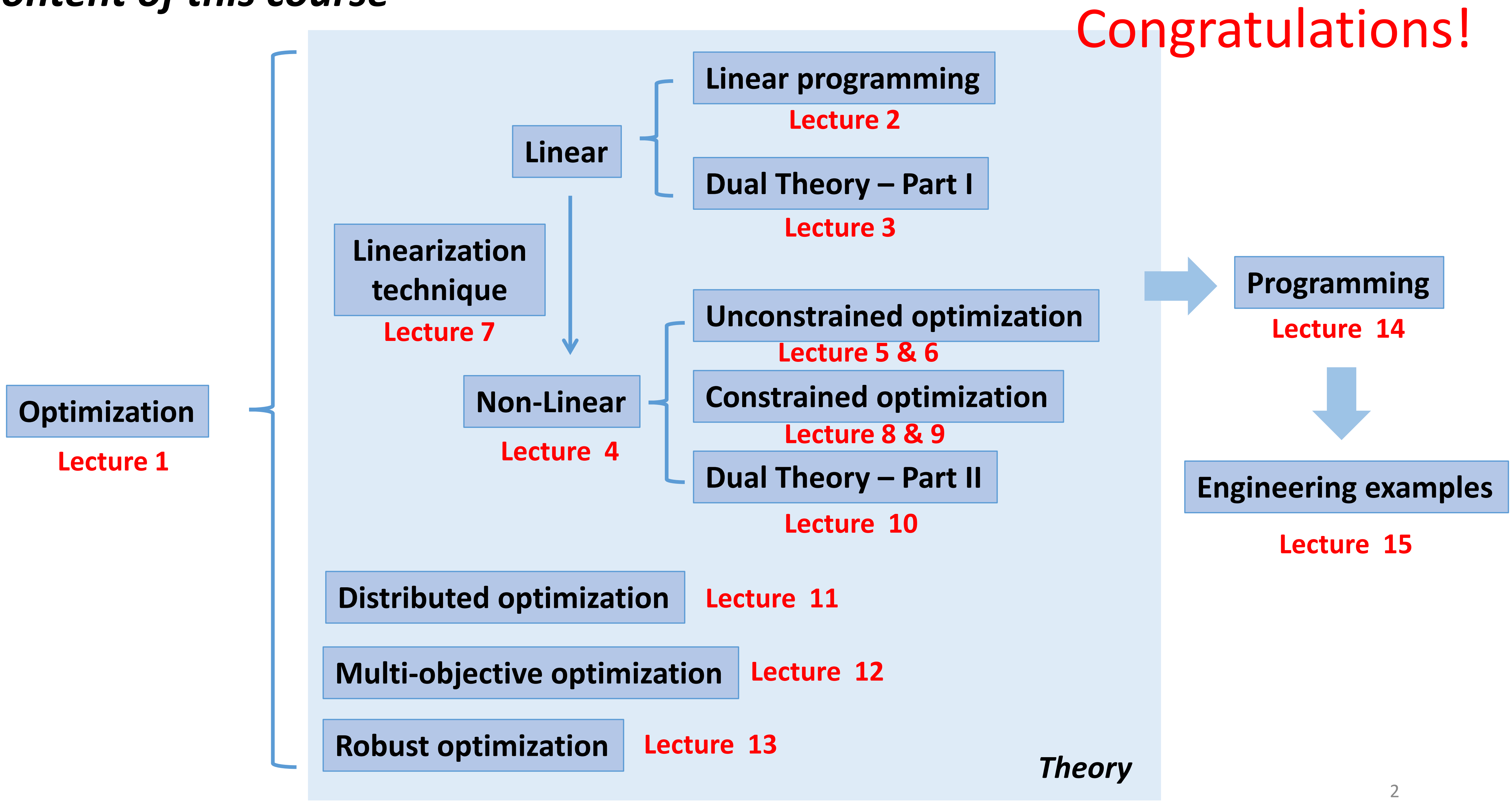
MAEG4070 Engineering Optimization

Lecture 15 Engineering Example
Electricity Market

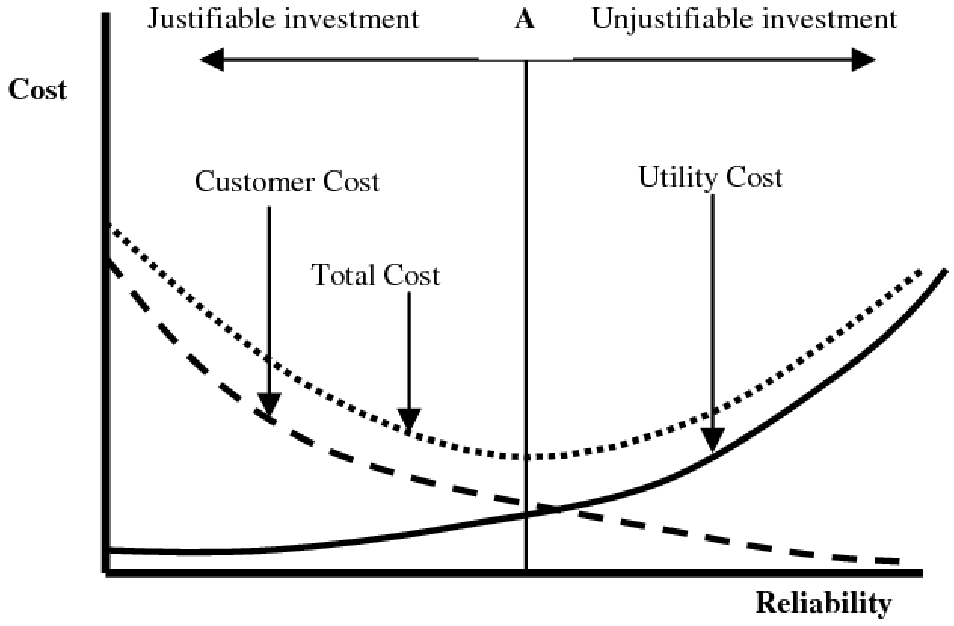
Yue Chen
MAE, CUHK
email: yuechen@mae.cuhk.edu.hk
Nov 23, 2022

Content of this course



Economic Environment of Power System

Total Welfare Maximization



Utility's investment

v.s.

Quality of electricity

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Economic Environment of Power System

Utility's investment & Quality of electricity

Long term provisions:

- 2-15 years, or even more
- Examples:
  - ✓ Type, capacity, timing of new generations or lines
  - ✓ Fuel contracts
- Earnings over the whole service life, uncertainty is a determining factor

Medium-term planning:

- 1-3 years
- Example:
  - Facility maintenance management: steam plants (interrupted 20 days/a year), nuclear plants (every 18 months to recharge the fuel)
  - hydroelectric management

Rough approximation of technical behaviors of the system is enough

Economic Environment of Power System

Utility's investment & Quality of electricity

Short-term specifications:

- Weekly scale, a few days up to a month
- Examples:
  - ✓ Generating unit connection: steam power plants (8-10h), Gas plants (1-2h or a few minutes), hydroelectric plants (zero lead time)
  - ✓ operating capacity in reserve

Real-time operation:

- Based essentially on the safety criteria rather than the financial consideration
- Examples:
  - ✓ Economic dispatching
  - ✓ Frequency regulation
  - ✓ Response to emergency situations

System Details are extremely relevant

History of electricity markets

1980 — introduction of energy market concepts and privatization to electric power systems, Chile, influenced by “Chicago Boys”

1988 — A leap in electricity pricing theory, book “Spot Pricing of Electricity”, four profs at MIT and Boston University

1990 — The UK (under Margaret Thatcher) privatized the UK electricity supply industry, followed by other Commonwealth countries

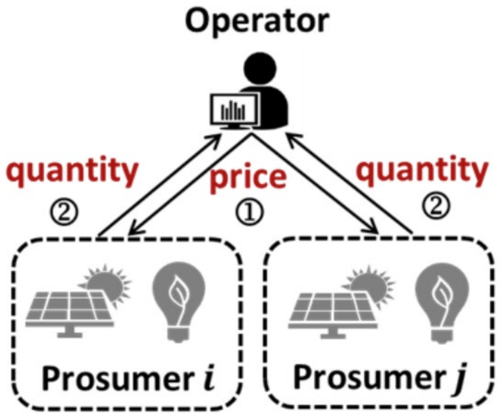
1996 — Deregulation in California, ISOs and RTOs were established.

