The Flow of Money: Electricity Markets Tutorial

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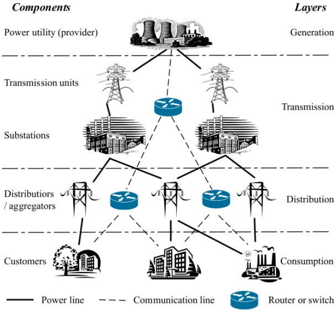
Electricity Markets: a Brief History

The Vertically Integrated Monopoly

- Traditional model until ∼1993
- Single entity owns and operates
  generation, transmission, distribution, retail
- Why? because building a complete power system is expensive, doesn't make sense to have competing dist and trans networks premium on reliable, uninterrupted power supply
- Geographic monopoly
  - private (investor-owned utilities)
  - public (state/municipally owned)

Generation
Transmission
Distribution
Retail



The Need for Regulation

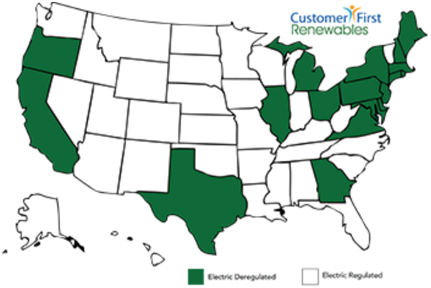
- Private monopolies must be regulated so they don't abuse their power
  - utility gets local monopoly rights
  - agrees to controls on its retail tariff
- Public utility commission sets tariffs so that (in medium and long-run)
  - utility recovers operating costs
  - utility recovers capital costs
  - utility can pay its investors a "fair" rate-of-return

Problems with this Model

- No competition $\implies$ monopolies are inefficient:
  - utility earns more if it invests more
  - cost of mistakes are passed on to rate-payer
  - no penalty for poor investment choices
  - public picks up bankruptcy costs
- Assuming that 3-5 elected officials at PUC do the right thing!
  - ignorance
  - they want to be re-elected!
- Consequences:
  - retail rates are "higher than they should be"
  - systemic waste, public picks up the bill

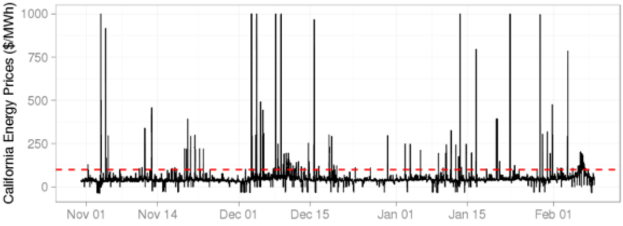
The New Deregulated Model

- Objective: introduce competition
- Unbundle different functions of the utility
  - treat electricity as a commodity
  - create markets for trading this commodity
  - energy transmission and distribution remain "natural" local monopolies
  - generators compete against each other
  - retail choice



Expected Benefits and Problems

- Benefits:
  - consumers pay fairly for what they receive
  - transparency in pricing
  - long-term: greater efficiency
- Resulting problems:
  - greater (wholesale) price volatility
    ex: feb 02, 2011, ERCOT wholesale price spike to \$3K/MWh for 3 h
    generators made profit of \$0.5B (courtesy S. Meyn)
  - possibly lower reliability



Has the experiment worked?

- It is complicated!

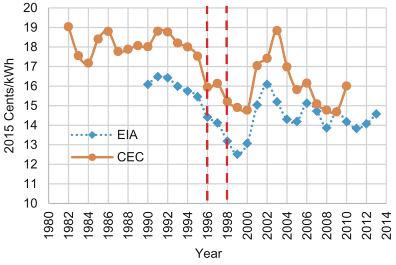
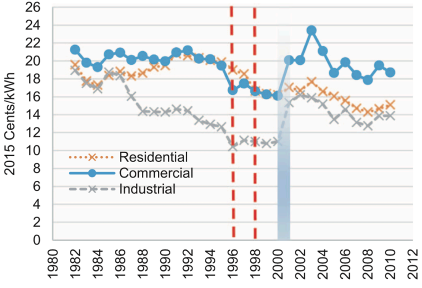


Fig. 5. Average electricity retail price for CA (California Energy Commission, 2016; Energy Information Administration, 2015c).



- Current prices are slightly lower than those in 1980s and early 1990s
- Is it due to deregulation?
  - Razeghi, Shaffer and Samuelsen. "Impact of electricity deregulation in the state of California." Energy Policy 103 (2017): 105-115.
  - Borenstein and Bushnell. "The US electricity industry after 20 years of restructuring", Annu. Rev. Econ. 7.1 (2015): 437-463.

