

Tariff freezes, demand growth and the grace time of electricity distribution networks: Evidence from Buenos Aires

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Research Article

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Abstract

How long can the quality of an electricity distribution network be sustained after the real tariff falls below cost? Using firm-level data for the two Buenos Aires distributors and official quality series, this paper shows that quality deteriorated after the 2002 tariff freeze not because capital wore out—it barely changed until 2012—but because demand outgrew it. The elasticity of the System Average Interruption Duration Index (SAIDI) to capacity relative to demand is -2.9 in levels and -1.7 in first differences for Edenor, and larger for Edesur. It survives weather controls, 285 of 320 alternative measures of capital and instrumenting capacity with lagged demand. No threshold is detected, although with 32 observations only an initial margin above 16% can be ruled out. Estimated on 2003–2019, the model predicts SAIDI in 2020–2024 without bias. The estimates yield a grace time, $T^*(X) = \ln(1 + X)/(\epsilon[\delta(1 - r) + g])$, the years until quality worsens by a tolerance X , given elasticity ϵ , depreciation δ , investment relative to replacement r and demand growth g . With growing demand a 50% deterioration arrives within 3 to 7 years; with stagnant demand and partial investment it takes more than 15. In a welfare model the optimal freeze lasts as long as the grace time at a tolerance set by the freeze’s benefit relative to its outage cost; ignoring the recovery period makes freezes 1.5 to 2.3 times longer. Brazilian data support the investment–quality link.

Keywords Electricity distribution · Tariff freeze · Service quality · Network capacity · SAIDI · Argentina

JEL Classification L94 · L51 · L98 · H54 · Q41

1 Introduction

Tariff freezes in inflationary environments are common in Latin America and in many developing economies. Their immediate political cost is low, and their cost in service quality appears years later, when the inherited infrastructure no longer suffices. This lag raises a question with direct regulatory consequences: how long does the period of apparent normality last, and what does it depend on?

The literature on regulation and network investment explains why tariff uncertainty and the lack of cost recovery discourage investment (Guthrie, 2006; Joskow, 2008; Foster & Rana, 2020), and the literature on service quality links investment to interruption indicators (Ter-Martirosyan & Kwoka, 2010; Cambini et al., 2016). There are, however, no estimates of the time that elapses between a tariff shock and the deterioration of quality, nor of its determinants.

This paper studies the Buenos Aires Metropolitan Area (AMBA), where the real distribution tariff fell by more than 70% between 2002 and 2015, was restored in 2016–2019 and was frozen again in 2019–2023. Few markets offer such tariff volatility. From the filings of Edenor with the U.S. Securities and Exchange Commission (SEC) and those of Edesur’s parent company, the investment, depreciation and energy sales of both distributors are reconstructed, and their official quality is measured from the annual

reports of the national regulator, the Ente Nacional Regulador de la Electricidad (ENRE), for 1997–2024.

There are three main results. First, quality did not deteriorate because capital wore out but because capacity fell relative to demand: with the tariff frozen, demand grew much faster than capital. The result holds for both AMBA distributors, each with its own investment series, and is not driven by weather. Second, quality responds continuously and no threshold is detected; pooling both firms rules out an initial margin larger than 16%, though not a smaller one. Each 10% loss of relative capacity raises SAIDI by 20% to 35% at Edenor, so the grace time depends on how much deterioration is tolerated and on how fast demand grows. Third, the tariff operates mainly through demand; its effect on investment depends on whether alternative financing exists, which in the AMBA it did for most of the period.

The contribution is threefold. Conceptually, the paper proposes a measure of grace time that incorporates demand growth, which is absent from models of capital wear and maintenance (Rioja, 2003; Kalaitzidakis & Kalyvitis, 2004; Agénor, 2009). Theoretically, it shows that the grace time is also the optimal length of a freeze for a regulator who weighs the benefit of the freeze against the cost of outages; this turns the tolerance X into an economic object—a benefit–cost ratio—and identifies a bias towards overlong freezes when the regulator’s horizon ends with the freeze, a form of the commitment problem studied by Levy and Spiller (1994). Empirically, it reconstructs the real capital of both AMBA distributors from their financial statements and their official quality over 1997–2024, controls for temperature with daily data, tests formally whether quality responds with a threshold and measures the power of that test. Section 2 reviews the literature, Sect. 3 describes the context, Sect. 4 presents the model, Sects. 5 and 6 the data and the empirical strategy, Sect. 7 the results, Sect. 8 their validity and Sect. 9 their implications.

2 Related literature

2.1 Regulation, regulatory lag and investment

Guthrie (2006) shows that regulatory design—price flexibility, the length of the regulatory cycle and cost-recovery rules—determines the risk borne by the firm and, with it, its willingness to undertake irreversible investment. Joskow (2008) warns that incentive schemes rewarding cost reduction can erode quality and investment unless accompanied by standards. Cambini and Rondi (2010) find for European utilities that the regulatory regime and the allowed return shape the investment rate. A tariff freeze under inflation is the extreme case of regulatory lag: the real tariff falls with no adjustment rule.

2.2 Service quality and its regulation

Sappington (2005) and Fumagalli et al. (2007) systematise the instruments of quality regulation (standards, rewards and penalties) and continuity indicators such as SAIDI and the System Average Interruption Frequency Index (SAIFI). Ter-Martirosyan and Kwoka (2010) show that in the United

States incentive regulation without quality standards is associated with longer outages. Cambini et al. (2016) find for Italy that both physical capital and operating expenditure affect quality, and Jamasb et al. (2012) estimate the marginal cost of improving it in the United Kingdom. For Latin America, Weiss et al. (2021) associate the introduction of quality regulation with falls of 40% in SAIDI and 45% in SAIFI, and Levy and Carrasco (2020) document that reliability improved much less than coverage.

2.3 Maintenance, depreciation and congestion of capital

A macroeconomic literature studies the allocation between new investment and maintenance. Rioja (2003) shows that insufficient maintenance accelerates the deterioration of infrastructure; Kalaitzidakis and Kalyvitis (2004) and Agénor (2009) endogenise depreciation as a function of maintenance spending. Dioikitopoulos and Kalyvitis (2008) add congestion of public capital and show that thresholds can arise. This paper borrows the idea that the service depends on the effective capital available, but measures that capital relative to its use: congestion appears here as demand growth on a network that does not expand.

2.4 Under-pricing and utility performance in developing countries

Foster and Rana (2020), Kojima and Trimble (2016) and Huenteler et al. (2017) document that the lack of cost recovery is widespread in developing countries and compromises the financial viability and maintenance of networks. McRae (2015) identifies a “subsidy trap” in Colombia: subsidies discourage investment in quality where supply is least reliable. Allcott et al. (2016) quantify the cost of electricity shortages for Indian manufacturing. This paper adds a time horizon to that diagnosis: how long under-pricing takes to translate into worse quality.

