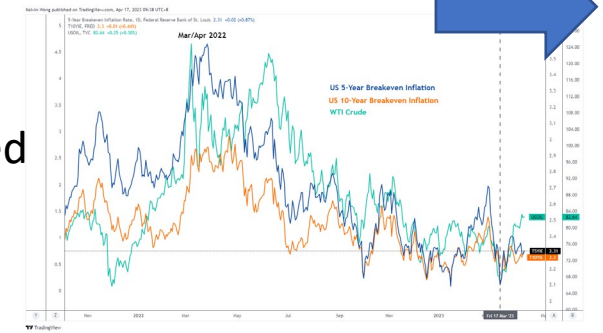
Inputs

Risk preference

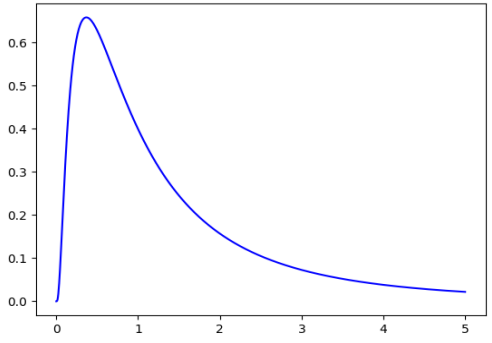
Cost of Capital

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

Anticipated prices



Distribution of hourly net demand

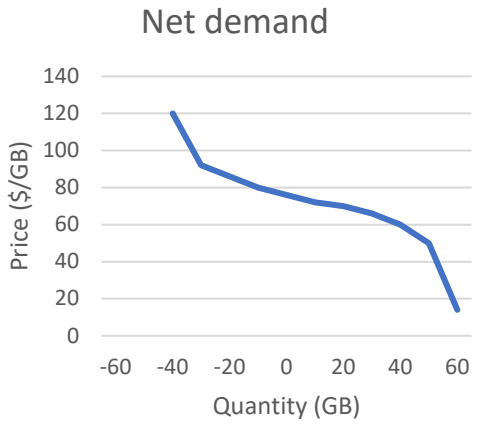


Trade-to-target strategy

Speed of trade

Price arbitrage

Piecewise linear net demand



Outputs

Prices

Hour	Year / Years Ahead: 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

Hour	Days Ahead: 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	0.006	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	11.299
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

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

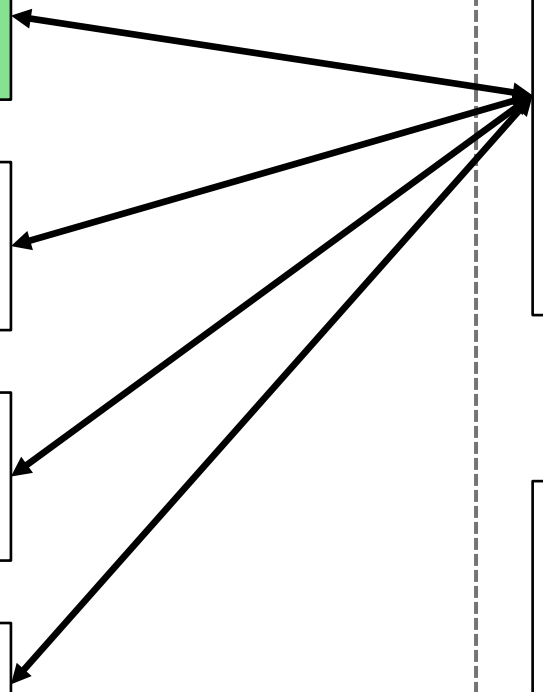
- 100,000 products, MWh by time and location
- Houston, 4pm, weekday, July 2027