Power System Operations

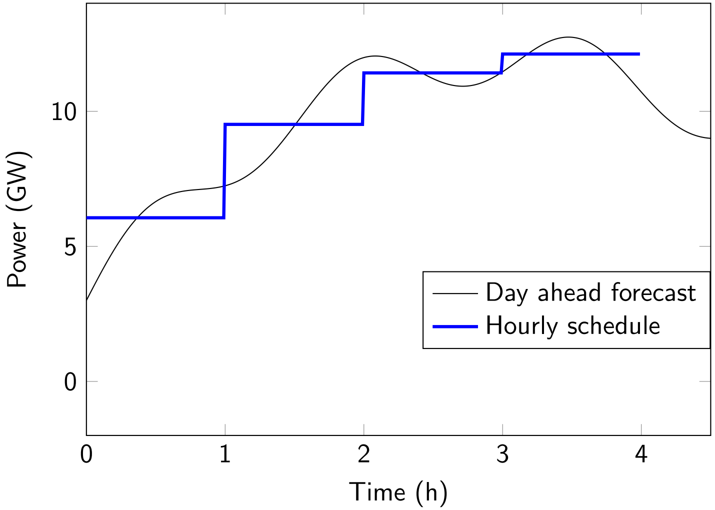
The Core Problem

- The Core Problem: Balancing Supply and Demand
  - economically through markets
  - with transmission constraints
  - while maintaining power quality (voltage, frequency)
  - and assuring reliability against contingencies
  - managed by system operator (SO)
- Today
  - All renewable power taken, treated as negative load
    subsidies: feed-in tariffs, etc
  - Net load $n(t) = \ell(t) - w(t)$
  - Tailor supply to meet random demand
- Tomorrow
  - Renewables are market participants
  - Tailor demand to meet random supply

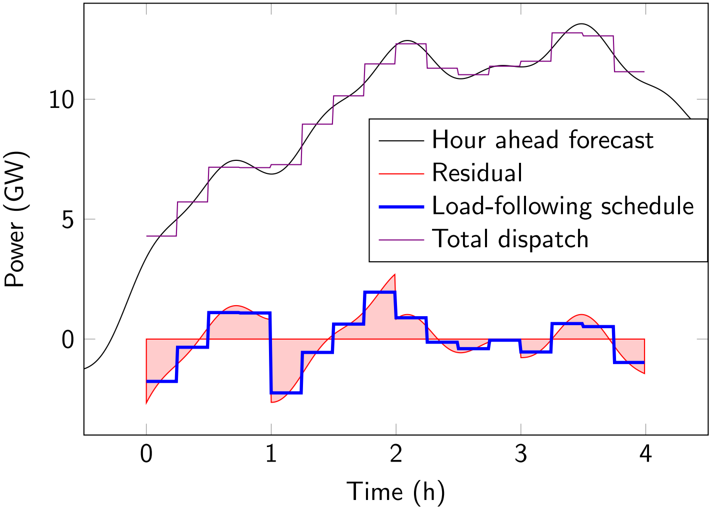
System Operations Today

- Complex, vary immensely across regions, countries
- Constructing the supply to meet random demand
  - Feed-forward: use forecasts of $n(t)$ in markets
  - Feedback: use power & freq measurements for regulation
- Markets (greatly simplified)
  - Day ahead: buy 1 hour blocks using forecast of $n(t)$
  - "Real-time": buy 5 min blocks using better forecast of $n(t)$
- Regulation
  - For fine imbalance (sub 5-min) between supply and demand
  - Must pay for regulation capacity
  - Various time-scales

