Georgia Tech College of Engineering
School of Electrical and Computer Engineering

Embedding Affordability Goals into Grid Planning

via Differentiable Optimization

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Introduction

- Talk is based on **joint work** with:
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  - Ryan Piansky
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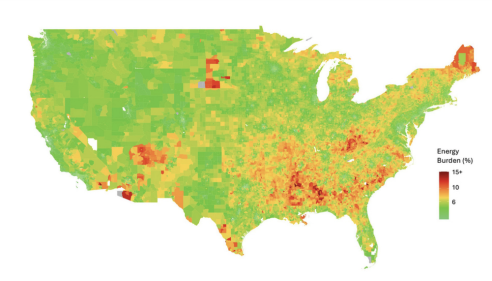
  - Daniel K. Molzahn

Energy affordability crisis i



MIT Sloan, “The changing geography of “energy poverty”

Pricing growth has unequal impacts.

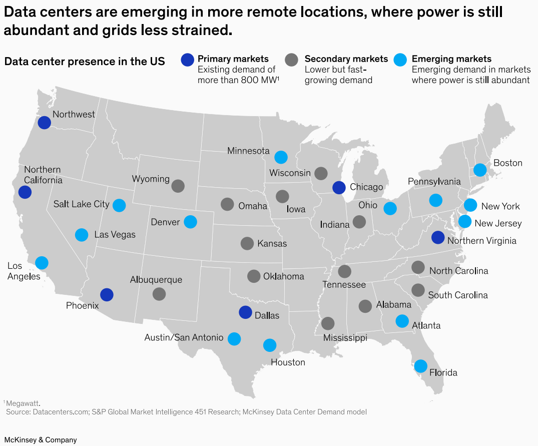
- Average US electricity bills **rose** 4.8% **per year** from 2019-2023[a]
- 1 out of 3 **US households** reported forgoing basic necessities, such as food or medicine, to pay household energy bills in 2024[b]
- US electricity **consumer debt totaled** $21.1 billion as of September 2024.

[a] S. Forrester, et al. “Retail Electricity Price and Cost Trends,” Lawrence Berkeley National Laboratory, 2024.

[b] U.S. Census Phase 4.2 Cycle 09 Household Pulse Survey: August 20 – September 16, 2024

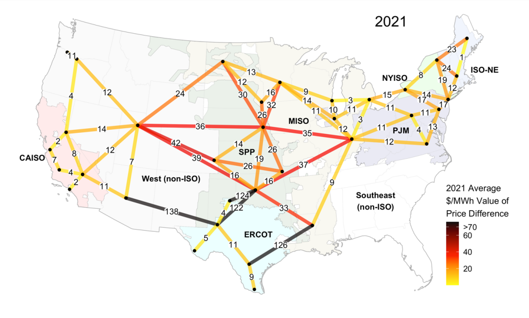
Rapid load growth dilemma i

- Vast numbers of new datacenters
- **Grid planners of tomorrow:** Stuck with **combinatorial** spaces
  - **At what node(s)** should we install a new datacenter?
  - **To what line(s)** should we interconnect?
  - etc...



McKinsey & Company

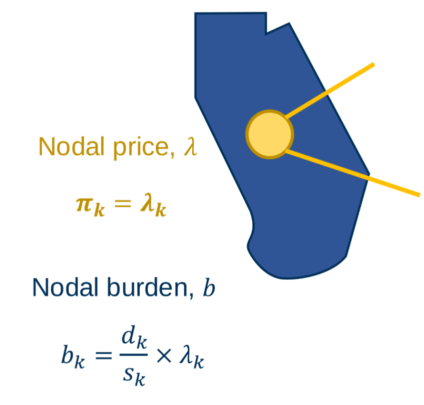
- **Line congestion** has an impact on our ability to:
    - integrate renewables
    - dispatch cheaper generators
    - meet demand
- This can impact consumer electricity costs.



