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DISCUSSION PAPER

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DISCUSSION PAPER

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CONTENTS

ABSTRACT

We examine electricity market reform in Brazil: from the 1990s till 2004 the largely hydro-powered market cleared using a market mechanism, and in March 2004 reformed to a single buyer structure. We model monthly log price differences using a two-state Markov Switching model, allowing water storage and natural inflows to affect both the mean and volatility of changes. Our results suggest that the single buyer structure decreased volatility during stable periods but worsened energy crises. Post-reform, we find that the market is safe from crises for a wider range of stored water/rainfall combinations; however the steady state levels of these variables can lead to energy crises developing.

Keywords: regulatory economics; electricity price; risk; wholesale market; Markov Switching model.

SINOPSE

Este estudo examina a reforma do setor elétrico brasileiro, ocorrida em 2004. A partir dessa reforma, o setor passou de um modelo onde os preços atacadistas eram estabelecidos a partir de mecanismos de mercado para um modelo baseado em planejamento centralizado. Neste trabalho, utiliza-se um modelo de mudanças de regime de dois estados (*two-state Markov Switching model*), permitindo que tanto o estoque quanto o fluxo natural de água (chuvas) no sistema afetem a média e a volatilidade das mudanças de preços. Ao compararmos o modelo de mercado com o modelo planejado, os resultados sugerem que volatilidade dos preços diminui em períodos de estabilidade e aumenta em períodos de crise. O trabalho também aponta que, após a reforma, o setor se tornou seguro para um conjunto mais amplo de combinações de nível de estoque de água e chuva. No entanto, os níveis de equilíbrio dessas variáveis levam ao desenvolvimento de crises.

Palavras-chave: regulação; setor elétrico; risco; mercado atacadista; mudança de regime.

1 INTRODUCTION

The debate around optimal energy market structures is one that captures the attention of regulators, retailers and generators around the world (Hogan, 2002; Zhang, Parker and Kirkpatrick, 2008; Mayes, Haas and Bowring, 2012). The argument for government control centres around lessening market power to increase consumer surplus. In contrast, the argument for privatisation is based on efficiency gains leading to increased total surplus in the market. Comparing the two structures has always been problematic because it is difficult to set side by side a single buyer model in one country with a free market in another, while remaining confident that results are not biased by technological differences, geographic effects, or political influences. The Brazilian market helps overcome this problem, as from 1996-2004, it was a free market, while since March 2004 it has operated under a single buyer structure. The single buyer model has the market's regulator dictate a price for electricity, and a quantity that each supplier must produce.

Brazil is the 10th largest energy consumer globally, and generates approximately 71% of its electricity from hydropower (Central Intelligence Agency, 2013). Due to the warm climate, electricity use generally peaks between November and February, when it is used for cooling. The market is connected by the *Sistema Interligado Nacional* (National Interconnected System) and divided into four regions. This study uses data from the *Operador Nacional do Sistema Elétrico* (the National Grid Operator, denoted ONS). The market underwent reforms in 1996 and again in 2004. The 1996 reforms were designed to encourage private investment and increase productivity in the market, but were not as straightforward as planned, primarily due to the complexity of the market (De Souza and Legey, 2010). The early 2000s saw electricity rationing due to a supply shortage from June 2001 to February 2002, which lead to further reforms to the market in March 2004. These second reforms created two separate contracting environments for the purchase of electricity; the Free Contracting Environment (denoted FCE) and the Regulated Contracting Environment (denoted RCE). The FCE is used by large companies who contract directly with generators. The RCE is the environment that retailers (and by extension, household consumers) must contract in, and prices are set by the regulator.

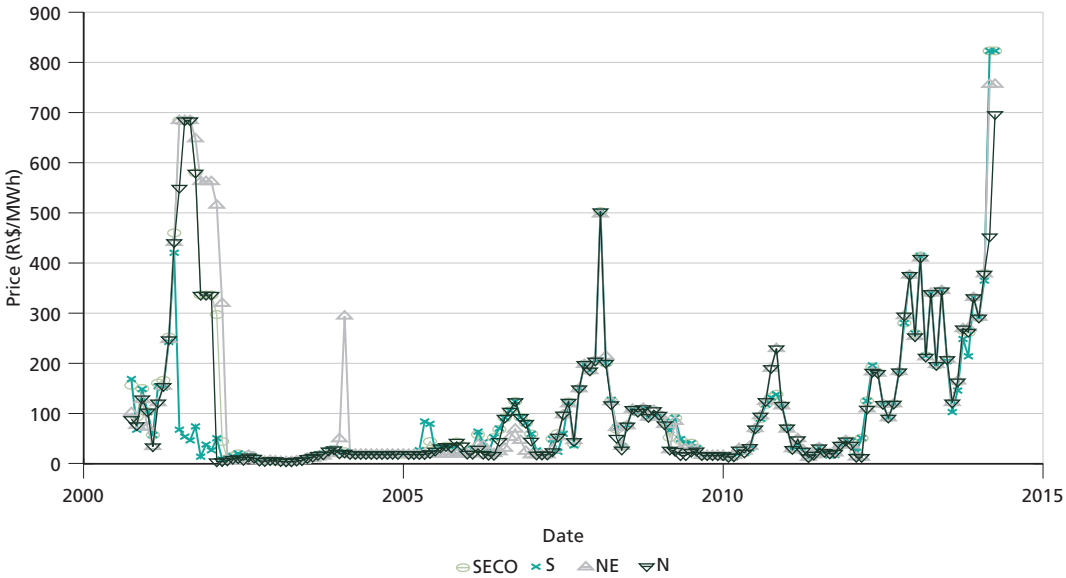
Our paper aims to evaluate the effect on electricity prices and their volatility of shifting from the earlier, *laissez faire*, electricity market to the single buyer model, using data from the free market and the RCE.

