Smart Rationing: Designing Electricity Blackout Policies for Extreme Events

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March 25, 2024

Rationing electricity

- I will talk about early work on **rationing** in the presence of energy scarcity.
- During 2022, growing concerns about the possibility of energy shortages in Europe.
- Several leaders announced the possibility of consumer-level planned systemic blackouts (e.g., Austria, France).
- Large blackouts have occurred recently in California and Texas.

- While consumer blackouts are *relatively unlikely*, it is important to study its design due to their welfare-relevance and the more likely blackouts due to climate change.
  - Supply-side failures due to extreme weather
  - Demand spikes correlated with extreme weather

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.

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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 to some households and neighborhoods,impact of a rolling blackouts fall on HHs that cannot afford resilience preparedness.

How to improve blackout policies?

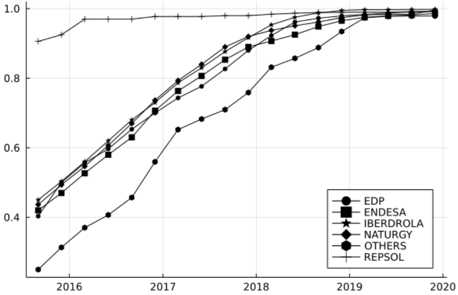
Our proposed solution

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

- We propose to use 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.

From smart meters to smart rationing

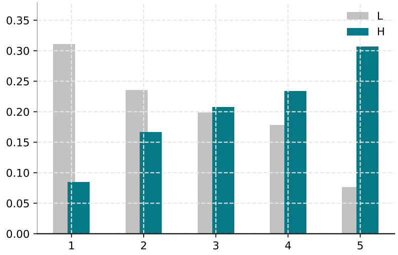
- Smart meters are now commonplace in many electricity markets.
- Its benefits are multiple: potential for dynamic pricing, reduction in distribution losses, better solar pricing, etc.
- Smart meters can also contribute to improved rationing via maximum power limits.
- Traditionally, this maximum limit used to be a "bug" in the device and had to be adjusted manually.
- Nowadays, it can be adapted digitally and become a feature.



From "Smart Meters and Retail Competition: Trends and Challenges."

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 of time (limited changes).
- In Spain, this is called "Potencia contratada."
  - Used for cost-allocation purposes: consumers with high potencia contribute more to fixed system costs, highly correlated with income.
- If a user goes over their contracted power, the circuit breaker trips.
- The user has to disconnect enough appliance to be back in balance (aka, below the limit).



From "The Distributional Impacts of Real-Time Pricing."

Smart rationing as a partial blackout

- In the traditional blackout setting, a customer was either disconnected or not.
- Smart meters allow to partially limit the available power to a user.

- Even using a crude rule and method, **better in many situations**!

When can this be 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 in situations where network topology is very important (e.g., wildfires).

- Useful for situations like European crisis, Texas, California (non-fire): 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 this be useful?

- Some conversations with the transmission system operators in Spain and France!
  - Seen as a very 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.

What I will show you today

- We propose to use power limits, which are now feasible with smart meters.
- The proposed solution is technologically feasible and a clear welfare improvement.
- We use detailed hourly smart-meter data from millions of households to quantify the implications of smart rationing policies (from a demand point of view).

- **To do (and many more):** We are still exploring its design when targeting is allowed under alternative welfare considerations.

Literature review

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

- **Theoretical literature**: Joskow and Tirole (2007), Gerlagh, Liski and Vehviläinen (2023), Bobtchef, De Donder and Salanie (2022), Tokasrki et al (2023).
- **Empirical literature**: Brehm, Johnston and Milton (2024), Lee et al (2022), Ryan and Sudarshan (2022).

