Blackouts and Resilience

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Mar Reguant
IAE-CSIC and BSE

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Electrification makes reliability scarcer and more valuable

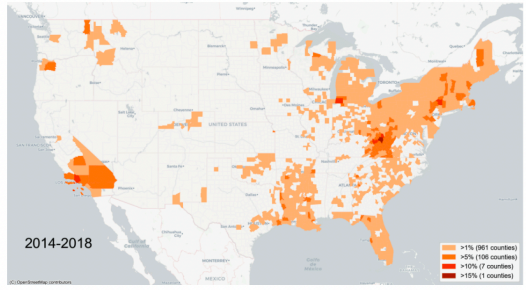
- Electricity demand is rising: electrification, cooling, data centers, industrial decarbonization.
- Supply is changing: more renewables, more weather dependence, more need for flexibility.
- Infrastructure is stressed: aging grids, delayed transmission, local bottlenecks.
- Climate shocks hit both sides of the market: supply disruptions and demand spikes.

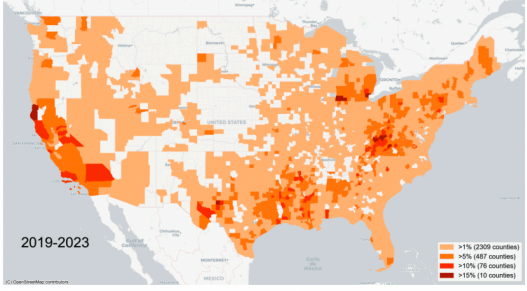
Reliability becomes more valuable when it becomes harder to guarantee.

US blackout exposure is rising

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

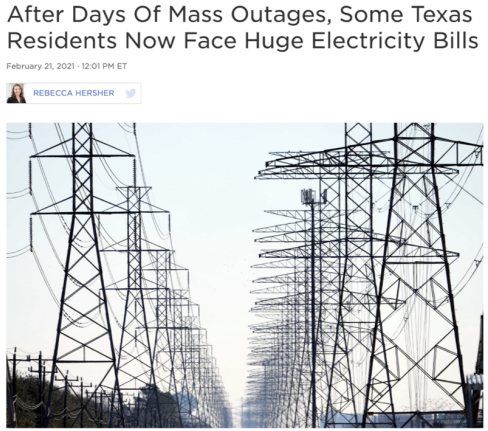
Graph: Li et al. (2024). Data: Oak Ridge National Laboratory. Cumulative percentage hours with blackouts at the county level.





Blackouts are an extreme outcome with growing relevance

- Chile, February 25, 2025: more than 90 percent of the population affected.
- Iberian Peninsula, April 28, 2025: Spain and Portugal experienced a large system-wide outage.
- Texas, February 2021: prolonged outages during Winter Storm Uri.
- In many countries, load shedding is not exceptional; it is part of ordinary economic life.



Blackouts raise measurement and design questions

- Blackouts are becoming more salient across many electricity systems.
- The energy transition raises the value of electricity reliability and changes how it is provided.
- We need to measure the economic cost of lost load as it actually unfolds over time.
- Once scarcity is unavoidable, blackout rules shape who bears the cost.

Growing tensions with resource adequacy, reliability, and their costs

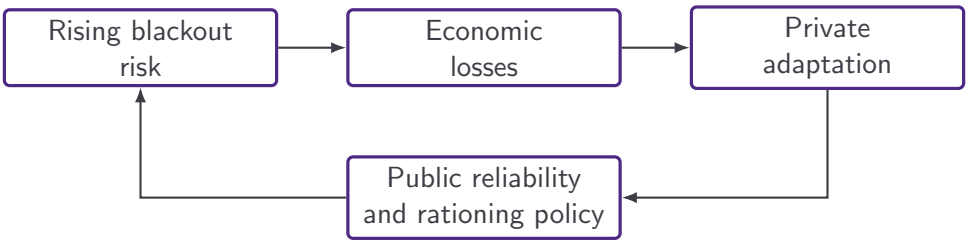
- Need to do more research on what the right mechanisms and prices can ensure the best outcomes.
- This may require updating how regulators and consumers form expectations about interruptions.
- Gowrisankaran et al. (2016) anticipate the need to re-think reliability rules in the face of growing renewable 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.