We use data spanning 2000-2014 (from 4 years prior to the reform to 10 years post-reform) and use a Markov Switching model for electricity price changes in the market to examine the reform effect. Since electricity prices are often characterised as facing periods of extreme volatility, interspersed with quiet periods, we model two states in the market, in which we allow control variables to influence electricity price changes in different ways (Huisman and Mahieu, 2003; Mount, Ning and Cai, 2006). The flexibility of the Markov Switching model is attractive as it allows each state to vary in mean and volatility. Behaviour of electricity prices is not only characterised by high volatility, but also by strong seasonality, mean reversion and price spikes (Le Pen and Sévi, 2010; Higgs and Worthington, 2008), making the modelling of these prices particularly interesting. In our case, we work with monthly data, which removes consideration of spikes. Nevertheless, as illustrated in graph 1, electricity price drift and volatility in Brazil has varied greatly over the period studied.

Our quantitative approach complements other papers in this field, such as Rego and Parente (2013), who analyse the outcome of Brazilian electricity procurement auctions in the context of electricity generation from new and old generators, using graphical analysis and dummy variable regression analysis. Though their data spans until 2010, there is little direct emphasis on the 2004 reform effect. Most other studies of the Brazilian electricity sector have focused on its effect on the productivity of other sectors.[1]

1. Santos, Haddad and Hewings (2013) study the long-run regional and sectoral effects of tariff policy in the Brazilian electricity market, focusing on the reform process that started in the 1990s. Through a general equilibrium model, they find that increases in electric power prices may have a negative effect on income in the regions with scarce possibility of energy substitution. Ramos-Real *et al*. (2009) examine productivity of the Brazilian distribution sector, using a panel of seventeen firms between 1998–2005. Reforms do not seem to have incentivized firm efficiency, as results denote a generally poor performance in terms of total factor productivity. The same dataset is used in the econometric study by Tovar, Ramos-Real and Almeida (2011), who show that firms size fosters productivity. Stimulating economic efficiency in the sector is also an aim of the study by Carpio and Pereira (2007), who build a theoretical model showing how generation in different subsystems can be coordinated to enhance sector competition.

GRAPH 1
Monthly average spot prices per region
(R$/MWh)



Note: Seco refers to the South-East Central-West electricity grid, that covers the states of Mato Grosso, Goiás, Distrito Federal, São Paulo, Rio de Janeiro and Espírito Santo. S refers to the South region of Brazil, covering Mato Grosso do Sul, Paraná, Santa Catarina and Rio Grande do Sul. N refers to North (covering Amazonas, Pará, Amapá and Tocantins) and NE refers to North-East (covering Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe and Bahia).
Elaborated by the authors

We find that the reform appears to decrease volatility in prices in quiet periods However, the market still spends some periods in an unstable state both pre- and post-reform. This unstable state becomes more volatile after the introduction of the RCE. By examining the relationship between water levels and rainfall (the "hydrological" state), and market state transitions, we characterise the reform as creating a more "forgiving" environment, where a wider range of hydrological states are consistent with not seeing energy crises develop. Here, an energy crisis refers to entering a volatile state for a protracted period. However, when we examine the steady state of the hydrological system pre- and post-reform, we find that the system has frequently been managed in such a way as to make crises possible, as is evidenced by the periods of volatility in graph 1.

The rest of the paper is organised as follows: section 2 outlines our methodology for the Markov Switching Model and section 3 describes our dataset. In section 4 we analyse the construction of our model and the key results. Lastly, section 5 concludes.

2 METHODOLOGY

We use a two-state regime switching model to model the day-ahead log price changes in an electricity market. We allow each state to have separate mean and volatility equations (Hamilton, 1989; Huisman and Mahieu, 2003; Mount *et al.*, 2006) with normally distributed residuals. We model log price changes as follows:

$$r_t = \mu_{s_t} + \beta_{s_t} X_t + \epsilon_{s_t t}$$
$$\epsilon_{st} \sim N(0, \sigma_s^2) \tag{1}$$

$$\sigma_s = e^{(\delta_s X_t)}$$
$$s_t \in \{1, 2\}, \tag{2}$$

where r_t are the deseasonalised log price changes, μ_s is the intercept in the model, and X is a vector of covariates. E_s represents the residuals in the mean equation. Throughout the paper we will use β_s to describe coefficients in the mean equation and δ_s for coefficients in the volatility equation. s_t denotes the unobserved state variable at time t. At each time t, s_t is labelled as 1 or 2.

