Locational marginal burden:

Quantifying the equity of optimal power flow solutions

Amanda West, Samuel Talkington, Rabab Haider

INFORMS 2024

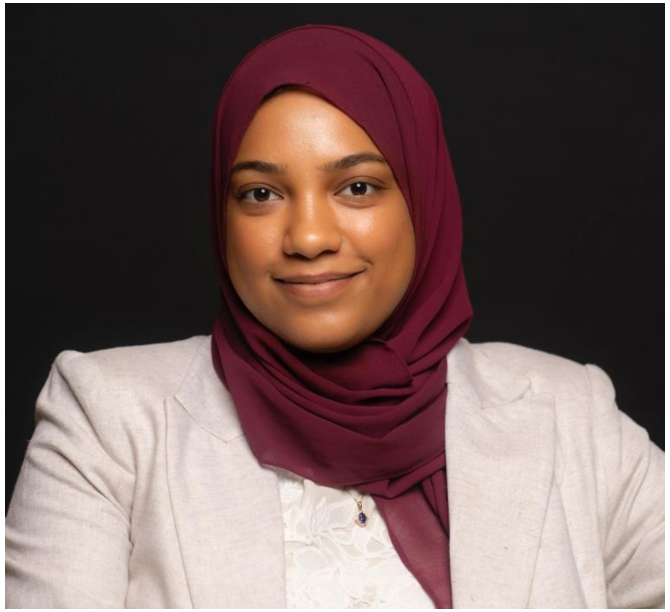
October 22nd , 2024

Georgia Tech

Contributors

Samuel Talkington
Ph.D. Student
Georgia Institute of Technology

Amanda West
Ph.D. Student
Georgia Institute of Technology



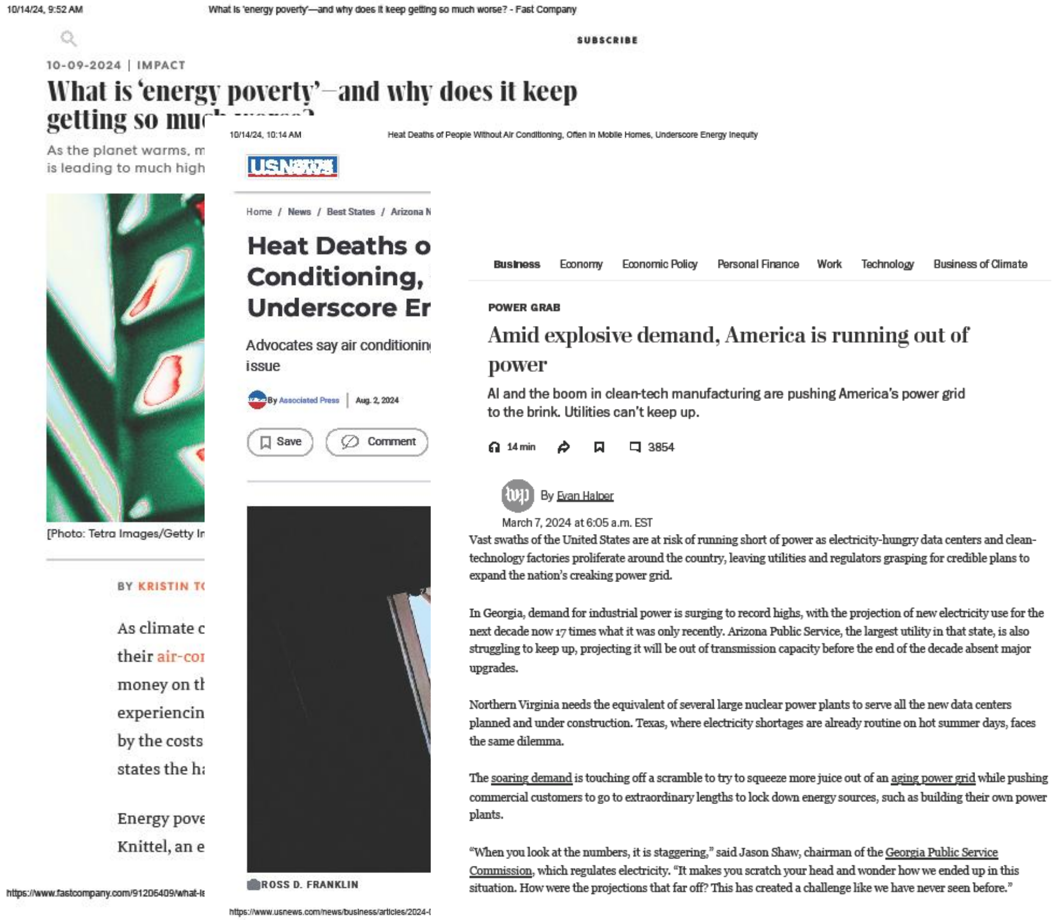
Rabab Haider
Assistant Professor (Jan 2025)
University of Michigan

Postdoctoral Fellow
AI4OPT and ISyE
Georgia Institute of Technology

Georgia Tech

Introduction to Energy Equity in Power Systems

- **Energy Equity:**
  - Fair distribution of benefits and burdens associated with the power system to all stakeholders
  - Traditionally a policymaking problem
- **Distribution:**
  - Electricity Rates [1]
  - PV Hosting Capacity [3]
- **Transmission:**
  - Capacity Expansion
  - Infrastructure Hardening [2]


10/14/24, 9:52 AM What is 'energy poverty'—and why does it keep getting so much worse? - Fast Company

SUBSCRIBE

10-09-2024 | IMPACT

What is 'energy poverty'—and why does it keep getting so muc

As the planet warms, m
is leading to much high

[Photo: Tetra Images/Getty Im

BY KRISTIN TO

As climate c
their air-cor
money on th
experiencin
by the costs
states the ha

Energy pove
Knittel, an e

https://www.fastcompany.com/91206409/what-is

10/14/24, 10:14 AM Heat Deaths of People Without Air Conditioning, Often in Mobile Homes, Underscore Energy Inequity

Home / News / Best States / Arizona N

Heat Deaths o
Conditioning,
Underscore Er

Advocates say air conditionin
issue

By Associated Press | Aug. 2, 2024

Save Comment

ROSS D. FRANKLIN

https://www.usnews.com/news/business/articles/2024-

Business Economy Economic Policy Personal Finance Work Technology Business of Climate

POWER GRAB

Amid explosive demand, America is running out of power

AI and the boom in clean-tech manufacturing are pushing America's power grid to the brink. Utilities can't keep up.

14 min 3854

By Evan Halper

March 7, 2024 at 6:05 a.m. EST

Vast swaths of the United States are at risk of running short of power as electricity-hungry data centers and clean-technology factories proliferate around the country, leaving utilities and regulators grasping for credible plans to expand the nation's creaking power grid.

