Why Pay Rent?

Load Flexibility for Congestion Limiting Dispatch

Jonathan Mather, UCB
Enrique Baeyens, Valladolid
Kameshwar Poolla , UCB
Pravin Varaiya, UCB

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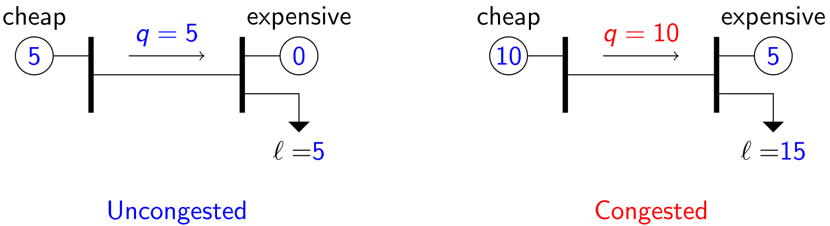
Congestion

- Actual and scheduled power flows over a transmission line have constraints
  - thermal limits, stability limits on MVA ratings
  - ignore reactive power
  - look at simpler problem of active power flows
- Congestion causes prices to rise
  - loads pay more, system (fuel) costs increase
  - congestion forces use of more expensive generators
  - two bus example, line capacity $C = 10$



Value Proposition

- Congestion costs are real:
  - loads paid $\sim$\$0.7bn extra per year year in PJM's service area
  - system costs are higher, may be forced to use inefficient generation
  - safety margins are lower, grid is less resilient
    (hard to monetize avoided costs)
- Load flexibility and storage can reduce congestion
  - could be far more lucrative than price arbitrage,
    supporting capital costs of strategic storage
  - may avoid or delay need for expensive upgrades to transmission infrastructure
  - increased safety margins in the event of a contingency

Load Flexibility

- Can shift power consumption:

  temporal – defer consumption now, use more power later
  spatial – use less power here, more power there

- Examples:
  - temporal: smart appliances, EVs, HVAC systems
  - spatial: data centers

- Applications:

  balancing services to enable renewable penetration,
  frequency regulation, peak shaving, volt/var control
  many are commercialized (EnerNOC, Comverge, Opower)

Storage

- Can shift power consumption in time
- Similar to temporal load flexibility
- Economic reality:
  - storage is expensive: \$300/Kwh for Li-Ion
  - but perceived as having strategic value ...
    California mandate: 1.3GW of ramping capability through energy storage by 2020
  - must monetize all revenue streams [Denholm, 2013]

Simple Models

- Nominal consumption at fixed bus, T time slots

$$n = (n_1, n_2, \cdots, n_T)$$

- Consumption under flexibility $n + \delta, \quad \delta \in \Delta$
- Temporal flexibility:

$$\Delta = \left\{ \delta : \quad |\delta_t| \leq F, \ \sum_t \delta_t = 0 \right\} \quad F : \text{flex capacity}$$

- Storage: initially half charged

$$\Delta = \left\{ \delta : \quad |\delta_t| \leq R, \ \left| \sum_1^t \delta_k \right| \leq C/2 \right\} \quad \begin{array}{ll} R : & \text{charge/discharge rate limit} \\ C : & \text{storage capacity} \end{array}$$

Load Flexibility as Storage

- Load flexibility models
  - nominal consumption n
  - flexible consumption $p = n + \delta,\ \delta \in \Delta$
  - conservative model $\mathbb{S} \subseteq \Delta$

$$\mathbb{S}(m, C, \alpha) = \{\delta:\ \dot{x} = -\alpha x + \delta, |x| \leq C, |\delta| \leq m\}$$

- Load flex can be conservatively modeled as a virtual battery
  - includes rebound effects, efficiency programs, etc
  - battery params capacity C, ramp rate m, dissipation α
  - parameters are random
  - depend on exogenous, ex: random processes occupancy, weather, etc
  - previous CERTS research (with A D-G) to determine params
- Loads need lead time to organize and deliver their storage