At each time, the probability of the market being in state j depends upon its state in the preceding period:

$$P(s_t = j \mid s_{t-1} = i, s_{t-2} = k, \ldots) = P(s_t = j \mid s_{t-1} = i) = P_{ij},$$
$$i, j, k \in \{1, 2\}. \tag{3}$$

The transition probabilities are $\{P_{ij}\}_{i,j=1,2}$ in our two state case. These give the probability that state i will be followed by state j.[2] since we wish to allow the hydrological situation to affect the market's transition in general, we allow our covariates to affect the probability of persistence in each state, specifically:

$$P_{11} = \frac{e^{(\gamma_1 X)}}{1 + e^{(\gamma_1 X)}} \tag{4}$$

2. Note that $P_{i1} + P_{i2} = 1$.

$$P_{22} = \frac{e^{(\gamma_2 X)}}{1 + e^{(\gamma_2 X)}}. \tag{5}$$

We use a logistic transformation to ensure that these probabilities are bounded between zero and one. These transition probabilities are combined into the transition matrix *P*:

$$\mathbf{P} = \begin{pmatrix} P_{11} & P_{21} \\ P_{12} & P_{22} \end{pmatrix}.$$

Parameters of the model are estimated using Maximum Likelihood Estimation. We use the method laid out by Hamilton (1994). We maximise the following log likelihood function for the observed data to estimate the parameter vector $\theta = \{\mu_1, \mu_2, \beta_1, \beta_2, \gamma_1, \gamma_2, \delta_1, \delta_2, P(s_0 = 1)\}$:

$$\mathcal{L}(\theta) = \sum_{t=1}^{T} \log f(r_t \mid X_t, \mathscr{Y}_{t-1}; \theta), \tag{6}$$

Where Y_t denotes information available at time *t*, and:

$$f(r_t \mid X_t, \mathscr{Y}_{t-1}; \theta) = \mathbb{1}'(\hat{\xi}_{t|t-1} \odot \eta_t). \tag{7}$$

Here $\xi_{t|t}$ denotes the vector of conditional probabilities, inferred by our knowledge of the population parameters and past observations. 1 is a vector of ones. The symbol $\odot$ denotes element by element multiplication. η_t represents the vector whose *s*th element is the conditional density given by:

$$\eta_t(s) = \frac{1}{\sqrt{2\pi}\sigma_s} e^{-\frac{(r_t - \mu_s - \beta_s X_t)^2}{\sigma_s^2}}.$$

$\hat{\xi}_{t|t-1}$ is defined by:

$$\hat{\xi}_{t+1|t} = \mathbf{P}.\hat{\xi}_{t|t}, \tag{8}$$

$$\hat{\xi}_{t|t} = \frac{(\hat{\xi}_{t|t-1} \odot \eta_t)}{1'(\hat{\xi}_{t|t-1} \odot \eta_t)}, \tag{9}$$

where P represents the transition matrix given earlier. With a starting value $\hat{\xi}$ and an estimated value for the population parameter vector θ, we can use equations (8) and (9) recursively for $t = 1, 2, \ldots, T$ to find the values of $\hat{\xi}_{|t}$ and $\hat{\xi}_{+1|t}$ for each date in the sample, allowing us to evaluate the log likelihood (6). To estimate the variance covariance matrix for our parameter estimates we use the Outer Product of Gradients method.

If the Markov Switching system is allowed to run for a long period of time, and P is constant, the proportion of time that the system will spend in each of the states will be given by the system's ergodic probabilities.[3] Using these we can calculate the unconditional mean and volatility of log price changes in our two-state model using the following formulae:

$$\begin{aligned} E(r) &= \lambda_1 E(r|s=1) + \lambda_2 E(r|s=2) \\ &= \lambda_1 \mu_1 + \lambda_2 \mu_2 \\ E(r^2) &= \lambda_1 E(r^2|s=1) + \lambda_2 E(r^2|s=2) \\ &= \lambda_1 [Var(r|s=1) + \mu_1^2] + \lambda_2 [Var(r|s=2) + \mu_2^2] \\ &= \lambda_1 [\sigma_1^2 + \mu_1^2] + \lambda_2 [\sigma_2^2 + \mu_2^2] \\ Var(r) &= E(r^2) - [E(r)]^2. \end{aligned} \tag{10}$$

3 DATA

Our raw data consist of monthly average spot prices from the Brazilian electricity market, as recorded by the Brazilian regulator ONS. The market itself is divided into four regions: South-East/Central-West, South, North-East and North. The analysis in this paper primarily focuses on the data from the South-East/Central-West (Seco) region of Brazil, as it is the largest in size and electricity usage. However, in section 4.4, we do also extend our analysis to other regions in Brazil. The dependent variable in our model is the log price change series (*rt*). We use three covariates in our model. The first is a binary variable representing post-reform, equal to zero before March 2004 and equal to one otherwise. The second is *energia armazenada* (EAR) or stored energy measured in monthly mean MegaWatts (MW). The EAR is a measure of electricity related to the volume of water stored in a reservoir or watershed. The calculation takes into account the productivity of the hydroelectric plants downstream and excludes the dead volume

3. The ergodic probabilities are those eigenvectors of the transition probability matrix associated with the unit eigenvalue.