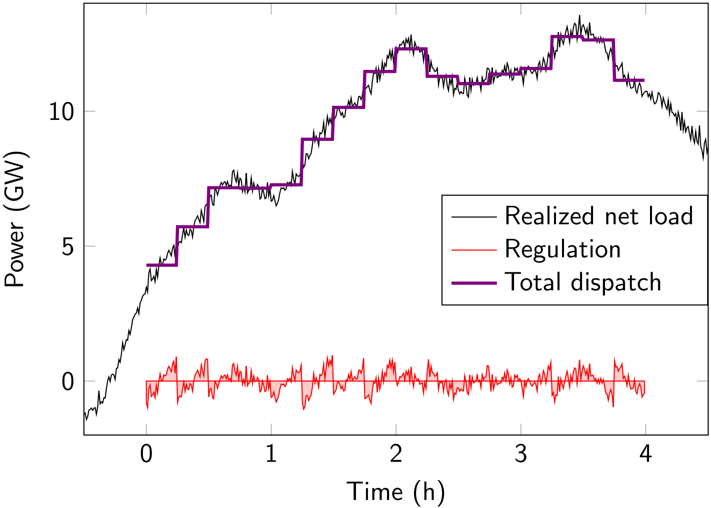
Day Ahead Market Dispatch



Real Time Market Dispatch

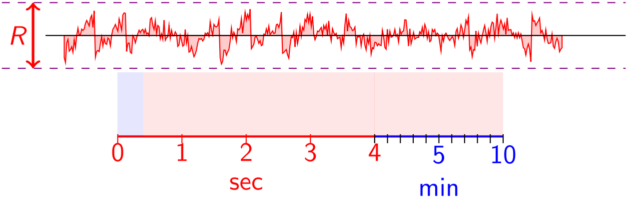


Regulation



10
5
0
0
1
2
3
4
Power (GW)
Time (h)
Realized net load
Regulation
Total dispatch

Regulation Time-scales



Capacity R for various regulation services procured in advance

time-scale	ancillary service	detail
< 4s	governor control	decentralized
4s to 5m	AGC automatic generation control	centralized control generators on call respond to SO commands

Day Ahead and Real-time Markets

Pools vs Bilateral Trading

- Sellers: generating companies   Buyers: load serving entities or utilities

- Many jurisdictions use long-term bilateral contracts
  - decentralized
  - private arrangement between parties
  - could be long term or short term (OTC)
  - SO must be informed of the volume of trade to assure security
  - unsuitable for real-time market

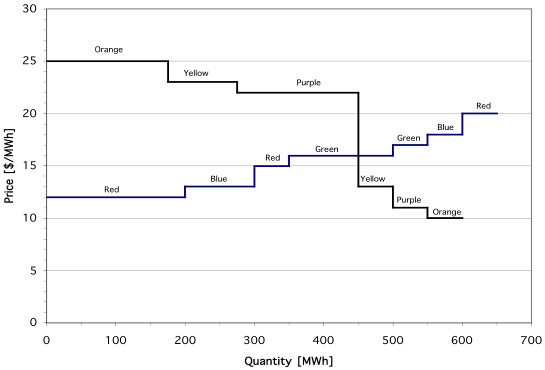
    balancing is too important to leave to bilateral contracts
    must be centrally assured
  - most renewables are traded in bilateral contracts

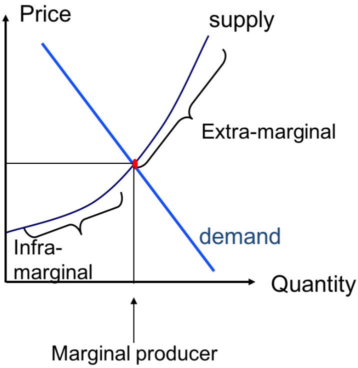
- Others use organized pool markets: our focus
  - centralized
  - generators submit price/quantity bids
  - SO determines dispatch (who produces and how much)
  - SO determines prices

Pool Markets: Merit-ordering

- Assume no transmission constraints, negligible losses
- Generators submit supply offers
  - price and quantity
  - min/max constraints
- LSE submits demand bids
  - based on forecasts
  - usually very inelastic, so essentially quantity only
- SO constructs a merit order stack
- SO determines prices and quantities
- Comments:
  - generators receive uniform clearing price, not pay as bid
  - bilateral contracts can be traded simultaneously
  - supply bids are strategic: gaming opportunity
  - result is efficient, maximizes social welfare under truthful bidding

Merit-ordering ...





Network Case: Setup

- Load ℓ, generation g, net power injection $q = g - \ell$
- Generator model:

$$\begin{aligned} \text{piecewise linear/convex fuel costs} \quad & J_i(g_i) \\ \text{capacity limits} \quad & \underline{g} \leq g \leq \overline{g} \end{aligned}$$

- Load model: inelastic demands, i.e. ℓ is given
- DC power flow model

$$\begin{aligned} \text{power balance at each bus} \quad & Y\theta = g - \ell \\ \text{line capacity constraints} \quad & M\theta \leq C \end{aligned}$$

- Social cost $J(g) = \sum_i J_i(g_i)$

Problem data: $Y, M, C, \underline{g}, \overline{g}, \ell, J(\cdot)$
decision variables: g, θ