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

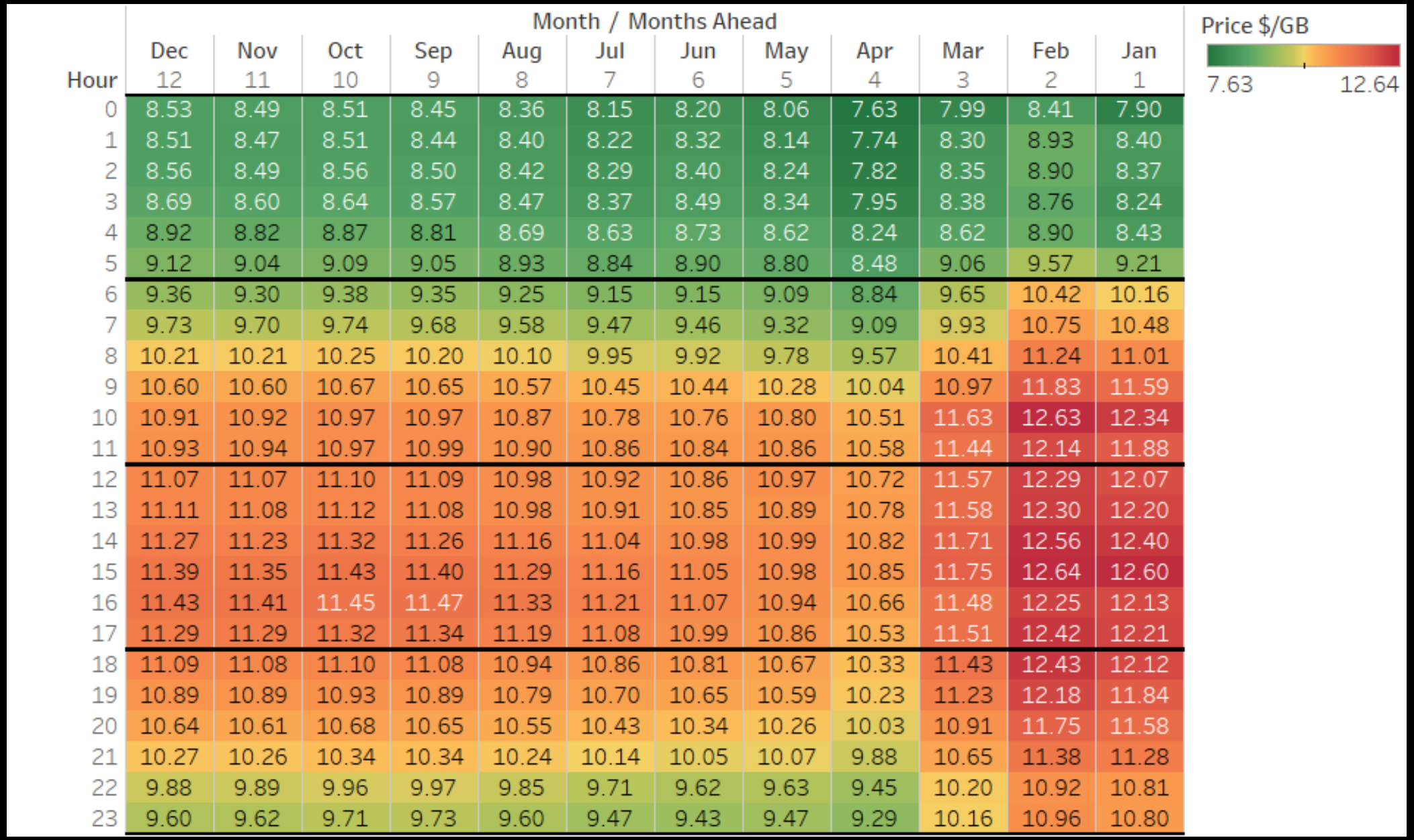
Forward Market System

- 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**

Monthly forward prices, New York, premium, weekday ($/GB)
12 to 1 month ahead



Month / Months Ahead

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

Price $/GB

7.63 12.64

Hourly forward prices, New York, premium, weekday ($/GB), 30 to 0 days ahead (odd shown)

Hour	Days Ahead 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

Price $/GB

2.26 11.53

Hourly and weekend effects dominate