Set-up

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

$$\begin{aligned} \text{convex fuel costs} \quad & J_i(g_i) \\ \text{capacity limits} \quad & 0 \le g_i \le G_i \end{aligned}$$

- Load model: inelastic demands
- DC power flow model

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

- Social cost $J(g) = \sum_i J_i(g_i)$
- Economic Dispatch $\min J(g)$: constraints
  determine generation levels to meet a given load at minimum cost

Day-ahead 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,
  virtual bids, out-of-merit generators, security constraints
- Key point: all participants at bus i face price λ_i, regardless of bids

Economic Dispatch

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

$$\text{subject to} \quad q = Y\theta$$
$$M\theta \leq C$$
$$-g \leq 0$$
$$g \leq G$$

g generation

ℓ load (demand forecast)

q net injections, $q = g - \ell$

θ voltage angles

$J(g)$ total fuel cost

C line capacities

G upper 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
  - $\lambda_i =$ marginal cost of supplying 1 extra MW at bus i
  - λ_i could be negative!
  - λ_i could be greater than marginal cost of most expensive generator
  - no congestion $\implies \lambda =$ constant
  - if even one line is congested, all LMPs change
- Payments
  - total fuel costs $J(g)$
  - total payment to generators $\lambda^* g$
  - total payment from loads $\lambda^* \ell$
- Merchandizing surplus
  - what is left over: $MS = \lambda^*(\ell - g)$
  - thm: $MS \geq 0$ always
  - MS used to support transmission expansion costs

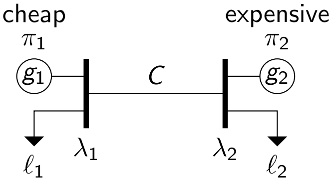
Geometry of LMPs

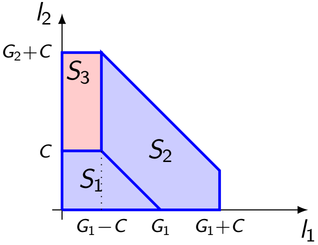
- Feasible load set F
- Geometry of F: union of polytopes

$$F = \bigcup_i S_i$$

  - S_i defined by congested lines and marginal generators
  - LMPs fixed in each S_i
- Example:

set	LMP	congestion?
S_1	π_1, π_1	no
S_2	π_2, π_2	no
S_3	π_1, π_2	yes





- What happens to the congestion free set $S_1 \cup S_2$ under flexibility/storage?

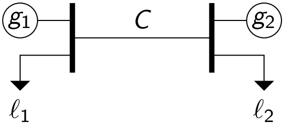
Feasible Load Set $\mathbb{F}$

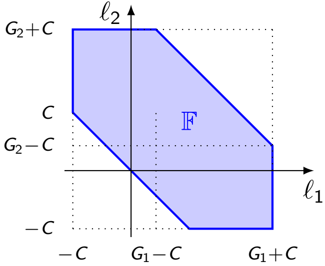
Feasible load set $\mathbb{F}$

Set of loads that can be served while respecting power flow, generation limits, line constraints:

$$\mathbb{F} = \{\ell : \exists\, \theta, g \;\; \text{with } Y\theta = g - \ell, \;\; M\theta \leq C, \;\; 0 \leq g \leq G\}$$

- could restrict loads to be non-negative: $\ell \geq 0$
- we won't because storage allows for negative load
- $\mathbb{F}$ is a polytope





Feasible injection set $\mathbb{Q}$

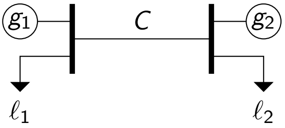
Feasible injection set $\mathbb{Q}$

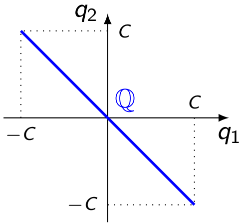
Set of nodal power injections that respect power flow, line constraints:

$$\mathbb{Q} = \{q : \exists\, \theta \ \text{ with } Y\theta = q, \ \ \mathbf{1}^* q = 0, \ \ M\theta \leq C\}$$

