Empirical Methods for the Analysis of the Energy Transition

Slide Set 10

Prof. Mar Reguant

2025/2026

Roadmap

Big push in the electricity sector to decarbonize and electrify

- Need to reduce Green House Gas emissions (GHGs).
- Electricity sector ($\approx$35-40% of CO_2 emissions) has been **most active** and has the greatest potential in making the transition.
- Ambition to move towards **carbon-free electricity** by 2035-2040.
- **Limits to decarbonization**:
  - ▶ **Renewables' intermittency** might lead to a potential mismatch between supply and demand, increasing need for flexibility.
  - ▶ **Extreme events** with adverse outcomes for households also intensify impacts on infrastructure and lead to extreme demand.
  - ▶ **Growing pressures** due to decarbonization of other sectors.

Blackouts as an extreme outcome

- When the system becomes stressed, **blackouts** become a possibility.
- During 2022, growing concerns about the possibility of energy shortages in Europe.
- Several leaders announced potential consumer-level planned systemic blackouts (e.g., Austria, France).
- Large blackouts have occurred recently in California and Texas and are a *daily occurrence* in many developing countries.

- While system-wide sustained blackouts are *relatively unlikely* in the US/Europe, likely to become more relevant due to energy transition and climate change.
  - ▶ Supply-side failures due to extreme weather
  - ▶ Demand spikes correlated with extreme weather and large changes in demand due to electrification

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Blackouts can become an important challenge

- The energy transition needs to happen very fast while climate impacts increase.
- The impacts of this transition can be highly uneven.
- Low-income households are already suffering the worst impacts of climate change.
- During extreme events, the grid and power plants are under extreme temperatures while demand soars.

Persistent blackout conditions are costly

Texas energy demand may exhaust supply this summer, ERCOT warns

Texas' energy grid operator warned that extreme scenarios may lead to rolling blackouts this summer.

Michael Murney, Chron
May 5, 2023

At least 111 people died in Texas during winter storm, most from hypothermia

The newly revised number is nearly twice the 57 that state health officials estimated last week and will likely continue to grow.

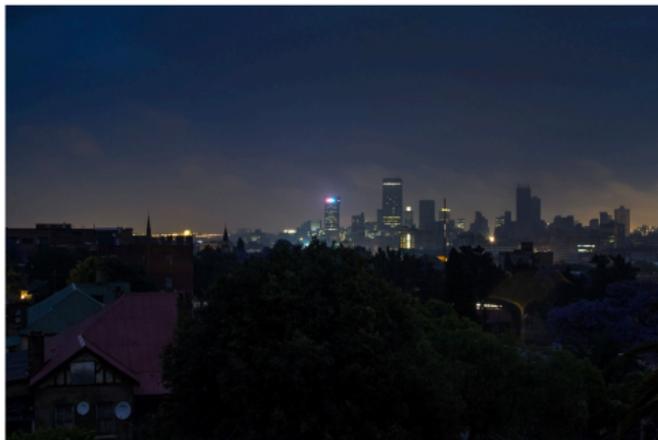BY SHAWN MULCAHY   MARCH 25, 2021   4 PM CENTRAL

Persistent blackouts common in other countries

South Africa Faces Most Severe Nationwide Power Cuts in Months

Darkness due to a load shedding in the Troyeville suburb of Johannesburg. *Photographer: Dean Hutton/Bloomberg*

By Adelaide Changole

February 10, 2024 at 9:57 AM GMT+1

Hanoi residents, firms struggle with blackouts amid heatwave

Sunday, June 04, 2023, 19:21 GMT+7

A security guard of a company in Hoai Duc District, Hanoi works in a narrow room. He must use a paper fan during a power cut. Photo: Pham Tuan / Tuoi Tre

Long power cuts made life harder for residents and enterprises in suburban areas of Hanoi amid the scorching weather on Saturday.

Highlights

Breakfast @ Tuoi Tre

Individual/public investments can help, but highly unequal

- High-income households can avoid blackouts with solar + battery systems that are oversized absent blackout concerns.
- With the rise of solar + batteries (microgrids), one can also build electrical shelters during blackouts.
- All these solutions will ease the burden on some households and neighborhoods.
- The impact of rolling blackouts can fall on HHs that cannot afford resilience preparedness.

Solar Microgrids for Santa Barbara Unified School District are set to move forward
A groundbreaking RFP process and PPA contract ensure massive bill savings and unparalleled resilience value for free at a California school district.

More generally, growing tensions with resource adequacy, reliability, and their costs

- Renewable power, extreme weather, and geopolitical tensions all make scarcity conditions and grid instability more likely.
- Need to do more research on what the right mechanisms and prices can ensure the best outcomes.
- This may require updating how regulators and consumers form expectations about interruptions.
- Gowrisankaran et al. (2016) anticipate the need to re-think reliability rules in the face of growing renewable power.
- Davi-Arderius and Graf (2025) highlight the trade-off between operational risk and consumer costs after the Spanish blackout.
- Gerlagh, Liski and Vehvilainen (2025) argue that more blackouts might be optimal if consumers are inattentive, and it might be better for them.

Rest of today

- Cover several empirical papers examining blackouts in detail:
    - ▶ The willingness to pay to avoid blackouts
    - ▶ The implications for grid reliability
    - ▶ The distributional aspects of these choices
    - ▶ Potential alternatives to blackouts using smart meters (my research)

- In all of these papers, equity concerns/uneven impacts of blackouts play an important role.

Central questions

When the grid becomes unreliable:

1 How much is reliability worth to households?

2 Do households privately adapt?

3 If they do, what should regulators do?

4 How do these responses depend on income?

5 If planned blackouts still occur, are there ways to improve them?

As explained before, electricity Reliability Is Deteriorating

- Weather-related outages increasing rapidly in the US
- Wildfires → Public Safety Power Shutoffs (California)
- Cold stress → Texas 2021 freeze and rolling blackouts
- Large increases in outage duration (SAIDI)

Graph: Li et al. (2024) - Data: Oak Ridge National Laboratory. Cumulative percentage hours with blackouts at the county level.
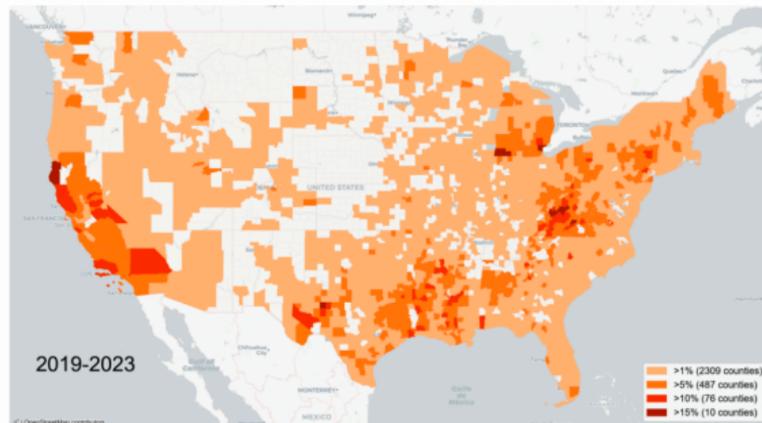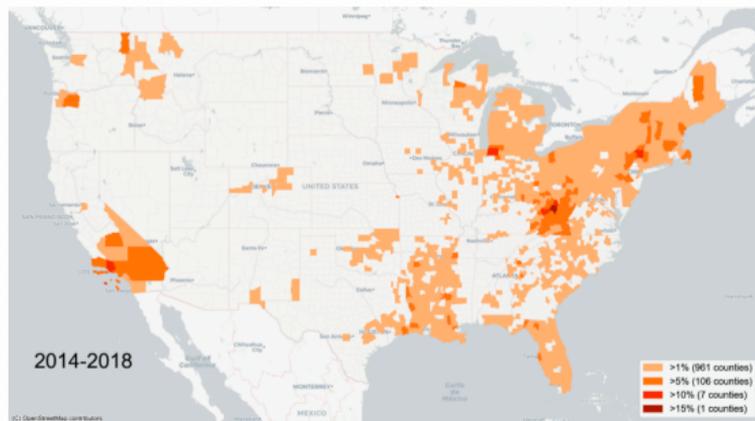
Roadmap