In Georgia, demand for industrial power is surging to record highs, with the projection of new electricity use for the next decade now 17 times what it was only recently. Arizona Public Service, the largest utility in that state, is also struggling to keep up, projecting it will be out of transmission capacity before the end of the decade absent major upgrades.

Northern Virginia needs the equivalent of several large nuclear power plants to serve all the new data centers planned and under construction. Texas, where electricity shortages are already routine on hot summer days, faces the same dilemma.

The soaring demand is touching off a scramble to try to squeeze more juice out of an aging power grid while pushing commercial customers to go to extraordinary lengths to lock down energy sources, such as building their own power plants.

"When you look at the numbers, it is staggering," said Jason Shaw, chairman of the Georgia Public Service Commission, which regulates electricity. "It makes you scratch your head and wonder how we ended up in this situation. How were the projections that far off? This has created a challenge like we have never seen before."

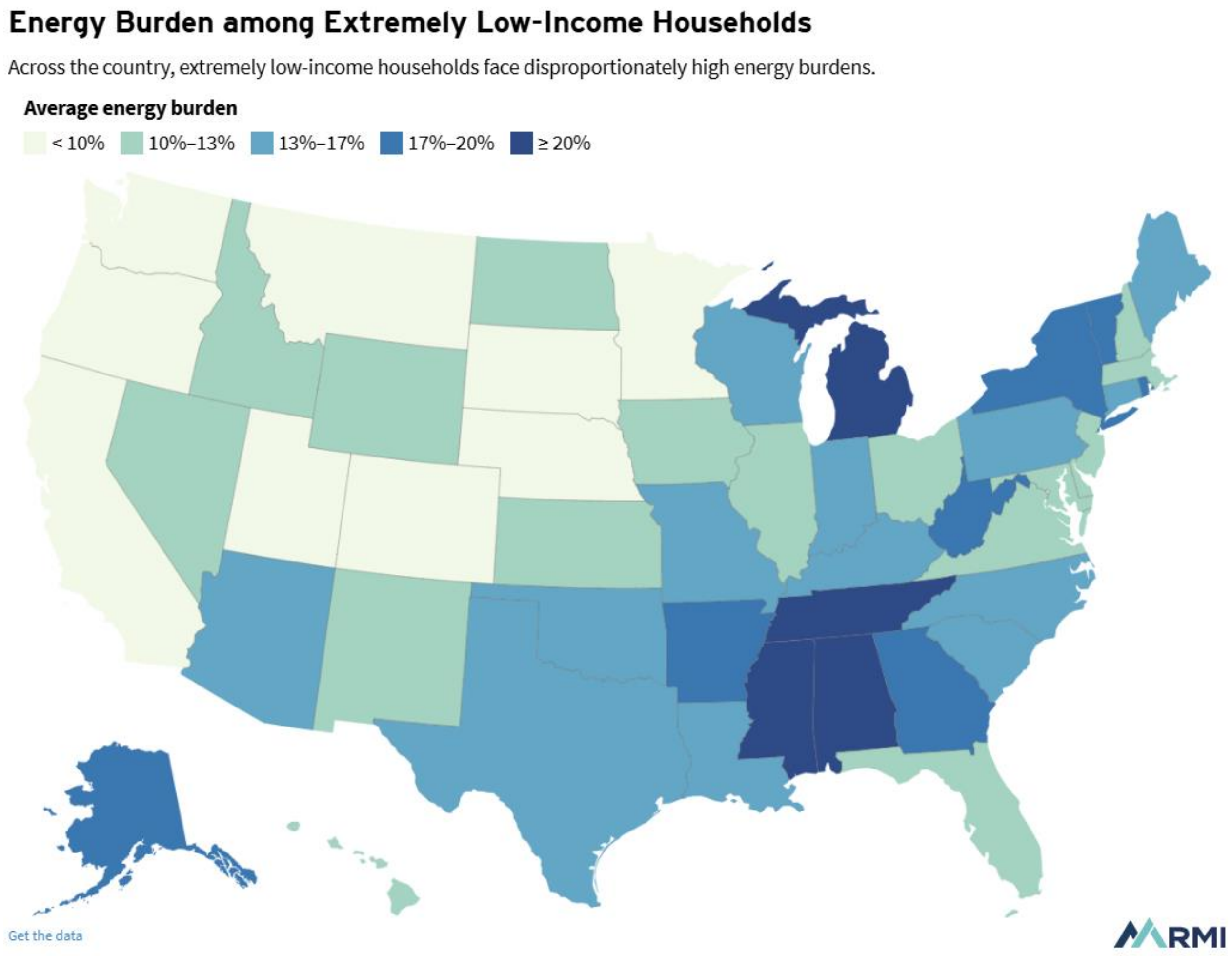
- [1] M. Ansarin, Y. Ghiassi-Farrokhfal, W. Ketter, J. Collins, "A review of equity in electricity tariffs in the renewable energy era", Renewable and Sustaina Volume 161, 2022
- [2] M. Pollack, R. Piansky, S. Gupta, A. Kody and D. K. Molzahn, "Equitably allocating wildfire resilience investments for power grids: The curse of aggregation and vulnerability indices", Power System Computation Conference, 2024.
- [3] E. Hartvigsson, E. Nyholm, and F. Johnsson, "Does the current electricity grid support a just energy transition? Exploring social and economic dimensions of grid capacity for residential solar photovoltaic in Sweden", Energy Research & Social Science, Volume 97, 2023,

Quantifying Energy Affordability

- Affording energy without sacrificing other basic living expenses
- Commonly used metric:

  Energy Burden
  - Percent of income spent on energy expenses
  - Above 6% is *energy poor*

- Need methods to quantify energy affordability **within network operations**



https://rmi.org/1-in-7-families-live-in-energy-poverty-states-can-ease-that-burden/

U.S. Department of Energy. "Making Clean Energy More Accessible and Affordable." Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy, https://www.energy.gov/eere/energy-accessibility-and-affordability.

Georgia Tech

What is the impact of network infrastructure on energy affordability?