2.5 The Argentine case

Pollitt (2008) evaluates the Argentine electricity reform of the 1990s and the deterioration after the 2002 crisis, and Haselip and Potter (2010) analyse the subsequent interventions, including the tariff freeze. Urbiztondo et al. (2020) assess the structure of tariffs and subsidies in the sector, and Bertín et al. (2025) show that the progressivity of electricity subsidies weakens once their financing is considered. Casarin and Delfino (2011) are the closest antecedent for the demand channel: with data for Greater Buenos Aires they show that, with frozen tariffs, the diffusion of air conditioning drove residential consumption. Long-run price elasticities estimated for the region are low but not negligible, between -0.25 and -0.33 according to the meta-analysis of Zabaloy and Viego (2022), in line with the global meta-analysis of Labandeira et al. (2017).

2.6 Contribution

The literature establishes that under-pricing discourages investment and that investment improves quality, but it does not quantify the time between the two or the role that demand growth plays in that time. This paper integrates both channels into a single measure of relative capacity, tests with the

methods of Hansen (1996, 2000) whether quality responds with a threshold, and translates the estimated response into a grace time conditional on investment and demand.

3 Context: electricity distribution in the AMBA, 2002–2025

Edenor and Edesur serve the AMBA under concessions granted in the 1992 privatisation. They are regulated by ENRE, which measures technical service quality every six months and imposes penalties when limits are exceeded. After the 2002 devaluation, the Public Emergency Law (Law 25,561) converted tariffs to pesos and froze them. Adjustments in the following years were partial and the real tariff fell steadily. From 2013 investment was partly financed by a specific charge, the FOCEDA fund. In 2016–2017 a comprehensive tariff review restored the tariff and set new quality targets. At the end of 2019 the tariff was frozen again, and the distributors accumulated debt with CAMMESA, the wholesale market administrator, until the tariff was restored in 2024.

4 Model

4.1 Capital wear

If investment stops, capital decays at rate δ and the time until it reaches a technical minimum $K_{\min}$ is

$$T^* = \frac{1}{\delta} \ln \left(\frac{K_0}{K_{\min}} \right) \quad (1)$$

With positive investment and $r = \text{investment/depreciation}$, $K(t+1) = K(t)[1 + \delta(r-1)]$. With δ between 2% and 3.3% and $K_{\min}/K_0$ between 0.7 and 0.9, the time ranges from 3 to 18 years without investment and is longer with partial investment, exceeding 20 years when investment covers most of replacement. The model assumes that the load on the network is fixed.

4.2 Capacity relative to demand

Let $A(t) = K(t)/D(t)$ be relative capacity, where D is energy demand. Its rate of change is approximately

$$\frac{d \ln A}{dt} = \delta(r-1) - g \quad (2)$$

where g is demand growth. If quality responds to relative capacity with a constant elasticity ε , $\ln \text{SAIDI} = c - \varepsilon \ln A$, the time until SAIDI exceeds its initial level by a proportion X is

$$T^*(X) = \frac{\ln(1+X)}{\varepsilon[\delta(1-r) + g]} \quad (3)$$

A lag of about one year is added until deterioration shows up in annual indicators. X is a tolerance set by the regulator or by society (for example, +50% or a doubling). If instead of a continuous response there were a threshold A^* below which quality starts to worsen, the time would be $\ln(A_0/A^*)/[\delta(1-r) + g]$ plus the time implied by Eq. (3) once the threshold is crossed; Sect. 7.2 tests which form better describes the data. With $g = 0$ the wear model is recovered.

4.3 Equilibrium investment

To keep A constant, investment must cover depreciation and keep pace with demand:

$$r^* = 1 + \frac{g}{\delta} \quad (4)$$

With $g = 3.7\%$ and $\delta = 2.5\%$, $r^* \approx 2.5$: replacing the capital stock is not enough when demand grows.

4.4 Two buffers and a scope condition

The observed grace time combines a financial buffer (how long the firm can sustain investment without an adequate tariff) and a physical component (how much quality deteriorates per point of relative capacity lost). The tariff affects T^* through two channels: through r , only when investment is financed by the tariff, and through g , because a low real tariff stimulates demand (Casarin & Delfino, 2011).

4.5 The regulator's choice of freeze length

Equation (3) takes the tolerance X as given. This subsection derives it from the trade-off faced by a regulator, or a government, that decides how long to keep a tariff freeze. Three assumptions are made. (A1) During a freeze of length τ relative capacity erodes at the rate $h = \delta(1 - r) + g$, so $\ln A(t) = \ln A_0 - ht$ for $t \leq \tau$. (A2) When the freeze ends the tariff is restored and investment above r^* rebuilds relative capacity at the rate $\kappa > 0$ until it returns to A_0 . (A3) Quality follows $\ln S = c - \varepsilon \ln A$, where S denotes SAIDI and S_0 its initial level; each hour of interruption per customer above S_0 costs v per year (customers times average load times the value of lost load), and the freeze yields a benefit flow b per year to consumers or to the government (lower bills, lower measured inflation, political support). Ignoring discounting, the regulator chooses τ to maximise

$$W(\tau) = b\tau - vS_0 \int_0^\tau \left(\frac{S(t)}{S_0} - 1 \right) dt \quad (5)$$

Proposition 1. *Under A1–A3, W is strictly concave in τ and the optimal freeze length is*

$$\tau^* = \frac{\ln(1 + X)}{\varepsilon h}, \quad X = \frac{b}{vS_0 \left(1 + \frac{h}{\kappa}\right)} \quad (6)$$

that is, the grace time $T^*(\hat{X})$ of Eq. (3) evaluated at a tolerance $\hat{X}$ equal to the ratio between the benefit of the freeze and the cost of the outages it causes, scaled up by the recovery period. The proof is in Appendix A. The freeze should end when the marginal cost of one more year—the extra outages during that year plus the longer recovery it leaves behind, $(\exp(\varepsilon h \tau) - 1)(1 + h/\kappa)vS_0$ —equals its benefit b .

Four implications follow. First, τ^* falls with ε , δ , g and v and rises with r , b and κ . Demand growth acts twice: it speeds up the erosion of capacity and, through h/κ , lengthens the recovery that each year of freeze leaves behind. Second, alternative financing that keeps investment up during the freeze (raising r) lengthens the optimal freeze; it shifts the cost to whoever provides the funds rather than eliminating it. Third, if quality only deteriorates below a threshold A^* , τ^* rises by $\ln(A_0/A^*)/h$, the time needed to use up the margin; a lag ℓ between capacity and measured quality adds ℓ . Fourth, a regulator whose

horizon ends with the freeze—who does not bear the recovery—sets the tolerance at $b/(vS_0)$ instead of $\hat{X}$ and chooses

$$\tau_m = \frac{\ln\left(1 + \frac{b}{vS_0}\right)}{\varepsilon h} > \tau^*, \quad \frac{\tau_m}{\tau^*} \rightarrow 1 + \frac{h}{\kappa} \text{ as } X \rightarrow 0 \quad (7)$$

The bias is larger the faster capacity erodes relative to how fast it can be rebuilt. Discounting reinforces it, since the recovery costs come later. The model is deliberately simple: it takes the response of quality, the erosion rate and the recovery rate from the empirical analysis and asks how long a freeze should last given them; Sect. 7.7 calibrates it.

