Gradual and Flexible Procurement
A Note on Germany’s Power Station Strategy

Peter Cramton and Axel Ockenfels
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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, lumpiness)
    • For the long run, an efficient, reliability, and resilience electricity market
    • For the near term, a lower-cost, forward-looking procurement of immediate needs
Key insights

• Procure 10 GW of hydrogen-ready generation with best-practice methods
• Use prices to encourage efficient operation and investment of critical infrastructure as we transition to net-zero
• Address market failures and immediate needs with a consistent and proven approach that is simple, responsive, and sustainable
  • Incomplete markets: allow products to be defined with any desired time and location granularity (e.g., Bonn energy, weekday, 8-9am, February 2029)
  • Market power: allow generators to sell (or buy) forward products gradually with persistent piecewise-linear supply curves (e.g. auctions every hour)
  • Uncertainty: Gradual trade of forward products allows participants to follow simple trade-to-target strategies that respond as uncertainties are resolved
  • Regulator's commitment to purchase coordinates trade
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...)

- SO/PE independent boards
  - Approves market rules to send to AA

- System operator/power exchange
  - Develops & implements market rules

- Technical advisory committee
  - Helps develop market rules

- Independent market monitor
  - Analyzes market, identifies problems
Factors to consider in electricity market design

• Measure real-time use and encourage competitive prices
  \[ \text{price} = \text{marginal social cost} = \text{marginal social value} \rightarrow \text{max social welfare} \]

• Complete market with time and location derivative forward products
  \text{efficient performance; deviations settled at real-time prices}
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)

Yearly cost varies more by market than node!

Source: ReWEP tool, Berkeley Labs
Product design

Financial energy option

- Obligation to deliver energy when day-ahead price is above strike price of about 1000 euros

Physically backed

- Hydrogen-ready gas units to be converted on a future date specified in 2032

Hydrogen price risk borne by the government

- Supplier receives **green hydrogen price – natural gas price – carbon price**
Traditional best-practice procurement

- Uniform-price auction better than pay-as-bid
  - All are paid the clearing price
  - Less strategic behavior, more truthful bidding, improved efficiency
  - More competitive market structure, market power is self-correcting
  - Easier participation and improved privacy, more competitive
- Sequence of smaller auctions is better
  - Less market power, improved efficiency
  - Less risk, "don't put all your eggs in one basket"
  - Meaningful outcome discovery helps regulator and participants manage demand curve and offers to best achieve goals
- Slight advantage to descending clock if few auctions
  - Outcome discovery helps bidders manage bids as market information is revealed
  - But advantage is reduced or vanishes if many auctions
- Easy prequalification
- Regulator specifies reserve price and downward-sloping demand
- Aggregate Q and P at end of round or auction revealed
## Market structure
(shares based on energy volume 2023)

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<td>Uniper</td>
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<td>Others</td>
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Source: Generation from BNetzA and company reports; Retail service provider from company reports.

*Procurement auction should be competitive*
Can we do better?

✓ Procure 10 GW of hydrogen-ready generation with best-practice methods

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

  • Address market failures and immediate needs with a consistent and proven approach that is simple, responsive, and sustainable
    • Incomplete markets: allow products to be defined with any desired time and location granularity (e.g., German energy, weekday, 8-9am, February 2029)
    • Market power: allow generators to sell (or buy) forward products gradually with persistent piecewise-linear supply curves (e.g. auctions every hour)
    • Uncertainty: Gradual trade of forward products allows participants to follow simple trade-to-target strategies that respond as uncertainties are resolved
    • Regulator's commitment to purchase coordinates trade
Yes, with a few adjustments

• Instead of 4 auctions, conduct many much smaller auctions
  • Same motivation as moving from 1 to 4
    • Less market power
    • More outcome discovery
    • Greater flexibility to buy and sell what is needed and minimizes risk
  • Example: auction every hour

• Complete the market by expanding the products in time and type
  • Energy option
  • Forward energy
  • Emission allowances (RECs in US)

• Let participants buy and sell what they want subject to coordination led by demand curve specification
  • Government procures 10GW hydrogen-ready after 4-year purchase period
Price depends largely on the gas price and net load = (load – renewable production)