2000-2001 — California electricity crisis: wholesale market price ↑, retail price is bounded, lack of supply, blackouts,…

From regulated to deregulated

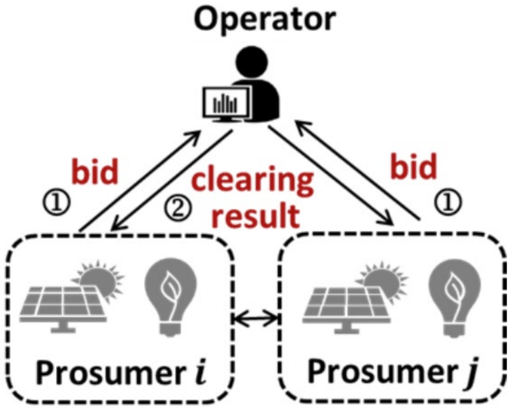
Regulated:

- Prices (energy, transmission, distribution) are all determined by the operator
- Vertically centralized structure
- Cannot choose supplier
- Not motivating enough, needs local information



Deregulated:

- Prices are determined by the market
- Horizontal peer-to-peer structure
- Competition among producers, prosumers,…
- More flexible, possible market power → market failure



Reference: Gómez-Expósito, Antonio, Antonio J. Conejo, and Claudio Cañizares, eds. Electric energy systems: analysis and operation. CRC press, 2018.

Participants of the electricity market

Regulator

- Responsible for the market design and its specific rules
- Monitors the market to spot misbehaviors

Market Operator

- Organizes and operates the marketplace
- Definitions of bid products/forms, maintenance of the trading platform, etc.

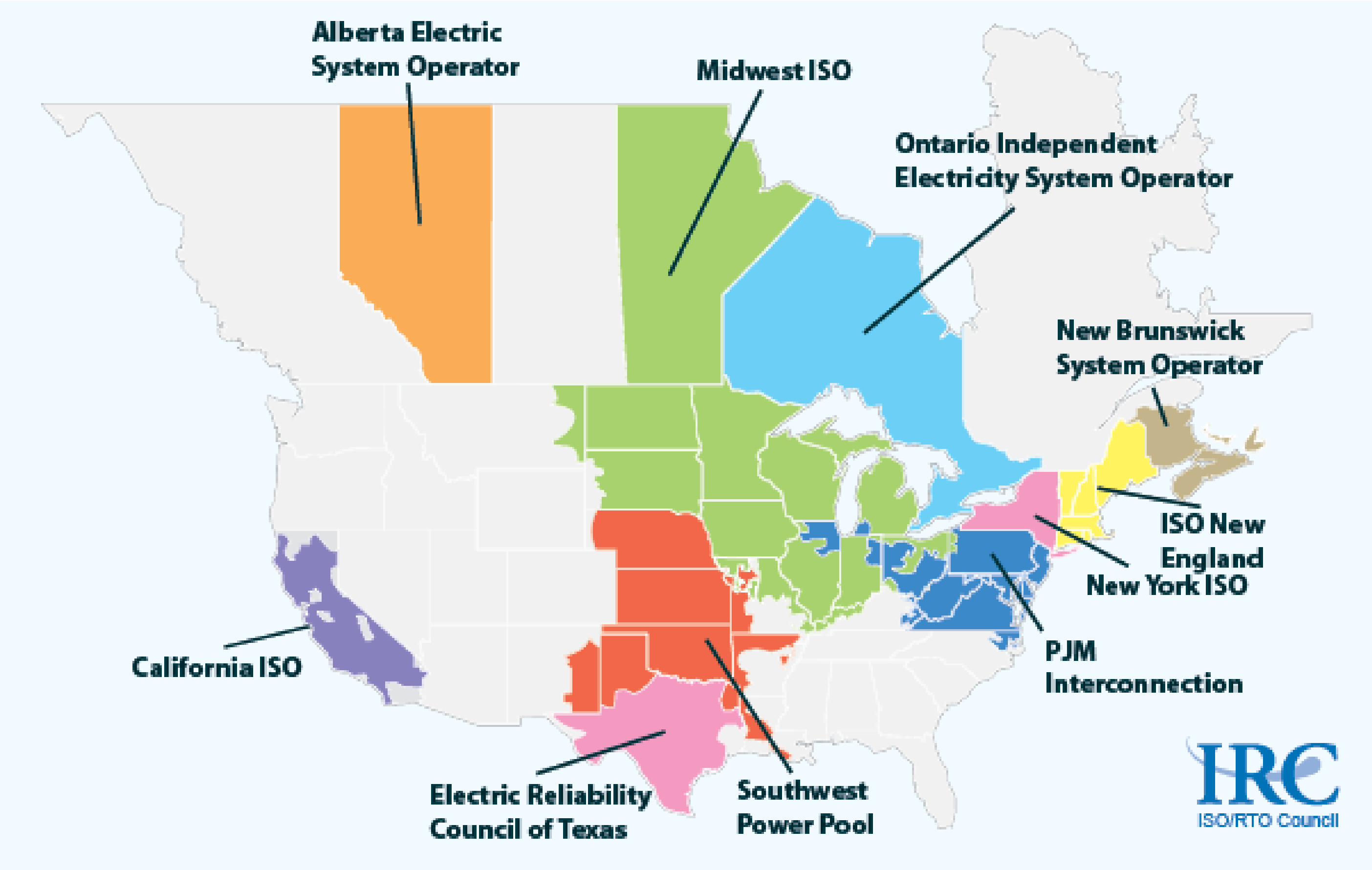
Regional transmission organization (RTO)

- Coordinates, controls, and monitors a multi-state electric grid
- Initiated by FERC Order No. 2000, issued on December 20, 1999

Independent System Operator (ISO)

- Coordinates, controls, and monitors operation within a single state

Participants of the electricity market



RTOs typically perform the same functions as ISOs but cover a larger geographic area