Lawrence Berkeley National Laboratory

Prices and their impact

- Network structure $\rightarrow$ electricity prices $\pi(\cdot)$; **function of** the locational marginal price (LMP) $\boldsymbol{\lambda}$.
- LMP: the cost of serving an additional unit of load, constrained by network congestion and losses in the wholesale market.
- **Energy burden**: Fraction of income spent on energy (we'll focus on electricity)



The paradox of grid upgrades: Just one more line? i

Catch-22

- Unprecedented load growth
- **Unprecented unaffordability**
- Grid infrastructure has to adapt
- ...but how?

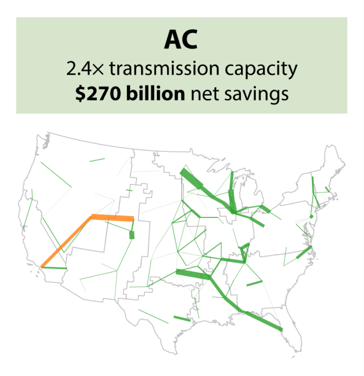
Credit: Getty Images/Futurism

The paradox of grid upgrades: Just one more line? ii

One approach (but not the only one):

Expanding transmission capacity

- Lower overall system costs ✓
- Lower emissions ✓
- Lower customer prices ✓
- ...but does it always?

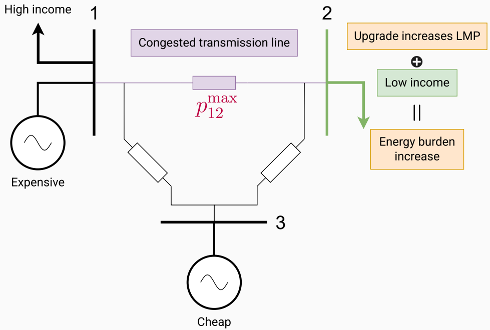


Credit: Christopher Schwing, NREL

U.S. Department of Energy, Grid Deployment Office. 2024. The National Transmission Planning Study. Washington, D.C.: U.S. Department of Energy.

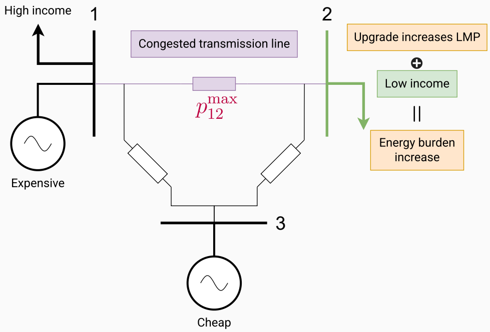
The paradox of grid upgrades: Just one more line? iii

- Just like roads, water pipes, and arteries: **Power grid transmission lines can become congested.**
- Congestion has an increasingly large impact on electricity prices.

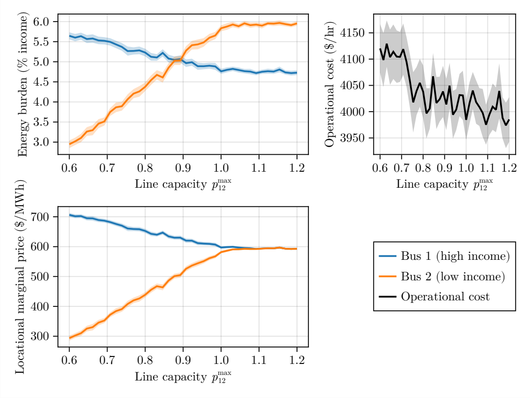


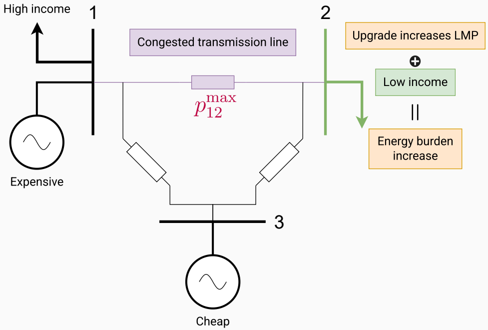
The paradox of grid upgrades: Just one more line? iv

- Just like roads, water pipes, and arteries: Power grid transmission lines can become congested.
- Congestion has an increasingly large impact on retail prices for electricity.
- Consumer costs:
    - typically reduce as congestion is reduced, but...
    - ...may counterintuitively rise† as a result of reducing congestion



†B. C. Lesieutre and J. H. Eto, "Electricity Transmission Congestion Costs: A Review of Recent Reports", Tech Rep. LBNL-54049, 2003.