Two Central Problems

- Economic Dispatch
  given a set of committed generators
  determine generation levels to meet a given load at minimum cost
  - linear or convex program
  - can be extended to include full nonlinear power flow model (nonlinear programming)
  - output is optimal generator levels, prices
- Unit-commitment
  which generators to use?
  - additional binary decision variables α
  - requires solving economic dispatch repeatedly
  - mixed-integer program

Economic Dispatch

- Simplified time-line:
  1. generators submit bid curves (usually piece-wise linear), 1 hr blocks
  2. loads submit demand forecasts, 1 hr blocks
  3. system operator determines

     economic dispatch, i.e. how much each generator should produce
     clearing prices at each bus λ_i = location marginal prices
  4. loads at bus i are obligated to purchase power ℓ_i
  5. generators at bus i are obligated to supply power g_i
  6. then proceed to real-time market ...
- Lots of other important details omitted:

  a/c power flow model, elastic demand bids
  bilateral contract constraints, market power,
  out-of-merit generators, security constraints
- Key point: all participants at bus i face price λ_i, regardless of bids

Economic Dispatch ...

$$\min_{g,\theta} J(g) = \sum_i J_i(g_i)$$

subject to $q = Y\theta$

$$M\theta \leq C$$

$$-g \leq -\underline{g}$$

$$g \leq \overline{g}$$

g generation

ℓ load (demand forecast)

θ voltage angles

$J(g)$ total fuel cost

C line capacities

$\overline{g}, \underline{g}$ generation limits

- Standard convex optimization problem
- Dual variables

  λ - locational marginal prices — from power balance $Y\theta = q$

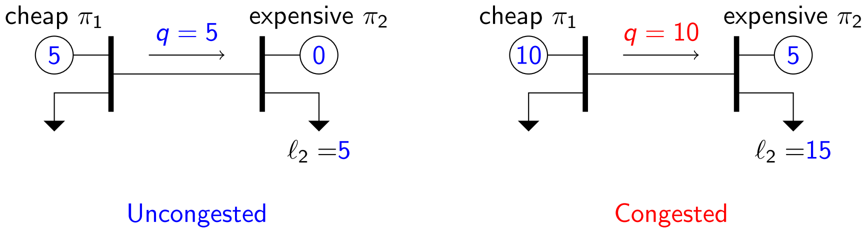
  μ - shadow congestion prices — from line limits $M\theta \leq C$

Key Concepts and Facts

- Economic Dispatch g
- Locational Marginal Prices (LMPs) λ
  - λ_i = marginal cost of supplying 1 extra MW at bus i
  - no congestion $\implies \lambda = \text{constant}$
  - if even one line is congested, all LMPs change
- Payments
  - total fuel costs $J(g)$
  - total payment to generators $\lambda^T g$
  - total payment from loads $\lambda^T \ell$
- Merchandizing surplus
  - what is left over: $MS = \lambda^T(\ell - g)$
  - thm: $MS \geq 0$ always
  - MS used to support transmission expansion costs

Example

- line capacity $C = 10$
- market power exerted by G_2
- if line is congested, LMPs are $\lambda_1 = \pi_1, \lambda_2 = \pi_2$
- else, LMPs are $\lambda_1 = \lambda_2 = \pi_1$



Counter-intuitive Prices and Flows

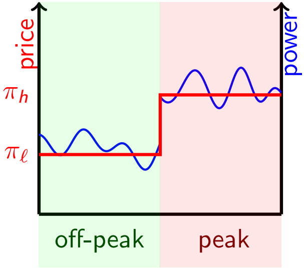
- Electricity is not like wheat or other commodities
  - must respect KVL, KCL
  - cannot be stored (at reasonable prices in large amounts)
- LMPs
  - λ_i could be negative!
  - λ_i could be greater than marginal cost of most expensive generator
- Braess' paradox
  - strengthening a congested line (i.e. increase line limits) may increase LMPs!

Band-aids

- Electricity markets in practice are balkanized, arguably inefficient
- Many extra-market payments, policies
  - start-up/shut-down costs, no-load costs, and other make-whole payments
  - subsidies, preferential treatment, production credits
- Attempts to retain critical market participants, assure liquidity
- Increase inefficiencies
- Economic orthodoxy:
  true spot markets and real-time pricing is all we need!
  consumers who are volatility-sensitive can buy insurance products

Retail Tariffs

- Large industrial consumers participate directly in wholesale markets
- Smaller commercial and residential consumers buy from the Utility
- Retail tariffs
  - generally "fixed", known in advance, not much volatility/uncertainty
- Economic orthodoxy: real-time pricing
- Changes are coming to approximate this ...
  - volumetric or tiered pricing
  - critical-peak-pricing
  - time-of-use (already in CA)