Pictures from Google image

Participants of the electricity market

Producers

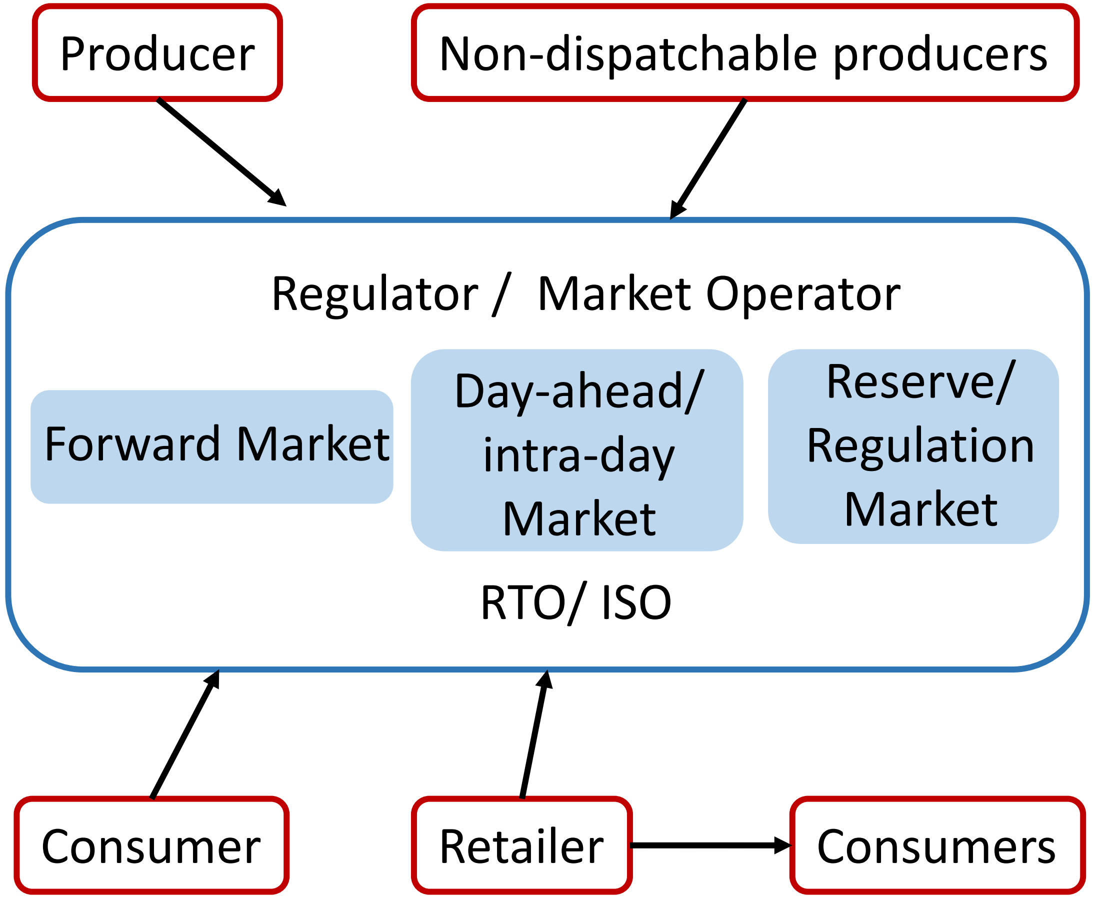
- Generating companies, own production assets, whose generation is offered through the electricity market

Retailers

- Buys electricity from the wholesale market and then sells to end-consumers

Consumers:

- Those eventually use the electricity for any purpose
- Large consumers can buy directly from the producers



Why electricity is special?

Electricity differs from other commodity:

1. **Real-time power balance**
   - ✓ Cannot be stored in large-scale
   - ✓ Batteries? price, performance, and inconvenience make this impractical

2. **Performed on a power network**
   - ✓ Pathways cannot be chosen
   - ✓ Determined by Kirchhoff's laws
   - ✓ Any variation in one transmission facility may influence others

Different types of markets

Energy per time unit

Power

Measured in watts (W)

- **Reserve market**
- **Regulation market**

Supports the power system operation

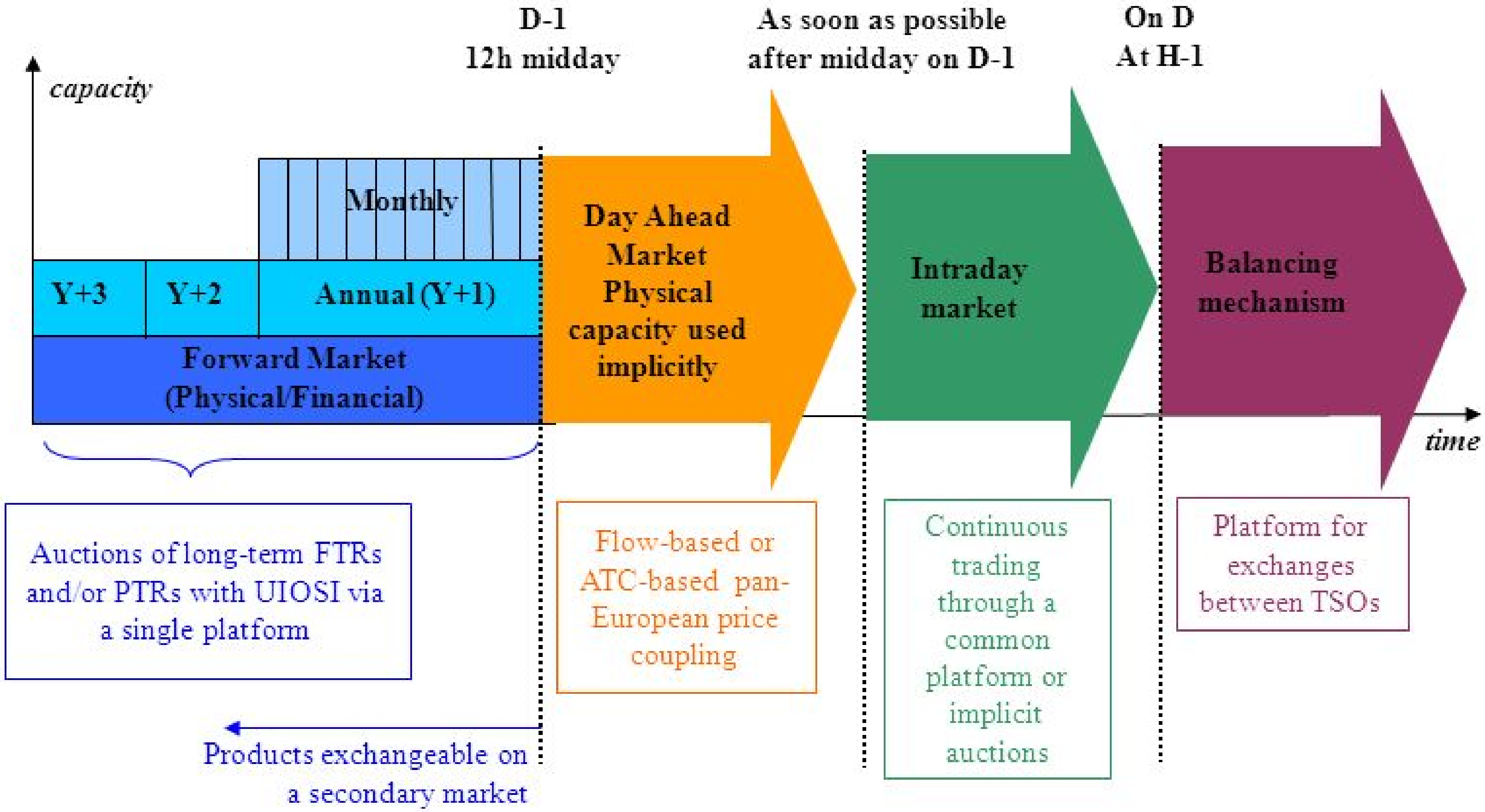
Energy

Measured in Wh

- **Forward markets**
- **Day-ahead markets**
- **Adjustment (intra-day) markets**
- **Balancing market**

Optimal scheduling and settlement of energy exchange

Different types of markets



Pictures from Google image

Roles of different markets

Forward markets

- Financial contracts with time horizons up to six years
- MW quantity, delivery period, fixed price per MWh