Puzzle: Solar + Battery Adoption in California

- **Context**: Fire-related outages due to wild fires: Public Safety Power Shutoffs (PSPS).
- Solar-only cannot provide power during outages
- Solar + battery has worse financial returns than solar alone
- Yet adoption explodes exactly in PSPS regions

People are not buying electricity savings. They are buying reliability.
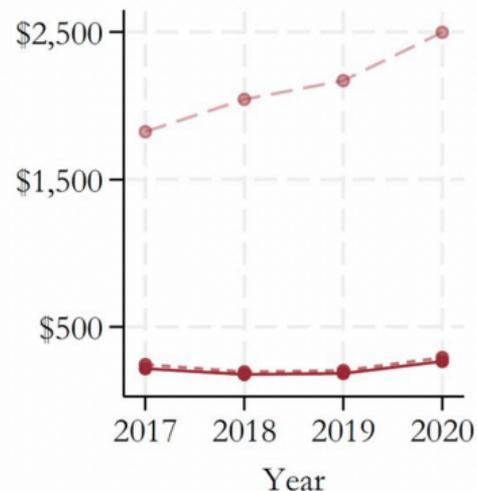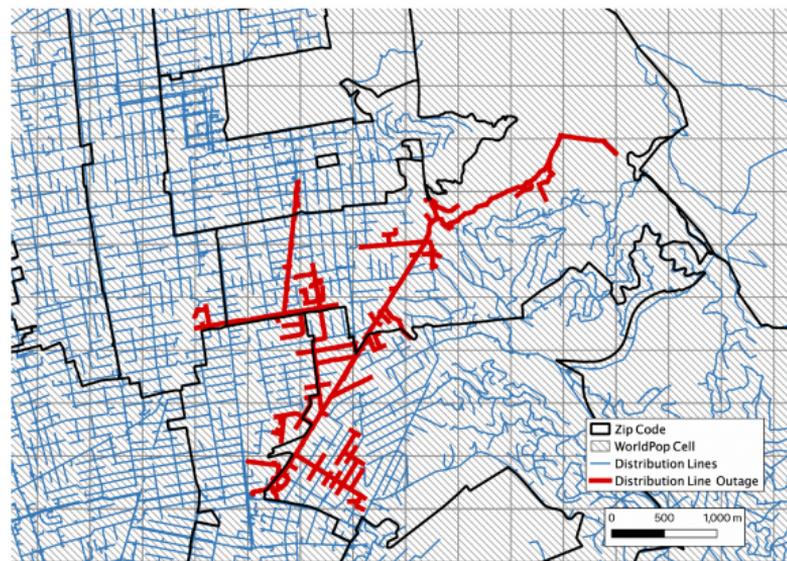
Brown & Muehlenbachs: What They Do

- Feeder-level PSPS outage exposure (extremely granular data).
- ZIP code solar and battery adoption data.
- Difference-in-differences + dynamic discrete choice model to get at effects.
- Interpret battery purchase as a *revealed choice* for reliability

Variation in outage exposure allows for a revealed-preference estimate of **Value of Lost Load (VoLL)**.

Main Insight from Brown & Muehlenbachs

- Households spend large capital costs to avoid outages ($15-20K).
- They build a discrete-choice model and exploit before-and-after expectations on outages and variation in subsidies.
- They find a **residential VoLL of $3500-6800/MWh**.
- A complement to existing estimates, often based on stated-preference surveys or macro data, using actual large capital purchases and credible granular variation.

Figure 4: Impact of Outage Intensity on Storage Capacity (Watts)
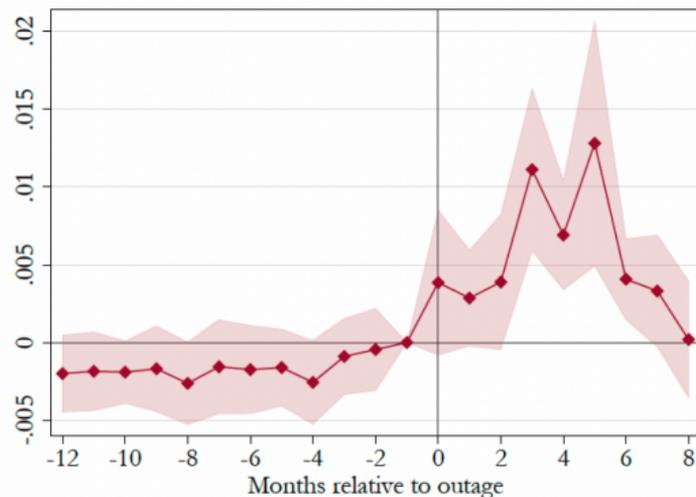
Additional heterogeneity: Income as a driver of VoLL (and adoption)

Table: Estimated VoLL by Income Quartile

	First Income Quartile	Second Income Quartile	Third Income Quartile	Fourth Income Quartile
VoLL ($/MWh)	3,451	4,188	5,471	6,809
	(60)	(65)	(134)	(42)

- **Comparison:** $1,444 - $6,555/MWh (Sullivan et al., 2015)
- Estimated damages: $406 million to residential customers

Roadmap

The Chicago-school view of reliability

- Households face outages and decide whether to invest in private protection
- Batteries and generators are voluntary, market-based responses
- These investments reveal households' true willingness to pay (VoLL) for reliability

Chicago intuition

- If reliability is valuable, households will buy it themselves
- If they do not buy protection, reliability must not be worth its cost
- Observed behavior (battery/generator adoption) reveals the *true* Value of Lost Load

No need for heavy-handed public intervention:
markets and private choices internalize the value of reliability.

Private Substitutes and Public Reliability: Equilibrium Effects

If households can self-insure with batteries and generators:

- Do we still want the same level of grid reliability?
- How does this affect electricity bills?
- Who gains and who loses?

Core Mechanism in Brehm et al. (2024): The rubberband

Private batteries and generators:

- Reduce the damage from outages
- Reduce the efficient level of grid reliability spending
- Reduce electricity bills for everyone

$\rightarrow$ This is a general equilibrium feedback from private behavior to public policy.

Brehm et al. (2024): Empirics + Calibration Strategy

Step 1 — Document who buys private substitutes

- Use RECS and AHS survey data to show generator and battery ownership (income effects)

Step 2 — Estimate behavioral response to outages

- City-level battery adoption data (California SGIP), outage data from wildfire-related shutoffs
- Event-study / TWFE design: major outage $\rightarrow$ spike in battery purchases

Step 3 — Structural model of public reliability with private substitutes

- Households differ in willingness to pay (WTP) for reliability
- Regulator chooses grid reliability to maximize aggregate welfare
- Private substitutes reduce the loss from outages for adopters
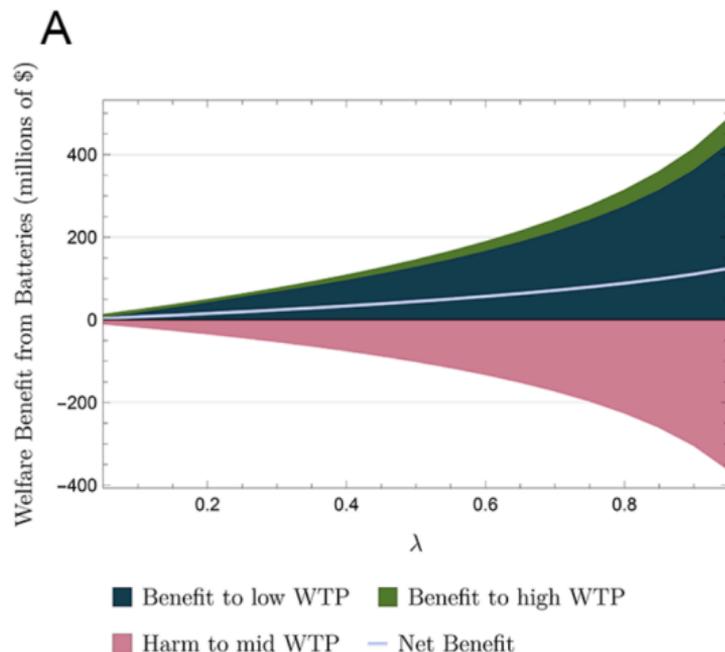- Calibrated based on previous steps

Heterogeneity: Who Benefits from Private Substitutes?