– injections $q = g - \ell$

– $\mathbb{Q}$ is a polytope





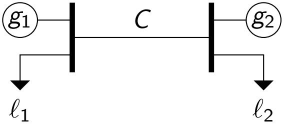
Merit-Ordered Generation Set M

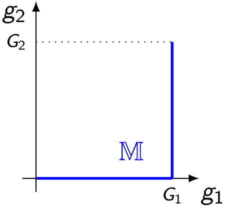
Merit-Ordered Generation Set $\mathbb{M}$

Least expensive generation vectors g that supply $1^T g$:

$$\mathbb{M} = \{g : \quad 0 \le g \le G, \;\; J(g) \le J(\hat{g}) \text{ for all } \hat{g} \text{ with } 1^T g = 1^T \hat{g}\}$$

- $\mathbb{M}$ is generally not convex
- very easy to compute $\mathbb{M}$ by merit ordering
- $g \in \mathbb{M}$ implies congestion free dispatch





Congestion Free Load Set

- L_F = set of loads ℓ for which the economic dispatch is congestion free
  - ℓ is being serviced as inexpensively as possible
  - line constraints are all slack: $M\theta < C$

Theorem

Congestion free load set L_F is the Minkowksi sum

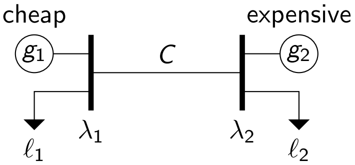
$$L_F = \mathbb{M} + \mathbb{Q}$$

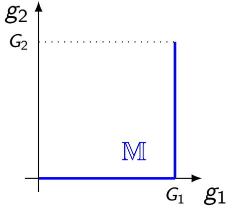
Congested load set is the complement

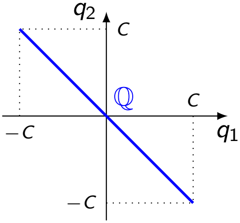
$$L_C = \mathbb{F} \setminus L_F$$

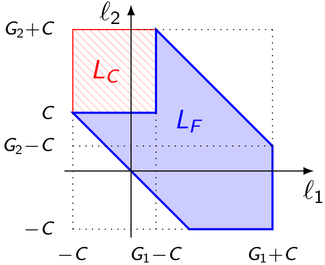
- L_F is generally not convex, because $\mathbb{M}$ is not convex

Two Bus Example Summary









General Geometry Results

Theorem

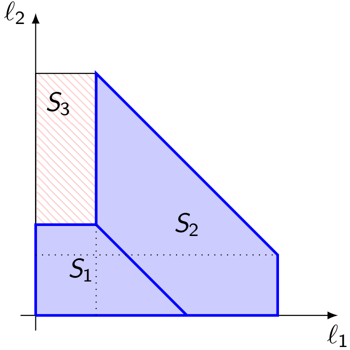
Assume piece-wise linear generation costs

(a) feasible load set is the disjoint union

$$\mathbb{F} = \bigcup S_k \qquad S_k \text{ polytope}$$

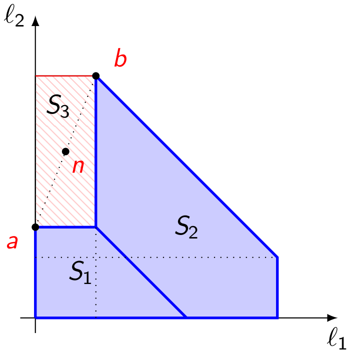
(b) LMPs constant in S_k

(c) S_k determined by
marginal generators and congested lines



$$L_F = S_1 \cup S_2 \qquad L_C = S_3$$

Key Idea: The Value of Flexibility



$$L_F = S_1 \cup S_2$$

- want to serve (n, n) over 2 time slots
  - this results in congestion
- with sufficient flexibility, can serve (a, b)
  - yields congestion free dispatch
  - total energy delivered is the same:

$$a + b = n + n$$

Alternatives	t_1	t_2	Congested?
Non flexible	n	n	Yes
Flexible	a	b	No

General Network Results

How big can we make L_F using demand flexibility?