5 Data

Table 1 lists the data and their sources (Edenor, 2008–2026; Enersis, 2005–2016; ENRE, 1994–2025; NOAA NCEI, 2026); Online Resource 1 lists every filing and URL used, datum by datum.

Table 1 Data sources

Data	Source	Treatment
Edenor: investment, depreciation, customers, energy sold, peak demand, SAIDI/SAIFI, debt with CAMMESA (2002–2025)	Forms 20-F and 6-K filed with the SEC (Edenor, 2008–2026)	Restated figures of each filing; one URL per datum
Edenor and Edesur: semi-annual SAIDI and SAIFI, 1996–2025	ENRE annual reports 1993–2024, quality charts (ENRE, 1994–2025)	Measured on the vector charts; calibrated against 16 published values (error $\leq 0.27\%$)
Edesur: investment 2003–2004 and 2008–2016, 2003 depreciation, energy sold	Enersis/Enel Américas (2005–2016), 6-K and Análisis Razonado; Edesur annual reports and press releases	Chilean pesos converted with average exchange rates of the Central Reserve Bank of Peru (BCRP); 2005–2007 interpolated
Real tariff and wholesale price index (IPIM), 1993–2025	National Statistics Institute (INDEC)	Official series; GDP deflator (World Bank) as alternative
Daily mean temperature, Buenos Aires, 1996–2025	NOAA GHCN-Daily, Aeroparque station (Menne et al., 2012)	Cooling degree days per March–February year; 23 of 10,592 days missing
Brazil 2011–2017: 5-year investment / regulatory depreciation; DGC continuity index	ANEEL sustainability indicators (processed public repository)	62 distributors
Brazil 2020–2024: DEC/FEC by distributor; capex and depreciation	ANEEL open data; CVM financial statements	National DEC computed: 10.46 vs 10.43 published (2023)

Note: DEC and FEC are the Brazilian equivalents of SAIDI and SAIFI. Detailed sources in Online Resource 1.

Measuring investment. Between 2003 and 2017 Argentine financial statements were not adjusted for inflation and depreciation remained at historical cost, so Edenor’s nominal capex/depreciation ratio reaches 7.5 and cannot be interpreted. Investment is therefore measured in real terms: capex deflated by the IPIM relative to the 2003 depreciation (the last year with inflation-adjusted statements), scaled by the size of the stock. On this measure Edenor invested between 46% and 83% of replacement in

2003–2006 and between 1.1 and 2.8 times replacement in 2007–2016. Edesur’s investment is taken from the reports of its parent company, Enersis (now Enel Américas), which publishes it in Chilean pesos. It is converted to Argentine pesos with the ratio of the annual average exchange rates published by the Central Reserve Bank of Peru, which replicates the accounting translation: for 2010 it yields 445 million pesos, against 448 million reported for the company in the press. The years 2005–2007 are missing and are interpolated; from 2014 the Enersis series exceeds the figure reported by Edesur by 17%, a gap used to splice 2016.

Measuring quality. ENRE publishes the semi-annual SAIFI and SAIDI of each distributor (all interruptions longer than three minutes, including force majeure) in bar charts in its annual reports. The 2024 report covers semesters 1 to 57 (September 1996 to February 2025). Because the charts are vector graphics, the height of each bar was measured directly in the file and calibrated against the 16 values that ENRE published for semesters 44 to 47 in its semester-47 report: the calibration factor is 0.987 (implied factors between 0.987 and 0.990), and the largest deviation from a published value is 0.27%. The same measurement on the 2017 report agrees within 0.1% for three of the four series and within 3.5% for Edenor’s SAIDI. The annual series adds the semesters from March to February. Edenor’s own annual reports use a different measure that coincides with ENRE’s in 2016 (about 27 hours) but is lower in most years (for example, 31.6 against 46.7 hours in 2012); the paper uses the ENRE series throughout.

Temperature. Daily mean temperature for the Aeroparque station of Buenos Aires is taken from the Global Historical Climatology Network–Daily (Menne et al., 2012; NOAA NCEI, 2026). Cooling degree days (CDD) are the sum over the March–February year of the excess of daily mean temperature over 18 °C (or 22 °C), rescaled to 365 days when days are missing.

Use of AI tools. A large language model (Claude, Anthropic) assisted in locating and extracting data from the cited public filings, in writing the statistical code and in drafting and translating the text. Every datum was checked against the primary source cited in Online Resource 1, all estimates are reproducible with the code in Online Resource 2, and the author takes full responsibility for the content.

6 Empirical strategy

6.1 Capital and relative capacity

The real capital of each firm is built by the perpetual inventory method, $K(t) = K(t - 1)(1 - \delta) + I(t)$, where I is real investment and the initial stock is $K(2002) = \kappa \cdot \text{depreciation}(2003)/\delta$. The baseline, $\kappa = 1$, assumes that the 2003 depreciation measures annual replacement. Demand D is energy sold (including transmission tolls). A is the ratio of the two indices, with 2002 = 100. Because the result depends on the deflator, on δ and on κ , it is re-estimated for 80 combinations for Edenor (two deflators, four values of δ , five of κ and two demand measures) and 240 for Edesur (two deflators, four values of δ , five of κ , three imputations of 2005–2007 and two series for 2014–2016).

6.2 Response of quality

Using 2003–2019, $\ln \text{SAIDI}(t) = c - \varepsilon \ln A(t - 1)$ is estimated with heteroskedasticity and autocorrelation consistent standard errors (Newey & West, 1987), in levels and in first differences. To test for a threshold, $\ln \text{SAIDI}(t) = a + b \cdot \max(0, \ln(A^*/A(t - 1)))$ is also estimated, choosing A^* over a grid. Because A^* is not identified under the null, p-values are obtained by bootstrap (Hansen, 1996), against no relationship and against the continuous relationship. Uncertainty about A^* is measured by bootstrap, by leaving out one year at a time and with the likelihood-ratio confidence set of Hansen (2000). Since with 15 to 17 years the test may lack power, power is measured by simulation: 400 series are generated from threshold models with $A^* = 97, 95, 92, 90, 85$ and 80 , each calibrated to the data (slope and residual standard deviation) along the observed path of A , and the share of rejections of the continuous model is recorded. The exercise is repeated for Edesur and for the pooled panel of both firms (32 observations).

6.3 Capital versus demand, and feedback

To check that the relevant variable is the ratio, $\ln \text{SAIDI}(t) = c + \beta \ln K(t - 1) + \gamma \ln D(t - 1)$ is estimated; the model predicts $\beta < 0$ and $\gamma > 0$. It is estimated for each firm and in a panel of both with firm fixed effects. Because investment may respond to quality—the regulator penalises and pressures firms when quality worsens—this feedback is tested, and ε is re-estimated by instrumental variables, using lagged demand as an instrument for relative capacity.

6.4 Temperature

Heat waves raise both demand and failures. To separate this effect, CDD are added: $\ln \text{SAIDI}(t) = c - \varepsilon \ln A(t - 1) + \theta \text{CDD}(t)$, with variants (days with mean temperature ≥ 26 °C, a linear trend, first differences, semi-annual data with a summer effect) and, separately, with weather-normalised demand.