Day-ahead (or spot) markets

- Everyday matching of supply and demand
- Cleared by LP, MILP, Stochastic programming, Robust optimization

Adjustment (or intra-day) markets

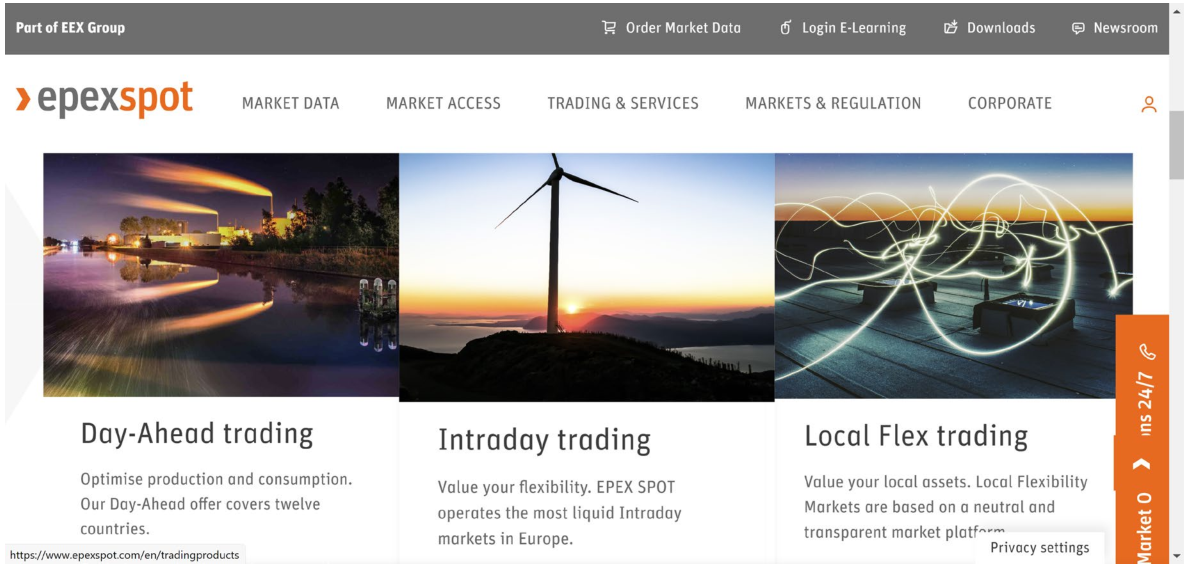
- Correct original schedules, between day-ahead and balancing markets
- Just like the day-ahead market but in a small scale

Balancing markets

- for operator to ensure power balance
- just minutes prior to energy delivery

Examples of electricity markets

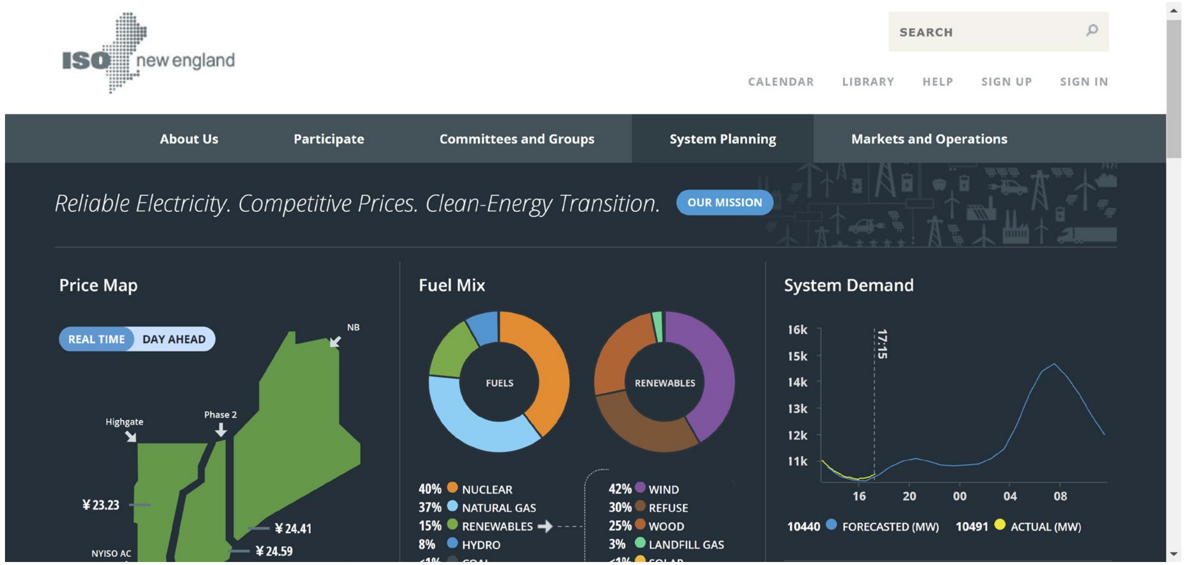
EEX: Germany spot and Futures
https://www.eex.com/en/



OMIE: Iberian Peninsula Spot
https://www.omie.es/

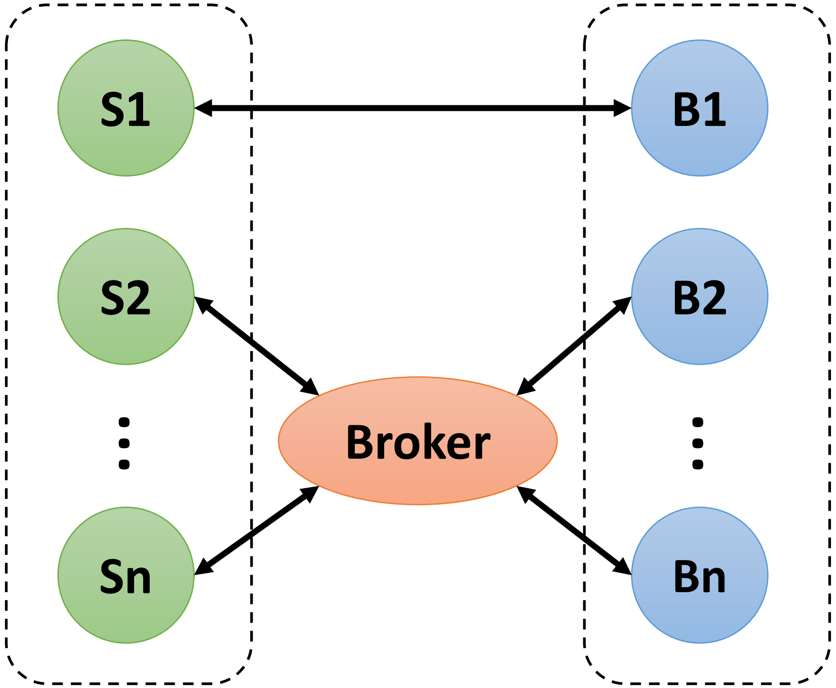
Examples of electricity markets

ISO New England Spot
https://www.iso-ne.com/



NordPool: Scandinavia Spot
https://www.nordpoolgroup.com/

Bilateral Contracts



Bilateral contracts

- Direct exchange between a buyer and a seller
- In a decentralized manner
- Most likely a broker is involved