Buyer's needs vary by hour, season, and circumstance
Forward energy = energy in an hour by month and type of day, includes physical hydrogen-ready nameplate newbuild milestones (12-1pm, weekday, January 2028)

Energy option = same as forward energy but with a high strike price (e.g., €1000)

All products are derivatives of day-ahead German energy

Products defined by delivery location (Germany), allowing for greater locational granularity in the future

Split between energy option and forward energy depends on time to day-ahead: more energy if nearer day-ahead
Forward energy = energy in an hour by month and type of day, includes physical hydrogen-ready nameplate newbuild milestones (12-1pm, weekday, December 2031)

Energy option = same as forward energy but with a high strike price (e.g., €1000)

All products are derivatives of day-ahead German energy

Products defined by delivery location (Germany), allowing for greater locational granularity in the future

Split between energy option and forward energy depends on time to day-ahead: more energy if nearer day-ahead
A Forward Energy Market to Improve Resiliency
Target Position Relative to Anticipated Real-Time Demand by Time Ahead

- Forward Reserve
- Energy Option
- Forward Energy
- Forward Energy + REC

+1 Day  +30 Days  +48 Months
Greater need for innovation and flexibility $\Rightarrow$ efficient price signals increasingly important

- Real-time market: security constrained economic dispatch (physical market)
  - Network and resources fully modeled
  - Co-optimize energy and reserves to maximize as-bid social welfare subject to network and resource constraints
  - High shortage price (e.g., $5,000/MWh during reserve shortage) to provide sufficient incentives for operation and investment
  - Nodal pricing to reflect scarcity at time and location
    - Pretending no congestion does not work
      - German redispatch cost of €1.5 billion in 2018; wrong price signal; poor location incentives

- Day-ahead (posted 4pm) and intraday (every hour until real-time) market
  - Financial market with physical report of plans
  - Network and resources modeled for unit commitment (mixed-integer non-convex optimization)
  - Co-optimize energy and reserves to maximize as-bid social welfare subject to network and resource constraints
  - Intraday: re-optimize every hour to reflect current system state
    - Rolling intraday settlement
  - Nodal pricing to reflect scarcity at time and location

- Forward energy market (48 months to 1 day ahead)
  - Purely financial market
  - Network and resources are not modeled
  - Product is delivered energy in some future hour (MWh)
  - Delivery point may be an aggregation of withdrawal nodes into a load zone (as in done today in all markets)
  - For risk management, operation, and investment (resource adequacy)
Vibrant forward trade

Foster innovation

Efficient operation & investment

Encourage resiliency

Forward prices
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
- Anticipated prices
- Distribution of hourly net demand

**Trade-to-target strategy**

- Speed of trade
- Price arbitrage
- Piecewise linear net demand

**Outputs**

- Prices
- Flow trade rate
- Balanced position

Arbitrage

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.
Spot Market

Data
- Hourly load and renewable generation
- Resource structure
- Cost function parameters by technology

Profit functions
- $\pi^{LSE} = \pi p - pq - (f - p)h - (t - v)z$
- $\pi^{GEN} = pq - C(q) - (f - p)h - (t - v)z$
  - $p$: retail price; $q$: spot price; $q$: spot quantity; $C(q)$: generation cost; $f$: forward price; $h$: forward quantity; $t$: option strike price; $v$: put option value; $z$: put option quantity

Product specifications
- Time granularity (monthly and daily by hour)
- Option type and strike price
- Renewable energy certificates (RECs)

Competitive spot market equilibrium
- Hourly spot market equilibrium prices
- Hourly equilibrium quantities and profits for each market participant

Forward Energy Market

Distribution of spot market quantities
- Joint distribution of spot prices, and individual quantities and profits

Preference specification
- Constant absolute risk aversion utility function
  $$U(\pi_n) = \sum_{n=1}^{N} -e^{-\lambda \pi_n} \left(1 + i\right)^n$$
  - Risk coefficient $\lambda$
  - Discount rate $i$ captures cost of capital

Flow trade rate
- Exogeneous parameter

Administrative purchase obligation

Optimal portfolio of forward contracts and options
- Maximize individual expected utilities via numerical optimization
  $$\argmax_{h_n, z_n} E[U(\pi_n)]$$