Other Markets

- Ancillary services: frequency regulation, spin, non-spin reserves
- Reliability
- Inertia Markets
- Capacity markets
- Transmission expansion
- Financial transmission right auctions
- Virtual bids

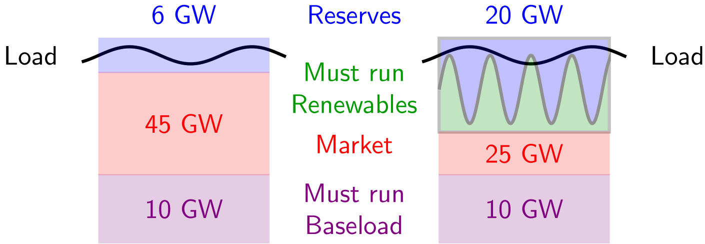
Will focus on material most relevant to real-time decision making

Things Fall Apart

Facts & Figures

- Market Evidence
  - 75% of US utilities have BBB credit rating or lower (2011)
  - Top 20 European utilities have lost 500B$ in market value (since 2008)
  - E.ON net income down 35% since 2010
- More Troubling Facts
  - GDF Suez mothballed 30GW of gas plant capacity (Europe)
  - Large customers generating own power (ex: Google)
  - Net metering leaving fewer customers to share infrastructure costs
  - Solar PV module prices fell by 80% from 2008 and 2012
  - PV output reduces afternoon peak load depressing peak prices
  - Since 2009 electricity demand has fallen by 3% (US)
- Legacy utility business model under threat
  because of renewables

The Crisis is Driven by Renewables



- Change in needed generation assets
  - displacing gas plants

    Vattenfall (Sweden): written off 6% of gen assets
    E.ON, RWE and EnBW: capacity cuts of over 15GW
  - post-Fukushima mothballing of nuclear plants
  - renewables cause more need for dispatchable generation *capacity* but small *capacity factor*
- Utilities remain responsible for regulation, stability, power quality

Tomorrow: Things Fall Apart

- Too much variability
  - 33% renewables → lots of variability → 3X reserves
  - variability at many time-scales and magnitudes
    need distinct regulation services

      solar → more frequency regulation
      wind → more operating reserves
      large wind ramps → ???

- Solution: tailor demand to meet random supply by exploiting flexible loads

Addressing the Crisis

- New business models for Utilities
  - post-net-metering tariffs
  - shared electricity services
  - exploiting strategic storage
  - market for DER micro-transactions
- Reduced op-ex costs
  - efficiency programs, ex: PG&E, EnBW, RWE
  - cheaper procurement of regulation and other ancillary services
  - congestion relief
- New revenue streams
  - investing and managing renewables
  - better monetization of infrastructure
  - developing and running new energy markets for DERs
  - products and services for developing countries

A Critique of Legacy Markets

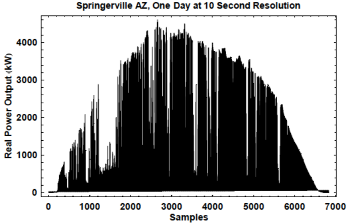
- Designed for slow-acting conventional generation
  - coal-fired plants need lots of lead-time
  - nuclear plants cannot change output easily/quickly
- Information
- New problems and opportunities:
  - uncertain, uncontrollable, random renewables
  - some parts of load are controllable: demand response
  - new information paradigm

New Ideas for Electricity Markets

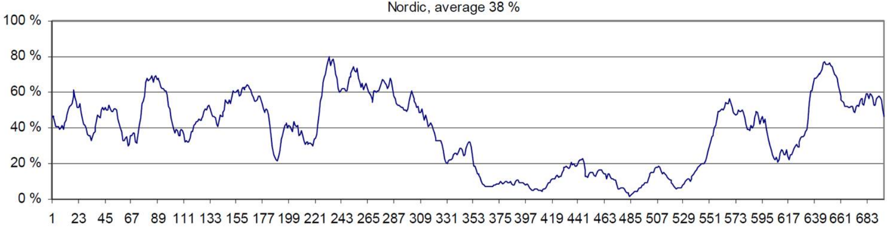
Renewable Variability

Renewables are random, intermittent, uncontrollable

Solar variability: one day in AZ, 10s sampling



Wind variability: one month in Nordic grid, 1h sampling



1. Selling Random Renewables

- How are renewables sold today?
  - cannot participate in day-ahead wholesale market ...
    $\approx$ 25% day ahead forecast error, not firm in 1h blocks
  - could participate in real-time market ...
    $\approx$ 3% 30 min ahead forecast error, firm on 5 min blocks
  - but volume is $\approx$ 10% of demand
  - wind is mostly sold through long term bi-lateral contracts
  - small PV is sold through net-metering (extra-market mechanism)
- Future possibilities ..
  - bundling with storage to firm renewables
  - sharing to take advantage of statistical diversity
- Need real-time decision making
  - ex: when to charge/discharge storage
  - ex: coordination with other renewable assets