6.5 Brazilian panel

For the investment–quality channel, panel regressions with firm and year fixed effects and errors clustered by firm are estimated. For 2011–2017 the dependent variable is the logarithm of ANEEL’s DGC continuity index (DEC and FEC relative to their limits; higher is worse), and the regressor is investment over the previous five years relative to regulatory depreciation over the same period. For 2021–2024 the dependent variable is the logarithm of DEC computed from the data by network set, and the regressors are capital reconstructed from CVM data and the number of consumers.

6.6 Simulation and validation

T^* is simulated 200,000 times with ε uniform between the first-difference and the levels estimates and δ uniform between 2% and 3.3%, for different values of r and g . Edenor’s official SAIDI for 2020–2024, not used in estimation, serves as an out-of-sample test, with relative capacity projected from Edenor’s inflation-adjusted financial statements.

7 Results

7.1 Capital did not fall; demand grew

Table 2 and Fig. 1 summarise the mechanism. Between 1997 and 2002 the SAIDI of both firms fluctuated between 7 and 19 hours with no trend. After the freeze, Edenor's real capital stayed between 96 and 100 until 2012 while demand grew by 59% and relative capacity fell to 63. The same happened at Edesur: capital between 97 and 100, demand +46% and relative capacity down to 68. Edenor's SAIDI started to rise in 2005 and Edesur's in 2006, and both peaked in 2012–2013. After the 2016 tariff review demand fell, investment rose and quality improved. From 2020 Edenor's relative capacity fell slightly again and its SAIDI remained between 10 and 22 hours.

Table 2 Real capital, demand and relative capacity (indices, 2002 = 100) and SAIDI (hours)

Year	Edenor capital	Edenor demand	Edenor A	Edesur capital	Edesur A	SAIDI Edenor	SAIDI Edesur
2002	100.0	100.0	100.0	100.0	100.0	11.8	9.4
2005	96.9	120.3	80.6	97.2	84.2	12.8	8.5
2007	97.5	137.2	71.1	97.1	74.5	20.2	18.8
2012	100.2	159.3	62.9	99.5	68.1	46.7	78.7
2015	109.9	171.9	63.9	112.5	73.9	28.6	36.1
2019	134.1	149.2	89.9	—	—	21.3	28.6

Note: $\delta = 2.5\%$, $\kappa = 1$. SAIDI per March–February year (ENRE). Edesur: investment interpolated in 2005–2007; no investment data after 2016.

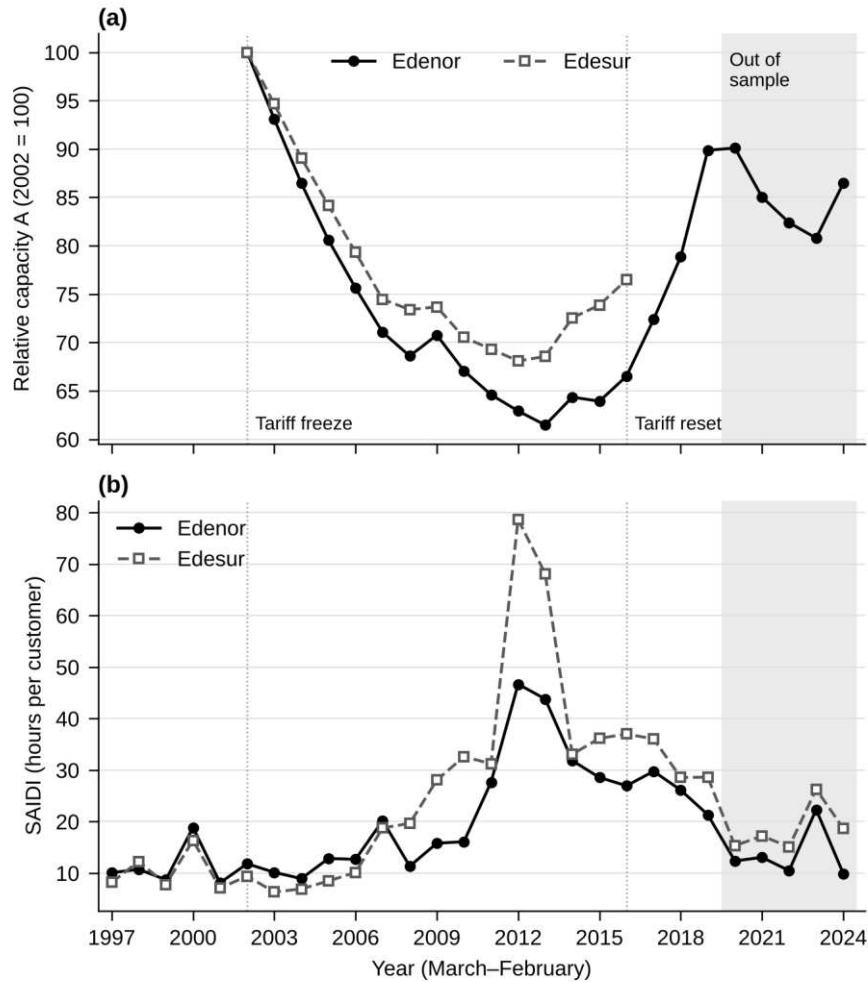


Fig. 1 Relative capacity (a) and SAIDI (b) of Edenor (solid line, circles) and Edesur (dashed line, squares). Relative capacity is real capital over energy sold, 2002 = 100. Dotted vertical lines mark the 2002 tariff freeze and the 2016 tariff review. The shaded period (2020–2024) was not used in estimation; Edenor’s relative capacity in those years is projected from its financial statements

7.2 Continuous response, no detectable threshold

Table 3 reports the estimates for Edenor. The elasticity of SAIDI to relative capacity is -2.9 (Sect. 7.5 re-estimates it with other measures of capital) and survives in first differences (-1.7 , $p = 0.03$), which rules out a common trend between two series. In the joint estimation, demand raises SAIDI strongly (elasticity 2.8 , $p < 0.001$) and capital lowers it, though less precisely ($p = 0.12$).

Table 3 Service quality and relative capacity, Edenor 2003–2019 (n = 17)

Model	Coefficient	p-value	R ²
$\ln \text{SAIDI} \sim \ln A(t-1)$	-2.88	< 0.001	0.67
$\ln \text{SAIFI} \sim \ln A(t-1)$	-1.72	< 0.001	0.68
$\Delta \ln \text{SAIDI} \sim \Delta \ln A(t-1)$ (first differences)	-1.72	0.031	0.09
$\ln \text{SAIDI} \sim \ln K(t-1) + \ln D(t-1)$: capital	-1.44	0.12	0.72
$\ln \text{SAIDI} \sim \ln K(t-1) + \ln D(t-1)$: demand	+2.79	< 0.001	0.72
Threshold: p against no relationship / against continuous	A* = 92	0.001 / 0.27	0.69

Note: Newey–West standard errors; threshold p-values by bootstrap (Hansen, 1996). The two rows with $\ln K$ and $\ln D$ come from one regression. The low R² of the first-differences model is expected: differencing removes the common trend.