Procedure

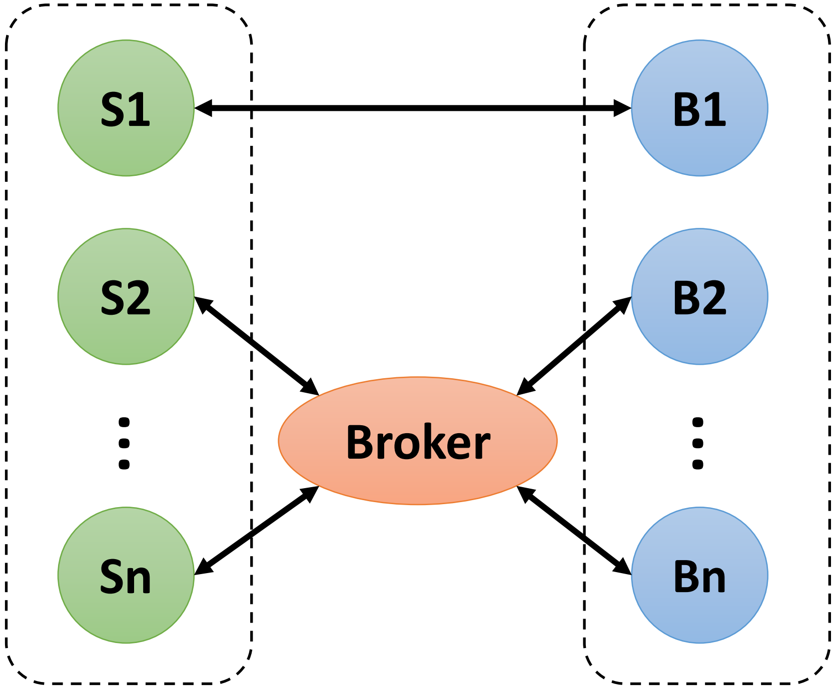
- First, both the buyers and sellers submit offers
- When a match is found
- Approved by the operator
- Removed from the list

Key Challenge

- Hard to find the optimal match
- Ensure the feasibility of the outcome

Reference: Morstyn T, Teytelboym A, McCulloch M D. Bilateral contract networks for peer-to-peer energy trading[J]. IEEE Transactions on Smart Grid, 2018, 10(2): 2026-2035.

Bilateral Contracts



Customized long-term contracts

- Flexible (can negotiate whatever you want)
- High transactions costs
- Large amount of energy, over a long time

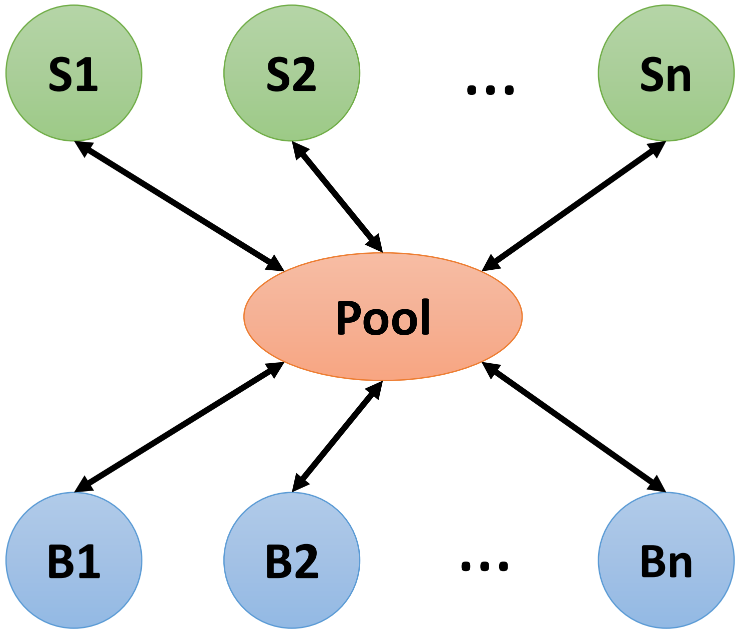
Over the counter (OTC) trading

- Standard contracts
- Low transactions costs
- Smaller amount of energy, over a short time

Electronic trading

- Electronic platform supported
- Nearly zero transactions cost
- Very fast, “until the last second”

Pool markets / auctions



Procedure

- All sellers and buyers bid at the same time
- Offers consist of quantity $\boldsymbol{P}$ and price $\boldsymbol{\lambda}$
- No one knows others' offers
- The market is cleared centrally

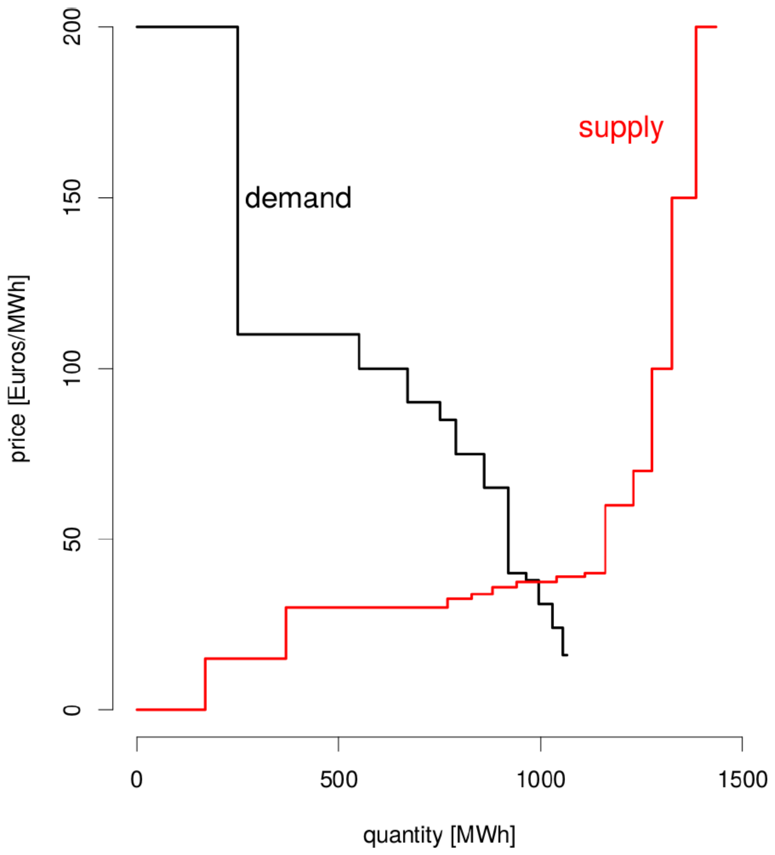
Sellers (N_G generators G_j)

- Maximum quantity P_j^G
- Price for offer λ_j^G

Buyers (N_D loads D_i)

- Maximum quantity P_i^D
- Price for offer λ_i^D

Pool markets / auctions



Sellers (N_G generators G_j)

- Maximum quantity P_j^G
- Price for offer λ_j^G

Buyers (N_D loads D_i)