2. Re-thinking the Product

- Today $\rightarrow$ utilities must supply on-demand power
- But, some customers will accept flexible power
- Two paradigms:
- Reliability differentiated: Tan & Varaiya, *J. Econ Dyn Cont*, 1993
  - Get constant power s with probability $> \rho$
  - Price depends on ρ
- Deadline differentiated: Bitar & Low, *CDC*, 2012
  - Get energy E on service window $[t, t+h]$
  - Price depends on h

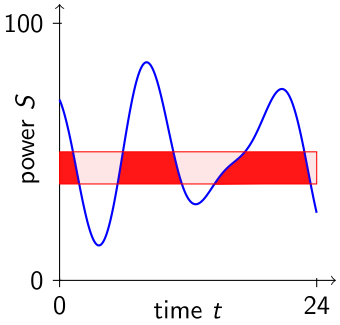
Chevron

h (hrs)	0	0.5	1
price ($/KWh)	0.35	0.3	0.2

Product: differentiated service, not undifferentiated good

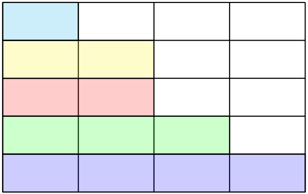
3. Duration Differentiated Contracts

- Consider generation for next 24 hrs
- Idea: sell slices (x, h) of x MW for h hrs
- Availability period is chosen by supplier
- Issues
  - Supply is random
  - Auditing is easy
  - Consumers must plan consumption with uncertain supply
- Negrete-Pincetic, Poolla, Varaiya [2013]



Set-up

- Time is slotted, say 24 x 1h slots
- Supply s: random, revealed causally
- Demand: known in advance, flexible
  - customer k needs a total of q_k units of energy for h_k hours
  - indifferent to which hours are allocated
- Example: 4 slots, 5 customers

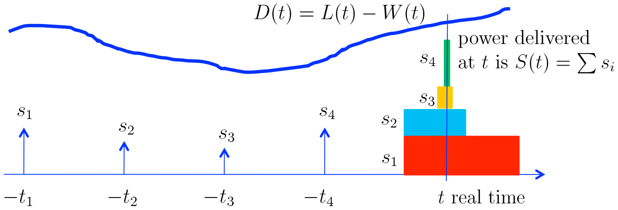


Real-time decision-making ..

- Agenda:
  1 If s is known, is supply adequate?
  2 If adequate, what is the allocation of s to consumers?
  3 If not, need to purchase x to make s adequate.
  What is the min $\sum x_t$?
  4 What is the optimal purchase policy if s is revealed in run-time
  5 Pricing of products $\pi(q, h)$?
- Lots of interesting questions!

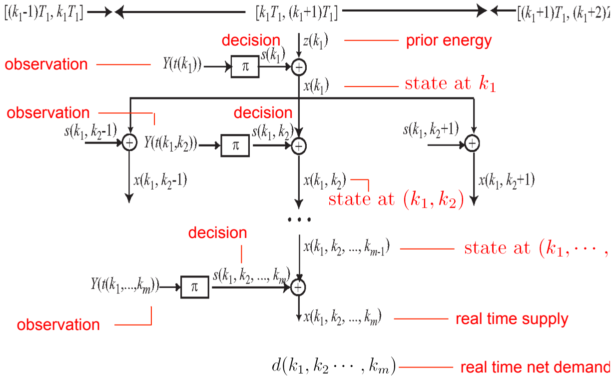
4. Risk-Limiting Dispatch

- Multiple intermediate markets
- Leverage increasing information (ex: load/renewable forecasts)
  - construct supply to meet random load $\ell(t)$
  - m forward markets
  - successively better forecasts of ℓ
  - real-time decisions in each market
  - decision made with awareness of future recourse opportunity



RLD: Real-time Decision Making ...

- Optimal stage decisions: threshold policy
- Bitar, Rajagopal, Varaiya [2014]



5. Electricity Storage

- Very expensive: \$300/KWh for Li-ion
- But prices are falling fast
- Game-changer at transmission scale
- Many distribution-side applications
  - price arbitrage
  - voltage support
  - trading between peer firms
- example: industrial firm faces critical-peak-pricing or real-time tariffs
  - storage can be used to significantly reduce electricity bill
  - real-time decision making: must make charge/discharge decisions based on price and load forecasts
  - yet another stochastic control problem
  - simple sub-optimal policies?