There is no evidence of a threshold. The threshold model fits the data ($p = 0.001$ against no relationship) but does not improve on the continuous relationship ($p = 0.27$). Its point estimate (92, i.e. an 8% fall) has a 95% bootstrap interval of 75 to 100 and ranges from 71.5 to 94.5 when one year is left out. The continuous relationship is not rejected for SAIFI ($p = 0.26$), for two-year moving averages ($p = 0.14$) or excluding the extreme years 2012–2013 ($p = 0.35$). Nor is the continuous relationship rejected for Edesur ($p = 0.13$) or for the panel of both firms ($p = 0.25$).

Absence of evidence is not evidence of absence, and with few observations the distinction matters. Table 4 shows that the test would detect a large margin but not a small one. With a 15–20% margin, the pooled panel would reject the continuous model in 55% to 71% of the simulations, and Edesur alone in three out of four. With a margin of 10% or less, power falls to 6–32% for Edenor and for the panel. The confidence set for the panel summarises what the data can support: a margin larger than 16% before quality starts to deteriorate is ruled out, but a smaller one is not. The continuous model is the simplest description consistent with the data, not the only one. Section 7.7 computes how much the grace time would change if the largest compatible margin existed.

Table 4 Power of the threshold test against the continuous model

True threshold A* (initial margin)	Edenor (n = 17)	Edesur (n = 15)	Panel (n = 32)
97 (3%)	0.06	0.10	0.07
95 (5%)	0.10	0.13	0.10
92 (8%)	0.15	0.34	0.20
90 (10%)	0.15	0.51	0.32
85 (15%)	0.28	0.75	0.55
80 (20%)	0.49	0.77	0.71
No threshold (size of the test)	0.06	0.03	0.04
95% confidence set for A* (Hansen, 2000)	69 to 100	83 to 100	83.5 to 100

Note: share of rejections at 5% in 400 simulations with 199 bootstrap replications each. Each threshold model is calibrated to the observed data.

7.3 Temperature

Cooling degree days in Buenos Aires range from 670 to 990 per year and rise over time: seven of the ten hottest years in the series fall between 2012 and 2023. Weather alone therefore appears to explain SAIDI ($R^2 = 0.31$), because hot years coincide with years of low capacity (correlation -0.70). Once capacity enters the regression, weather ceases to be significant in every specification of Table 5, and the elasticity to capacity remains between -2.3 and -3.0 , unchanged from the baseline. The same holds with semi-annual data, which separate summers from winters, and in first differences. Nor is demand driven by weather: energy sold responds little to CDD (0.02 per hundred, $p = 0.15$), and with weather-normalised demand the elasticity is -3.0 . The result is the same for Edesur (Sect. 7.4). Temperature matters for specific events, such as the heat waves of 2013 and 2023, but does not explain the trend in SAIDI.

Table 5 Relative capacity and temperature, Edenor (ln SAIDI; $n = 17$ unless stated)

Specification	ln A(t - 1)	Weather (p-value)	R ²
Baseline, no weather	-2.88***	—	0.67
+ CDD, base 18 °C	-2.98***	-0.04 (0.78)	0.67
+ CDD, base 22 °C	-2.66***	+0.13 (0.45)	0.67
+ days with mean ≥ 26 °C	-2.47***	+0.13 (0.10)	0.69
+ CDD 18 °C and linear trend	-2.34***	-0.13 (0.27)	0.74
First differences + Δ CDD ($n = 16$)	-1.81**	-0.04 (0.62)	0.10
Semi-annual, summer effect + semester CDD ($n = 34$)	-3.00***	-0.04 (0.79)	0.62
Weather-normalised demand	-2.98***	—	0.65
Weather only, no capacity	—	+0.52***	0.31

Note: CDD in hundreds of degree days per March–February year (NOAA, Aeroparque). Newey–West standard errors. *** $p < 0.01$; ** $p < 0.05$. A dash means the variable is not in the specification.

7.4 Edesur

With Edesur's investment as reported by its parent company, its relative capacity is built with the same method as Edenor's. Edesur invested 48% and 63% of replacement in 2003 and 2004, in Edenor's range, and its real capital remained flat until 2012 while demand grew by 46%. Its SAIDI rose from 6.3 hours in 2003 to 78.7 in 2012. Table 6 shows an elasticity to relative capacity of -6.1 in levels and -2.5 in first differences. In the joint estimation both channels are significant and have the predicted sign (capital -4.3 , $p = 0.002$; demand $+6.0$, $p < 0.001$); for Edenor the capital channel fell short of significance. The complete model, not only the demand channel, is therefore verified in both firms.

Table 6 Edesur: quality and relative capacity with its own investment series, 2003–2017 (n = 15)

Model	Coefficient	p-value	R ²
$\ln \text{SAIDI} \sim \ln A(t-1)$	-6.10	< 0.001	0.86
Same, excluding 2012–2013 (n = 13)	-5.42	< 0.001	0.88
$\Delta \ln \text{SAIDI} \sim \Delta \ln A(t-1)$ (first differences)	-2.51	0.039	0.07
$\ln \text{SAIFI} \sim \ln A(t-1)$	-2.08	< 0.001	0.69
$\ln \text{SAIDI} \sim \ln K(t-1) + \ln D(t-1)$: capital	-4.31	0.002	0.89
$\ln \text{SAIDI} \sim \ln K(t-1) + \ln D(t-1)$: demand	+5.96	< 0.001	0.89
$\ln \text{SAIDI} \sim \ln A(t-1) + \text{CDD}$	-5.52	< 0.001	0.87
Panel Edenor + Edesur, firm fixed effects: $\ln A(t-1)$	-4.16	< 0.001	0.72
Panel: difference in slope, Edesur	-3.14	< 0.001	0.82

Note: $\delta = 2.5\%$, $\kappa = 1$. Newey–West standard errors. The two rows with $\ln K$ and $\ln D$ come from one regression, as do the two panel rows (the last row is the slope-interaction model, R^2 0.82). The low R^2 of the first-differences model is expected: differencing removes the common trend.

Edesur's response is stronger than Edenor's in levels (the difference is significant in the panel), although in first differences the two are similar (-2.5 and -1.7). It does not depend on the extreme years 2012–2013 (-5.4 without them) or on weather (-5.5 with CDD). A network with less initial slack or a heavier summer load could explain it; the model accommodates it with a firm-specific ε , which shortens Edesur's grace time.

7.5 Measuring capital

Real capital depends on three assumptions: the deflator, the depreciation rate and the initial stock. Table 7 summarises the 320 variants. With $\kappa = 1$ Edenor's elasticity ranges from -2.2 to -3.0 and every variant is significant. The most influential assumption is the initial stock: if the 2003 depreciation overstated replacement (a small initial stock) and depreciation were high, the investment of 2007–2016 would have been enough for capacity barely to fall, and the relationship would weaken. All 35 non-significant variants use the IPIM deflator and a small initial stock ($\kappa = 0.5$, or $\kappa = 0.75$ with δ of 3.3% or more). These variants, however, describe the data poorly: their R^2 averages 0.10 (maximum 0.27), against 0.67 on average for the others. If κ is chosen by fit (R^2 within 0.05 of its maximum on a grid from 0.4 to 2.6), the compatible values range from 0.5 to the top of the grid depending on the deflator, and the elasticity between -1.6 and -3.7. With $\kappa \geq 0.75$ the elasticity is significant in 61 of 64 cases for Edenor and in 189 of 192 for Edesur, and the reference grace time ranges between 3.7 and 6.4 years. The result is robust to measurement except in a region of the assumptions that the data themselves reject.