(regular minimal volume) of the reservoir.[4] The third control variable is *energia natural afluente* (ENA) or natural hydropower, also measured in monthly mean MW. The ENA is the aggregate amount of electricity that can be generated by the natural hydraulic inflow to each hydro plant in a river, not considering the interference of the upstream plants.[5] We can thus think of ENA as the inflow to the particular hydro system, and EAR as measuring the stock of water in the hydro system

TABLE 1
Summary statistics from the Seco region dataset (September 2000-March 2014), where EAR denotes *energia armazenada* or stored energy and ENA denotes *energia natural afluente* or natural hydropower. Data is deseasonalised by regressing on month dummies and extracting the residuals

	Deseasonalised variables			Non-deseasonalised variables		
	r	EAR ($10GW$/month)	ENA ($10GW$/month)	r	EAR ($10GW$/month)	ENA ($10GW$/month)
mean	0.0000	0.0298	-0.0053	0.0103	11.4852	3.2769
median	0.0274	0.9148	-0.0564	0.0000	12.0982	2.8252
std. dev.	0.4585	2.9391	0.9547	0.4743	3.5778	1.6418
min	-1.8714	-9.2194	-3.0971	-1.9129	3.3196	1.1405
max	1.1968	4.8544	3.7594	1.3370	17.4172	9.1575
skewness	-0.4619	-1.1069	0.6945	-0.4793	-0.5341	1.1327
kurtosis	4.6206	4.1170	6.3711	4.5269	2.3700	4.0763

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4.In particular,

$$EAR(MWmed) = \frac{1}{2,6298} * (V_i(hm^3) - Vmin(hm^3)) * (prodeq_i(MW/m^3/s) + \sum_{j=1}^{n} prodeq_j(MW/m^3/s)),$$

where Vi is the volume stored in the reservoir i, $Vmin$ is the dead volume or minimal regular volume of reservoir i, $prodeq_i$ is the equivalent productivity of hydro plant associated with reservoir i, and $prodeq_j$ is the equivalent productivity of the n hydro plants downstream of reservoir i. m^3 denotes cubic metres, hm^3 denotes cubic hectometres, and s stands for second. See ONS (2010) and Duke Energy (2015).

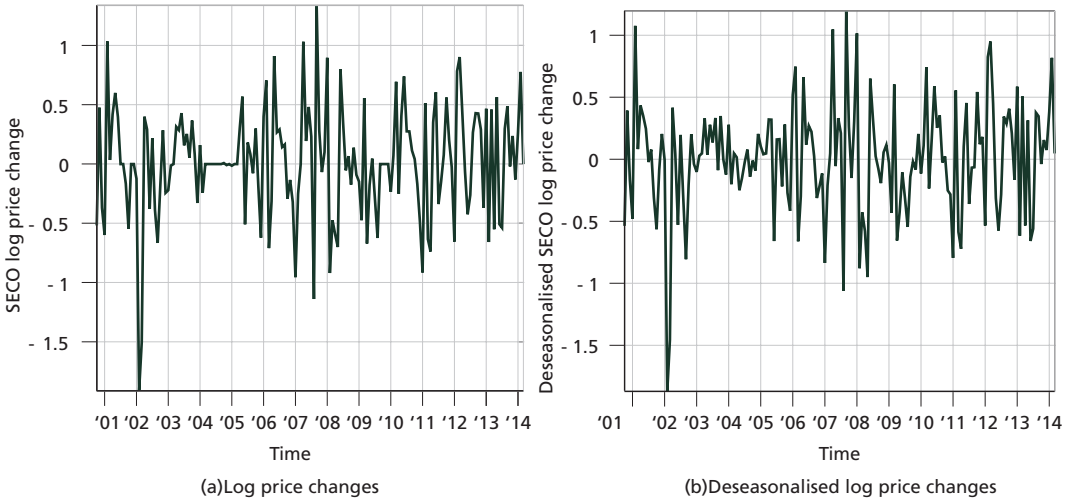
5. In particular,

$$ENA(t) = \sum_{i=1}^{n} (Qnat_{(i,t)} * p_{(i)}),$$

where i refers to a specific hydro-plant of a considered watershed, t is the time interval considered (in our case a month), $Qnat_{(i,t)}$ is the natural hydraulic inflow to plant i in period t, and $p(i)$ is the average productivity of hydro plant i taking into account 65% of its maximum useful storage level and the average downstream level. See ONS (2010) and Duke Energy (2015).

These two continuous variables are interesting in our model because, for a largely hydroelectric system such as Brazil, the level of potential energy stored in the reservoirs and the quantity of kinetic energy generated purely through rainfall are likely to have a substantial effect on electricity pricing. Both will affect the supply decisions taken by generators or the regulator, and will thus affect prices, whether market generated or regulator set. For our estimation, ENA and EAR are scaled down by 10,000, and are thus measured in units of 10 GigaWatts (GW). In order to remove seasonal effects, we separately regress log price changes, EAR, and ENA on a dummy variable for each month, then use the residuals of this regression as the deseasonalised series. Graph 2 plots the electricity log price change, for the Seco region, over the sample period. Graphs 3 and 4 show the EAR and ENA time series, respectively. Interestingly, seasonal effects are far more apparent in the hydrological variables than in the price series. Lastly, in table 2, we note that both variables are negatively correlated with log price changes, and negatively correlated with squared log price changes, suggesting that rainfall and reservoir levels both reduce prices, and dampen volatility in the market on average.