When households can purchase private backup power, the welfare effects are uneven:

- **High WTP**: benefit — they buy a battery and self-insure.
- **Middle WTP**: lose — value reliability but do not self-insure.
- **Low WTP**: benefit — suffer from worse reliability but can benefit from lower reliability costs.

These effects are amplified the more effective the battery is as a substitute for grid reliability (higher λ).

Open questions: Do regulators internalize private investments in practice?

A

Welfare Benefit from Batteries (millions of $)

■ Benefit to low WTP   ■ Benefit to high WTP
■ Harm to mid WTP   — Net Benefit

Roadmap

Texas 2021 Freeze: A Different Context

- Cold stress, not wildfire
- Rolling blackouts across ZIP codes
- Feb 2021 Texas Winter Storm Uri:
  - ▶ 246+ deaths (Svitek, 2022)
  - ▶ Lost economic activity $4.3 Billion (Dallas Fed, 2021)

Hours with 20%+ of customers without power

- 0
- 1–4
- 4–8
- 8–24
- 24–48
- 48+
- No data
- ⬜ ERCOT boundary
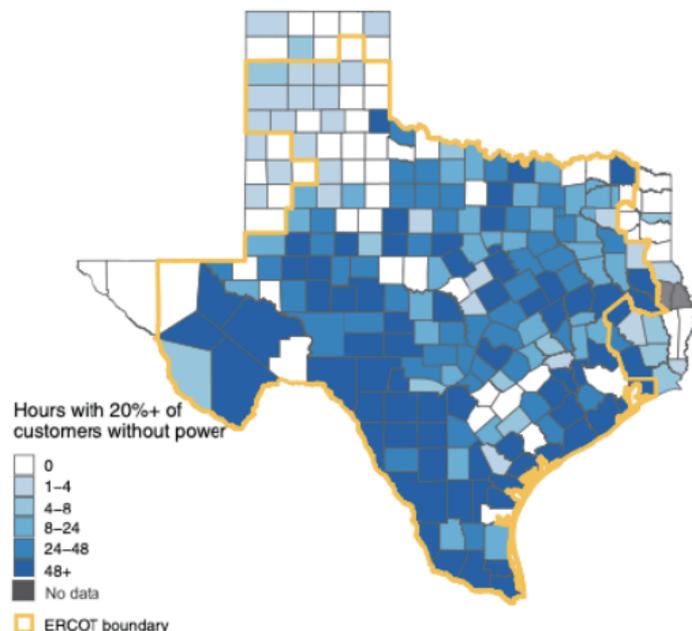
Source: Flores et al. (2022)

Adelowo (2025): Data

Paper combines quasi-random blackout exposure with rich administrative data on who invests in private backup power.

Blackout exposure

- ZIP code level data on hours without electricity during the February 2021 Texas freeze
- Variation in exposure across neighborhoods within the same city (Austin)

Household adaptation

- Administrative permit data for **standby generators** and **solar + battery** installations
- Permits allow observation of *intent to adapt* at high spatial and temporal resolution

Socio-economic characteristics

- ZIP code demographics: income, race, housing characteristics
- Ability to study heterogeneity in adaptation across neighborhoods
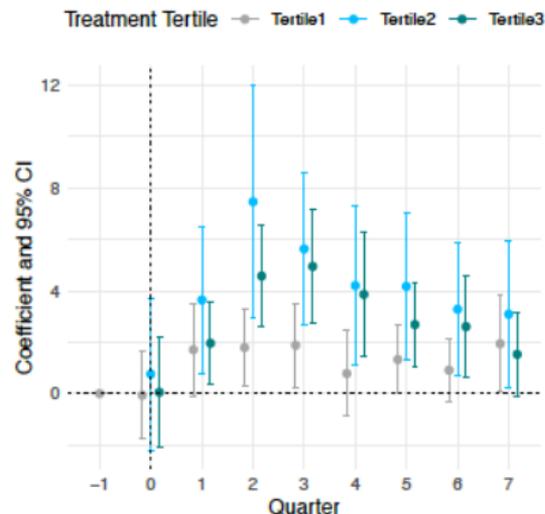
Main findings for City of Austin

Figure 7: Treatment effect coefficients for generator-related permits

(a) Continuous treatment
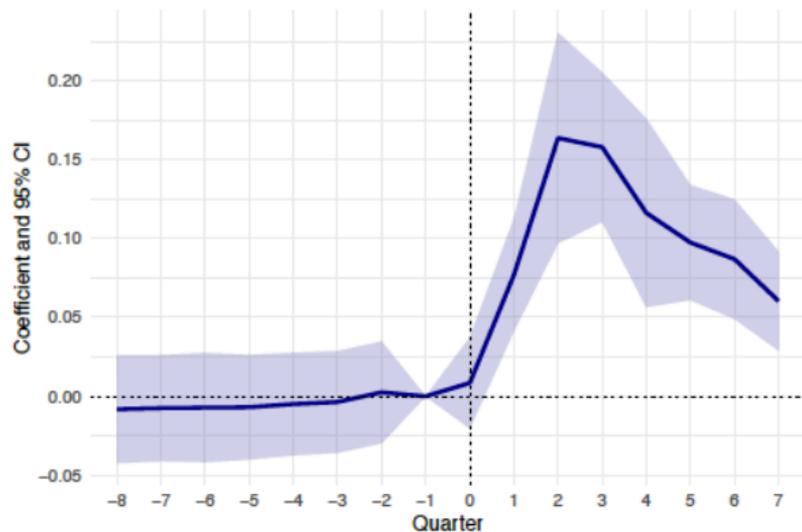
(b) Tertile treatment

The period preceding the treatment period is omitted ($t = -1$).

Inequality in Private Adaptation

- Low-income and minority neighborhoods respond less
- They also respond later
- Adaptation capacity appears to be unequal

Note: As data are at the ZIP code level, important heterogeneity is potentially lost. Likely a lower bound on differences across households.

Median household income

Sample split — Below median (main effect) — Above median (total effect)
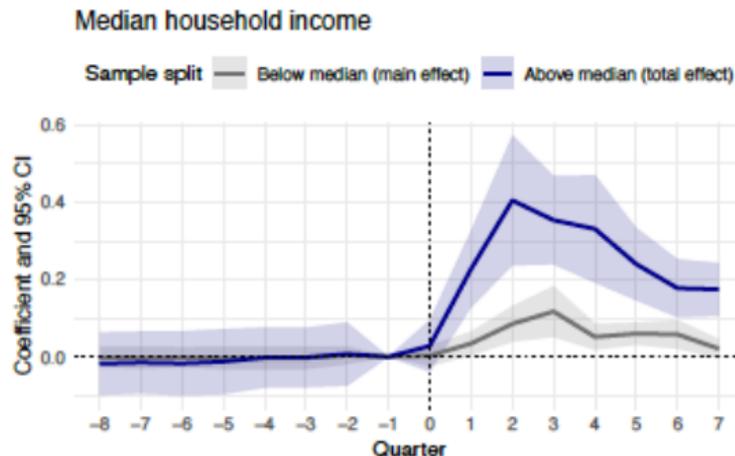
Private adaptation, public investment, and distributional concerns

The findings so far:

- Private adaptation occurs in response to outages and blackouts (Brown and Muehlenbachs, Adelowo)
- Private adaptation reduces optimal public reliability (Brehm et al.)
- But private adaptation is unequal (Adelowo)

Public underinvestment in reliability can become regressive.

Main conclusions

- Blackouts do not only create losses.
- They trigger private adaptation.
- Private adaptation changes optimal reliability policy.
- But because adaptation is unequal, reliability policy becomes a distributional issue.

Despite adaptation, blackouts are still likely to occur and disproportionately impact the poor.

Can we do blackouts in a better way?
Will these ease the burden on low-income households that are unable to adapt?

Roadmap

Power limits as a solution

- Traditionally, "rolling" blackouts for system-wide shortages have been used to deal with scarcity.
    - ▶ Very costly and "secret recipe" often undisclosed.