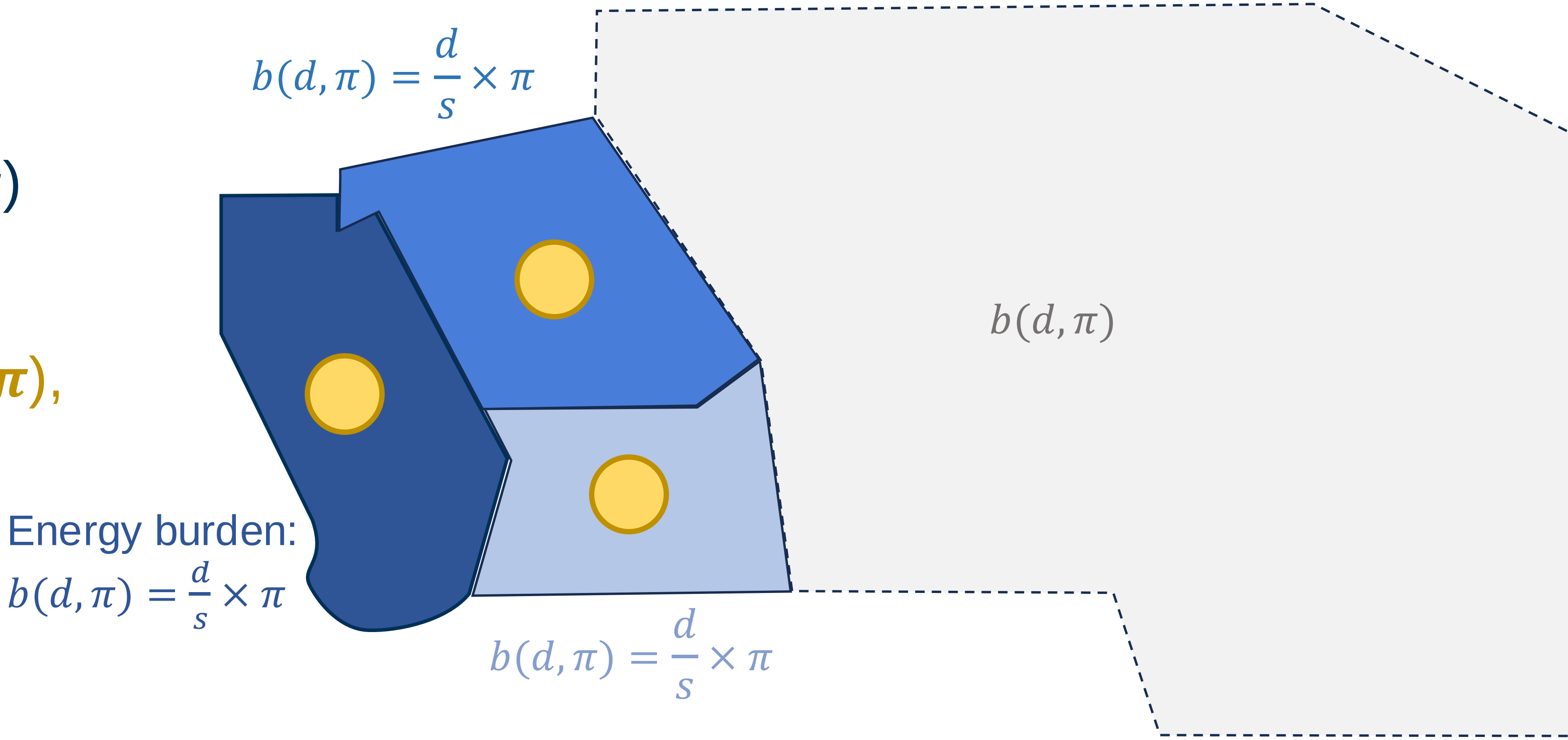
Georgia Tech

Energy Burden: Engineering Definition

Census tract:
average income data ($\boldsymbol{s}$)

Bus in power system:
retail electricity prices ($\boldsymbol{\pi}$), aggregate electricity demand ($\boldsymbol{d}$)

Map census tract to power system bus



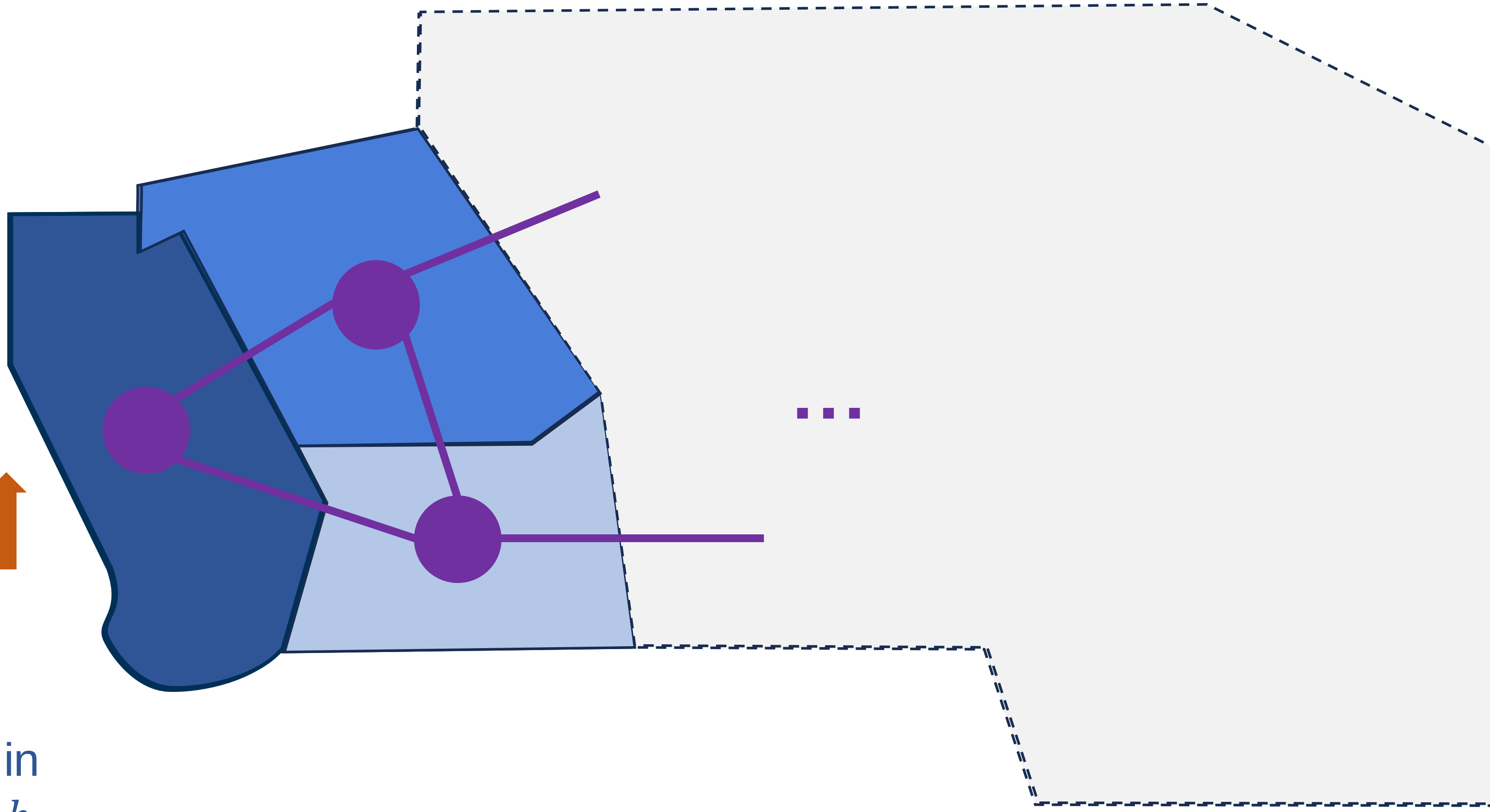
Energy burden function for network:

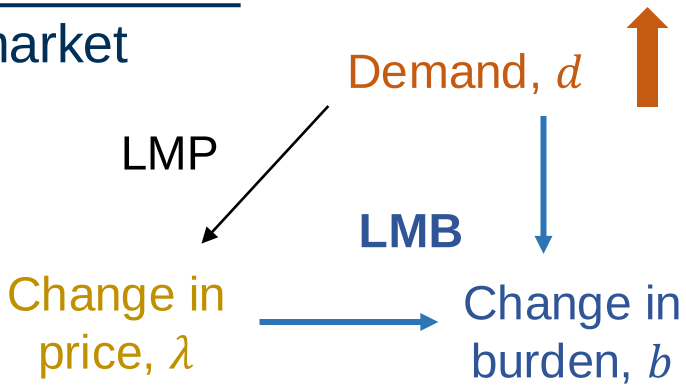
$$\boldsymbol{b}\,(\boldsymbol{\pi};\ \boldsymbol{d}) \coloneqq \mathrm{diag}(\underbrace{\boldsymbol{d} \oslash \boldsymbol{s}}_{\text{Element-wise multiplication}})\boldsymbol{\pi}$$

Locational Marginal Burden

Underlying network structure impacts electricity prices, described by the locational marginal price (LMP).

LMP: the cost of serving an additional unit of load, constrained by network congestion and losses in the wholesale market





We develop an analogous concept:
Locational marginal burden (LMB) describes the change in energy burden incurred by serving one additional unit of demand at that bus

Connecting households to the transmission retail rate

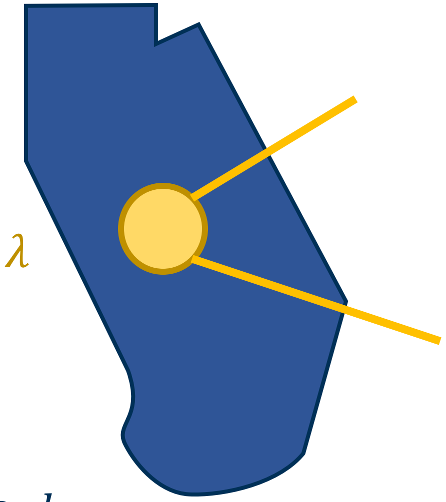
In each distribution network D_k, each household pays at the **retail price ($\boldsymbol{\pi}$)**

Approximate this by the transmission-level LMP ($\boldsymbol{\lambda_k}$) at transmission node k:

$$\boldsymbol{\pi_k = \lambda_k}$$

For every household (i) in a distribution network (D_k), the approximate energy burden of each household is:

$$b_{k,i} = \frac{\lambda_k}{\#\text{households}} \sum_{i \in D_k} \frac{demand_{k,i}}{salary_{k,i}}$$



Nodal price, λ

$$\boldsymbol{\pi_k = \lambda_k}$$

Nodal burden, b

$$b_k = \frac{d_k}{s_k} \times \lambda_k$$

Household burden, $b_{k,i}$

LMP from Parameterized DC OPF

The LMP can be calculated using a standard DC Optimal Power Flow (OPF)

We *parameterize* the DC OPF program as $P(\boldsymbol{\theta})$ where $\boldsymbol{\theta}$ includes the cost of generation (α, β) and the demand (d):

$$P\left(\boldsymbol{\theta}\right) = \min_{\boldsymbol{g},\boldsymbol{p}} \sum_{i=1} \alpha_i g_i^2 + \beta_i g_i,$$

Minimize operational cost, subject to:

$$\text{s.t. } \boldsymbol{F}(\boldsymbol{B}\boldsymbol{g} - \boldsymbol{d}) = \boldsymbol{p}$$