Framework

Traditional "rolling" blackouts can have very large costs

- Individual net surplus is defined as a function of rationing:

$$w_i(p,\kappa) \equiv S_i(p,\kappa) - pD_i(p,\kappa),$$

- κ reflects the degree of rationing at a given moment in time.
- Let $\kappa = 0$ be full rationing and $\kappa = 1$, none.
- Under random rationing, we can use the aggregate welfare and establish that total welfare equals

$$W^B(p,\alpha_t) = \alpha W(p,0) + (1-\alpha)W(p,1),$$

  where W represents aggregate welfare, i.e., $W(p,\kappa) = \int_i \theta_i w_i(p,\kappa)di$.
- Notice that α might be small, but costs to selected consumers can be very large if the blackout is severe (e.g., Texas).

Blackout-equivalent 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,
$$\Omega : i \to \omega_i.$$
- 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
$$W^*(p,\alpha) \equiv max_\Omega \int_i \theta_i w_i(p,\omega_i)di \quad \text{s.t.} \quad \int_i D_i(p,\omega_i)di = (1-\alpha)D(p).$$
- Notice that ω 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 limited power ($\kappa \in (0, 1)$), while the rest remains with full provision of service ($\kappa = 1$).

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

$$W^P(p, \beta, \kappa) = \beta w(p, \kappa) + (1 - \beta) w(p, 1).$$

- For a given β and κ, one can obtain demand cuts that are equivalent to a blackout α.

Limits to power limits

- Because power limits provide an allowance to rationed households, they can never be equivalent to a full blackout.
- It is useful to understand the blackout size that they can approximate.

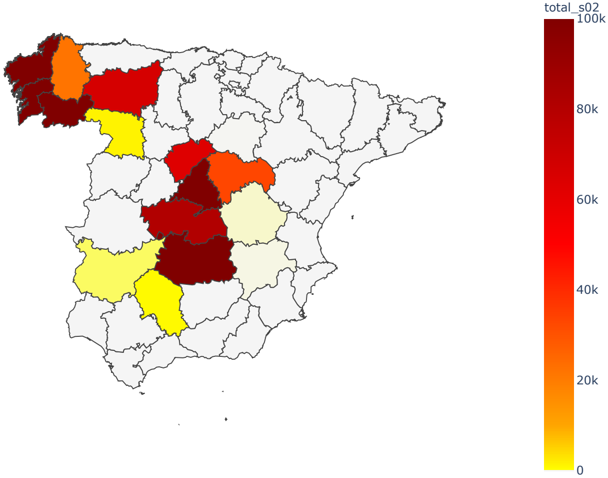
- We define the maximum amount of rationing that can be achieved by a partial rationing policy ω as
$$\overline{\alpha}(p, \kappa) = 1 - D(p, \kappa)/D(p),$$

Data

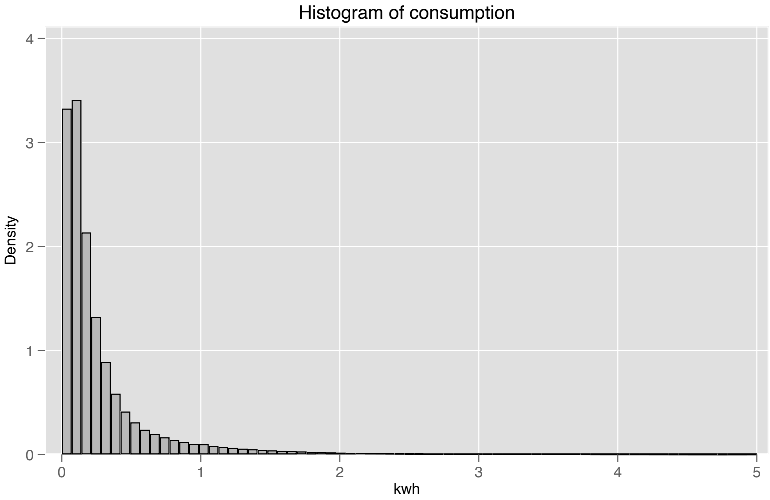
Data

- Data as in Fabra et al (2020, 2023).
- We obtained data for over 4M smart meters 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



Data: some notes

- For this first analysis, we consider all meters as valid (even if they appear to be empty houses).
- We want to focus on realistic distributions of demand available for rationing, and traditional blackouts do not account for "infra-marginal" meters (empty houses).
- When looking at distributional implications, we might narrow it down to "households" that are active.