Theorem

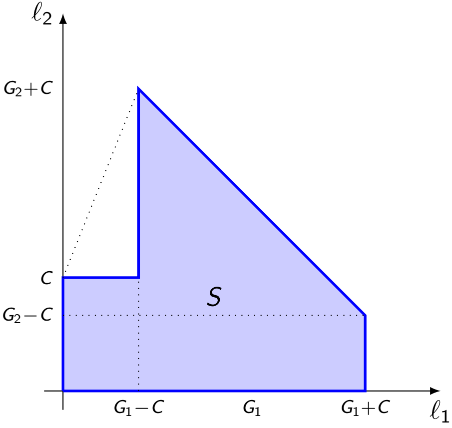
Congestion free load set under flexibility is the convex hull $co(L_F)$.

- proved using Shapley-Folkman theorem
- requires longer windows over which flexibility is offered
- needs a lot of flexibility (too much) for CF dispatch
- finite resource result is open

Shapley Folkman Theorem

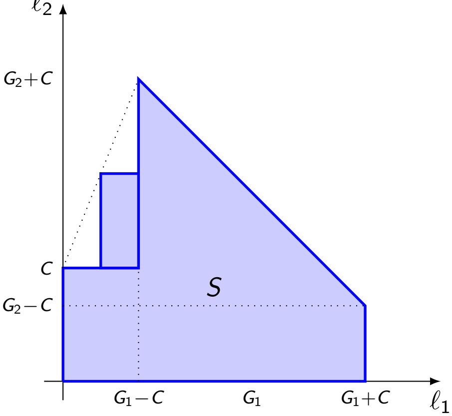
For any set $S \subset \mathbb{R}^n$, $\quad \lim_{N\to\infty} \frac{1}{N} \sum_{k=1}^{N} S = \mathrm{co}(S)$