DC approximation of power flow physics

$$1^\top \boldsymbol{B}\boldsymbol{g} = 1^\top \boldsymbol{d},$$

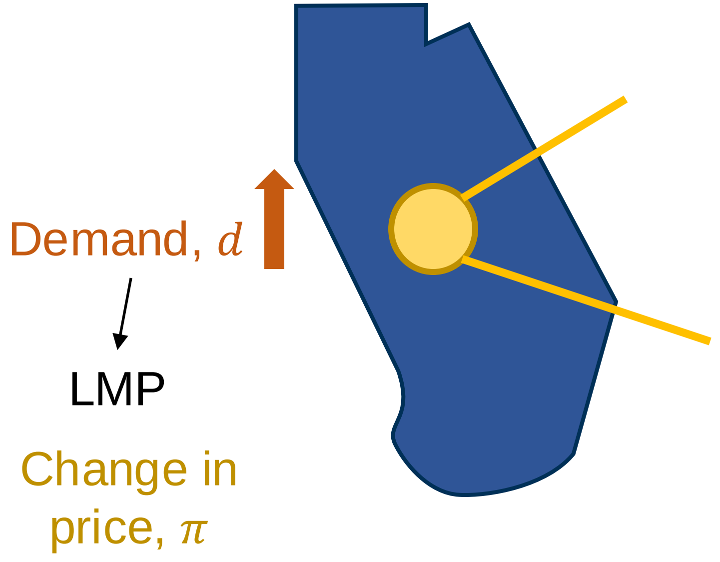
Power balance constraints

$$-\boldsymbol{p} \leq \boldsymbol{p} \leq \boldsymbol{p}$$

Line flow limit constraints

$$0 \leq \boldsymbol{g} \leq \boldsymbol{g},$$

Generation capacity constraints



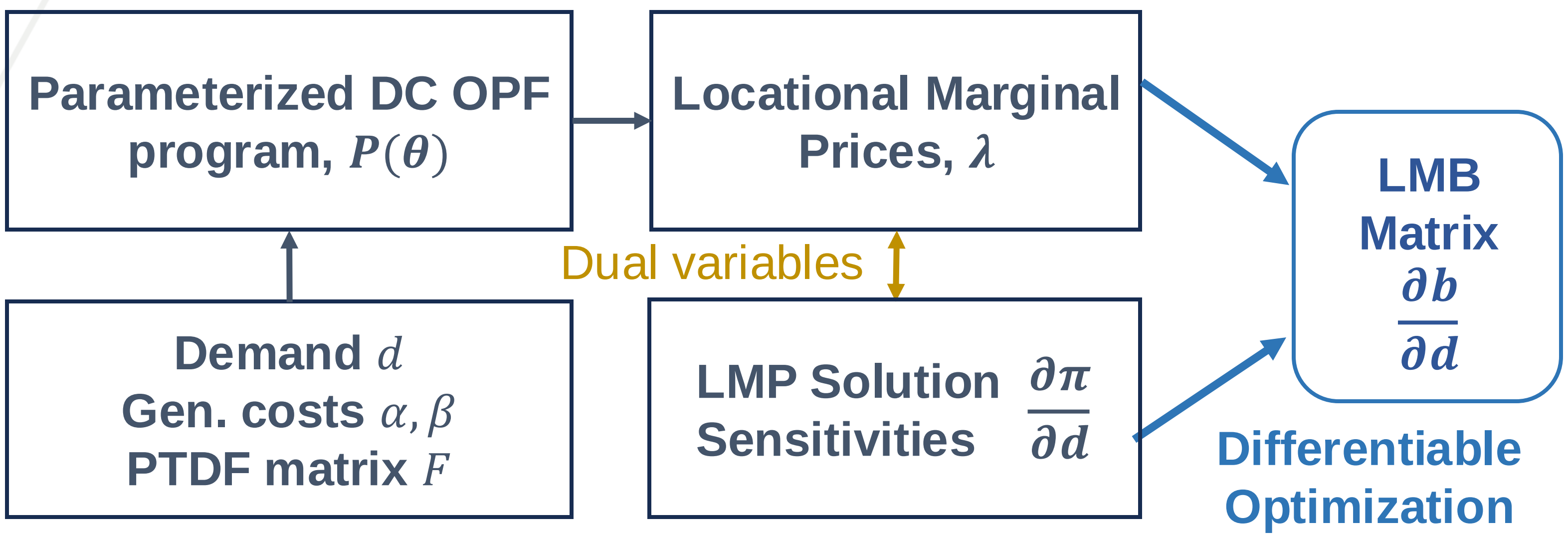
Take the dual and derivative

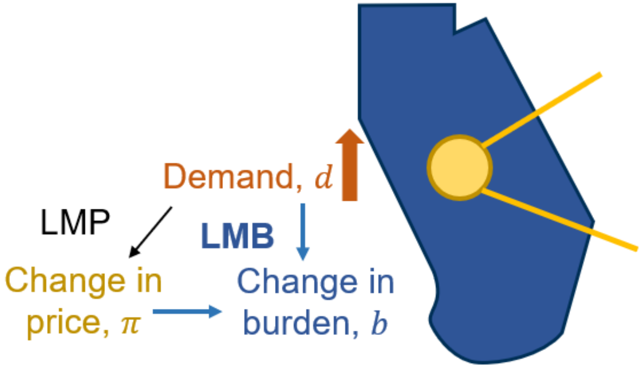
LMP Solution Sensitivities

$$\frac{\partial \pi}{\partial d}$$

Georgia Tech

Computing LMB using differentiable optimization





$$\frac{\partial \boldsymbol{b}}{\partial \boldsymbol{d}} = -\,\mathrm{diag}(\boldsymbol{d} \oslash \boldsymbol{s})[\boldsymbol{F}^\top \; 1]\frac{\partial \boldsymbol{v}^*}{\partial \boldsymbol{d}} + \mathrm{diag}\left(\boldsymbol{\pi}\left(\boldsymbol{v}^*(\boldsymbol{d})\right) \oslash \boldsymbol{s}\right)$$

Demand ($\boldsymbol{d}$)

Customer income ($\boldsymbol{s}$)

Implicit LMP sensitivities ($\frac{\partial \boldsymbol{v}^*}{\partial \boldsymbol{d}}$)

Retail prices (transmission approx.) ($\boldsymbol{\pi}(\boldsymbol{v}^*(\boldsymbol{d}))$)

Georgia Tech

LMB Matrix Representation

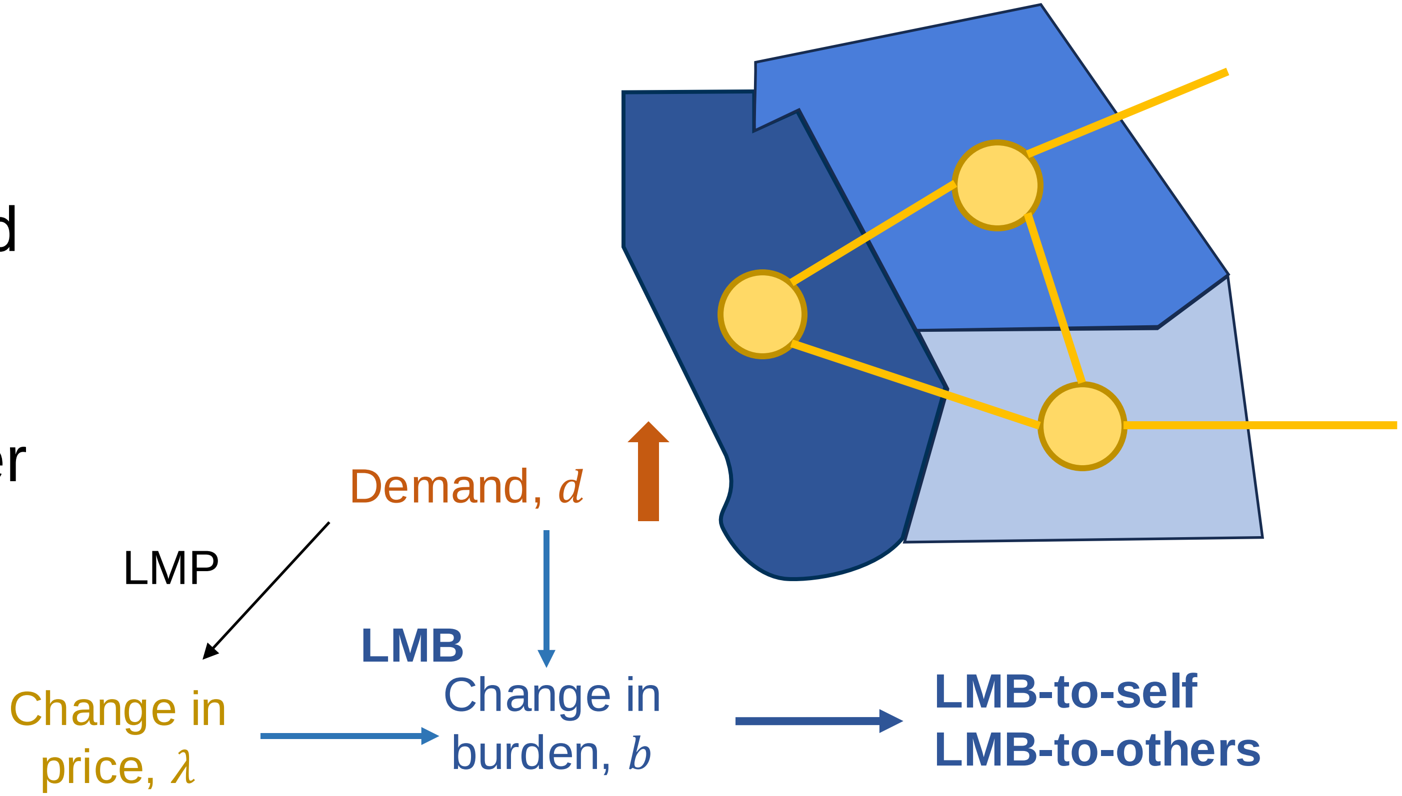
- **LMB-to-self** are the diagonal entries of the LMB matrix
- **LMB-to-others** are the off-diagonal entries of the LMB matrix

$$\frac{\partial \boldsymbol{b}}{\partial \boldsymbol{d}} = \begin{bmatrix} \frac{db_1}{dd_1} & \cdots & \frac{db_1}{dd_k} \\ \vdots & \ddots & \vdots \\ \frac{db_k}{dd_1} & \cdots & \frac{db_k}{dd_k} \end{bmatrix}$$