- We examine the use of power limits, which are now feasible with smart meters.
- The proposed solution is technologically feasible and a clear welfare improvement.
- We are still exploring its design when targeting is allowed.

Maximum power limits offer a better solution...

- Consumers in many countries can contract their maximum power level at any instantaneous point for the duration of a certain period (limited changes).
  - ▶ Used for cost-allocation purposes: consumers with high power contribute more to fixed system costs, highly correlated with usage and income.
- If a user goes over their contracted power, the circuit breaker trips.
- The user has to disconnect enough appliances to be back in balance (i.e., below the limit).
- Traditionally, this maximum limit was a "bug" in the device and had to be adjusted manually.
- Nowadays, it can be adapted digitally and become a feature.

...*but* they can be controversial

Metering   Transmission and Distribution   News   Southern Africa

Four strikes and it's lights out: Eskom to implement load limiting in Gauteng

By **ESI Africa** February 2, 2024

SOUTH AFRICA

'Stop talking and let's see some action' — Reactions to City Power's load-limiting and exemption plans

26 May 2023 - 11:02

Kyle Zeeman
Digital Editor

City Power also announced plans for load-limiting of households through a smart meter which can control power usage. If you are using below the load-limit threshold, your electricity supply will remain. If you are above the threshold, the smart meter will switch off high-energy appliances.

"Instead of switching off the entire house [as Eskom's load-shedding does], we would like to keep the minimum electricity use to your lights, television, and Wi-Fi," said City Power's executive for energy management, Meyrick Ramatlo.

While some applauded the initiative, others questioned how it would work in practice and cautioned about it being implemented fairly.

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We show smart rationing as a partial blackout has desirable properties

- In the traditional blackout setting, a customer was disconnected.
- Smart meters allow to limit the available power to a user partially.
- Even using a crude rule and method, **better in many situations**!

- **Preview:**

    Get *blackout-equivalent policies*

    with no consumer at zero

    while bothering *fewer* people.

When are power limits useful?

- This is not useful for blackouts that happen unexpectedly or need immediate action due to the communications protocol with the smart meters.
- This is also less useful when network topology is essential (e.g., wildfires).

- Useful for situations like European crisis, Texas, California (non-fire), South Africa: expected and persistent.
- In some sense, similar to water scarcity problems, as a way to reduce demand once other channels have failed (or might not be feasible).

Will power limits be useful?

- Some conversations with the transmission system operators in Spain and France.
  - ▶ Seen as a last resource option in Europe, less common than in places like Texas and California.
  - ▶ Large rationing programs for the industrial sector and higher investment in reliability/redundancies.
  - ▶ However, implementation cost is very low and could still be useful under unprecedented events.
- In the US, smart meters do not always have this capability, but power maximums recently explored as part of pricing in some states, useful in the future.
- Power limits introduced as pilots by Eskom in South Africa, but also need capital investment. However, benefits can be potentially very large due to persistent blackouts.

Framework

- Consider the following individual net utility from electricity (Weitzman, 1977):

$$w_i(p; \lambda_i, \epsilon_i) \equiv u_i(x_i(p); \epsilon_i) - \lambda_i \ p \ x_i(p),$$

  where x_i is individual-specific and can depend on ϵ_i and λ_i.

- In a shortage situation, at $\overline{p}$,

$$D(\overline{p}) \equiv \sum_i x_i >> S(\overline{p}).$$

- A rationing mechanism will limit consumption to κ:

$$w_i(\kappa) = \min\{\kappa, x_i\}.$$

Traditional "rolling" blackouts can have very large costs

- Let $\kappa = 0$ be full rationing and $\kappa = \overline{\kappa}$, none.

- Under *random rationing*, we can use the aggregate welfare and establish that total welfare equals

$$W^B(\alpha) = \alpha W(0) + (1 - \alpha)W(\overline{\kappa}),$$

where W represents aggregate welfare, i.e., $W(k) = \sum_i \theta_i w_i(k)$.

- Notice that α might be small, but costs to selected consumers can be considerable if the blackout is severe (e.g., Texas).

Smart rationing

- Under very reasonable assumptions, it is trivial to show that a form of "smart rationing" should be preferable to full blackouts for a small subset of the population.

- Consider a set of smart rationing rules that can be flexible and allow for individualized rationing policies,

$$\mathbf{K} : i \to \kappa_i.$$

Blackout-equivalent smart rationing

- Under a general setting, we define the optimal unconstrained smart rationing rule to achieve a demand reduction equivalent to a blackout of size α, as

$$W^*(\alpha) \equiv max_{\kappa} \sum_i \theta_i w_i(\kappa_i) \quad \text{s.t.} \quad \sum_i \min\{x_i, \kappa_i\} = (1-\alpha)D.$$

- Notice that the simple blackout is a special case of this problem.

- Intuitively, having some power should be much preferable than none at all, so potentially $W^*(p, \alpha) >> W^B(p, \alpha)$.

Power limits as a special case

- Under power-limit random rationing, a fraction β gets selected for partial rationing.
- If selected, a household gets *possibly* limited power ($\kappa \in (0, \overline{\kappa})$), while the rest remains with full provision of service ($\kappa = \overline{\kappa}$).

- Under partial rationing to a share β of households, with a limit κ, welfare becomes:

$$W^P(\beta, \kappa) = \beta W(\kappa) + (1 - \beta)W(\overline{\kappa}).$$

- For a given κ, one can obtain the amount of people that need to be selected β to achieve a blackout of size α.

On bothering fewer people...

- For a blackout-equivalent policy, $\beta > \alpha$ as long as $\kappa > 0$.
- More households are *selected* for partial rationing.
- But only those with $x > \kappa$ notice.
- Due to conditional expectations, the rationed amount per bothered household is equal to

$$E[x|x > \kappa].$$

- For a blackout-equivalent partial rationing,

$$\beta Pr(x > \kappa)(E[x|x > \kappa] - \kappa) = \alpha E[x].$$

- $\beta Pr(x > \kappa) < \alpha$ depending on the shape of the distribution, sufficient if it has heavy tails.

Limits to power limits

- Because more people need to be *selected*, partial blackouts have a ceiling.
- It is also useful to understand the blackout size that they can approximate, which will be maximized at $\beta = 1$.

- We define the maximum amount of rationing that can be achieved by a partial rationing policy ϕ as

$$\overline{\alpha}(\kappa) = 1 - D(\kappa)/D,$$

where $D(\kappa) \equiv \sum_i x_i(\kappa)$.

Stylized optimal policy is simple

- With decreasing utility of consumption and no heterogeneity ($\epsilon_i = 0$) other than income (λ_i), it is optimal to set $\beta = 1$ and maximize κ.
- For a blackout-equivalent policy of size α, the optimal policy becomes:

$$\beta^* = 1, \kappa^* \text{ s.t. } D(\kappa) = (1 - \alpha)D.$$

Is this a Pareto improvement? It depends.

- For households with $x < \kappa$, absolutely.
- For households with $x > \kappa$, depends on how they value the lottery, will depend on utility, odds and x.

Some welfare results

Observation

Under CRRA utility function and $\gamma_{CRRA} \geq 1$, all households are better off with partial rationing. Under CARA utility function and for an α-equivalent power limit policy $\{\beta, \kappa\}$, there exists a risk aversion parameter $\overline{\rho}$ above which all households are better off, given by $\overline{\rho} = -\frac{\log(1/\delta)}{\kappa}$, with $\delta \equiv \beta/\alpha$.

Observation

Under CRRA utility function and $\gamma < 1$, households with consumption $\overline{c}_{CRRA} = \left(\frac{\delta}{\delta-1}\right)^{\frac{1}{1-\gamma}} \kappa$ experience a Pareto improvement. Under CARA utility, for a given level of risk aversion ρ, households with consumption below $\overline{c}_{CARA} = \frac{1}{\rho} \log\left(\frac{\delta-1}{\delta-e^{-\rho\kappa}}\right)$ experience a Pareto improvement.

Heterogeneity and welfare considerations

- What if κ is allowed to be individual specific?

- Optimal blackout-equivalent policy depends critically on:
    - Idiosyncratic value of ϵ_i
    - Income distribution λ_i

- If ϵ_i and λ_i negatively correlated, then monotonic ordering equity-efficiency.
- Typical assumption: higher income consume more, true on average, but plenty of heterogeneity $\rightarrow$ an empirical question.