Shapley-Folkman Theorem



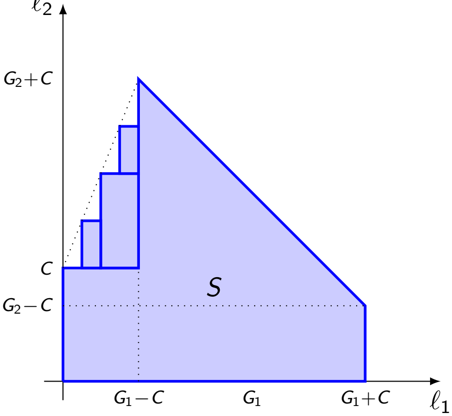
S

Shapley-Folkman Theorem



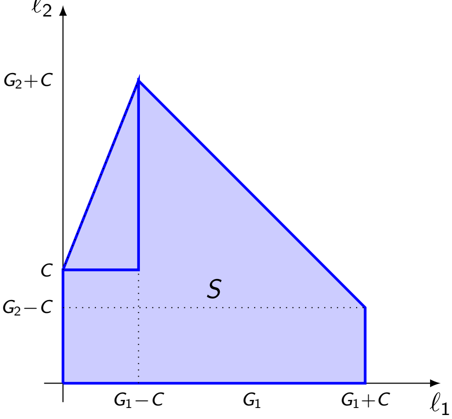
$(S + S)/2$

Shapley-Folkman Theorem



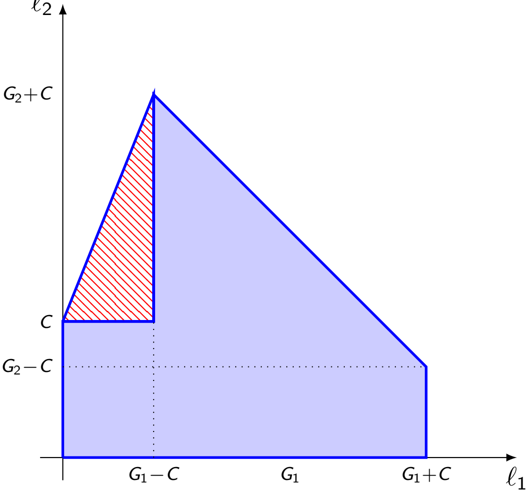
$$(S + S + S)/3$$

Shapley-Folkman Theorem



$$\frac{1}{N}\sum_{k=1}^{N} S, \quad N \to \infty$$

Congestion free load set under Flexibility



Economic Analysis

- consider loads as a collective
  - loads pay less under congestion free dispatch if $C > G_1/2$
  - some loads pay more, so must redistribute savings fairly
- consider generators as a collective
  - generator revenue is unchanged under flexible dispatch
- system (fuel) cost is same under flexible dispatch
- Loads benefit as a collective with CF dispatch, under network condns
- Savings come from redistributing MS

Flexible Bidding

- Congestion free dispatch requires too much flexibility/storage
- More realistic to study marginal benefits of small amounts ϵ of flexibility/storage
- Flexible bidding
    1. LSEs at each bus recruit some demand flexibility, install some storage
    2. LSEs submit available flexibility to SO
    3. LSEs submit demand needs to SO
    4. SO conducts multi-period economic dispatch
- SO determines optimal use of flexibility
- Demand flexibility and storage models add convex constraints
- Flexible economic dispatch is still a convex program

Flexible Bidding: setup

- k bus index
- t time index
- Quadratic generation costs

$$J(g_k) = \alpha_k g_k^2$$

- Demands in slot t at bus k is $\ell_{t,k}$
- Simple flexibility model: small flex capacity at bus k is ϵ_k
- Loads will accept $\ell + \delta$ if

$$|\delta_{t,k}| \leq \epsilon_k, \quad \sum_t \delta_{t,k} = 0, |\delta_{t,k}| \leq \epsilon_k$$

Flexible Bidding: analysis

- LMP sensitivity matrix

$$G_t = \left[\frac{\partial \lambda_{t,k}}{\partial \ell_{t,k}}\right] \text{(we have closed-form expressions for } G_t\text{)}$$

Theorem

Optimal dispatch under flexible bidding:

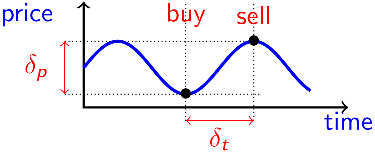
$$\min_{\delta_t} \sum_t \ell_t^T G_t \delta_t \quad s.t. \sum_t \delta_t = 0, |\delta_t| \leq \epsilon$$

This is a linear program!

- – loads benefit as a collective
- – some loads may pay some
- – savings result from congestion relief

Congestion Relief vs. Arbitrage

- Small storage or flex demand ϵ
- Price arbitrage:
  - benefit = small storage × big price difference δ_p
  - limited opportunity (i.e. once/day)
  - daily profit = $\epsilon \times \delta_p \times 1$



- Congestion relief:
  - small storage ϵ causes small LMP changes $\delta\lambda = G\epsilon$
  - total load at each bus benefits from $\delta\lambda$
  - benefit = $\ell \times \delta\lambda$
  - could be a frequent opportunity (i.e. r times/day)
  - daily profit = $G\epsilon \times \ell \times r$

Conclusions

- Flexibility/Storage enables congestion limiting dispatch
  - enlarges set of loads that can be served economically without congestion
  - flexibility brings economic benefits to all market participants under certain network conditions
- Small amounts of flexibility/Storage enable congestion relief
  - realized through multi-period flexible bidding
  - SO determines optimal use of flexibility
  - savings could be a constant income stream,
    not just a once a day arbitrage opportunity

Current/Future work

- Algorithms
  - efficient computation of congestion limiting load sets
  - full AC-OPF extension
- Control & Operations:
  - what degree of coordination between loads is required?
  - what happens under partial participation
  - flexible bidding in economic dispatch?
- Simulation studies:
  - real-world networks and data to determine potential savings
  - enough to pay for capital costs of storage?
- Economics:
  - exploration of the economic incentives for participants
  - fair sharing of savings among loads?