Piecewise linear demand curves and trade-to-target strategy
- Optimal portfolio is a function of forward prices and option premia

Forward energy market equilibrium using the flow trading algorithm
- Equilibrium forward prices and option premia on a granular level
- Forward and option quantities for each market participant

Multi-year simulation of market outcomes in the ERCOT market
- Simulate individual profits in the forward energy and spot market for LSEs and generators with varying risk preferences and technologies
An example:
2 products, 3 participants

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[Interactive Demo]
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

Other Applications
- Bonds, equities, or other commodities
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

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Optimization Engine

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

Net demand by order graph

- Bar graph showing net demand by order
  - Legend: [Net demand by order graph legend]
Monthly forward prices, Houston, weekday ($/MWh)
48 to 1 month ahead (48 × 24 = 1152 monthly products per load zone)

Prices are highest at 4pm in July (seasonal and hourly effects)
Flow trade rate (MW) of 4GW Load Serving Entity using straightforward strategy

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

cramton.umd.edu/electricity
• 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 energy + renewable energy certificate

Forward energy

Energy option

Forward reserve

Month-ahead

Day-ahead

Real-time

Time

120 months ahead

48 months ahead
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

Transparent forward prices updated hourly with ample liquidity
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

California 2000-2001: arid year, unhedged utilities
Northeast 2003: poor tree trimming, software bug
Texas February 2021: cold snap, electric heat, little gas
Europe 2022: Russia’s invasion of Ukraine, poor hedging

*Traditional resource adequacy eliminates none of these events!*
Resilience

Before
• Prepare

During
• Alleviate

Learn
• Observe
• Improve

After
• Recover
“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

Elasticity coefficient vs Time difference from price shock

1% price increase reduces demand by .26%

Emmanuele Bobbio, Simon Brandkamp, Stephanie Chan, Peter Cramton, David Malec, and Lucy Yu,
Low-carbon technologies increase price response

EV ownership increases price response by a factor of three

Price-responsive demand improves resiliency

A normal weekday at 8 am on a cold Texas day in February

What if 44% of Texans responded to the electricity price in crisis?

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
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

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

\[ V_i(x) = p^H_i x - \frac{p^H_i - p^L_i}{2q_i} x^2 \] (6)

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

\[
\max_x \sum_{i=1}^I V_i(x_i) \quad \text{subject to} \quad \begin{cases} \sum_{i=0}^I x_i \ w_i = 0 \quad \text{(market clearing)} \\ 0 \leq x_i \leq q_i \text{ for all } i \quad \text{(order execution rate)} \end{cases}
\] (7)

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

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

\[ g^* = V(x^*). \] (12)

**Corollary 1 Uniqueness of quantities and prices.** Prices and quantities are unique with the closest-to-prior-prices rule.
Can we find unique prices and quantities quickly?

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

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<th>Price $/MWh</th>
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Summer hourly price impacts are large
Intraday Prices, Houston, 26 August 2023 ($/MWh), odd hours 
(24 × 7 + 23 + 22 + ... + 1 = 444 new prices)

Rolling settlement especially important on summer net peak days!
Detailed market simulation
(to be done)

• Backcast for ERCOT, 2011-2023
  • Forecast load and renewable production (net load)
  • Forecast day-ahead price on forward basis
  • Develop parameterized trade-to-target strategies for natural buyers and sellers
    • LSEs have target positions increasing from 0% to 100% from 48 months to day-ahead, including portfolio of forward energy + energy options
    • LSEs deviate from target positions based on slope parameter (net demand)
    • Generators have target positions increasing from 0% to 100% from 48 months to day-ahead
    • Generators deviate from target positions based on slope parameter (net demand)
  • Optimize parameters to determine equilibrium (approximate best responses)
  • Evaluate risk relative to unhedged positions except day-ahead market hedges real-time price risk
  • Develop collateral requirements that assure resiliency

• Forecast same market but with simulated spot market using estimated resource structure
  • Midway through the energy transition (2040?)
  • At the end of the energy transition (2060?)
Computation at secure umd.edu facility

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