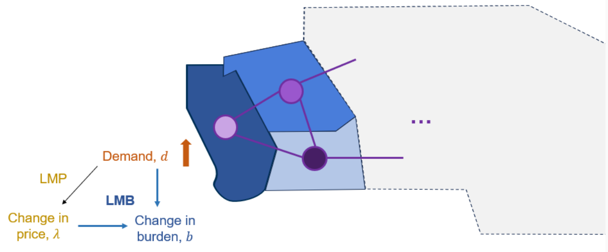


Well-intentioned grid upgrades can cause unfair pricing impacts on consumers.

Locational marginal burden (LMB)

What is locational marginal burden?

- **LMP:** the cost of serving an additional unit of load, constrained by network congestion and losses in the wholesale market
- **LMB:** Analogous Concept, for *energy burden*, fraction of income spent on energy.



LMB as a Decision-Making Tool for Regulators

- **Quantifies affordability** in electricity pricing relative to grid infrastructure
- Evaluates **affordability implications** of grid investments and operations
- Enables data-driven regulatory decisions on infrastructure fairness

LMB bridges performance incentives and affordability goals

How do we measure affordability? i

Choices: Set of grid planning decisions $\mathcal{U}$, e.g.:

- **Expansion planning:** All possible ways to add q lines to an initial network configuration $\boldsymbol{s}_0 \in \{0,1\}^m$:

$$\mathcal{U}_q(\boldsymbol{s}_0) = \left\{ \boldsymbol{s} \in \{0,1\}^m \ : \ \sum_{l \in E} s_l \leq q, \quad \text{and} \quad s_l = 1 \quad \forall l \in \operatorname{supp}(\boldsymbol{s}_0) \right\}.$$

- **Load allocation:** All ways to allocate a total of Δ MW of new load to an existing demand vector $\boldsymbol{d}_0$ (e.g., data centers)

$$\mathcal{U}_\Delta(\boldsymbol{d}_0) = \left\{ \boldsymbol{d} \in \mathbb{R}^n \ : \ \boldsymbol{d}_0 \leq \boldsymbol{d} \leq \boldsymbol{d}_0 + \Delta \mathbf{1}_n, \quad \text{and} \quad \sum_i d_i = \Delta + \sum_i d_{0,i} \right\}$$

The energy burden function

Given **customer incomes** $\boldsymbol{s} \in \mathbb{R}^n_+$, and grid parameters $\boldsymbol{u} \in \mathcal{U}$, the *energy burden function* $\boldsymbol{b} : \mathcal{U} \to [0,1]^n$ is

$$\boldsymbol{b} = \mathrm{diag}(\boldsymbol{d} \oslash \boldsymbol{s})\boldsymbol{\pi}^\star(\boldsymbol{u}).$$

A node i is said to be suffering from *energy poverty* at a threshold $t > 0$ if $b_i > t$.

Responsible grid planning

Framework i

Find the best upgrades $\boldsymbol{u} \in \mathcal{U}$ to minimize an **energy insecurity function** $E(\pi)$, where π is a vector of electricity prices that are an implicit function of the **dual solution of an OPF problem**, $\pi \in P(\boldsymbol{u})$, solved on the *upgraded grid*.