Dynamic implications of simple policy

- Most affected households are those with persistent high energy consumption.
- From consumption expenditure surveys, these are on average high-income households that are also more likely to have (or install) solar panels.
- For these households, mechanism provides an incentive to invest in solar+battery systems.

- On the negative side, households without metered consumption may not be rationed.
- It can set bad incentives, need to make adoption attractive.
  - ▶ Avoid blackouts only if metered, but unclear if this is technically feasible.
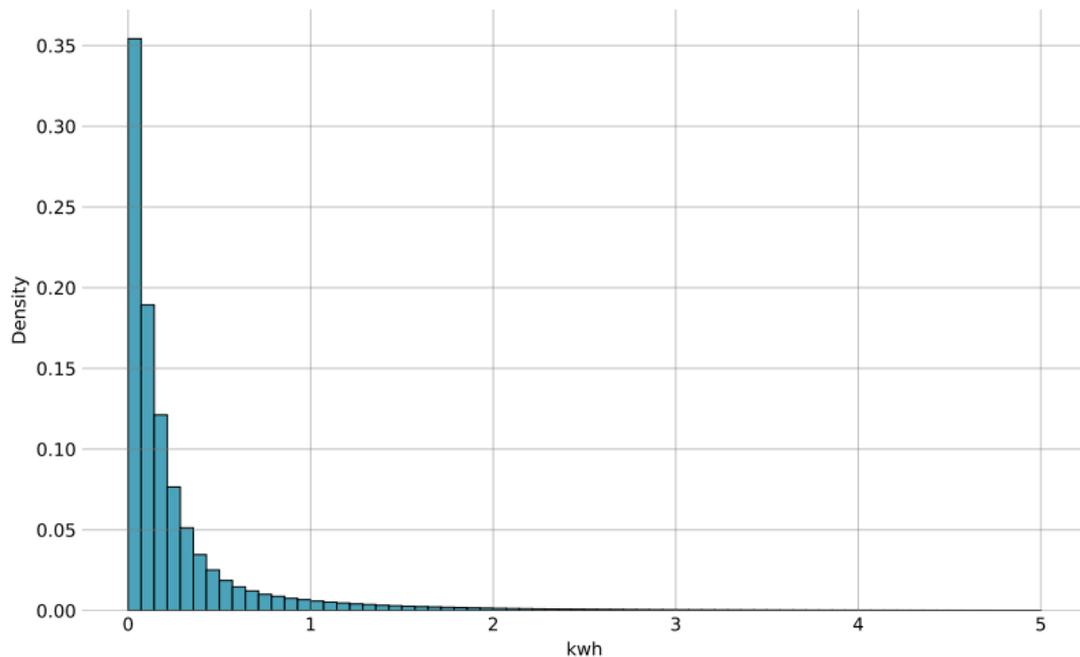
Data

- Data as in Fabra et al (2020, 2024).
- We obtained over 4M smart meters data from one large Spanish utility (Naturgy).
- For each meter (January 2016-July 2017), we have:
  - ▶ hourly electricity consumption
  - ▶ plan characteristics (pricing, contracted power)
  - ▶ postal code
- We link the postal code with detailed Census data on postal-code income.
- From previous work, use ML tools to infer heating mode and individual income distribution.

Data: electricity consumption area
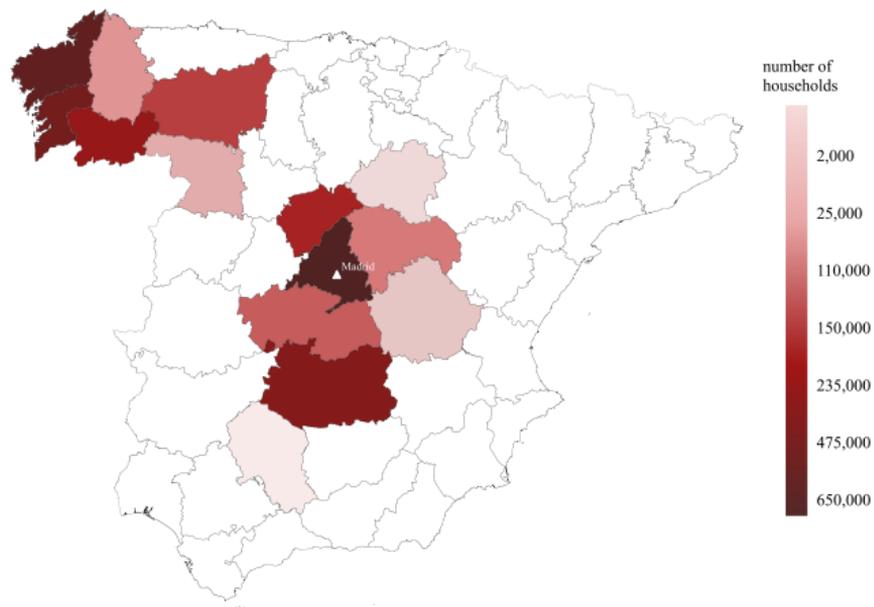
Data: consumption distribution

Simulations

- We simulate simple rationing policies with our smart meter data to understand the blackout-equivalent policies.
- We only use a couple of months of data for now.

- We assume random rationing, which can be complete (blackout) or partial (reduced maximum power).
- We also consider geographically correlated blackouts, which reduce household heterogeneity and might limit the effectiveness of smart rationing policies.

Simulation details

- For each household i, with our implementation of "smart" rationing, demand equals to:

$$x_{it}(p, \kappa) = \min\{x_{it}(p), \kappa\}.$$

- κ is the limit per household (in kW).
- We consider $\kappa = \{0.0, 0.5, 0.75, 1.0, 2.0\}$.
- This allows us to trace an equivalence frontier for different levels of partial rationing.
- We also test an equivalent policy that gives households a limit proportional to their contracted power.

- **Note:** This is an upper-bound of the consumption of households after the smart-rationing event, assuming that they manage to stay at the limit, thus, conservative for rationing effectiveness.
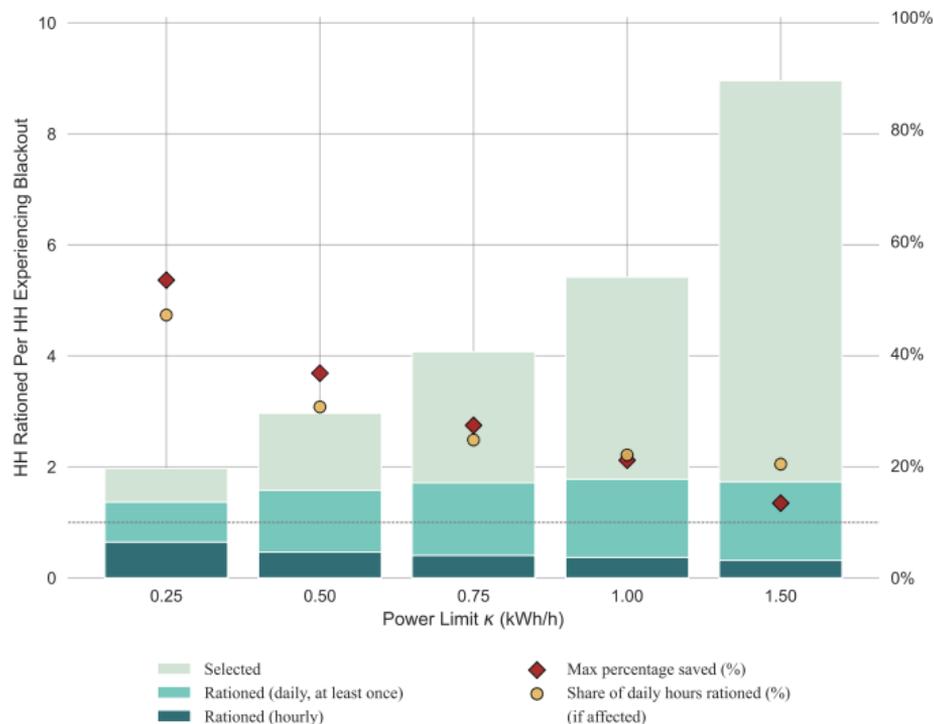
Equivalence frontier

- All lines are below the 45-degree line: partial random rationing must select more households.