Resilience and adaptation is necessary

- Growing need to prepare infrastructure and households for extreme weather.
- Protocols and investments are improving, but grid and capacity often behind, leaving the probability of effects higher.
- Households and firms adapt privately, often unequally (e.g., see Adelowo (2025), Brown and Muehlenbachs (2024)).
- Regulators need last-resort tools for scarcity.

What are the effects of scarcity? What should resilience look like when the system is under stress?

Reliability policy needs to be optimized



- We need to study how these pieces interact.
- For example, private adaptation might affect optimal public reliability, economic losses and the probability of a blackout itself (e.g., Brehm et al., 2023).

How to design policies to reduce expected costs?

$$\mathbb{E}[\text{blackout cost}] = \Pr(B \mid \text{rules}, \text{adaptation}) \times \mathbb{E}[\text{VoLL} \mid B, \text{rules}, \text{adaptation}]$$

- Reliability investments mostly act on the probability term.
- Adaptation acts on both terms, with uneven effects across households and firms.
- Restoration and rationing rules mostly act on damages conditional on a blackout.
- A low-probability blackout can still be a large policy problem if the damage state is severe.

The same outage can mean very different welfare losses

Event	Shock	Anticipated?	Effect	Conditional VoLL
Texas 2021	Extreme demand plus supply failure	Partly forecastable	Managed load shedding	Very high: cold, long duration, safety risks
Fire-related shutoffs	Grid operation creates wildfire risk	Often anticipated	Preventive shutoffs	High, targeted, adaptation-intensive
Spain/Portugal 2025	System instability in oversupply / high-renewables context	Largely unanticipated	Cascading outage and restoration	Sudden, system-wide disruption
Chile 2025	Transmission / protection failure	Unanticipated	System collapse and restoration	Large losses with substantial recovery
Chronic load shedding	Persistent scarcity	Highly anticipated	Rotating schedules	Adaptation lowers marginal losses, growth costs

Today: Two pieces of the puzzle

- "Zero Energy Day", joint w/ L. Gonzales and K. Ito, measures losses and recovery from a real zero-energy event in Chile.
- "Smart Power Limits", joint w/ M. Wagner, explores how to design the last-resort policy when scarcity is forecastable.

1. Chile: A Zero-Energy Day

February 25, 2025: a rare nationwide blackout

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REGIÓN METROPOLITANA: $1000
Regiones I, II, III, XI, XII y XV: $1700
Regiones de la IV a la X y XIV: $1000
FUNDADO EN VALPARAÍSO EL 12 DE SEPTIEMBRE DE 1827 / AÑO CXCVII N° 66.118 / MCM
SANTIAGO DE CHILE, MIÉRCOLES 26 DE FEBRERO DE 2025
FUNDADO EN SANTIAGO EL 1 DE JUNIO DE 1900 / AÑO CXXV N° 43.533 DE PROPIEDAD

Cientos de miles de personas tuvieron que caminar para movilizarse, como en el sector de Baquedano, en el centro de la capital. En gran parte del país la población sin suministro eléctrico vivió seriamente trastornado su cotidianidad. Los problemas en el transporte y en las comunicaciones telefónicas impidieron desarrollar normalmente la jornada laboral o volver a los hogares.

Ejecutivo decreta estado de catástrofe y toque de queda:

Masivo corte eléctrico paraliza servicios, hace colapsar el transporte, interrumpe las comunicaciones y altera la jornada de más de 19 millones de personas

- Inédita falla en la línea de transmisión, a la altura del Norte Chico, provoca la caída total del sistema y un extendido apagón entre las regiones de Arica y Parinacota y Los Lagos.
- Luego de sucesivos intentos por recuperar el suministro, después de cinco horas de emergencia, La Moneda decide ordenar el despliegue nocturno de militares en las calles.