Simulations

Simulations

- We have started to run some simulations with our smart meter data to understand the equivalent-blackout policies under different assumptions of rationing.
- 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.

Simulation details

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

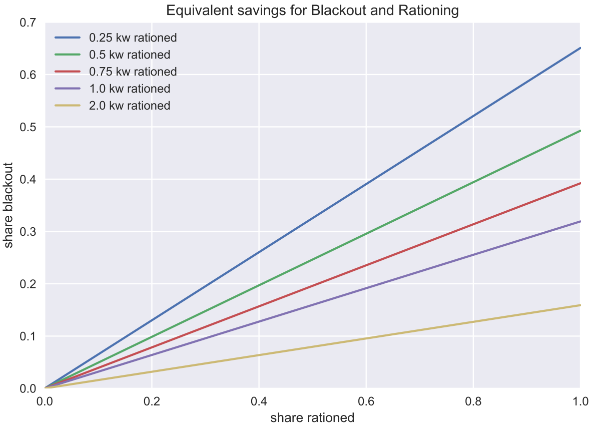
$$D_{it}(p, \kappa) = \min\{D_{it}(p), \kappa\}.$$

- 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.

Equivalence frontier

- All lines are below the 45-degree line: partial random rationing necessarily need to impact 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.



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Some notes

- Under partial rationing, not all households are partially rationed.
- We separate **effectively rationed** vs. **selected but unrationed** households.
- This is a useful concept to think about welfare and incidence.

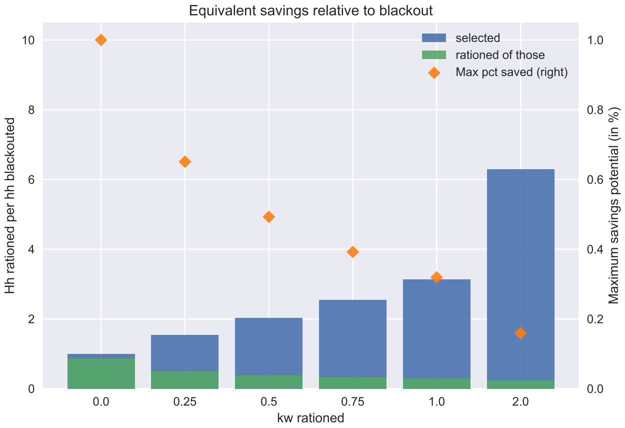
- Under random rationing, conditional on a given κ, the *share* of "effectively rationed" and "selected but unrationed" remains constant.

- Also important to notice that there are natural limits to partial rationing: a 100% full blackout cannot be replicated by any partial rationing policy.

Impacted consumers and limits to partial rationing

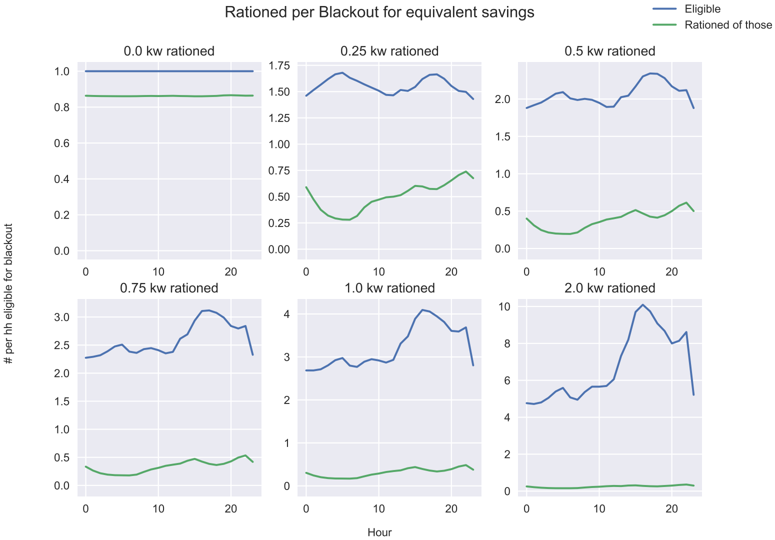
- The more generous the partial rationing, the more people need to be selected.
- However, rationing effectively affects fewer and fewer people.
- Note: this is an empirical question, driven by the shape of consumption.