LMB Captures Network Wide Effects

- **LMB-to-self**: the change in burden at a node due to the same node’s change in demand

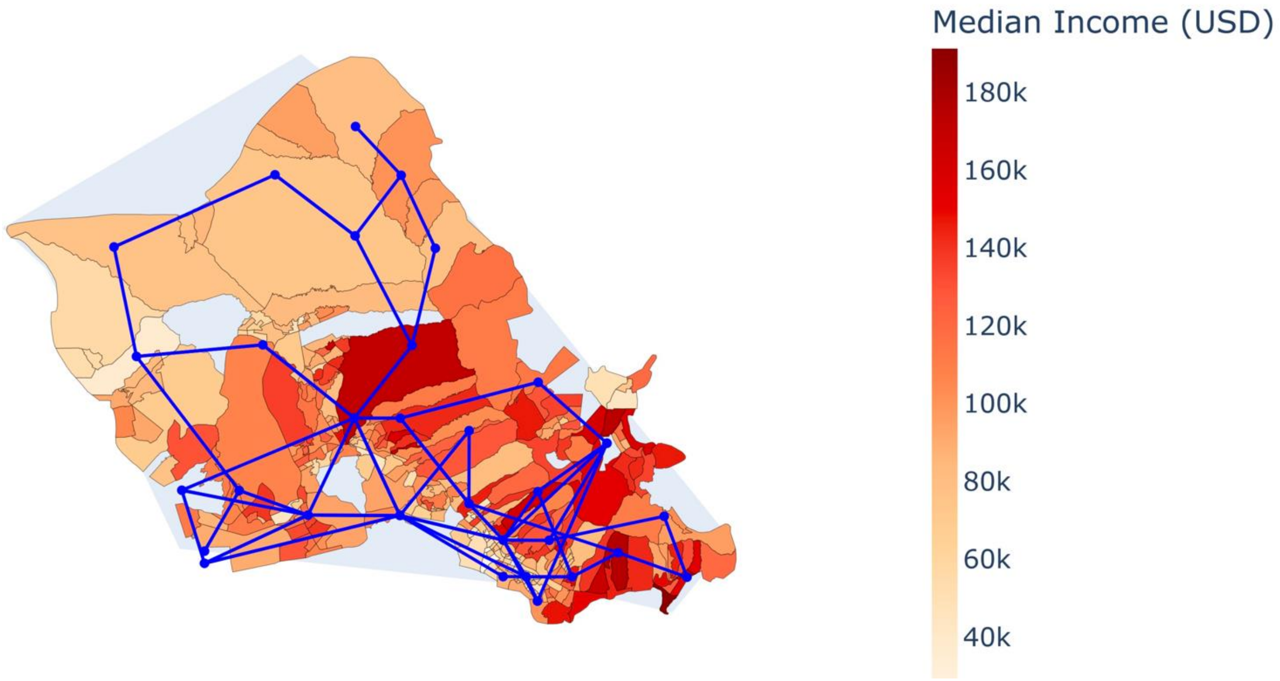
- **LMB-to-others:** the change in burden at a node due to another node’s change in demand; *captures network-wide effects*



Case Study: Hawaii

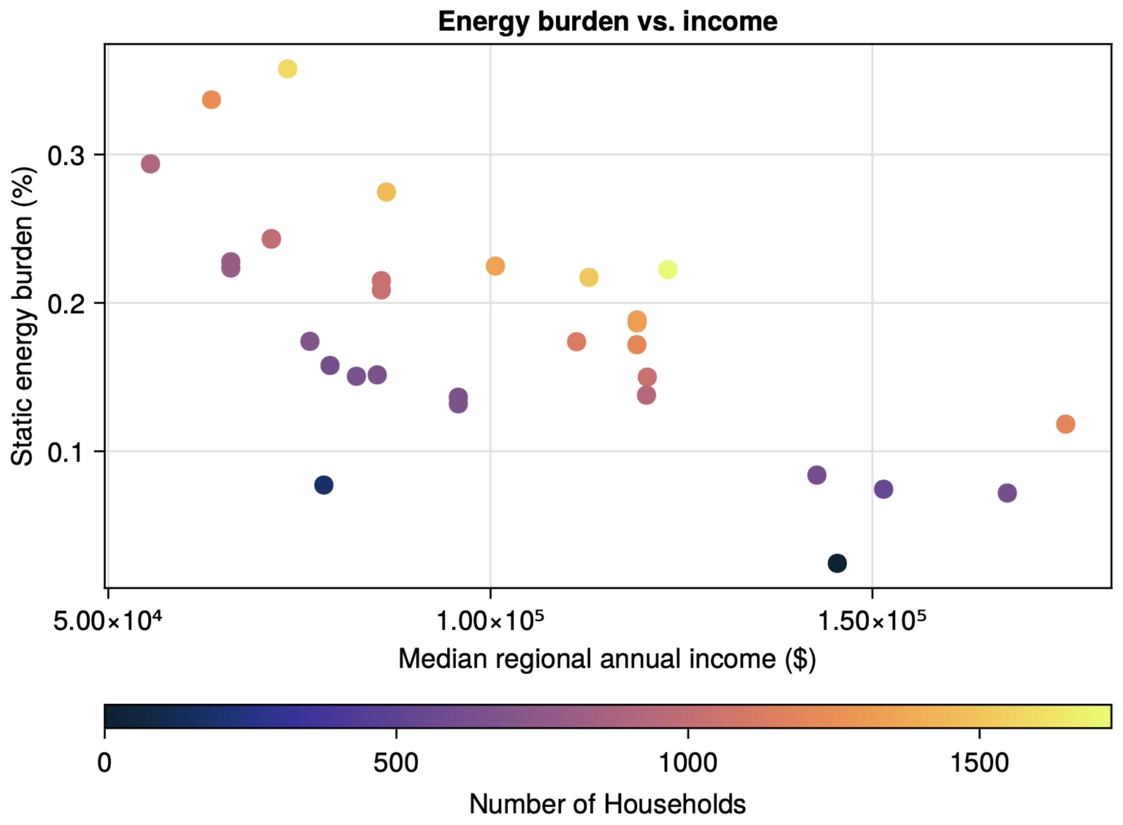
Case Study: Hawaii Synthetic Transmission Network