GRAPH 2
Log price change series in the Seco region



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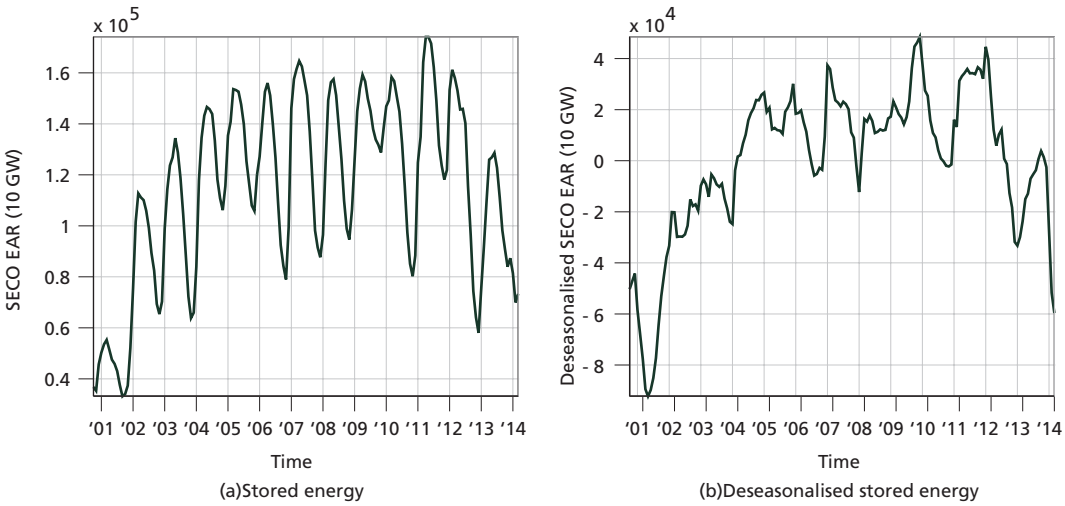
GRAPH 3
Stored energy (EAR) series in the Seco region



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GRAPH 4
Natural hydropower (ENA) series in the Seco region

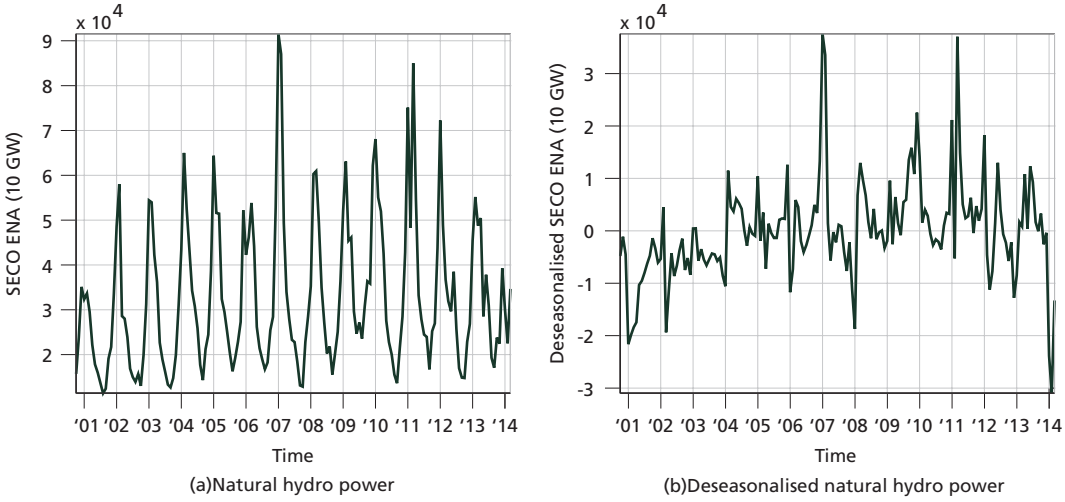

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TABLE 2
Correlations between deseasonalised log price changes or squared log price changes and deseasonalised EAR (stored energy) or deseasonalised ENA (natural hydropower)

Correlations	
corr(r,EAR)	-0.054367
corr(r^2,EAR)	-0.021051
corr(r,ENA)	-0.43393
corr(r^2,ENA)	-0.05723

