Smart Rationing:
Designing Electricity Blackout Policies for Extreme Events

Mar Reguant (IAE-CSIC) Mayra Wagner (UPF)

ICMAB
November 2025

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 2050.
- **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

- I will talk about work on **rationing** in the presence of energy scarcity.
- 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

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

COPY LINK REPUBLISH

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 raise of solar + batteries (microgrids), blackouts, one can also build electrical shelters (see Brehm et al., 2024).
- All these solutions will ease the burden on some households and neighborhoods. The impact of rolling blackouts falls on HHs that cannot afford resilience preparedness.

How to improve blackout policies?

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.
- 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**.

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.
- France put the possibility into law and run a tiny experiment (Enedis, 2024).

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,
$$\mathbf{K} : i \to \kappa_i .$$
- It cannot be worse on average, as it includes blackouts as a possibility.

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

- Power limits are not always feasible if blackout size is large.
- Because power limits maintain access to electricity for all households, partial blackouts have a ceiling.

- We define the maximum amount of rationing that can be achieved ($\beta = 1$) by a partial rationing policy κ as

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

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

Are power limits a good thing?

- *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 (utility function, odds, and x).
- Many households can be better off if they are sufficiently averse at having zero power.
- Rationed households can still be better off as they get consumption κ, rather than zero, even if they get rationed more often.

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.*

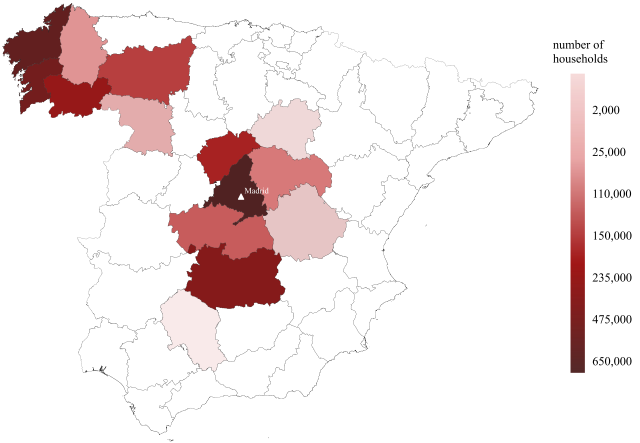
Heterogeneity and welfare considerations

- 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.

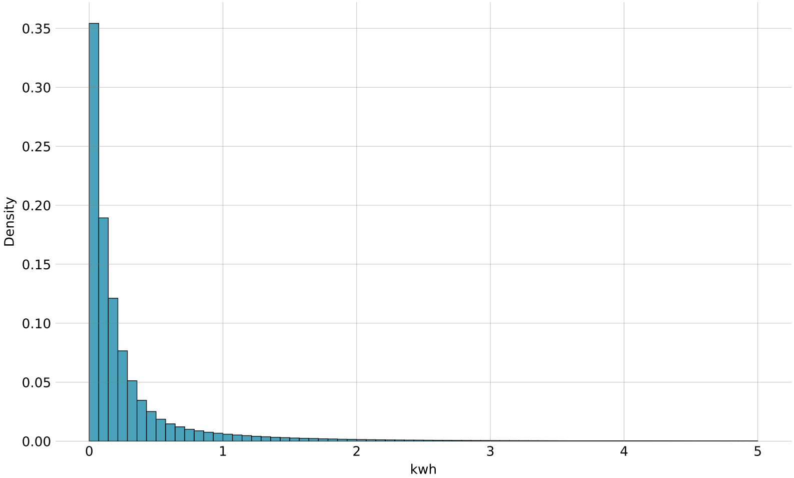
Data

- Data as in Fabra et al (2020, 2023).
- 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 assume random rationing, which can be complete (blackout) or partial (reduced maximum power).
- We consider two alternative power limits: uniform and proportional.

Uniform power limits

- For each household i, with a **uniform power limits**:

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

- κ is the limit per household (in kW).
- We consider $\kappa = \{0.5, 0.75, 1.0, 1.5\}$.
- Create policies equivalent to a 5% blackout by finding β (number of selected households).