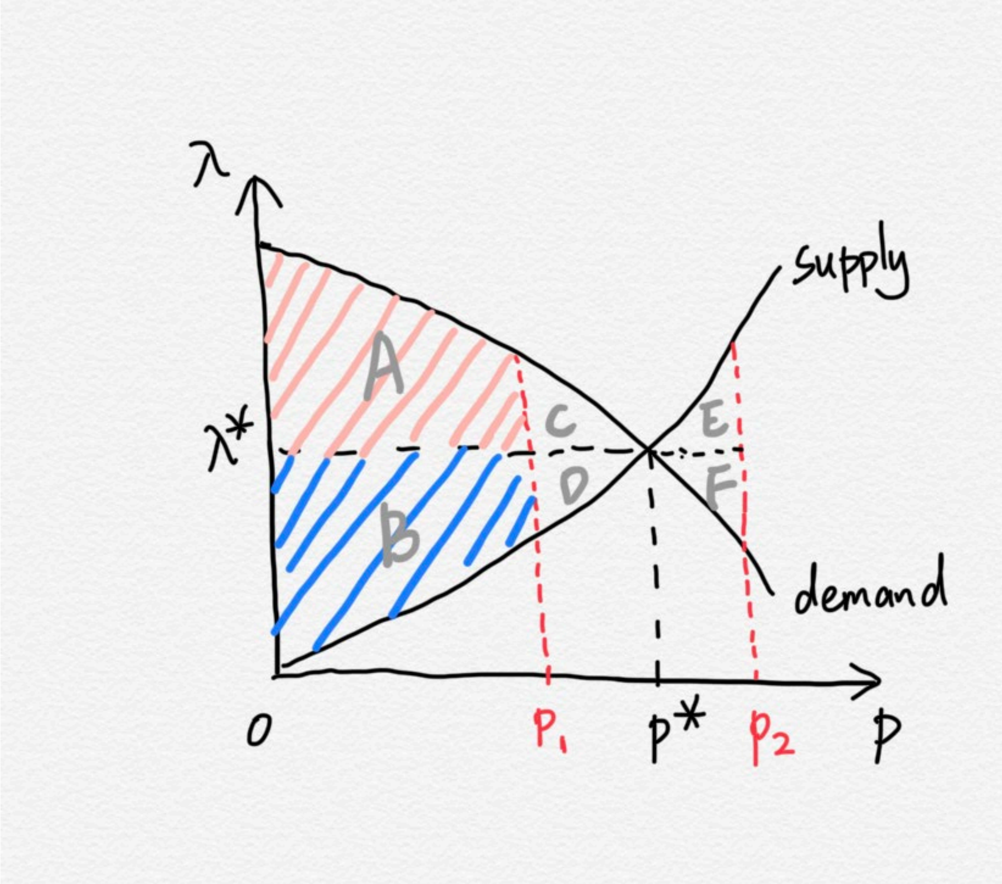
- Maximum quantity P_i^D
- Price for offer λ_i^D

Outcome

- Generation schedule $p^G = \left[p_j^G\right]^T, 0 \leq p_j^G \leq P_j^G$
- Consumption schedule $p^D = \left[p_i^D\right]^T, 0 \leq p_i^D \leq P_i^D$
- Total Welfare Maximization

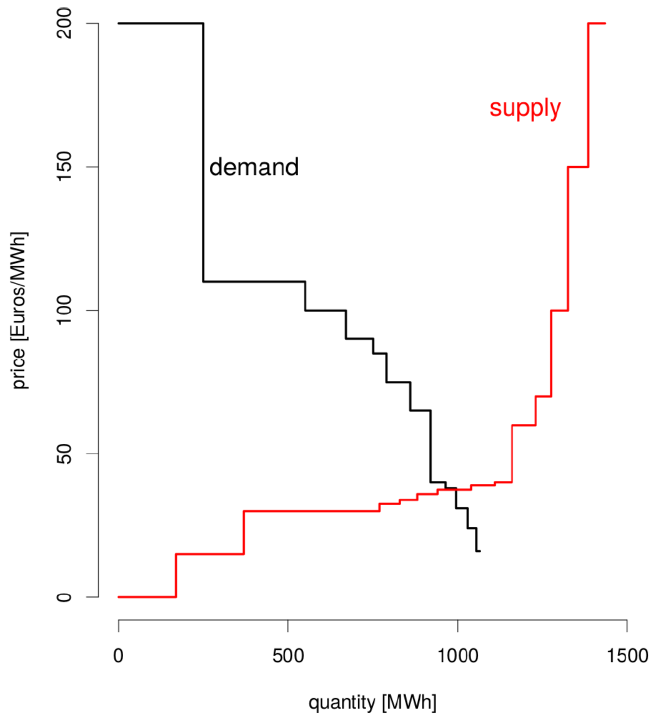
Reference: Morales J M, Conejo A J, Madsen H, et al. Integrating renewables in electricity markets: operational problems[M]. Springer Science & Business Media, 2013.

Pool markets / auctions



	p_1	p^*	p_2
Consumer surplus	A	A+C	A+C-F
Producer surplus	B	B+D	B+D-E
Total welfare	A+B	A+B+C+D	A+B+C+D-E-F

Market clearing optimization problem – without network



$$\max_{\{p_j^G\},\{p_i^D\}} \sum_{i=1}^{N_D} \lambda_i^D p_i^D - \sum_{j=1}^{N_G} \lambda_j^G p_j^G$$

$$\text{s.t.} \sum_{j=1}^{N_G} p_j^G - \sum_{i=1}^{N_D} p_i^D = 0 : \lambda^S \quad \text{Dual variable}$$

$$0 \leq p_i^D \leq P_i^D, \ \forall i = 1, \ldots, N_D$$

$$0 \leq p_j^G \leq P_j^G, \ \forall j = 1, \ldots, N_G$$

- Sellers/buyers which sell/buy (mostly $p_j^G = P_j^G, p_i^D = P_i^D$) and which don't ($p_j^G = 0, p_i^D = 0$)
- Linear programming
- Can be solved by Matlab, GAMS, Gurobi, etc
- Can directly output the dual variables

Market clearing optimization problem – pay as bid/uniform price

Lagrange:

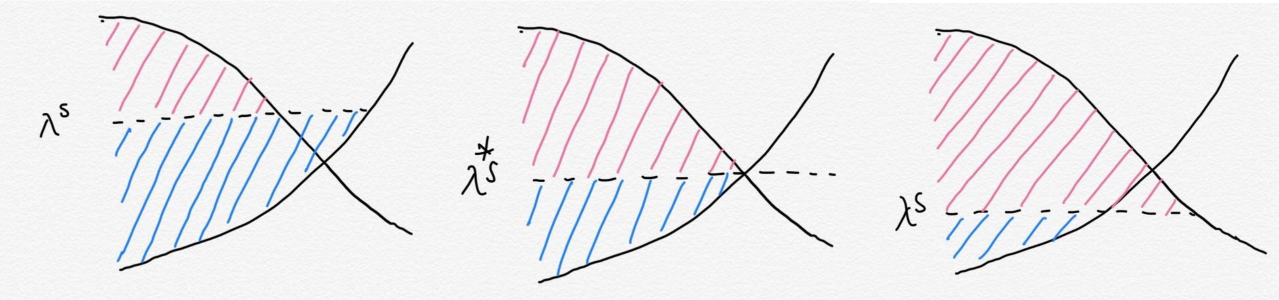
$D(\lambda^S)$

$$\min_{\lambda^s} \max_{\substack{p_i^D \in [0, P_i^D], \forall i \\ p_j^G \in [0, P_j^G], \forall j}} \sum_{i=1}^{N_D} (\lambda_i^D - \lambda^S) p_i^D + \sum_{j=1}^{N_G} (\lambda^S - \lambda_j^G) p_j^G$$

For a given λ^S, the maximizer is

$p_i^D = P_i^D$ if $\lambda_i^D \geq \lambda^S$; otherwise, $p_i^D = 0$

$p_j^G = P_j^G$ if $\lambda_j^G \leq \lambda^S$; otherwise, $p_j^G = 0$



Therefore, the $D(\lambda^S)$ can be shown in the figure, and is minimized at λ^{S*}.