Elaborated by the authors

4 RESULTS

4.1 Parsimonious representations

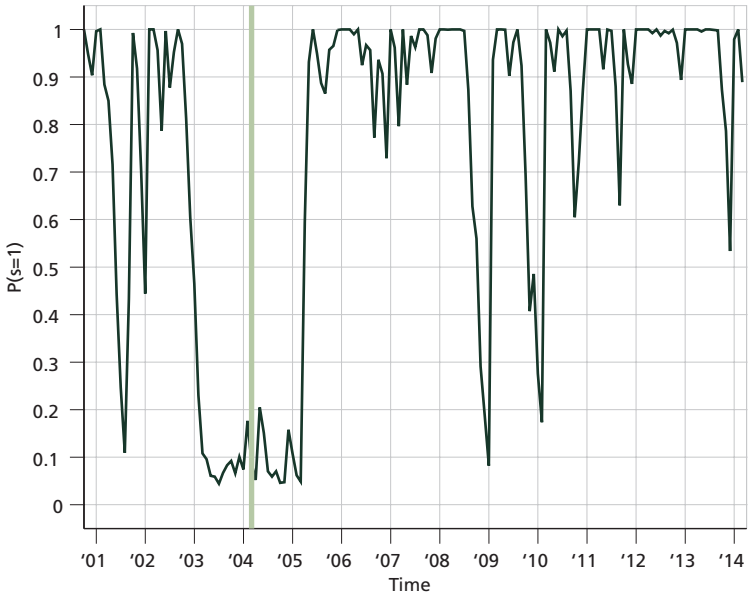
We focus our attention on the effects of the reforms on volatility and state persistence, as well as examining the role played by EAR and ENA in the Seco market. To this aim, we first estimate the model with no independent variables and constant Markov switching probabilities, then build in the reform dummy variable and finally the covariates EAR and ENA in the mean, volatility, and probability equations (see equations (1-5) in section 2). The results from our estimation are found in table 3. In what follows, we define state 1 as the state with the higher baseline volatility pre-reform ($\delta_{1intercept} > \delta_{2intercept}$).

As a first step, we estimate the model without covariates (column 1). In this initial model, state 1 experiences low negative drift of around 1.7% in log prices. Volatility is high in this state, at $e^{-0.6527} = 0.5206$, indicating that monthly log price differences have a standard deviation of 52%. This state has a probability of persisting (p_{11}) of $\frac{e^{3.1791}}{1 + e^{3.1791}} = 0.96$. In contrast, state 2 experiences positive drift, with log prices rising by 4.9% per month on average, and lower volatility of $e^{-1.7758} = 0.1693$. This state has a lower probability of persisting, with $p_{22} = \frac{e^{2.0761}}{1 + e^{2.0761}} = 0\ .89$. Initially at least the model describes a relatively benign state with positive drift and low volatility (state 2), and a relatively turbulent state with high volatility, partly mitigated by negative drift (state 1).

In column 2 we introduce the reform variable into the mean equation. The results show that, whereas pre-reform state 1 was characterised by volatile prices with a substantial negative drift, in the post-reform period, state 1 drift is close to zero, leading to a generally increasing electricity price. Both states are strongly persistent, although state 2 more so than state 1 ($P_{11} = 0.90$ versus $P_{22} = 0.95$).

In column 3, we also introduce EAR and ENA to the mean equation. The trend of reform increasing price growth in state 1 remains (in fact, this pattern is robust across all our specifications in table 3). As we would expect, ENA (naturally occurring hydropower from unexpected rainfall) generally has a negative effect on prices. In contrast, EAR does not appear to have a consistent effect, but rather it switches from positive to negative depending on the state. This may be due to the different decision making that occurs at high or low levels of water storage, which is discussed further in section 4.3

GRAPH 5
The probability of being in state 1, over time, generated with only the binary variable reform (equalling one post-reform) included in the mean and volatility equations (see column 4 of table 3)



Note: The solid vertical line shows the date of reform.
Elaborated by the authors

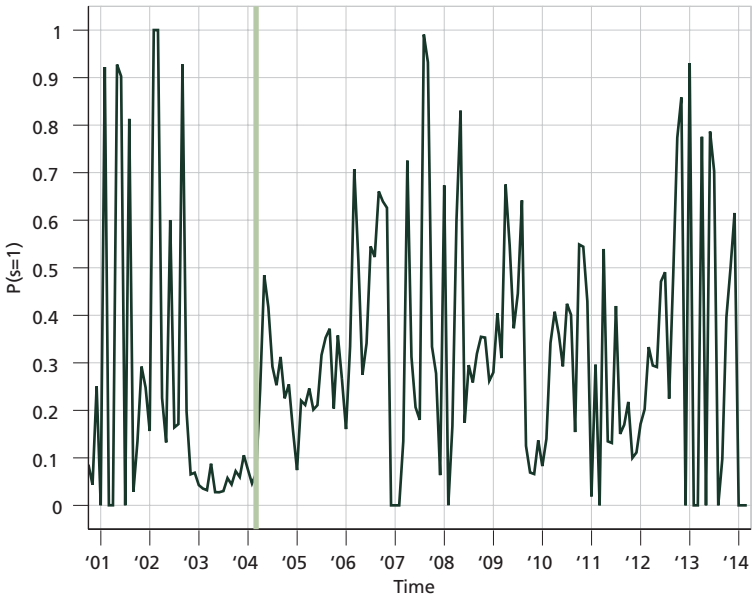
Column 4 contains the results from including reform in the mean and volatility equations. The reform appears to have had a significantly dampening effect on volatility, in both states. In this specification, state 1 is highly persistent. We plot the probability of being in state 1 in graph 5, with a reference line at the date of reform. The figure clearly shows that with reform as the only explanatory variable for drift and volatility, the series spends the majority of the time in state 1, the more volatile state.