Proportional power limits

- We observe hosueholds' chosen power limit (*potencia contratada*).
- It reveals their need (ϵ_i) and ability to pay (λ_i).
- We explore also a **proportional power limits**:

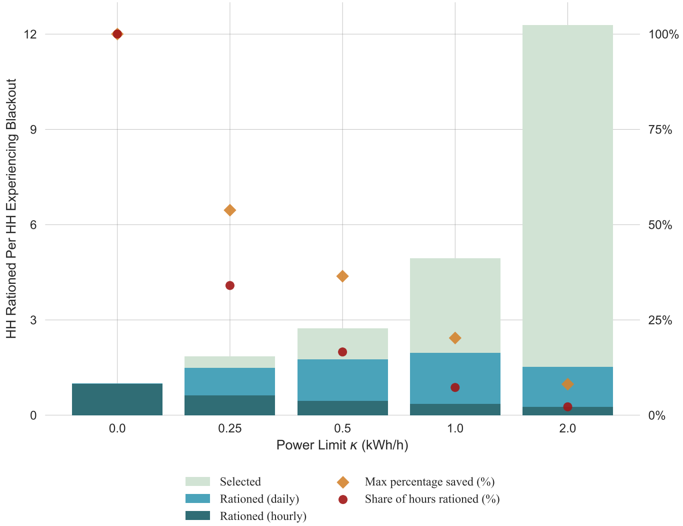
$$x_{it}^{P}(\kappa) = \min\{x_{it}, \gamma\kappa_i\}.$$

- κ is the limit per household (in kW).
- We consider $\gamma = \{0.07, 0.15, 0.25, 0.35\}$.
- Create policies equivalent to a 5% blackout by finding β (number of selected households).

Impacted consumers and limits to partial rationing

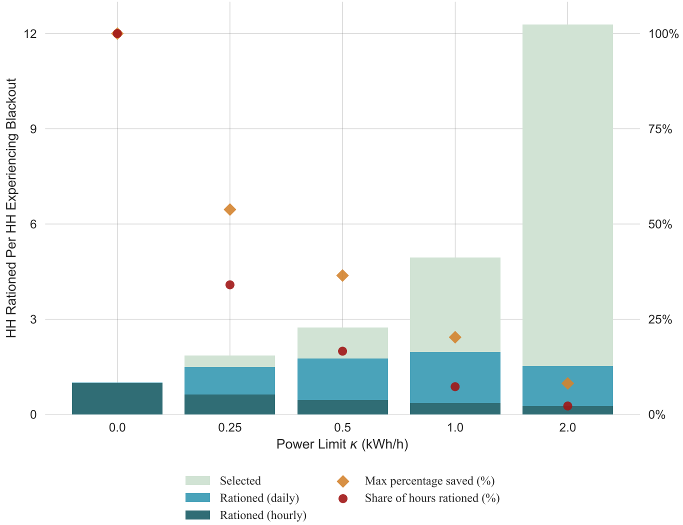
- The more generous the partial rationing, the more people must be selected (light teal).
- However, rationing *de facto* affects fewer and fewer people (dark teal).
- Note: this is an empirical question driven by the shape of consumption.

- Generalized partial blackouts can mimic large blackouts (see max size, orange diamond) affecting *much fewer* people.



Effectively rationed under hourly vs daily rationing

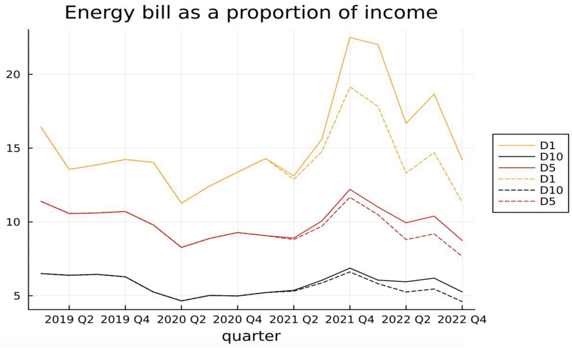
- Some households may not be affected by power limits in one hour, but notice at some point in the day (teal).
- The average amount of hours effectively rationed decreases (red dots).
- Some more households notice, but still far less than selected households.



How are income and consumption correlated?

Does it come for free? Is this a "good" or a "bad" thing?

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



Getting at ϵ_i and λ_i

- Both heterogeneous parameters are unobserved.

- Use previous results derived in Reguant et al. (2025):
  - 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 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.

How to improve it?