6. Selling Transmission-Scale Storage

- CA storage mandate: 1.3 GW by 2020
- Multi-period Economic Dispatch
  1. Utilities install some storage at various buses
  2. Utilities submit storage capacity to SO
  3. Utilities submit demand needs to SO
  4. SO conducts multi-period economic dispatch
- SO determines optimal use of storage
- storage models add convex constraints
- allows SO to shift demand temporally
- convex program!

7. Demand Response

- Flexible loads: EVs, HVAC systems, Industrial loads
- Some degree of flexibility or indifference to power consumption profiles
  - ex: EV owner needs full charge by 7am
  - ex: HVAC systems have thermal dead-band
- Can be viewed as a generation (up/down) resource
- Use cases:
  - peak-shaving
  - ancillary services, ex:frequency regulation, contingency reserves
- Architecture
  - direct load control
  - indirect control through price proxies
- Meyn *et al*, Callaway, etc focus on real-time control algorithms for DR

Modeling DR capability

- Aggregate Models
  - because individual models have low fidelity
  - residential consumers, commercial buildings, EV fleets
  - models are virtual batteries Batt(C, m)

$$\dot{x} = u, \quad |x| \leq C, |u| \leq m$$

  - C, m are random
    depend on exognenous processes θ: occupancy, weather
  - much cheaper than conventional generation: $\approx 10 - 30\$/KWh$ levelized
  - software tools to compute $C(\theta), m(\theta)$


Selling DR Capability

- Different than generation
  - greater uncertainty
  - needs lead time $\sim 4h$
  - not stationary, requires forecasting
- Sell DR capacity (random battery) in a forward market
- Sell options
  - sold at t_o
  - selling the right to use $Batt(C, m)$ for 1h starting at t_f
  - strike price π_s, energy use price π_e
  - option must be exercised by expiration time t_e
- Questions:
  - market prices for DR?
  - economic efficiency loss?

8. Capacity Markets for Balancing Resources

- Core problem: fine balance of supply and demand
  - balancing on a forward 1h window, broken into T time slots
  - "capacity" perspective for real-time market
  - deterministic approach
- Diverse controllable resources that remove uncertainty: generation, storage, demand response from flexible loads
- Uncontrollable agents that inject uncertainty: loads, renewables
- Set-up: all signals in $\mathbb{R}^T$

$e_i \in \mathbb{E}_i$	imbalance signal from agent k, convex set
$e = \sum_i e_i$	total imbalance signal
$\mathbb{E} = \sum_i \mathbb{E}_i$	set of possible imbalance signals
$\mathbb{S}_k$	capability of 1 unit of resource k, convex set
π_k	price per unit of resource k
q_k	quantity of resource k purchased

Optimal Reserve Procurement

- Optimal resource procurement under oracle information:
  - set-containment Linear Program

$$J^* = \arg\min \sum_k \pi_k q_k \quad \text{subject to} \quad \sum_k q_k S_k \supseteq \mathbb{E}$$

  - given imbalance signal $e \in \mathbb{E} \subseteq \mathbb{R}^T$,
    can allocate controllable assets:

$$e = \sum r_k : r_k \in q_k \mathbb{S}_k$$

- Problem: imbalance signal is revealed causally

Cost of Causality

- Optimal resource procurement under causal allocation
  - need a set of causal (i.e. real-time) policies $r_k = \Phi_k(e) \in q_k \mathbb{S}_k$

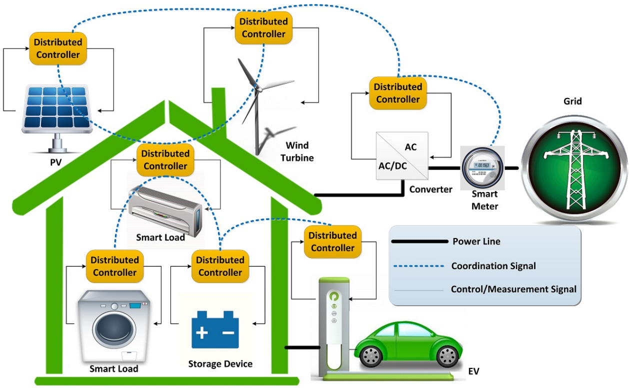
$$J^{**} = \arg\min \sum_k \pi_k q_k \;\; \text{subject to} \;\; \sum_k q_k S_k \supseteq \mathbb{E} + \text{causal allocation}$$