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



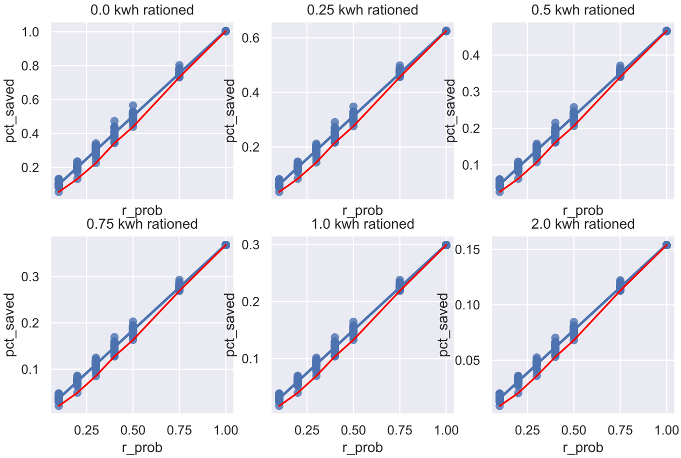
Impact of the rule depends on demand patterns

- Rationing policies have less impact at night.
- More homogeneous consumption across households during the night, impacts number of selected households and actually rationed households.



Geographical aggregation matters

- If rationing has to be done at the zip-code level, there is less amount of randomization.
- Lower envelope to ensure α-equivalent blackout is achieved becomes more aggressive.
- Particularly relevant for small blackouts where only one or two zip-codes need to be rationed.



Next steps

Many open questions to make this an implementable mechanism

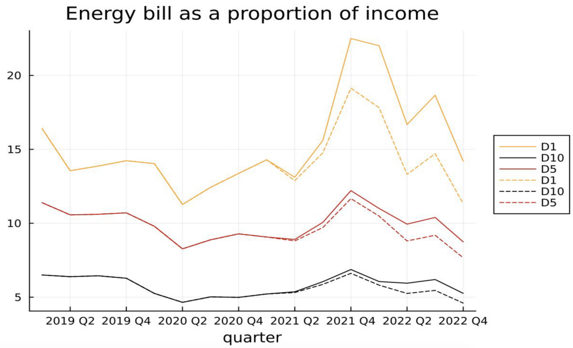
- What are the smart rationing protocols that ensure $\alpha D(p) = D(p, \omega)$ (technical aspects, notions of uncertainty/reliability)?
  - How does it depend on the communication protocol, e.g., if only a portion $\beta_t \geq \alpha_t$ can be modified in time? $\rightarrow$ "smart rationing" not 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?
  - Should rationing depend on heating mode and other relevant aspects of electricity use?
  - Should some of this be contractible? Why or why not?

Mostly in progress!

An example of an open question

Should households have limits proportional to their typical consumption?

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



Next steps

- Explore limiting factors to communication protocol: number of smart meters that can be reach at any time, minimum length of blackout for it to be optimal.
- Explore notions of welfare under rationing, budget constraints, and extreme events.
  - Incorporate appliance ownership and household-level income predictions from Cahana et al. (2023).

Thank you.

Questions? Comments?

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