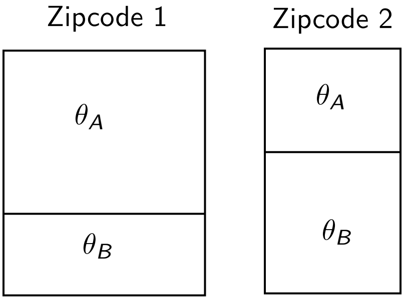
Inferring income: GMM approach

We introduce new additional objects:

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

- 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

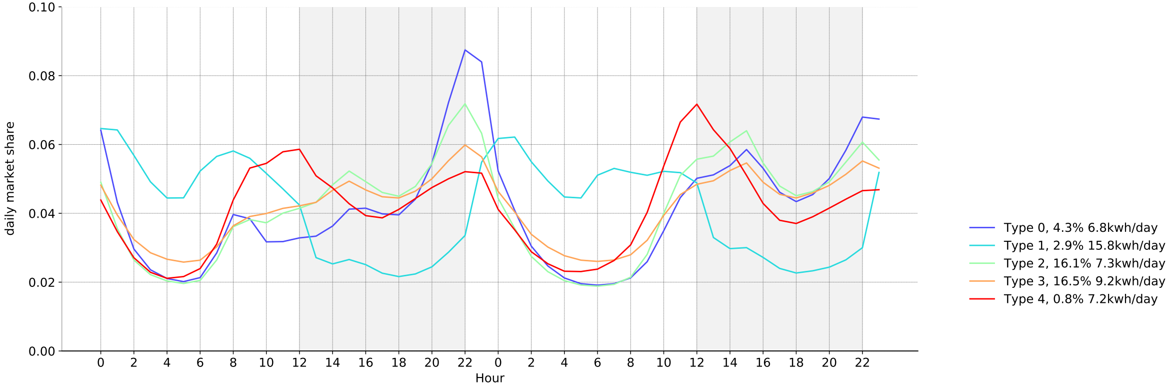


Figure: Flexible k-mean types with electric heating in a given province

Step 2: 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.

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

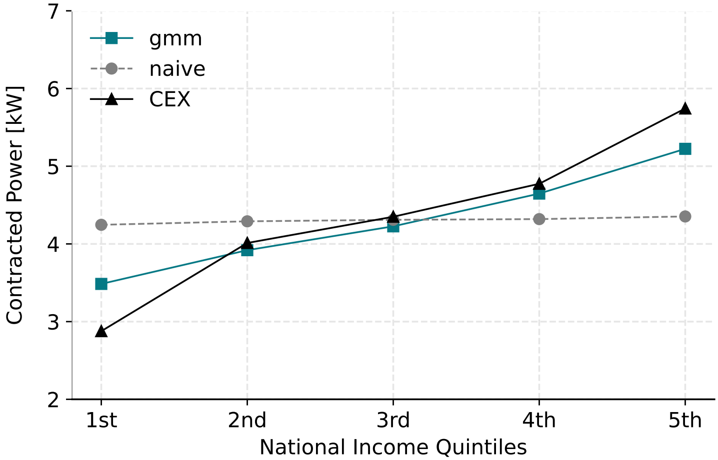
Step 2: Results

- 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

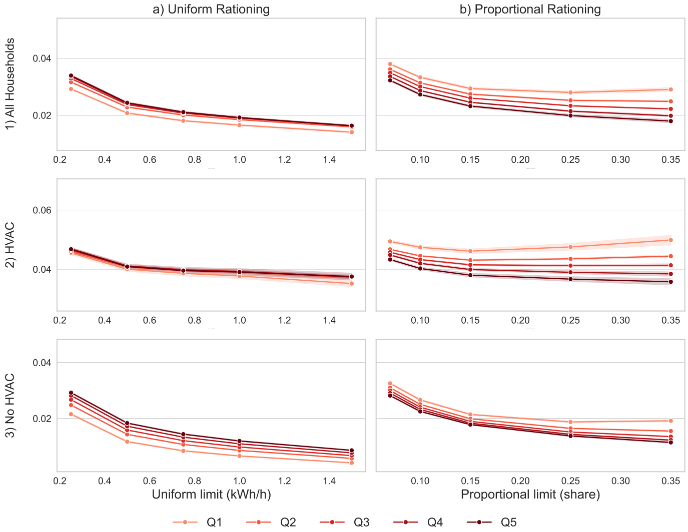
- Individual-level of contracted power strongly associated with higher income distribution, but not with naïve zip-code level data.
- Provides suggestive evidence that on average high income types will be rationed more, but still subject to heterogeneity.

Back to blackouts...!



Rationing policy appears to be progressive, but HVAC matters a lot

- 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?

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?

:mar.reguant@northwester.edu