- **Transmission Network**
  - Texas A&M Hawaii 37 Synthetic Transmission Network
- **Income Data**
  - 2021 American Communities Survey



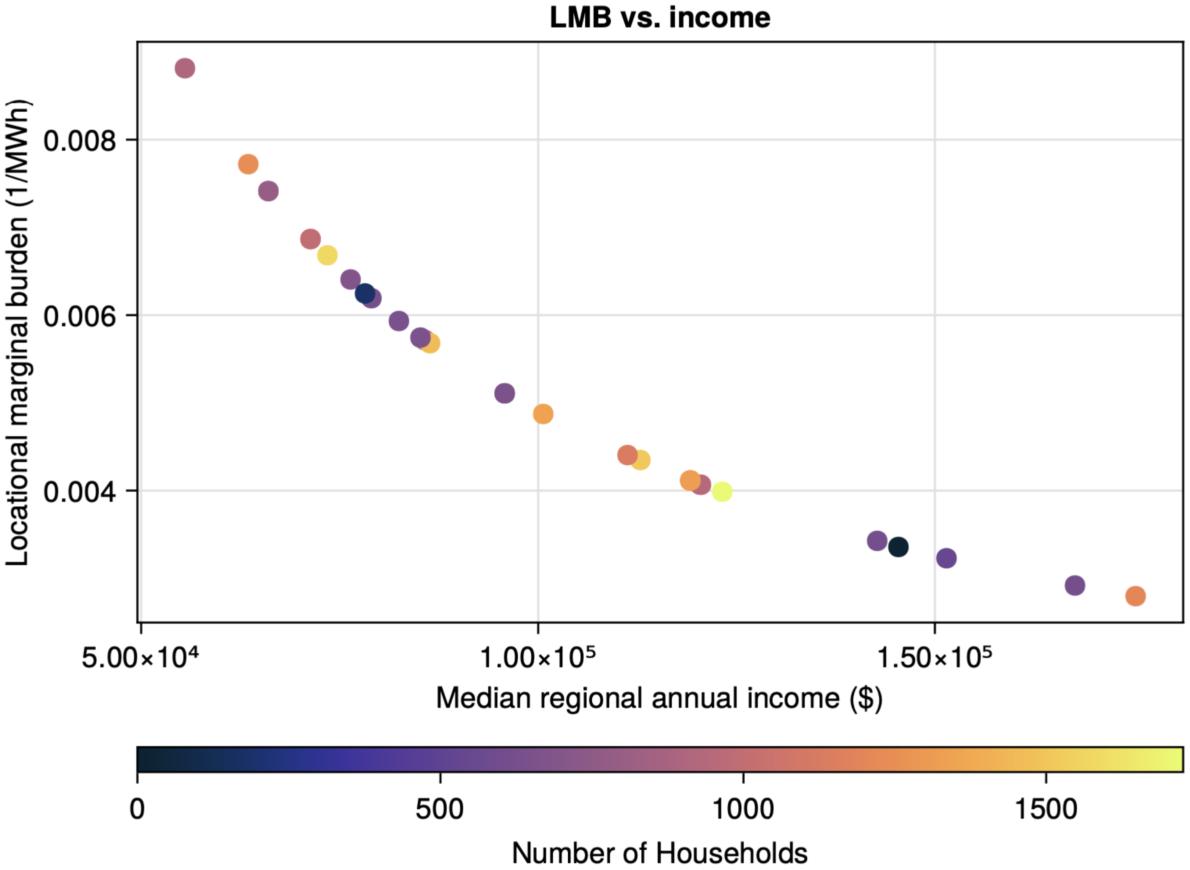
Case Study: Energy Burden

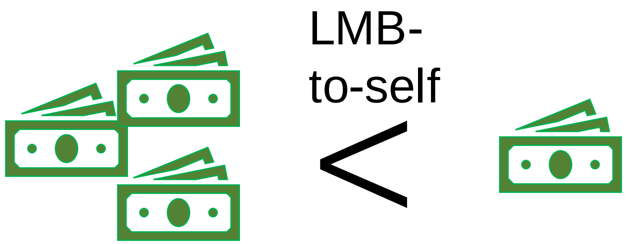
- Energy burden inversely correlated with income
- Within same income bracket, higher populous regions incur higher energy burden



Case Study: Energy Burden vs. LMB-to-self

- LMB is the rate of change in energy burden with respect to demand
- LMB-to-self inversely correlated with income
- No correlation with population