Table 7 Elasticity of SAIDI to relative capacity under alternative measures of capital

Variants	Cases	ε (range)	Significant	T* +50% (years)
Edenor, $\kappa = 1$ (deflator, δ , demand)	16	-2.2 to -3.0	16	4.0 to 5.1
Edenor, $\kappa \geq 0.75$	64	-1.5 to -3.2	61	3.7 to 6.4
Edenor, all (including $\kappa = 0.5$)	80	+0.4 to -4.1	69	3.0 to 6.2
Edesur, $\kappa = 1$	48	-4.3 to -6.1	48	2.3 to 3.0
Edesur, $\kappa \geq 0.75$	192	-3.0 to -7.1	189	2.3 to 3.7
Edesur, all (including $\kappa = 0.5$)	240	+0.8 to -9.8	216	1.8 to 3.7

Note: deflator IPIM or GDP deflator; $\delta = 2\%$, 2.5%, 3.3%, 4%; initial capital κ from 0.5 to 2; demand as energy sold or weather-normalised energy (Edenor only; Edesur variants add three imputations of 2005–2007 and two series for 2014–2016). Significant: $p < 0.05$. T* for the AMBA reference scenario (investment 65% of replacement, demand +3.7%), including a one-year lag, computed with each variant's own ε and δ . In the “all” rows T* is shown for the variants with a significant elasticity, because it is not defined when the estimated elasticity has the wrong sign.

7.6 The investment channel in a panel: Brazil

The Brazilian panel speaks to one link of the model, not to the whole model. In a large market with stable quality regulation, more cumulative investment relative to depreciation is associated with better continuity: one additional point reduces the index by about 16% ($p = 0.03$, Table 8). Annual capex is not significant, consistent with the idea that cumulative capacity is what matters. In 2021–2024 the signs are as expected but not significant, and the form of the response cannot be estimated: median relative capacity rose from 100 to 119, and only three of 22 firms saw it fall, by at most 11% from its previous peak. Brazil thus confirms the investment–quality channel; the form of the response and the grace time are identified with the AMBA data. The rule $r^* = 1 + g/\delta$ predicts that, with a market growing at about 5% and regulatory depreciation of about 4%, distributors should invest about 2.25 times depreciation; the observed median was 2.0 to 2.3.

Table 8 Panel of Brazilian distributors (firm and year fixed effects)

Model	Coefficient	p-value	n	Firms
2011–2017: $\ln \text{DGC} \sim 5\text{-year investment / regulatory depreciation } (t - 1)$	-0.180	0.032	170	62
Same, without firm fixed effects	-0.159	0.020	170	62
2011–2017: $\ln \text{DGC} \sim \text{annual capex/depreciation, CVM } (t - 1)$	+0.027	0.54	128	22
2021–2024: $\ln \text{DEC} \sim \ln \text{capital } (t - 1)$, with $\ln$ consumers	-0.10	0.68	88	22
2021–2024: $\ln \text{DEC} \sim \ln \text{consumers } (t - 1)$, with $\ln$ capital	+0.08	0.75	88	22

Note: errors clustered by firm. In 2021–2024, $\delta = 4\%$.

7.7 Grace time

Table 9 reports the simulated grace times. Under AMBA conditions in 2003–2006, SAIDI exceeds its initial level by 50% after 3 to 4 years and doubles after 4.6 to 6.7. At Edenor the observed values were +50% in 2007 (year 5) and a doubling in 2011 (year 9). The difference arises because from 2007 investment exceeded replacement and the erosion of capacity slowed; with the observed path of

capacity, the model predicts the +50% between 2005 and 2007 and the doubling between 2007 and 2012, in line with what happened. With stagnant demand the grace time exceeds 15 years if investment covers two-thirds of replacement, but is 6 to 11 years with no investment at all; with growing demand it is 3 to 7 years even if investment replaces the whole stock. For Edesur, with its elasticity in levels, the +50% would arrive after about 2 years under the 2003–2006 conditions; with its first-difference elasticity, after 3 to 4. The observed value lay between years 4 and 5 (2006–2007), consistent with that range.

Table 9 Years until SAIDI exceeds the tolerance, including a one-year lag

Scenario	Tolerance	r	g	P5	Median	P95
Physical wear only (no investment, stagnant demand)	+50%	0	0%	5.9	7.8	10.7
No investment, demand 3.7%	+50%	0	3.7%	3.2	3.8	4.7
Reference: investment 65%, demand 3.7%	+50%	0.65	3.7%	4.1	4.9	6.0
AMBA 2003–2006: investment 65%, demand 6.1%	+50%	0.65	6.1%	3.1	3.6	4.3
Investment that only replaces, demand 3.7%	+50%	1	3.7%	5.0	5.9	7.3
Investment 65%, stagnant demand	+50%	0.65	0%	14.9	20.4	28.7
AMBA 2003–2006: investment 65%, demand 6.1%	+100%	0.65	6.1%	4.6	5.4	6.7
Investment that only replaces, demand 3.7%	+100%	1	3.7%	7.8	9.3	11.7

Note: Monte Carlo with 200,000 draws: ε uniform between 1.72 and 2.88 (first-difference and levels estimates), δ uniform between 2% and 3.3%; demand growth enters Eq. (3) as $\ln(1 + g)$.

If instead of the continuous response the largest margin not ruled out by the data existed ($A^* = 83.5$), quality would not deteriorate until 16.5% of relative capacity had been lost, and would then deteriorate faster (slope 3.8 for Edenor). In the reference scenario (investment 65% of replacement, demand +3.7%, $\delta = 2.5\%$, $\varepsilon = 2.88$) the +50% would arrive after 7.3 years instead of 4.1. The reference grace time is therefore 4 to 7 years depending on the form of the response. With Edenor's observed path, the continuous model predicts the +50% between 2005 and 2007 and the model with that margin in 2008; the observed year was 2007.

The data identify the two rates in Proposition 1. Edenor's relative capacity fell by 4.6% a year in 2002–2012 and recovered by 6.3% a year in 2013–2019, so $h/\kappa \approx 0.7$; Edesur's fell by 3.8% a year and recovered by 2.9% a year in 2012–2016, so $h/\kappa \approx 1.3$. By Eq. (7), a regulator who ignores the recovery would choose a freeze 1.7 (Edenor) to 2.3 (Edesur) times the optimal one when the tolerance is small, and 1.5 to 1.9 times when $\hat{X} = 0.5$. The AMBA freeze lasted about 14 years (2002–2016), between two and three and a half times the reference grace time. Valuing b and v is beyond the scope of this paper, but Eq. (6) shows what such a length requires: with Edenor's elasticity in levels and its average erosion rate, a 14-year freeze is optimal only if the regulator accepts SAIDI rising to more than six times its initial level ($\hat{X} \approx 5.5$); Edenor's SAIDI peaked at about four times. Part of the gap was bridged by the

outside funds that raised investment after 2007 and lowered h , which is the second implication of Proposition 1.