- Due to random assignment, also by construction linear (in expectation and precise due to LLN).

- Example: to equal a 10% full blackout, 20% of households need to be rationed at 0.5 kW.
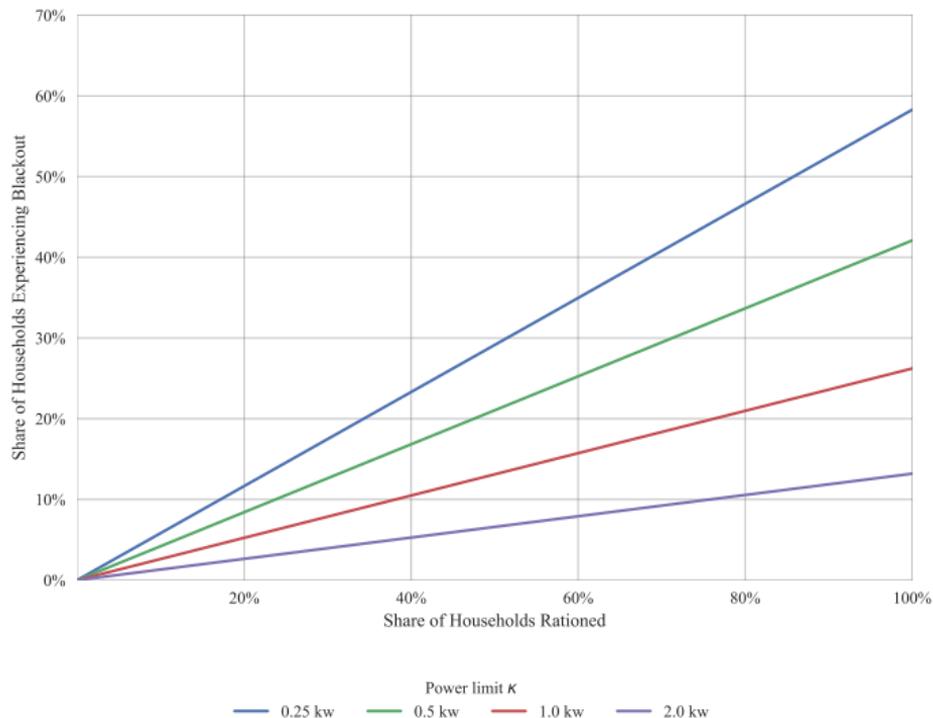
Impacted consumers and limits to partial rationing

- The more generous the partial rationing, the more people must be selected.

- However, rationing *de facto* affects fewer and fewer people.

- Note: this is an empirical question driven by the shape of consumption.

- Generalized partial blackouts can mimic large blackouts affecting *much fewer* people.

Legend:
- Selected
- Rationed (daily, at least once)
- Rationed (hourly)
- Max percentage saved (%)
- Share of daily hours rationed (%) (if affected)

X-axis: Power Limit κ (kWh/h)
Y-axis (left): HH Rationed Per HH Experiencing Blackout

Effectively rationed under hourly vs daily rationing

- Some households may not be affected by power limits in some hours.

- Probability of being effectively rationed at least one hour in a day is higher than the probability of being effectively rationed in a single hour.

- The average amount of hours effectively rationed decreases in κ.
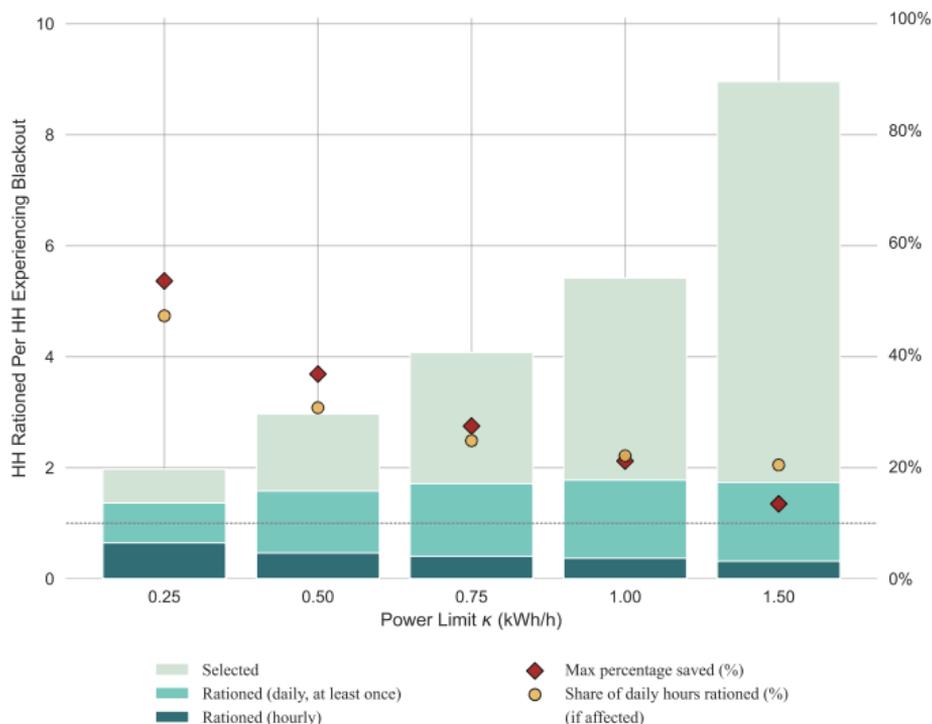
On the welfare frontier

- Graph displays indifference frontier under CRRA assumption.
- Households below the limit are always better off.
- Households above the limit are better off but only if they are sufficiently risk averse.
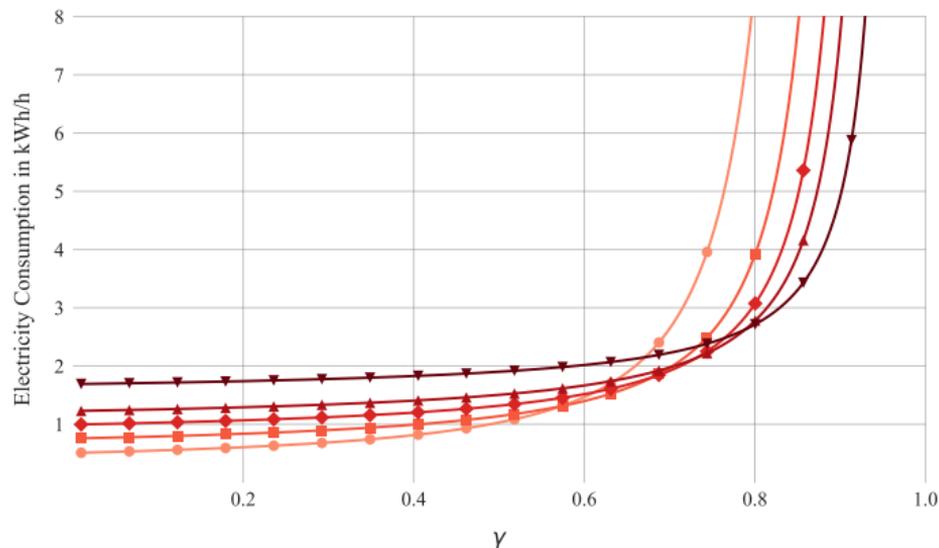
How are income and consumption correlated?

Should households have limits proportional to their typical consumption?

- Income and marginal declining utility of consumption suggest consumption could be socially less valuable, λ_i.
- However, high consumption reveals higher utility than other households (e.g., heating mode), ϵ_i.