Presidente Boric arremete contra compañías: "No es tolerable que por el actuar de unas empresas se altere la vida de las chilenas y chilenos",

Caos en la capital: Paraderos saturados, alta congestión vehicular y todas las estaciones del metro fuera de operación, entre las consecuencias del

Colegios cerrados: Trescientos mil escolares que recién habían retomado sus estudios se quedan hoy sin clases, según el balance de

Especialistas plantean que zigzagueantes resoluciones pueden causar "confusión".

Exalcaldesa Barriga reingresa a prisión preventiva por tercera vez tras fallo de la corte | C 10

Gobierno argentino presenta el primero de sus 25 cazas F-16 comprados a Dinamarca | A 5

CORTE PENAL INTERNACIONAL

Expertos explican alcances de presentación chilena ante La Haya por caso del homicidio del exmilitar disidente venezolano Ronald Ojeda | C 5

Análisis a por qué los jóvenes votaron por los partidos extremos en Alemania | A 5

India gana terreno entre los principales destinos para las exportaciones chilenas | B 2

Contraloría

Órgano instruye nueva fórmula para calcular déficit financiero en municipios, en medio de cosas judiciales y auditorías. | C 9

4-11 POLÍTICA

Inédita falla genera apagón desde Arica a Chiloé: gobierno decreta estado de catástrofe y toque de queda

Masivo corte eléctrico afectó a 19 millones de chilenos.

Desperfecto se generó en el norte chico, en línea de transmisión de la empresa ISA.

Boric: "Esto no lo vamos a dejar pasar, actuaremos con firmeza".

Tras una jornada caótica, se esperaba que de madrugada retornara el servicio.

2 PULSO

Estadounidense Christus presenta oferta por activos de Empresas Banmédica

14-15 NACIONAL

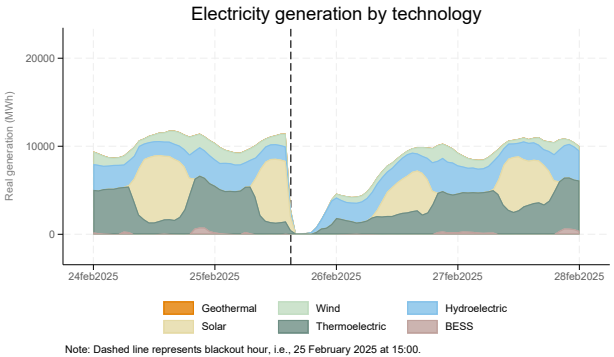
Megatoma: las garantías que la inmobiliaria le exige al Ejecutivo

21 NACIONAL

12 PULSO

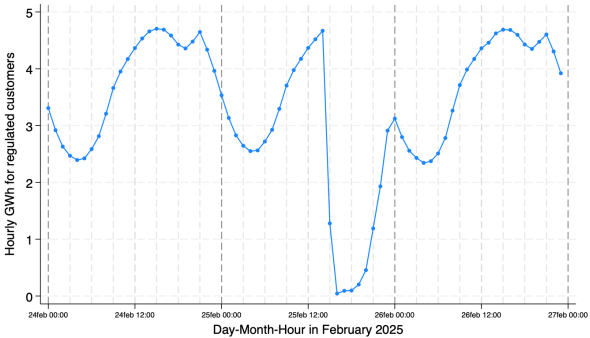
13 POLÍTICA

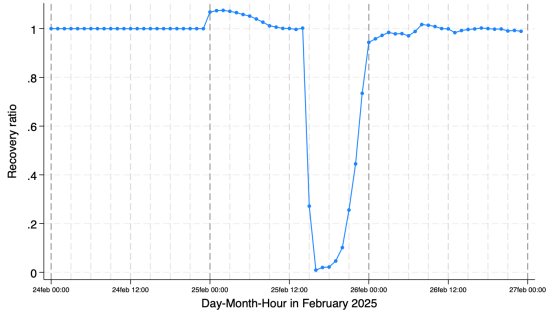
What happened in the electricity system?



