Smart Rationing: Designing Electricity Blackout Policies for Extreme Events

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Preview

- I will talk about how **alternative rationing mechanisms** affect heterogeneous households.
- To get at income and appliance use *heterogeneity*, I will build on the results from a previous paper.
- I will go over its methods as they are IO-ish.

- Paper:
  - The Distributional Impacts of Real-Time Pricing, with Michael Cahana, Natalia Fabra and Jingyuan Wang.

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 and limits to decarbonization.
  - **Growing pressures** due to decarbonization of other sectors.

Rationing electricity as an extreme outcome

- When the system becomes stressed, **rationing** becomes 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

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 soar.

What to do in moments of extreme forecastable scarcity?

Persistent blackout conditions are costly

NEWS // HOUSTON & TEXAS

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

WINTER STORM 2021

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

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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

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 (aka, 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

Home › Industry Sectors › Metering › Four strikes and it's lights out: Eskom to implement load limiting in...

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.

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 a pilots by Eskom in South Africa, but also need capital investment. However, benefits can be potentially very large due to persistent blackouts.

(Partial) Literature review

Growing area of study due to recent events (systemic blackouts in USA, geopolitical instability in Europe).

- **Theoretical literature**: Weitzman (1997), Joskow and Tirole (2007), Gerlagh, Liski and Vehviläinen (2023), Bobtchef, De Donder and Salanie (2022), Tokasrki et al (2023), Akbarpour et al (2023).
- **Empirical literature**: Brehm, Johnston and Milton (2024), Lee et al. (2022), Ryan and Sudarshan (2022).
- **“Tools” literature**: Borenstein (2012), Dyson et al. (2014).

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,

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

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

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

- Notice that ϕ trivially includes the simple blackout rationing.

- 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 the 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

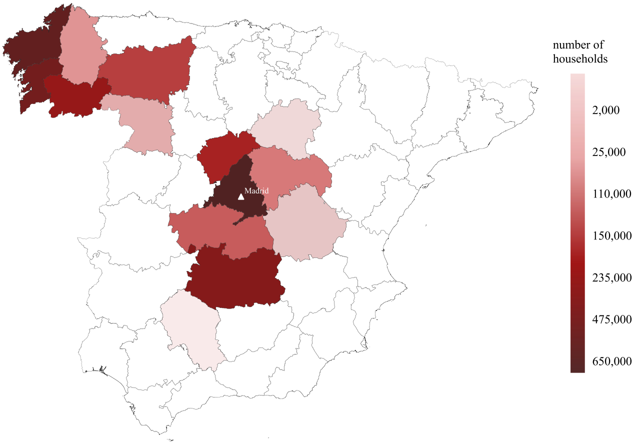
- Most affected households are those with persistent high energy consumption.
- From consumption expenditure surveys, these are on average also high-income households that have/can have solar panels.
- For these households, mechanism provides an incentive to invest in solar+battery systems.

- 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.

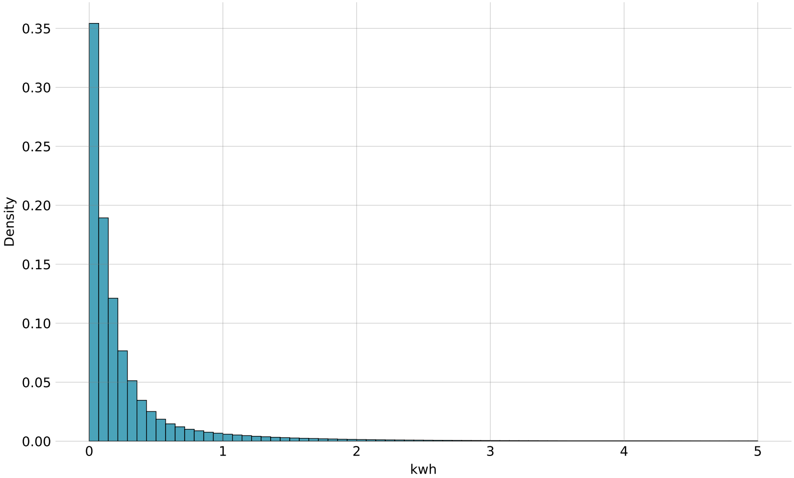
Data

- 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 zip-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:

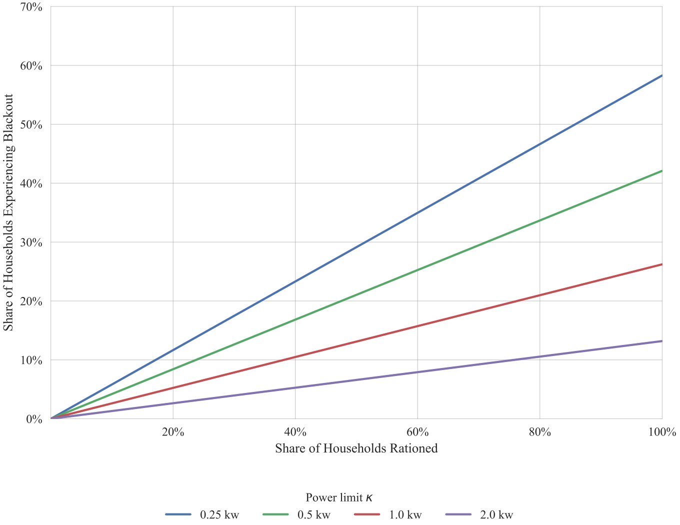
$$x_{it}(p, \kappa) = \min\{x_{it}(p), \kappa\}.$$

- 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 a large estimate 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

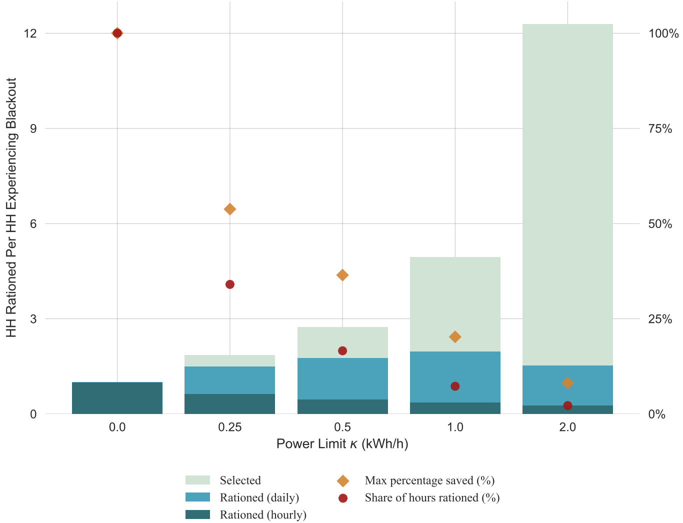
- All lines are below the 45-degree line: partial random rationing must select more households.
- Due to random assignment, also by construction linear (in expectation and precise due to LLN).
- Example: to equal a 10% full blackout, 20% of households need to be rationed at 0.5 kW.



Impacted consumers and limits to partial rationing

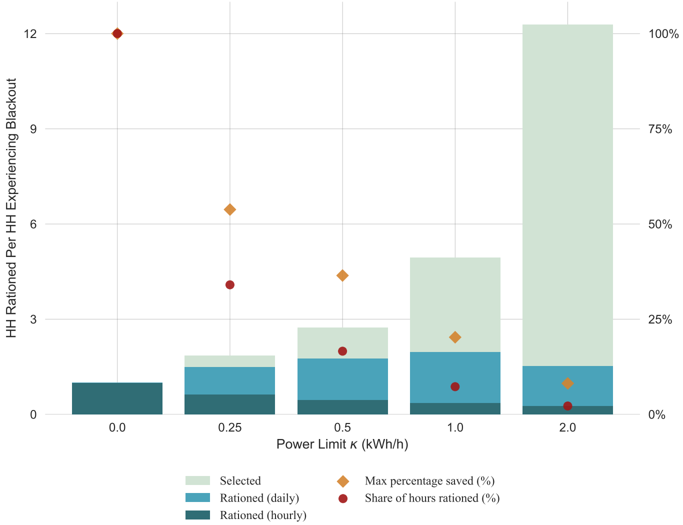
- The more generous the partial rationing, the more people must be selected.
- However, rationing *de facto* affects fewer and fewer people.
- Note: this is an empirical question driven by the shape of consumption.

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



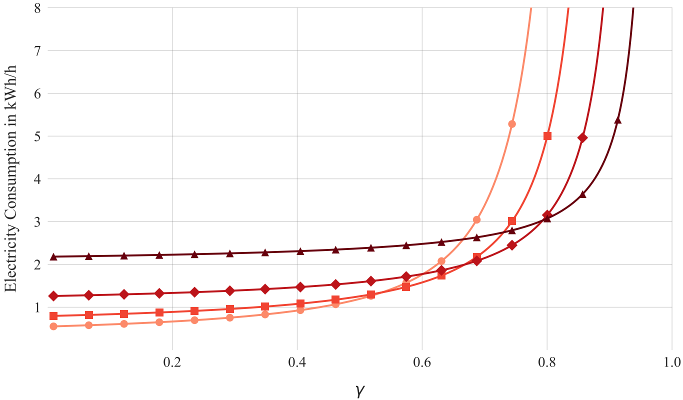
Effectively rationed under hourly vs daily rationing