7.8 Tariff, investment and demand

With the aggregate national capex/depreciation series (1994–2025, with a dummy from 2016), the lagged log real tariff appears to explain investment (coefficient +0.47, $p < 0.01$). With Edenor's real investment the sign reverses (-1.64 , $p < 0.01$, $n = 13$). Between 2007 and 2015 the real tariff kept falling while Edenor invested between 1.1 and 2.8 times replacement, with funds unrelated to the tariff (the PUREE programme and, from 2013, FOCODE). Between 2020 and 2022, with the tariff frozen, investment stayed between 1.5 and 1.7 times depreciation while the debt with CAMMESA grew from 12,372 to 38,650 million pesos. Investment fell below replacement only in 2003–2006, when it depended on the tariff.

The demand channel, by contrast, was present throughout. Between 2015 and 2019 the real tariff rose by 82% and Edenor's energy sales fell by 13%, implying an apparent elasticity of -0.24 . The figure has no controls for income (2018–2019 were recession years), but it lies within the regional range of Zabaloy and Viego (2022) and is consistent with the expansion of consumption under frozen tariffs documented by Casarin and Delfino (2011).

7.9 Out-of-sample test and composition of investment

With relative capacity projected for 2020–2024 (demand grew 2.6% a year in 2019–2024 and investment exceeded depreciation), the model predicts a SAIDI of 11 to 15 hours (Table 10). Observed values fluctuate around that prediction: the mean log error is 0.02 and the root mean squared error 0.30, similar to the regression's standard error (0.30). The year 2023 is high and 2024 low, with no systematic bias. A model with a level shift from 2018 (tariff review and new quality targets) finds no significant break ($+0.13$, $p = 0.25$).

Table 10 Out-of-sample prediction for Edenor, model estimated on 2003–2019

Year	A, previous year	Predicted SAIDI (h)	Observed SAIDI, ENRE (h)	Observed / predicted
2020	89.9	11.1	12.4	1.11
2021	90.1	11.0	13.1	1.18
2022	85.0	13.0	10.5	0.80
2023	82.4	14.3	22.3	1.56
2024	80.8	15.1	9.9	0.66

Edenor's quarterly reports show a larger improvement (from 15.9 hours in 2019 to 6.8 in 2025), but they measure quality differently from ENRE. That improvement coincides with a change in the composition of investment (Table 11): between 2017 and 2025 Edenor's SAIDI on that measure fell by 75%, -1.11 in logarithms from fewer interruptions and -0.28 from faster restoration (from 3.1 to 2.3 hours per interruption). The share of replacement rose from 8% to 23–29% of investment and that of

automation from 2% to 10–15%; remote-control points went from 140 in 2015 to more than 900 in 2017. Replacement reduces failures and automation isolates affected sections and shortens interruptions without adding capacity. This margin of improvement is not captured by the capacity model and may become important in the future.

Table 11 Allocation of Edenor’s investment

Period	Basis	Expansion	Replacement	Automation
2006–2012	Annual 2008, 2010–12	73%	8%	2%
2013–2014	Annual	74%	9%	3%
2017–2019	Fourth quarter	57–64%	17–23%	9–11%
2020	Fourth quarter	46%	23%	15%
2021	Annual	49%	29%	10%

Note: no breakdown is available for 2023–2025.

8 Validity of the results

Two firms in one region. The complete model is estimated for both AMBA distributors, with independent investment series. Three elements reinforce the result: Edenor’s series contains two episodes of opposite sign (deterioration in 2002–2015 and recovery in 2016–2019) described by the same elasticity; the relationship holds in first differences for both firms; and the investment–quality channel appears in 62 Brazilian distributors. Edesur’s series has a weakness of its own: its 2005–2007 investment is interpolated, although the three imputations tried give the same result.

Scope of the Brazilian evidence. Brazil confirms that cumulative investment improves continuity, but does not test the complete model: in 2021–2024 only three of 22 distributors saw relative capacity fall, and by at most 11%, so neither the form of the response nor the grace time can be estimated. Both rest on the AMBA data.

Form of the response. With 15 to 17 years per firm, the threshold test has little power against small margins (Sect. 7.2). The data rule out a margin larger than 16% but not a smaller one, so the continuous response is the simplest description consistent with the data, not a demonstration that the margin is zero. The grace time is reported for an explicit tolerance and with the range implied by this uncertainty (4 to 7 years in the reference scenario).

Causality. Demand growing under a frozen tariff is external to service quality, but investment is not: firms invest more when quality worsens, because the regulator penalises them and because extraordinary funds (PUREE, FOCEDA) were allocated to quality works. In the data, investment relative to replacement rises with the previous year’s SAIDI (elasticity 0.82 for Edenor and 0.64 for Edesur, $p < 0.001$), although the relationship disappears once a trend is included (0.05 and 0.16; $p = 0.62$ and 0.11). Such feedback biases the estimated elasticity towards zero: when quality worsens, investment rises and capacity falls less. To check this, relative capacity is instrumented with lagged

demand, which varies only on the demand side (first-stage $F = 52$ for Edenor and 65 for Edesur). The instrumental-variable elasticity is -3.3 for Edenor (s.e. 0.47) and -6.5 for Edesur (s.e. 0.68), slightly larger in absolute value than the least-squares estimates (-2.9 and -6.1), as expected if the bias attenuates. The instrument is not perfect: it assumes that demand affects quality only through the load on the network, which is precisely the hypothesis of the model, and Sect. 7.3 shows that weather, the main common factor, does not invalidate it. The estimates should therefore be read as lower bounds, in absolute value, of the effect of capacity.

Extreme events and temperature. The ENRE series includes force majeure, so heat waves and storms (2000, 2007, 2012–2013) weigh on the levels. The results hold with two-year moving averages and excluding 2012–2013, and once capacity is included cooling degree days are not significant (Sect. 7.3). That weather events cause more outages when the network is more loaded is part of the mechanism, not a bias.

Out-of-sample prediction. With the official SAIDI for 2020–2024, the model estimated on 2003–2019 predicts without bias and with an error of the same size as in sample. The larger improvement shown by Edenor’s quarterly reports reflects a different measurement and coincides with a change in the composition of investment (Sect. 7.9). Two cross-validation exercises adapted to time series point the same way. With k -fold cross-validation over contiguous blocks of years ($k = 4$ and 5), the elasticity estimated without each block ranges from -2.3 to -3.5 for Edenor and from -5.7 to -7.4 for Edesur, and the out-of-block error (0.35–0.37 in logs for Edenor) is moderately above the in-sample error (0.28). With rolling-origin one-step forecasts from 2008, which use only past data, Edenor’s root mean squared error is 0.36, against 0.56 for the historical mean and 0.40 for a random walk. The gain over the random walk is not significant (Diebold & Mariano, 1995; $p = 0.52$), but a random walk carries no information about the multi-year horizon that the grace time requires. Ordinary k -fold cross-validation with randomly assigned folds is not used because it would let the model learn from years adjacent to those it predicts.