Responsible Grid Planning

Our algorithm solves the parametric mathematical optimization problem:

$$\underbrace{\min_{\boldsymbol{u}} \; E(\boldsymbol{\pi}(\boldsymbol{u}))}_{\text{minimize energy insecurity}} \qquad \text{subject to} \qquad \underbrace{\boldsymbol{\pi} \in \mathcal{P}(\boldsymbol{u}), \quad \boldsymbol{u} \in \mathcal{U}.}_{\text{energy pricing under grid upgrades}} \tag{1}$$

Example 1: Load allocation (Hawaii Network) i

- **Energy insecurity objective**: Total (potentially thresholded) energy burden

$$E(\boldsymbol{u}; \boldsymbol{\pi}(\boldsymbol{u})) = \sum_{i=1}^{n} b_i(\boldsymbol{u}) = \sum_{i=1}^{n} \frac{d_i}{s_i} \cdot \pi(\boldsymbol{u})$$

- **Energy insecurity gradient**: Sum of LMB matrix rows

$$\nabla_{\boldsymbol{u}} E(\boldsymbol{u}; \boldsymbol{\pi}(\boldsymbol{u})) = \sum_{i=1}^{n} \nabla b_i(\boldsymbol{u}) = (\mathrm{LMB}(\boldsymbol{u}))^\top \mathbf{1}.$$

$$\min_{\boldsymbol{d}} \; E(\boldsymbol{\pi}(\boldsymbol{d}))$$
$$\text{s.t.} \quad \boldsymbol{d} \in \mathcal{U}_\Delta(\boldsymbol{d}_0),$$
$$\underbrace{\boldsymbol{\pi}(\boldsymbol{d}) \in \mathcal{P}(\boldsymbol{d})}_{\text{dual solution of DC OPF}}$$

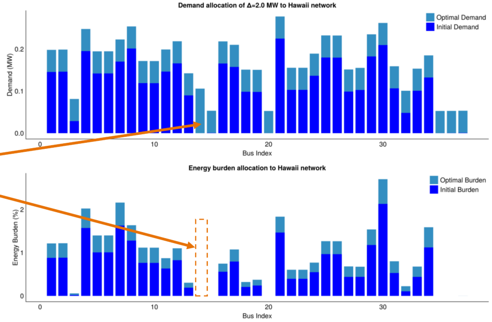
Key idea:

Improve energy insecurity by allocating new demand in **the right locations.**

$$\mathcal{U}_\Delta(\boldsymbol{d}_0) = \{\boldsymbol{d} \in \mathbb{R}^n \;:\; \boldsymbol{d}_0 \leq \boldsymbol{d} \leq \boldsymbol{d}_0 + \Delta \mathbf{1}_n, \quad \text{and} \quad \sum_i d_i = \Delta + \sum_i d_{0,i}\}.$$

Example 1: Load allocation (Hawaii Network) iii

As Δ increases, the algorithm begins allocating relatively more demand to an uninhabited node (defined to have 0 energy burden)



Example 2: Expansion planning i

$$\min_{\boldsymbol{u} \in \{0,1\}^m} E(\boldsymbol{u})$$

power flow eqns.

expansion budget $\quad (||\boldsymbol{u}||_1 \leq q)$

initial lines $\quad (s_e = 1 \quad \forall e \in S_0)$

Key idea:

Improve energy insecurity by **adding the right lines.**

Conclusion

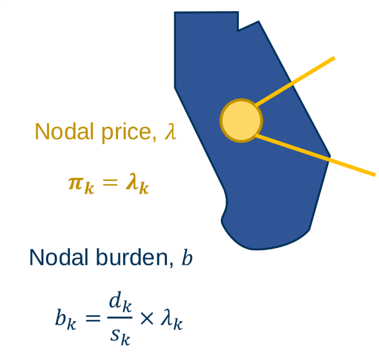
- Introduced LMB, sensitivity of energy insecurity to grid parameters.
- Operationalize decision making for policymakers, grid planners, etc.
- Admits fast, trustworthy algorithms for affordability-aware grid planning.

Thank you

job market paper

"Randomized Switching"

https://samueltalkington.com/



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