In column 5 we see the estimated coefficients including all three covariates in both the mean and volatility equations. The series begins in state 2, and it is the more persistent state. Pre-reform, state 1 is characterised by high negative drift and high

mean volatility (3.6053), while state 2 experiences low positive drift and low mean volatility (0.2174). Post-reform, we find state 2 remains relatively similar, with low positive drift and modest volatility of 0.3352. State 1, however, becomes characterised by very low drift and (relatively low) volatility of 0.1252. The conclusion here would be that (all other things being equal) the reforms resulted in an "evening out" of volatility between states. EAR has a positive effect on drift in state 2, and a negative effect on drift in state 1. EAR slightly lowers volatility in state 2, and has a big positive effect on volatility in state 1. ENA has a consistently negative effect on log price changes, but not so on volatility: in state 2, it has a positive effect and in state 1 a negative effect. EAR and ENA thus have opposite effects on volatility: larger amounts of stored water can offset volatility effects of low rainfall.

GRAPH 6

The probability of being in state 1, over time, generated from the model with reform, EAR and ENA included as covariates in the mean and volatility equations (see column 5 of table 3)



Note: The solid vertical line shows the date of reform.
Elaborated by the authors

We plot the probability of state persistence for this model in graph 6. By comparing graph 6 to 5, it is apparent that after the inclusion of covariates, we infer more transitions between the two states, implying that the states play a greater role in explaining short term movements in price.

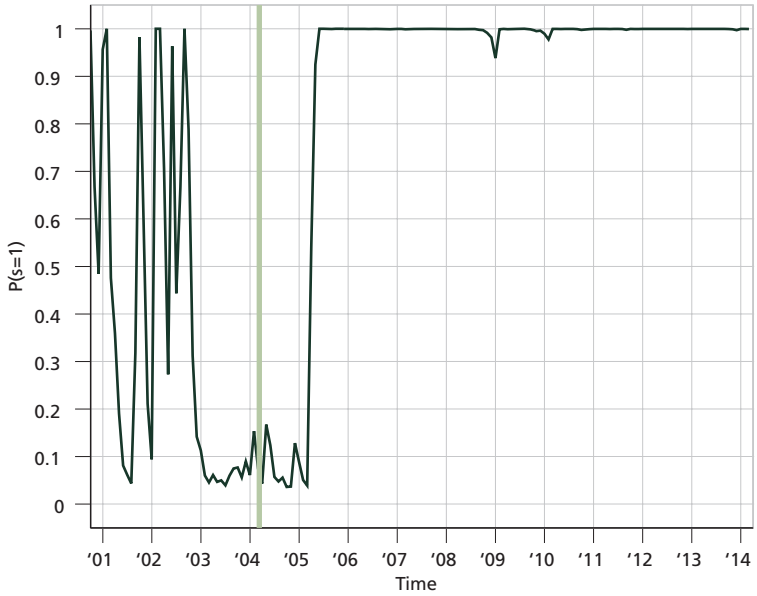
TABLE 3
Estimated coeffcients from our two state Markov switching model

	Progression of results from the Two State Markov Switching Model													
	1		2		2		4		5		6		7	
	coeff.	se.	coeff.	se.	coeff.	se.	coeff.	se.	coeff.	se.	coeff.	se.	coeff.	se.
μ1	-0.0172	0.0503	-1.6438***	0.4011	-2.0696*	1.1141	-0.2049	0.1600	-0.4097***	0.1557	-0.2903	0.2083	-0.2823	0.1820
μ2	0.0490	0.0359	0.0263	0.0595	-0.0224	0.0671	0.1010**	0.0494	0.0315	0.0687	0.1021**	0.0485	-0.1315	0.0925
β1*reform*			1.6708***	0.4151	2.7043	2.1001	0.2299	0.1695	0.4589***	0.1184	0.3129	0.2177	0.3353*	0.1919
β1*EAR*					-0.3518	0.3319			-0.0154	0.0193			0.0442*	0.0251
β1*ENA*					-0.0822	0.5308			-0.5805***	0.0280			-0.2682***	0.0683
β2*reform*			-0.0121	0.0763	0.0623	0.0806	-0.1107*	0.0579	-0.0071	0.0973	-0.1128*	0.0611	0.1252	0.1506
β2*EAR*					0.0425***	0.0140			0.0607***	0.0196			0.0235	0.0188
β2*ENA*					-0.3209***	0.0385			-0.2749***	0.0422			-0.5403***	0.1154
δ1*intercept*	-0.6527***	0.0958	-0.6148**	0.2439	-0.4146*	0.2385	-0.4575**	0.1806	1.2824**	0.6303	-0.3836*	0.1982	-0.3493	0.2228
δ1*reform*							-0.2748	0.1979	-3.3602***	0.7379	-0.3841*	0.2097	-0.9147***	0.2692
δ1*EAR*									0.6023***	0.0836			0.0280	0.0433
δ1*ENA*									-0.4256*	0.2220			-0.0134	0.0846
δ2*intercept*	-1.7758***	0.1559	-1.0469***	0.1572	-1.1782***	0.0752	-1.6807***	0.1623	-1.5260***	0.2432	-1.6567***	0.2022	-1.6107***	0.3843
δ2*reform*							-0.4311	0.2748	0.4331	0.3091	-0.4585	0.3145	0.4435	0.5250
δ2*EAR*									-0.0673	0.0451			0.0965	0.0793
δ2*ENA*									0.0353	0.0952			-0.2259	0.3823
γ1*intercept*	3.1791*	1.7093	2.1757	1.7563	0.6718	1.0000	3.3496***	0.8565	-0.3474	0.7440	1.3200	1.3060	0.3670	1.3817
γ1*reform*											7.6897***	1.7056	2.0685	1.6444
γ1*EAR*													0.1462	0.2933
γ1*ENA*													0.2076	0.6498
γ1*SecoEAR*														
γ1*SecoENA*														
γ2*intercept*	2.0761*	1.2066	3.0132***	0.7423	3.7603***	1.0232	2.1995***	0.6954	1.0517**	0.4577	2.0354	1.2695	2.6837**	1.2347
γ2*reform*											0.4780	1.6191	-1.0618	1.8066
γ2*EAR*													1.4577**	0.6624
γ2*ENA*													-2.2741	1.2692
γ2*SecoEAR*														
γ2*SecoENA*														
P 0	1.0000	1.1857	0.0000	1.0278	1.0000	1.8236	1.0000	1.1007	0.0000	1.8309	1.0000	1.0429	0.0000	1.0081