- The blackout started at 15:16 on February 25.
- Recovery was partial by midnight; full restoration took many hours.
- The event generated sharp variation in lost load across time and space.

The demand-side footprint





- Regulated customers lost a large share of load during the event window.
- The recovery path is central: a blackout creates a dynamic shock.

What data make this possible?

- Hourly electricity demand at the node level.
- Hourly generation and system operation data.
- Confidential Central Bank of Chile transaction data.
- Retail and business activity observed at high frequency.

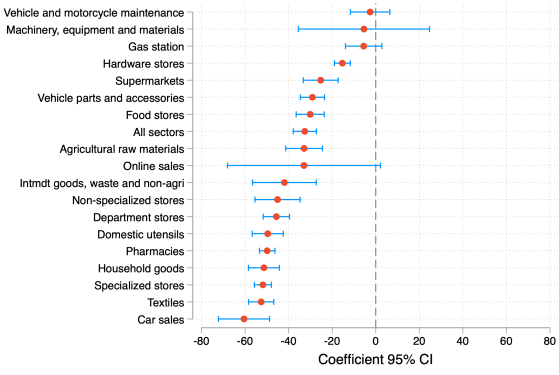
The empirical object is economic activity before, during, and after lost load.

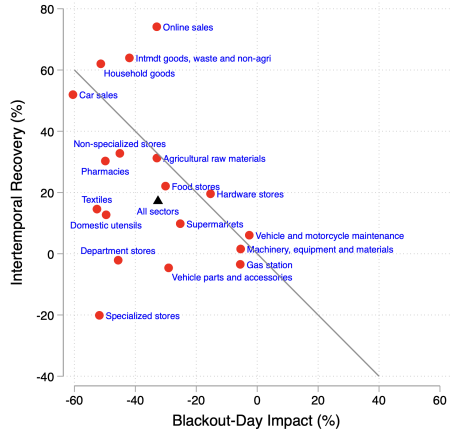
Zero-energy day cut activity by one third

- Economic activity fell by about 35 percent on the blackout day.
- About half of the loss was recovered over subsequent days.
- Static day-of comparisons overstate the net loss if they ignore intertemporal substitution.

	Static day-of effect	Dynamic net effect
Economic activity	large decline	about half recovered
VoLL implication	higher	lower
Policy lesson	immediate disruption	recovery matters

The same blackout is not the same shock for every sector





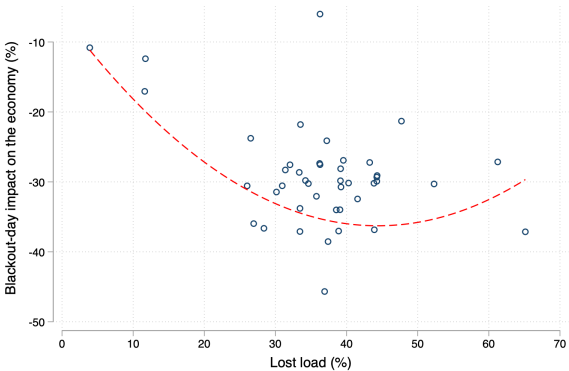
- Some activity is lost; some is delayed.
- Recovery is stronger for postponable purchases than for time-sensitive activity.

From aggregate loss to value of lost load

- Total card-based economic losses are estimated at roughly \$36–\$70 million.
- Lost load is about 32.2 GWh.
- Implied average VoLL is much lower once recovery is included.

The value of reliability depends on endogenous dynamic recovery.

Can spatial variation identify the marginal cost of lost load?