  - can compute upper bounds on J^{**} by restricting to class of policies: proportional, linear, time-varying, etc
  - reduces to collections of LPs
- Cost of causality

$$\gamma = \frac{J^{**}}{J^{*}} \geq 1$$

  Measures the importance of forecasting e
  can compute γ almost exactly in various cases of practical interest
- Warrington (2014), Sen + Shetty (2018)

9. Home Energy Management Systems

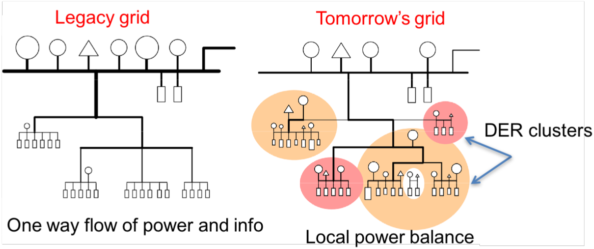


- Real-time decision making!
  - forecast needs, weather, PV production, grid prices
  - when to schedule appliance, charge EV, etc
  - when to charge/discharge storage or sell power back to grid
  - when and how much to curtail consumption

Grid2050

Grid2050

- supports $>40\%$ renewables, distribution and transmission side
- delays need for investing in high-voltage transmission infrastructure
- more power generated and consumed locally
- increased resilience, local ownership and management
- DERs organised into resource clusters example: interconnected microgrids, storage, PV, flexible loads

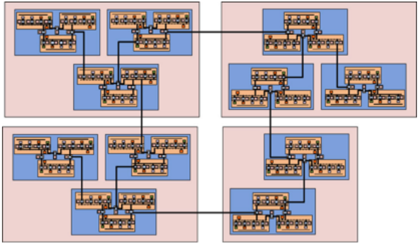


Architectures

- Supports flexible control structures decentralized and centralized
  - direct control of some assets
  - indirect control through price proxies
- Grid Operating System
  - manages sensing assets, coordinates control assets
  - scalable, interoperable platform
- Key Idea: Coordinated Aggregation
  - cluster manager firms demand
  - clusters exchange power in forward markets
- Research Questions
  - how big should clusters be?
  - how should they interact?
  - performance Metrics?

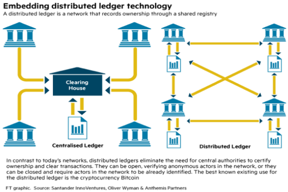
Necessary Technology and Market Infrastructure

- Many critical problems:
  - Power quality, reliability, and protection
  - Millions of micro-transactions: security, auditing, clearing
- Need common technology infrastructure:
  - Programmable switches [ex: VirtualPowerSystems]
  - Novel, inexpensive sensors/actuations [ex: Varentek]
  - Communication and computation [ex: C3IOT]
  - Inter-operability standards [ex: OpenADR]
- Need radically new market infrastructure:
  APEX: Automated Power and Energy eXchange



APEX: a matching market for DERs

- Objective: support clearing of millions of micro-transactions every hour
- Examples: buying excess PV, selling demand flexibility, reactive power, ...
- APEX: Automated Power Exchange [Qin+Rajagopal+Varaiya+Poolla]
  - key idea: Matching markets for atomic composable transactions
  - diverse constraints, ex: lead times, minimum trade size,
  - metrics: security, bid/ask spread, transaction costs, throughput
  - technology: blockchain-based for security, order book clearing algorithms
  - competition: transactional energy (PNNL), TeMIX, ENERChain



Many Other Ideas

1. Market power, competition models (Johari, Lin+Bitar, Oren)
2. Platforms (Weirman)
3. Virtual bids (Tang et al, A. Gupta + R. Jain)
4. Sharing Economy for Grid (Kalathil et al)
5. Financial Storage Rights (Taylor, Bitar)
6. Incentives for DR (Xie)
7. Data analytics (Rajagopal, Xie)
8. Gaming and Mechanism design in DR (Muthirayan et al, Chakraborty)

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- ... also by storage, sensing, electronics, data analytics ...
- Recent news
  - PV panel tariff of 30%
  - FERC being pushed to subsidize, bail out coal/nuclear that cannot compete economically with wind
  - 10B$ or more "resilience subsidies" for coal/nuclear

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  - today, at Davos, Rick Perry promotes US coal exports as "exporting freedom"
- I remain an optimist
  - there are enough sensible people out there
  - there are recourse opportunities: elections!

References

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