Energy bill as a proportion of income
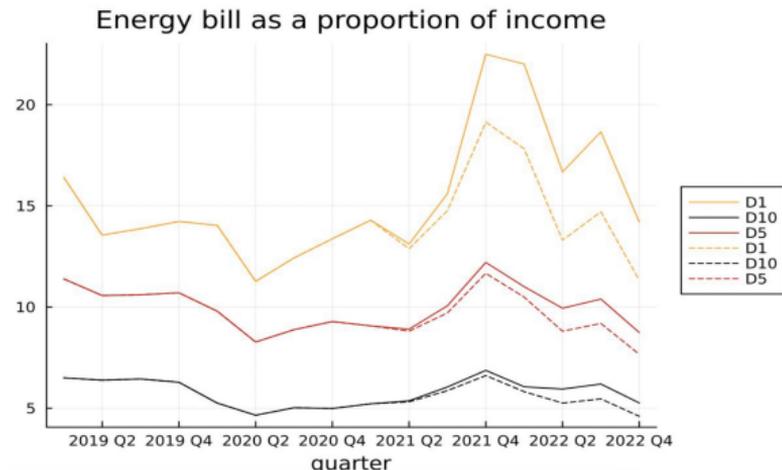
Getting at ϵ_i and λ_i

Both heterogeneous parameters are unobserved, derived from Cahana et al. (2024).

- We account for ϵ_i by focusing on HVAC mode (still residual heterogeneity remains).
- We account for λ_i by an estimating procedure exploiting household income distributions.

Inferring appliance ownership
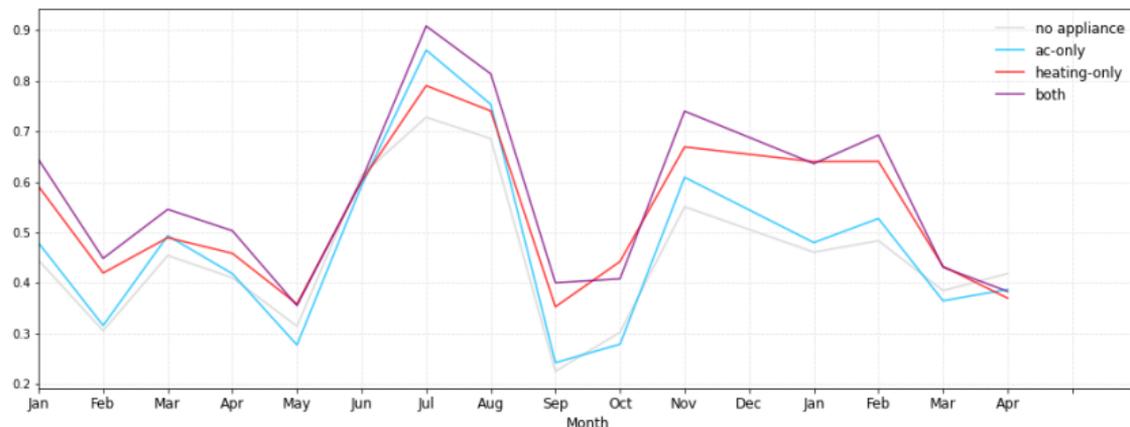
- We use algorithm to infer appliance ownership by households based on consumption structural breaks to local temperatures.
- We then treat appliance ownership as an explanatory variable in heterogeneity.
- Appliance ownership is very relevant to explain patterns, key driver behind within-income heterogeneity.

Inferring income: Naïve approach

- Assign income distribution at the postal code level $Pr_z(inc_k)$ to all households in that postal code.
- Captures across-postal-code heterogeneity, but can miss important within-postal-code heterogeneity.
- One can get somewhat at within-income bin variance, but it might be overstated due to the lack of classification.
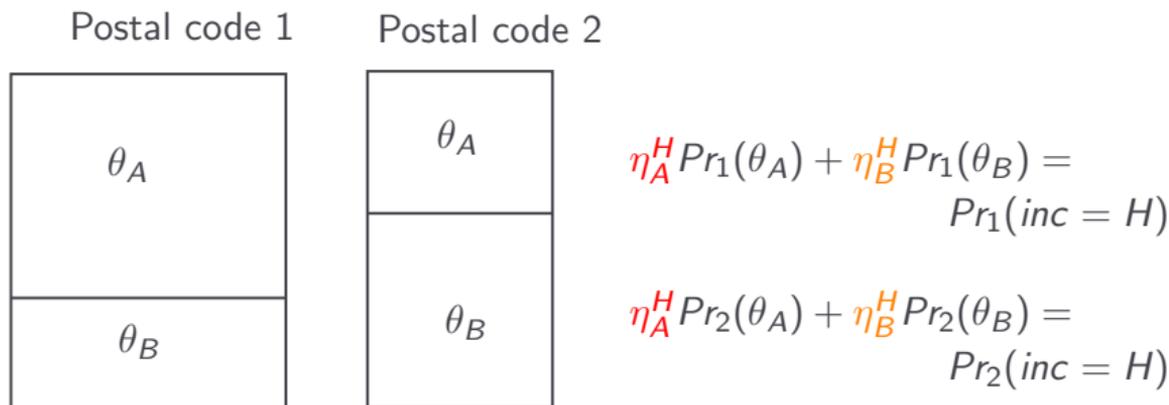
Inferring income: GMM approach

We introduce new additional objects:

- Postal code as $z \in \{1, \ldots, Z\}$.
- Income bins as $inc_k \in \{inc_1, \ldots, inc_K\}$.
- Households in postal code z as $i \in \{1, \ldots, H_z\}$.
- Discrete types as $\theta_n \in \{\theta_1, \ldots, \theta_N\}$.

- Observed postal-code income distribution: $Pr_z(inc_k)$.
- Unknown household income distribution: $Pr_i(inc_k)$.
- Unknown household type distribution: $Pr_i(\theta_n)$
- Unknown type-income distribution: η_n^k (probability that type n has income bin k).

Intuition follows similar settings (e.g., BLP, FKRB)

Postal code 1   Postal code 2

$$\eta_A^H Pr_1(\theta_A) + \eta_B^H Pr_1(\theta_B) = Pr_1(inc = H)$$

$$\eta_A^H Pr_2(\theta_A) + \eta_B^H Pr_2(\theta_B) = Pr_2(inc = H)$$

- Assume we have already inferred the distribution of types in each postal code.
- η_A^H represents the probability of income level H for type θ_A (similarly for θ_B), unknowns.
- Match postal code moments on the distribution of income, same underlying types across postal codes.

Step 1: k-means clustering of types

- We reduce dimensionality of data into market shares for daily consumption in weekdays and weekends for each individual household.
- We group nearby postal codes and cluster the population of consumers based on these market shares as well as the levels of production. Observable types based on contracted power.
- Our baseline has 12 types per province depending on contracted power, heating mode, and consumption patterns.
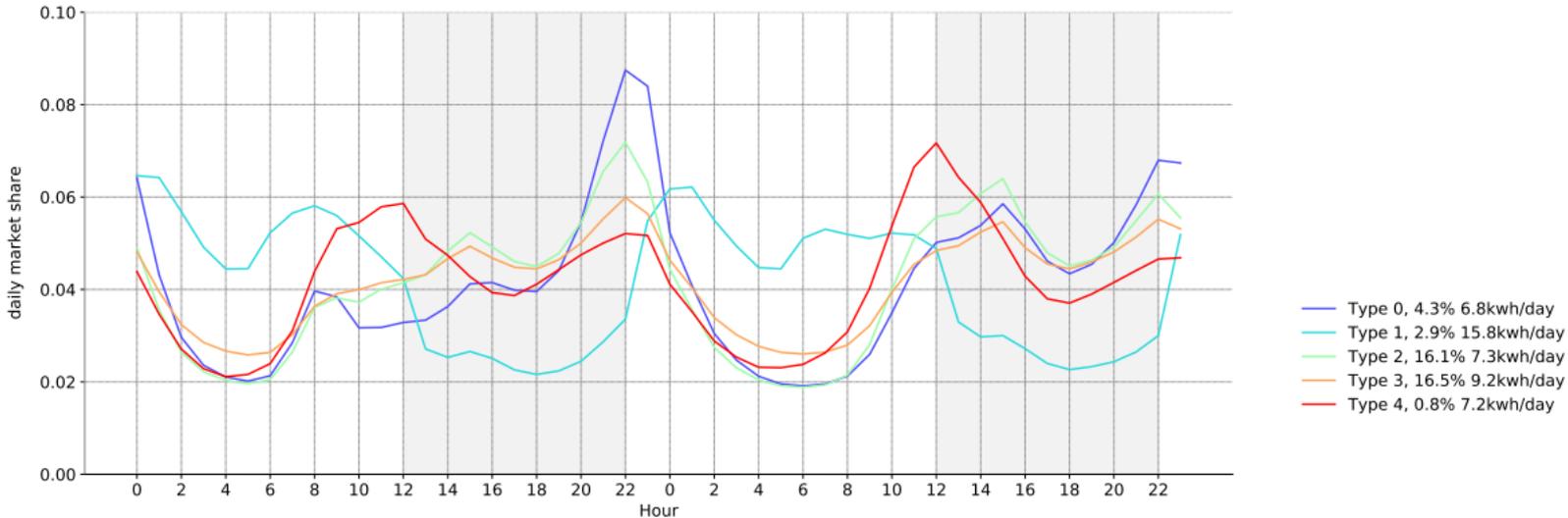
Step 1: Example of type assignment