- Different comunas experienced different lost-load shares.
- Restoration is not random.
- Operators may prioritize places where the cost of outages is higher.
- Naive OLS can understate the marginal effect of lost load.

Summary: Zero Energy Day

- Large blackouts create large immediate losses (about 35% of economic activity lost, VoLL \$1000-2000/MWh).
- Recovery is first order, and it is heterogeneous across sectors.
- Marginal lost load is hard to estimate because recovery and restoration are endogenous.
- Better reliability policy can benefit from high-frequency data and a dynamic view of economic activity.

2. From Blackout Costs to Blackout Design

Rolling blackouts are a design choice

- Traditional approach: rolling blackouts.
- Advantage: simple, visible, enforceable.
- Problem: selected households go to zero power.
- New possibility: smart meters can impose maximum power limits.

Instead of disconnecting some households, give many households limited access.

Load limiting preserves essential electricity

- Let x_i be household electricity consumption during a scarcity event.
- A power limit κ transforms consumption into

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

- $\kappa = 0$ is a blackout.
- $\kappa > 0$ preserves essential uses: lights, refrigerator, phone charging, some heating or cooling depending on the level.

Same load shedding, but no households with zero power

- A rolling blackout selects share α of households and sets them to zero.
- A power-limit policy selects share β and gives them limit $\kappa > 0$.
- Choose (β, κ) to achieve the same aggregate demand reduction:

$$\beta D(\kappa) + (1 - \beta)D = (1 - \alpha)D.$$

- Then compare welfare, affected households, and distributional incidence.

Heavy users do the marginal curtailment

- More households may be selected under power limits: $\beta > \alpha$.
- Some selected households are never actually constrained.
- A household only notices the policy when $x_i > \kappa$.
- With heavy-tailed electricity use, high users contribute a lot of the reduction.

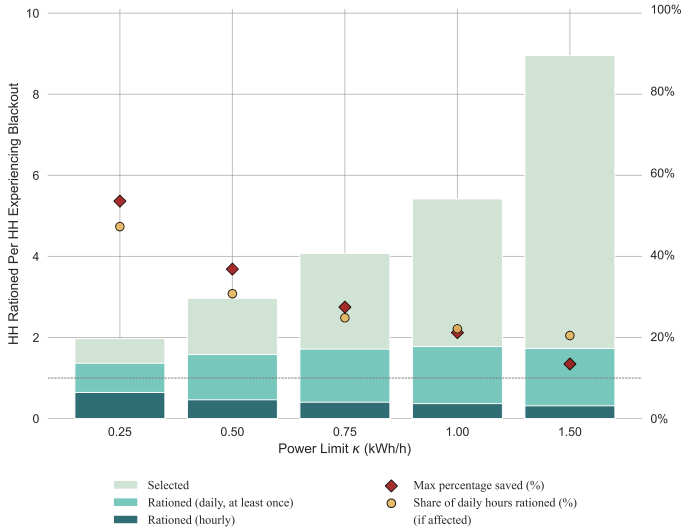
Partial rationing can mimic a blackout while bothering fewer people.

We simulate smart rationing policies using data from Spain

- More than one million households.
- Hourly consumption profiles.
- Contracted power, which is informative about household needs and income.
- Simulate blackout-equivalent policies under different uniform and proportional limits.

Partial rationing can cover large shortages

- More generous limits require selecting more households.
- The effectively rationed share can remain much smaller.
- There is a ceiling: partial rationing cannot mimic a 100 percent blackout.