Measurement. Real investment depends on the deflator, on δ and on the assumption that the 2003 depreciation measures annual replacement. Across 80 variants for Edenor and 240 for Edesur the elasticity survives except when the initial stock is small and the IPIM deflator is used, cases that fit the data much worse (Sect. 7.5). Edesur’s investment also depends on the conversion from Chilean pesos, verified against the figure reported for 2010 (difference of 0.6%). Quality values were measured on charts and calibrated against published values, with a largest deviation of 0.27%. The Brazilian data come from public repositories that process ANEEL’s databases; the national DEC computed from them matches the published figure.

9 Discussion and policy implications

- **Demand, more than wear, sets the grace time.** With δ of 2% to 3%, capital takes 5 to 8 years to lose 15% even with no investment at all, and much longer with partial investment; demand growing at 5% a year absorbs that capacity in about three years. A freeze with stagnant demand is much less damaging to quality than one with growing consumption.
- **A low tariff acts twice.** It reduces the funds available for investment when there is no alternative financing, and it stimulates demand. The 2016–2019 recovery is explained to a large extent by the fall in energy sold, not only by investment.
- **Who finances matters.** The AMBA sustained investment in 2007–2016 and in 2020–2022 with funds and debts unrelated to the tariff. In those cases the cost of the freeze does not disappear: it is shifted to the treasury or to the wholesale market, in line with the “subsidy trap” of McRae (2015).
- **Freeze length is a policy choice with a computable optimum.** Proposition 1 gives regulators a rule: end the freeze when the marginal cost of outages, including the recovery it leaves behind, reaches the benefit of the freeze. Because that cost falls partly on future administrations, institutions that lengthen the regulator’s horizon or commit to tariff indexation reduce the bias towards overlong freezes (Levy & Spiller, 1994).
- **An early-warning indicator.** Regulators should track capacity relative to demand, not only investment relative to depreciation: with demand growing, a firm that replaces its whole stock still loses relative capacity and quality. The requirement is $r^* = 1 + g/\delta$.
- **Which investment.** The 2017–2025 improvement suggests that, once capacity is secured, replacement and automation have a large effect on quality. Regulatory targets could distinguish investment in capacity from investment in quality.

10 Conclusions

The deterioration of electricity service quality after a tariff freeze is determined not by the wear of capital but by the erosion of capacity relative to demand. In the AMBA quality began to worsen three to four years after the 2002 freeze, with no detectable threshold: each 10% of relative capacity lost raised SAIDI by 20% to 35% at Edenor, and by more at Edesur. The mechanism is verified in both distributors with their own investment series, is not driven by temperature, survives the alternative ways of measuring capital and holds, slightly stronger, with instrumental variables. The data rule out a large initial margin before deterioration but not one smaller than 16%, which places the reference grace time in a range of 4 to 7 years.

The proposed grace time, $T^*(X) = \ln(1 + X)/(\epsilon[\delta(1 - r) + g])$, translates that response into years as a function of the tolerance, investment and demand growth: 3 to 7 years for SAIDI to rise by 50% with

growing demand, and more than 15 with stagnant demand when investment covers two-thirds of replacement. The same formula gives the optimal length of a freeze when the tolerance equals the ratio of the benefit of the freeze to the cost of the outages it causes, and a regulator who ignores the recovery period chooses freezes 1.5 to 2.3 times longer. The tariff operates through demand and, only when there is no alternative financing, through investment. Estimated on 2003–2019, the model predicts the official quality of 2020–2024 without bias, and the Brazilian evidence supports the investment–quality channel. Two questions remain open: Edesur’s 2005–2007 investment, which had to be interpolated, and estimation in a panel of firms that suffer falls in capacity, which would allow the form of the response to be tested outside the AMBA.

Appendix A: Proof of Proposition 1

Let $x(t) = \ln[S(t)/S_0]$ denote the log deviation of SAIDI from its initial level. By A1 and A3, $x(t) = \varepsilon ht$ for $0 \leq t \leq \tau$. By A2, after the freeze $\ln A$ rises at rate κ until it returns to $\ln A_0$, which takes $h\tau/\kappa$ years; during that period $x(\tau + s) = \varepsilon h\tau - \varepsilon \kappa s$. The integral in Eq. (5) is therefore

$$\int_0^\tau (e^{\varepsilon ht} - 1) dt + \int_0^{h\tau/\kappa} (e^{\varepsilon h\tau - \varepsilon \kappa s} - 1) ds = \frac{e^{\varepsilon h\tau} - 1}{\varepsilon h} - \tau + \frac{e^{\varepsilon h\tau} - 1}{\varepsilon \kappa} - \frac{h\tau}{\kappa} \quad (A1)$$

Differentiating with respect to τ , the derivative of the right-hand side of Eq. (A1) is $(\exp(\varepsilon h\tau) - 1)(1 + h/\kappa)$. Hence

$$W'(\tau) = b - vS_0 \left(1 + \frac{h}{\kappa}\right) (e^{\varepsilon h\tau} - 1), \quad W''(\tau) = -vS_0 \left(1 + \frac{h}{\kappa}\right) \varepsilon h e^{\varepsilon h\tau} < 0 \quad (A2)$$

W is strictly concave, $W'(0) = b > 0$ and $W'(\tau) \rightarrow -\infty$ as $\tau \rightarrow \infty$, so there is a unique maximum where $W'(\tau^*) = 0$, that is, $\exp(\varepsilon h\tau^*) = 1 + b/[vS_0(1 + h/\kappa)]$, which gives Eq. (6). A regulator who does not bear the recovery maximises $b\tau$ minus the first integral only; its first-order condition is $\exp(\varepsilon h\tau) - 1 = b/(vS_0)$, which gives τ_m in Eq. (7). Since $b/(vS_0) > \hat{X}$, $\tau_m > \tau^*$, and $\ln(1 + \hat{X}(1 + h/\kappa))/\ln(1 + \hat{X}) \rightarrow 1 + h/\kappa$ as $\hat{X} \rightarrow 0$. With a threshold A^* , $x(t) = \varepsilon h \cdot \max(0, t - \ln(A_0/A^*)/h)$ and the same steps shift τ^* by $\ln(A_0/A^*)/h$.

Declarations

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Data availability All data analysed are publicly available from the sources listed in Table 1 and Online Resource 1. The datasets generated during the study (ENRE quality series measured from the annual reports, Edenor and Edesur investment and capital series, daily temperature and cooling degree days, Brazilian panels) and the code that reproduces every table and figure are provided as Online Resource 2.

Use of AI tools A large language model (Claude, Anthropic) assisted in data extraction, statistical programming, drafting and translation, as described in Sect. 5. The author reviewed all outputs and takes full responsibility for the content.

Electronic supplementary material Online Resource 1 (ESM_1.pdf): list of primary sources by datum. Online Resource 2 (ESM_2.zip): data and code.

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