Market clearing optimization problem – pay as bid/uniform price

Pay as bid

- Seller: $R_j^{DA,G} = \boldsymbol{\lambda_j^G} p_j^G$ (revenue)
- Buyer: $R_i^{DA,D} = \boldsymbol{\lambda_i^D} p_i^D$ (payment)

Uniform pricing

- Seller: $R_j^{DA,G} = \boldsymbol{\lambda^S} p_j^G$ (revenue)
- Buyer: $R_i^{DA,D} = \boldsymbol{\lambda^S} p_i^D$ (payment)

Comments:

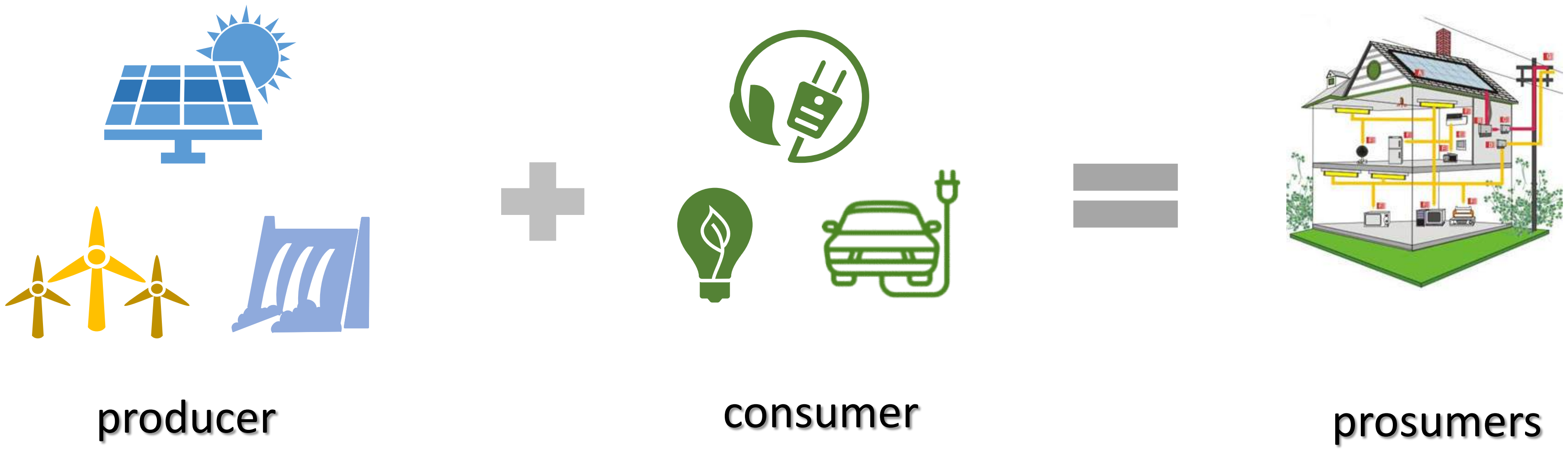
- Both approaches can guarantee individual rationality, $R_j^{DA,G} \geq \lambda_j^G p_j^G, R_i^{DA,D} \leq \lambda_i^D p_i^D$
- Both approaches can guarantee revenue adequacy, $\sum_i R_i^{DA,D} \geq \sum_j R_j^{DA,G}$
- Uniform pricing yields budget balance

Future Trends: supplier-centric → consumer-centric

Proliferation of DERs that are low-carbon

- 2003-2017 over 1076 MW distributed wind turbines
- 2004 to 2014 residential PV panels rise from 3,700 MW to 150,000 MW

Reduce the pressure on resource and environment



More flexibility & More unpredictable behavior

Future Trends: supplier-centric → consumer-centric

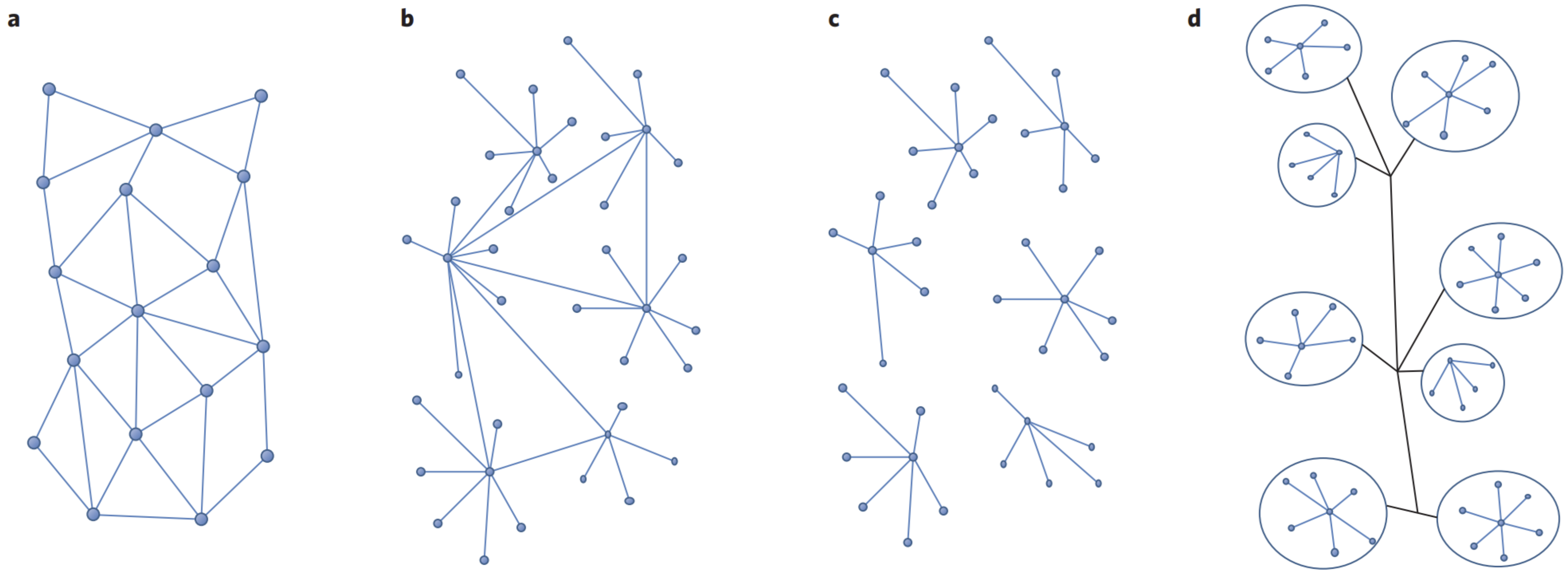
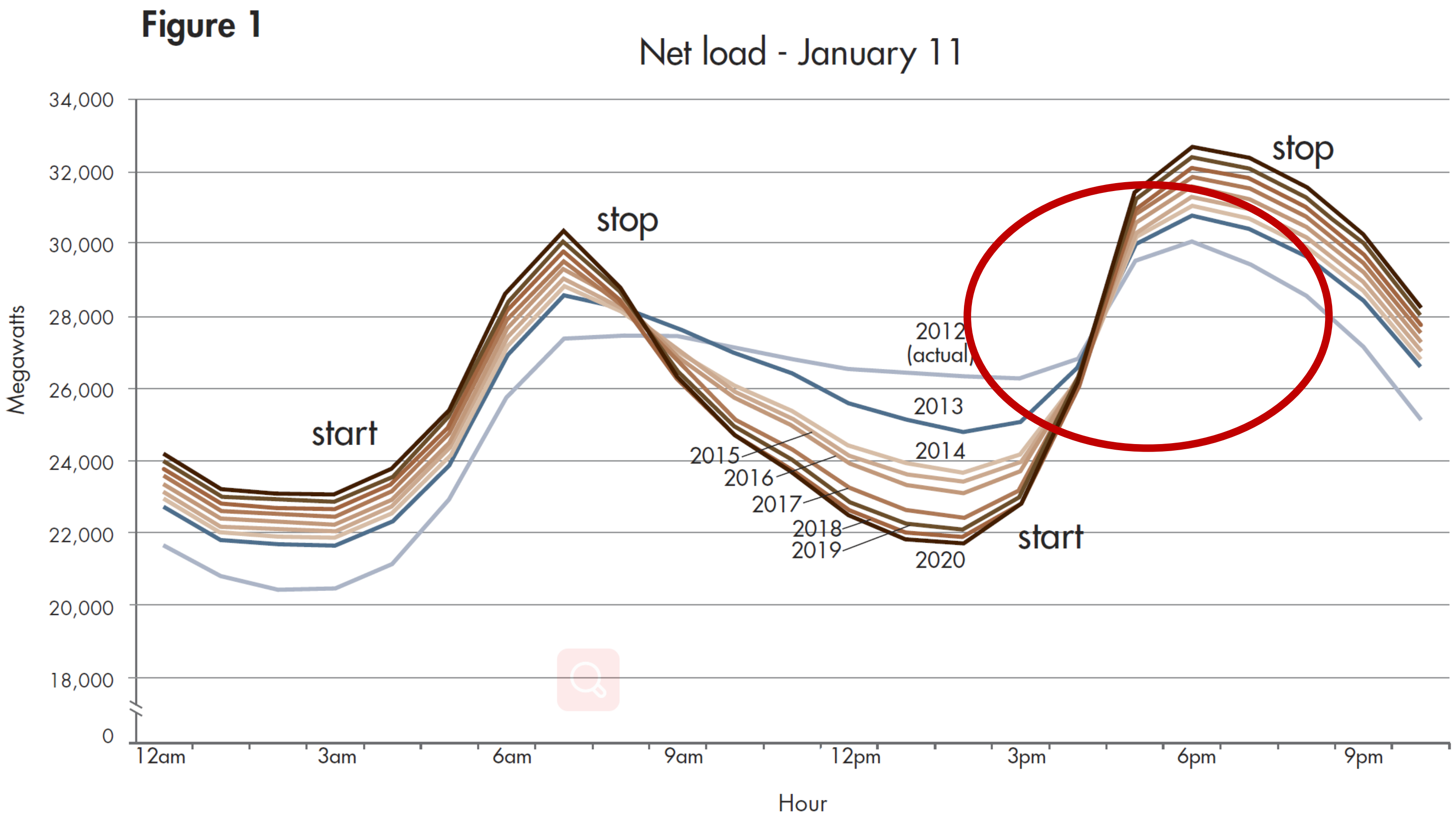