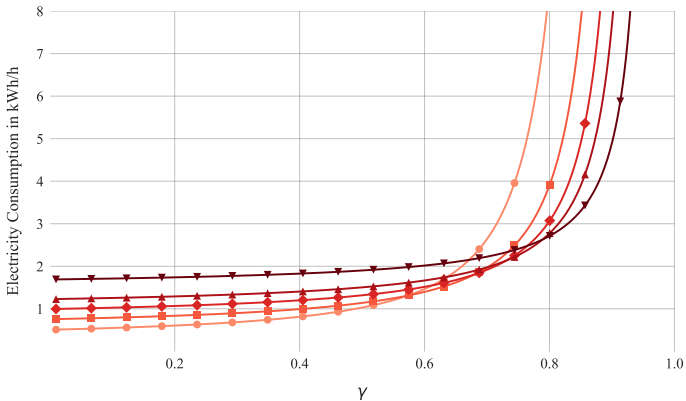


Power limits replace a zero-power lottery

- Rolling blackouts create a lottery between normal consumption and zero consumption.
- Power limits compress the bad state: households retain some electricity.
- Households below the limit are strictly better off.
- Households above the limit can also prefer power limits if the value of avoiding zero power is large enough.

Who prefers limits to blackouts?

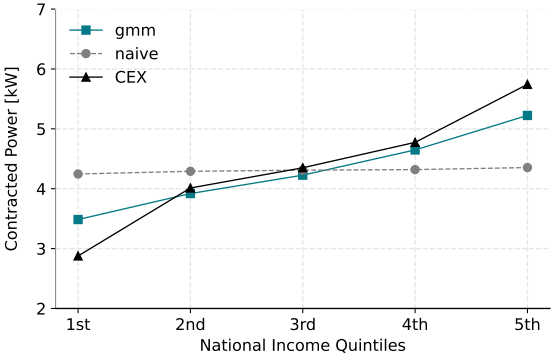
- The frontier shows which households prefer power limits under CRRA utility.
- More risk aversion expands the set of households that prefer partial rationing.
- The result is strongest when zero power is especially costly.

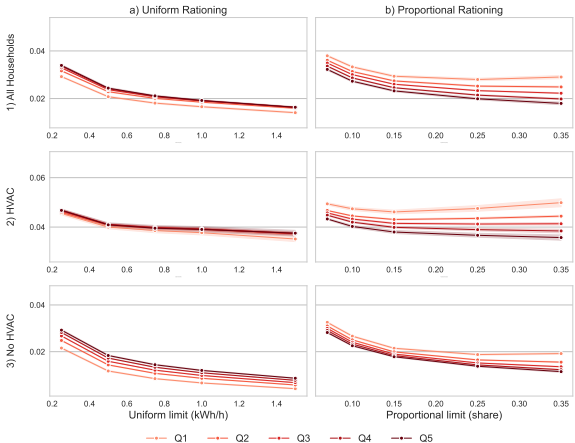


Fairness depends on why households consume

- High-consumption households tend to have higher income, with substantial heterogeneity.
- Contracted power is strongly associated with income.
- Uniform limits can look progressive because high users are more likely to be constrained.
- HVAC changes the welfare interpretation: high use may reflect need, not luxury.

Income, contracted power, and HVAC





Summary: Smart Power Limits

- Smart meters turn a binary policy into a menu of quantity limits.
- Power limits can preserve essential electricity access.
- They may reduce the number of households effectively affected.
- The policy is promising; fairness depends on how consumption maps to income, needs, and appliances.

Lessons and Questions for Resilience Policy

Reliability has to be measured and designed

- Chile: dynamic recovery changes the measured cost of blackouts.
- Chile: marginal lost load is endogenous because restoration is a policy choice.
- Spain: if scarcity is forecastable, the rationing mechanism is also a policy choice.
- Spain: the rationing mechanism can be used to reduce the expected cost.

Improved reliability and resilience policies essential going forward

- How should grid operators rank restoration when costs are heterogeneous and endogenous?
- Should rationing rules depend on income, heating or cooling technology, or contracted power?
- Can emergency-contingent contracts improve demand response before rationing is needed?
- How do private batteries, generators, and solar change the social value of public reliability?

Many questions!

Thank you!

mar.reguant@iae.csic.es