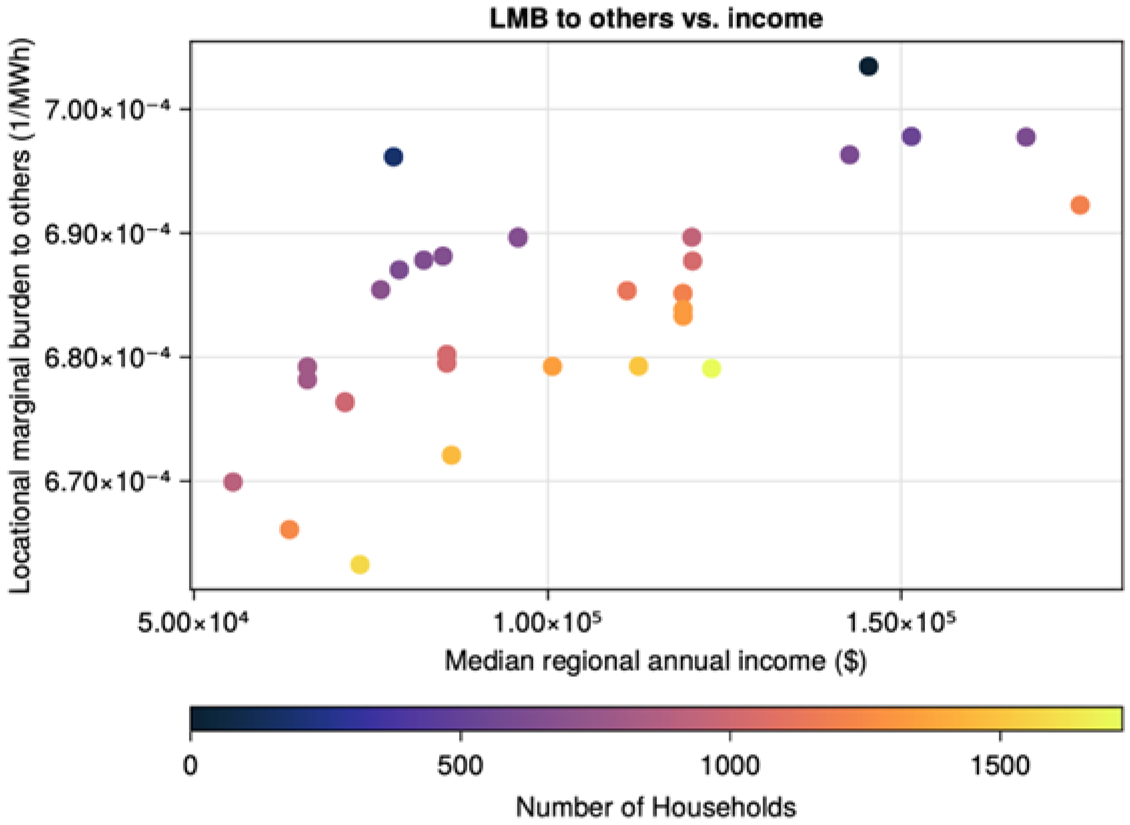


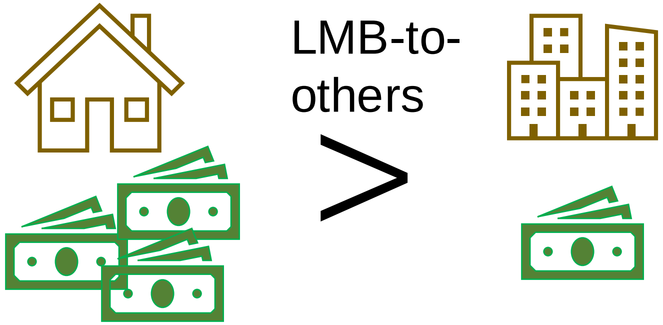


Case Study: LMB-to-Others, Income, and Population

- LMB-to-Others: the impact neighboring nodes have on each other's LMB.

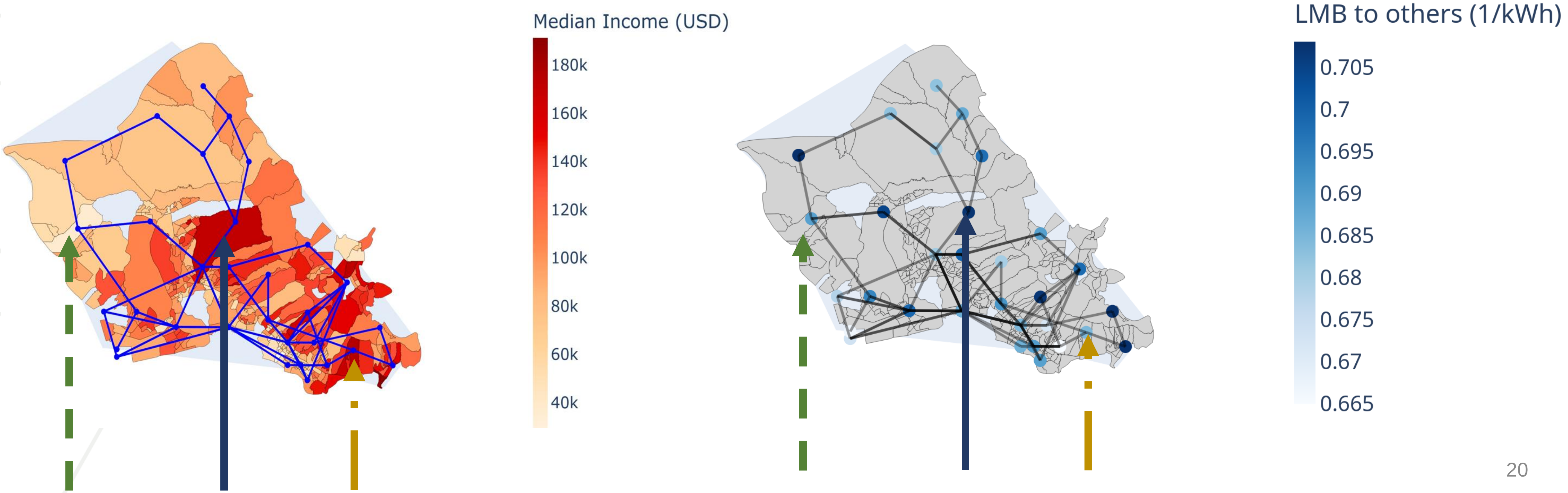
- Customers living in areas with **low population density and high income, have a higher impact of LMB to others** relative to customers living in high population density with low income.





Case Study: Hawaii Synthetic Transmission Network

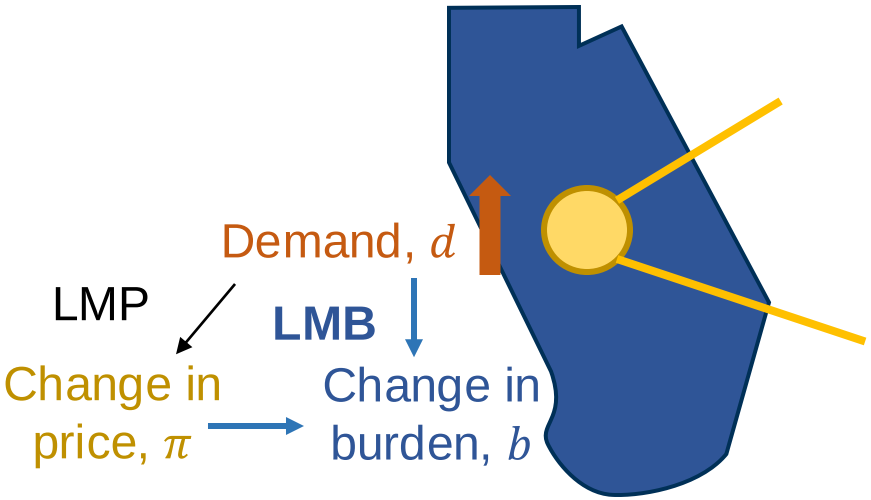
- **Low population density and high income, have a higher impact of LMB to others**



High income, high LMB-to-others
Lower income, lower LMB-to-others
High income, lower LMB-to-others

Bringing energy burden to power systems

- Locational Marginal Burden (LMB) reflects the operational impacts of power systems on energy burden
- Quantifies the impact of an additional unit of demand on energy burden – across network topology
- Next steps:
  - Closer alignment to real system
  - LMB population and income analysis



Thank you!

Read our paper!

Connect with us:

Amanda West

Rabab Haider: rababh@umich.edu
Sam Talkington: talkington@gatech.edu

Thanks to the NSF Graduate Research Fellowship Program and NSF Grant No. 2112533. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the NSF.

AI Institute for Advances in Optimization

National Science Foundation

Georgia Tech