Figure 1 | Structural attributes of three prosumer markets. a, Peer-to-peer model, in which prosumers interconnect directly with each other, buying and selling energy services. **b**,**c**, More structured models involving prosumers connected to microgrids. These entail prosumer-to-interconnected microgrids, in which prosumers provide services to a microgrid that is connected to a larger grid (**b**), or prosumer-to-islanded microgrids, in which prosumers provide services to an independent, standalone microgrid (**c**). **d**, Organized prosumer group model, in which a group of prosumers pools resources or forms a virtual power plant. Dots represent prosuming agents; lines represent a transaction of prosuming service; circles represent an organized group of prosumers.

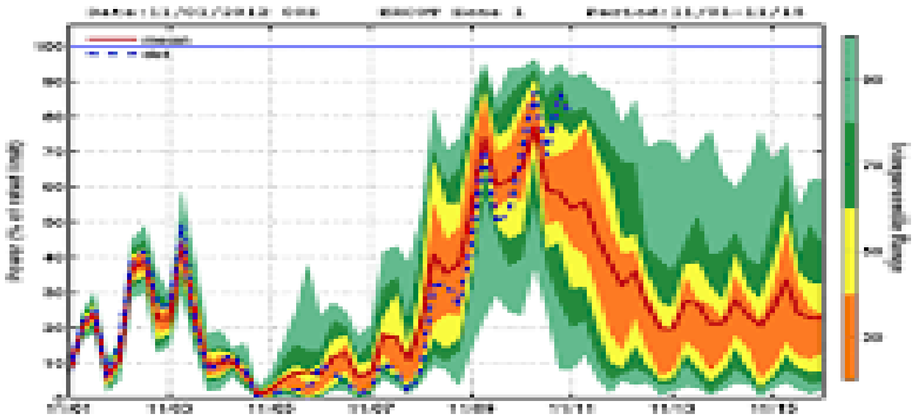
Reference: Parag Y, Sovacool B K. Electricity market design for the prosumer era[J]. Nature energy, 2016, 1(4): 1-6.

Future Trends: Integration of renewable energy

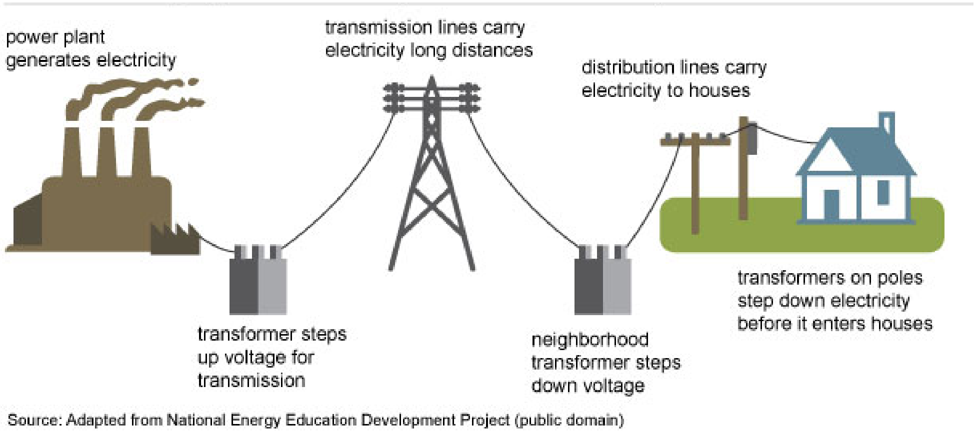


Reference: California ISO. What the duck curve tells us about managing a green grid. Available at: http://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf

Future Trends: Integration of renewable energy

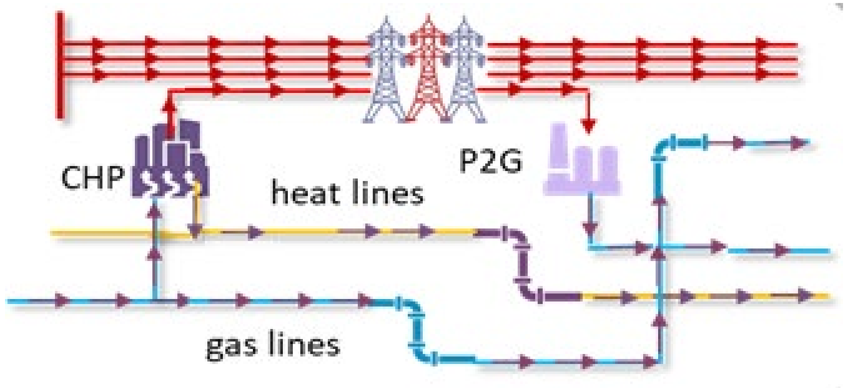


Volatile, intermittent, uncertain
Nearly zero cost



Generation units, power lines

Demand-side response



Integrated energy system

Thanks！