- 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

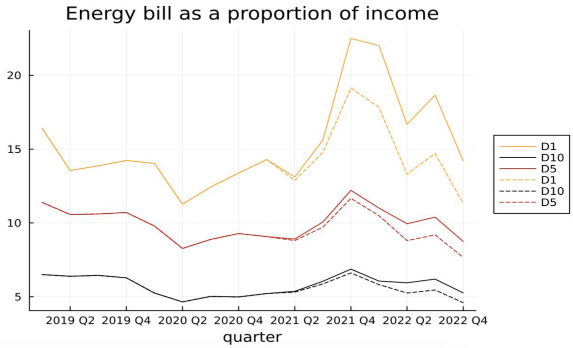
- Graph displays indifference frontier under CRRA assumption.
- Households below the limit are always better off.
- Households above the limit are better off but only if they are sufficiently risk averse.



How are income and consumption correlated?

Should households have limits proportional to their typical consumption?

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

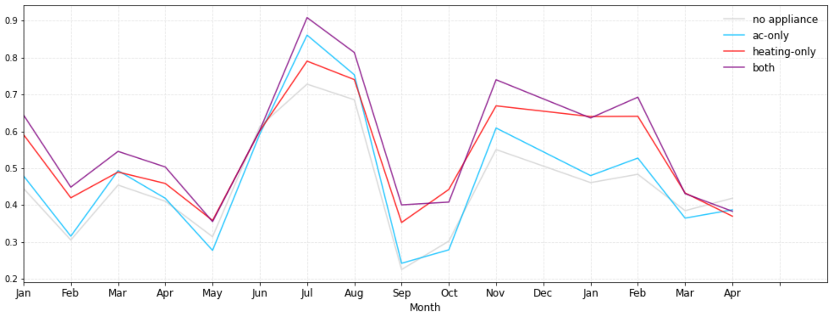


Getting at ϵ_i and λ_i

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

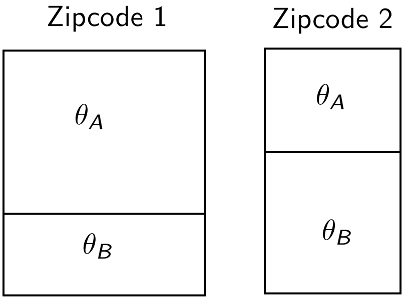
Inferring income: GMM approach

We introduce new additional objects:

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

- Observed zip-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)



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

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

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

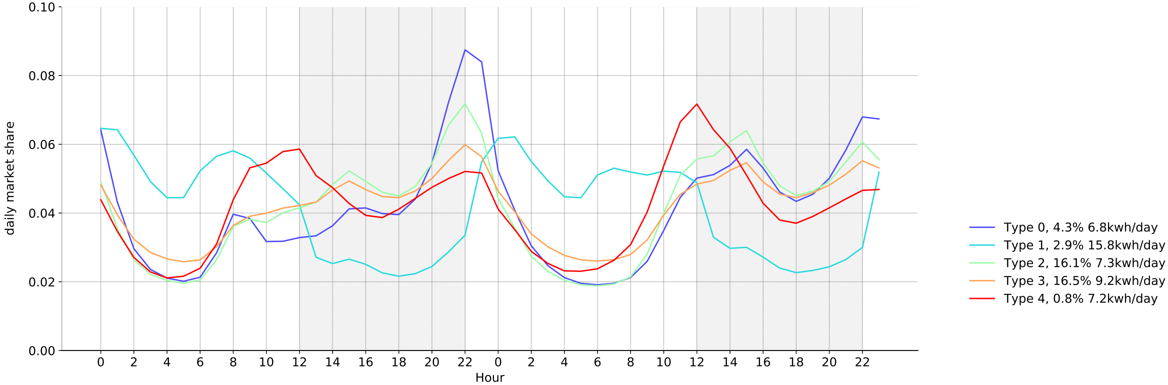


Figure: Flexible k-mean types with electric heating in a given province

Step 2: Non-parametric identifying equations

Conditional on having identified the distribution of types for each zip 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 zip-codes that share types.
- We consider a semi-parametric estimator that allows the distribution of income to depend on individual and zip-code demographics.
- The distribution of income is individual and zip-code specific even for the same type.