Figure: Flexible k-mean types with electric heating in a given province

Step 2: Non-parametric identifying equations

Conditional on having identified the distribution of types for each postal code:

$$min_\eta \sum_z \omega_z \sum_k \left(Pr_z(inc_k) - \sum_{i \in z} \sum_n \eta_n^k Pr_z(\theta_n) \right)^2$$

$$\text{s.t. } \sum_k \eta_n^k = 1, \forall n,$$

where ω_z is a sampling weight and

$$Pr_z(\theta_n) \equiv \sum_{i \in z} Pr_i(\theta_n)/H_z.$$

Step 2: Semi-parametric estimator

- Previous identification results is limited in types by the numbers of postal-codes that share types.
- We consider a semi-parametric estimator that allows the distribution of income to depend on individual and postal-code demographics.
- The distribution of income is individual and postal-code specific even for the same type.

$$\min_{\eta, \alpha, \beta} \quad \sum_j \omega_j \sum_{k=1}^{K} (Pr_k^j - \sum_{i \in \mathcal{I}_j} Pr_k(\theta_i, x_i, z_j)),$$

$$s.t. \quad Pr_k(\theta_i, x_i, z_j) = \frac{exp(\delta_{ijk})}{\sum_{k'=1}^{K} exp(\delta_{ijk'})}, \qquad \forall k \in [1, \cdots, K],$$

$$\delta_{ijk} = \alpha_k + \beta_0^{\theta_i} \times k + \beta_1^{\theta_i} x_i \times k + \beta_2^{\theta_i} z_j \times k.$$

Step 2: Results

- The above estimator gives us an estimated probability of a given household belonging to a certain income bin.

- Estimator does not say exact income of a given households (still measured with error).

- We show it can help correct the association between income and the policy impacts even if income is not perfectly observed, which can be biased with postal-code level income.

- Individual-level of contracted power strongly associated with higher income distribution, but not with naïve postal-code level data.

- Provides suggestive evidence that on average high income types will be rationed more, but still subject to heterogeneity.
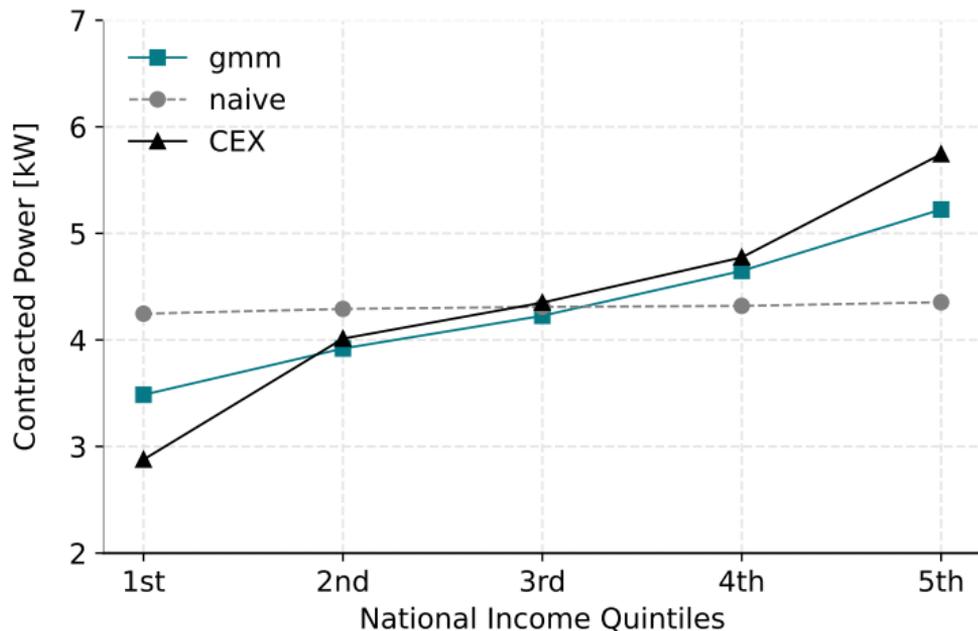
- Create policies equivalent to 5% blackout.
- Uniform rationing is progressive, proportional rationing is regressive.
- Rationing probability for households with HVAC is significantly higher and less heterogeneous across income groups.
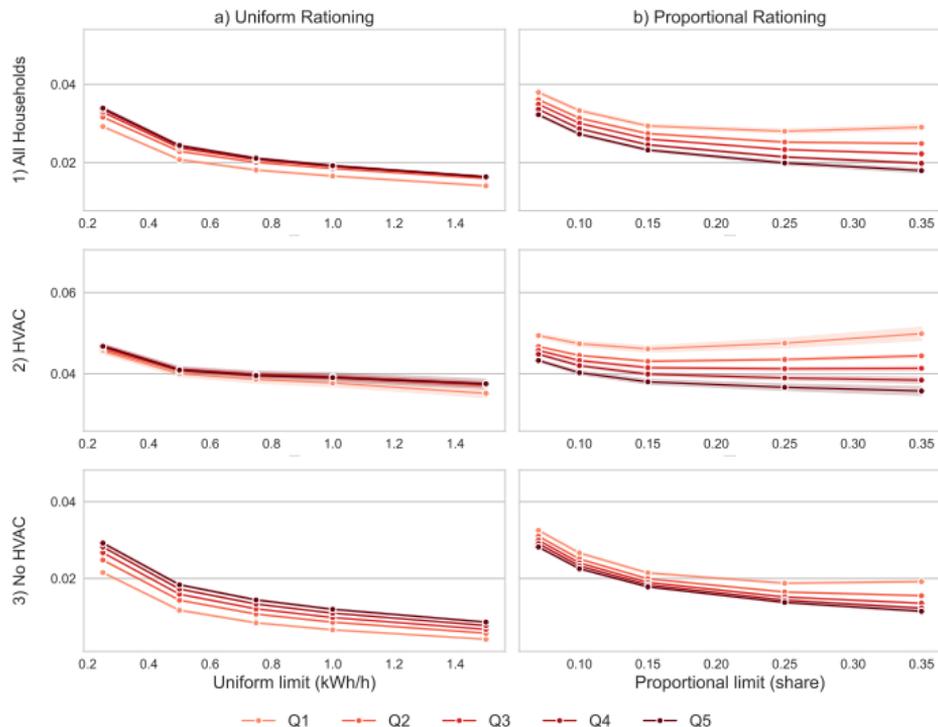
Many open questions to improve implementation

- What are the smart rationing protocols that ensure $\alpha D(p) = D(p, \phi)$ (technical aspects, notions of uncertainty/reliability)?
  - How does it depend on the communication protocol, e.g., if only a portion $\beta_t \geq \alpha_t$ can be modified in time? $\rightarrow$ "smart rationing" not always optimal
  - What if only a region at a time can be reached?

- What are the impacts of smart rationing on households of different income levels?
  - Should rationing depend on consumption levels or contracted power? What are the dynamic incentives?
  - Should rationing depend on heating mode / season and other relevant aspects of electricity use? What are the investment incentives?
  - Should some of this be contractible via further increases in p? Why or why not?

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Summary of today

- Planned and unplanned blackouts are becoming a real concern in electricity markets.
- Solar + batteries and generators are a private solution that is being adopted by households.
- These create potential benefits to consumers, but also leave poorer households behind.
- Smart meters can enable improving outcomes in the presence of persistent shortages.

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