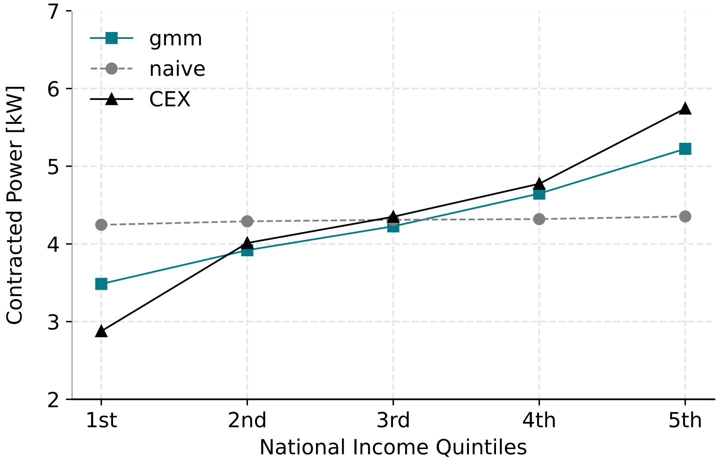
$$
\begin{aligned}
\min_{\eta,\alpha,\beta} \quad & \sum_j \omega_j \sum_{k=1}^{K} (Pr_k^j - \sum_{i \in \mathcal{I}_j} Pr_k(\theta_i, x_i, z_j)), \\
s.t. \quad & Pr_k(\theta_i, x_i, z_j) = \frac{exp(\delta_{ijk})}{\sum_{k'=1}^{K} exp(\delta_{ijk'})}, \qquad \forall k \in [1, \cdots, K], \\
& \delta_{ijk} = \alpha_k + \beta_0^{\theta_i} \times k + \beta_1^{\theta_i} x_i \times k + \beta_2^{\theta_i} z_j \times k.
\end{aligned}
$$

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 zip-code level income.

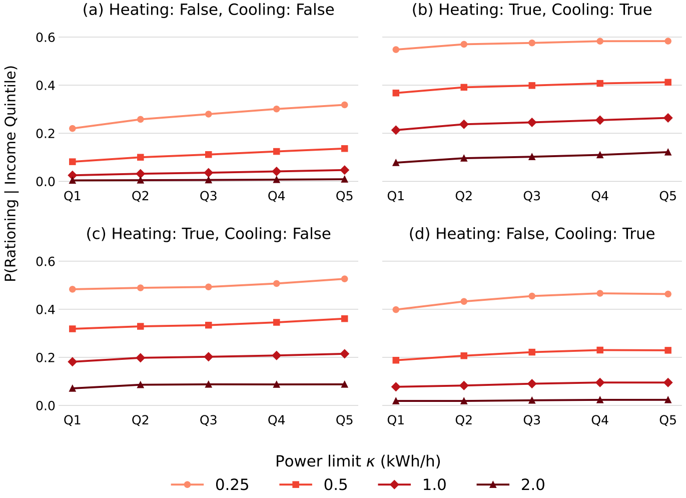
Step 2: Confirm relationship between income and contracted power

- Individual-level of contracted power strongly associated with higher income distribution, but not with naïve zip-code level data.
- Provides suggestive evidence that on average high income types will be rationed more, but still subject to heterogeneity.



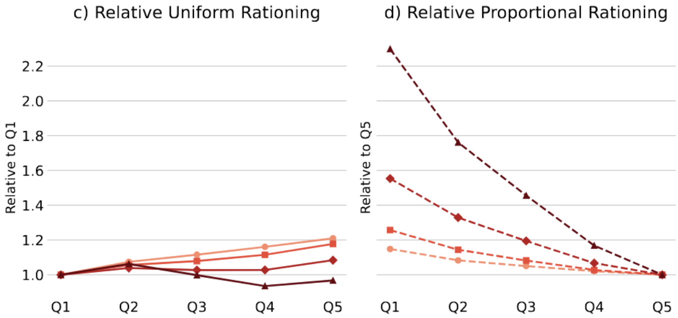
Rationing policy tends to be progressive, but HVAC matters

- Households for which HVAC mode is not significant have lower conditional probability of being rationed.
- In our sample, households for which HDD is significant face a higher probability of being rationed than those for which just CDD is significant.
- High limits can select HHs with high ϵ_i, and this might be low income, leading to a compositional regressive effect.



Limits proportional to contracted power become regressive

- An alternative based on contracted maximum power is very regressive.
- Low-income households are rationed much more.
- They get selected more and they are effectively rationed more often.
- This is due to the fact that low-income households optimize their contracted power more tightly.



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?

Summary

- Power limits can be a powerful to avoid blackouts.
- Results suggest that upside can be substantially large, but with some nuance.
- Once the door for individualized limits emerges, questions about targeting, pricing, and fairness open up.
  - To be continued...

Thank you.

Questions? Comments?

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