Note: Subscript 1 denotes state 1 and subscript 2 denotes state 2, with standard errors in parenthesis. β corresponds to coefficients in the mean equation, δ corresponds to coefficients in the volatility equation, and γ corresponds to coefficients in the probability equation. P0 represents the initial probability of being in state 1 (the lower volatility state) at the beginning of the series. Reform is a binary variable equal to one from March 2004, EAR denotes deseasonalised stored energy and ENA denotes deseasonalised natural hydropower. *, **, and *** denote statistically significant difference from zero at the 10%, 5%, and 1% significance levels, respectively.
Elaborated by the authors

GRAPH 7

The probability of persisting in state 1, over time, generated from the model including only the binary variable reform (0 pre-reform, 1 otherwise) as a covariate in the mean, volatility and probability equations (see column 6 of table 3)



Elaborated by the authors

We next include covariates in estimated state persistence. Since volatility and drift for the states change after the reforms, it seems reasonable that the persistence of each state may also change post-reform. We also suspect that high or low levels of EAR or ENA may facilitate or impair state transitions, so we also allow these to affect the transition probabilities (see section 4.2).

Our first foray into more complex modelling of state persistence involves including only reform in the mean, volatility and probability equations (see column 6 of table 3). From this estimation, as in our previous examples, we find that there continues to be a low volatility state and a high volatility state, and post reform, both of these volatilities decrease. We plot the model's estimated probability of being in state 1 in graph 7. This figure, together with column 6 of table 3, shows that the reforms decreased volatilities in both the good (1) and bad (2) states. Post-reform, the series appears to have spent most of its time in the higher volatility state (as opposed to the pre-reform period, where the market spends roughly equivalent amounts of time in each state).

To further investigate this phenomenon, we calculate the ergodic probabilities (see section 2); that is, the long term probabilities of the series being in each state. The value in row one of the following matrices is λ1, and that in the second row is

$$\lambda_{pre} = \begin{pmatrix} 0.3540 \\ 0.6460 \end{pmatrix} \quad \lambda_{post} = \begin{pmatrix} 0.9984 \\ 0.0016 \end{pmatrix}$$

As is apparent from these ergodic probabilities and graph 7, according to this model, post-reform, state 1 is the dominant state. This model includes neither EAR nor ENA, so this is not yet a conclusive interpretation of the outcome. However, using the ergodic probabilities, we can then evaluate the variance of log price changes pre- and post-reform using (10) to find:

$$Var(r_{pre}) = 0.3645$$

$$Var(r_{post}) = 0.4635.$$

The ergodic volatility for the post-reform period is higher than that of the pre-reform period; the rise in persistence for state 1 more than offsets the volatility reduction across the two states.

By examining these simpler models, we conclude three things.

1. The reforms reduced volatility on a per-state basis.
2. EAR and ENA have important effects on volatility and drift of electricity prices.
3. While the reforms may have reduced per-state volatility, their effects on state persistence are also important.

To obtain a clearer picture of these three effects, in the next subsection, we use a full covariate analysis where reform and hydrological variables affect drift, volatility *and* state persistence.

4.2 Full covariate analysis

Intuitively, the combination of EAR and ENA should affect whether the market moves to or remains in a volatile state. For this reason, in the final column of table 3 we include

these covariates in the probability equations as well as the mean and volatility equations.

Before the reforms, state 1 has a high negative drift of 28.23%, and high mean volatility at $e^{-0.3493} = 0.7052$. State 2 has negative drift of 13.15% in log prices, and low mean volatility at $e^{-1.6107} = 0.1997$. State 1 features extreme price shifts, while state 2 can be seen as a relatively stable situation. In both states, prices generally trend downwards. As can be seen from graph 1 this is not uncharacteristic of spot prices, which exhibit frequent large upward movements, generally followed by a return to normal (low) levels.

Post-reform drift in state 2 increases by 12.52%, giving the state a mean drift of 12.52% - 13.15% = -1.37%. In state 1, reform increases drift by 33.53%, giving a mean drift of -5.30%.

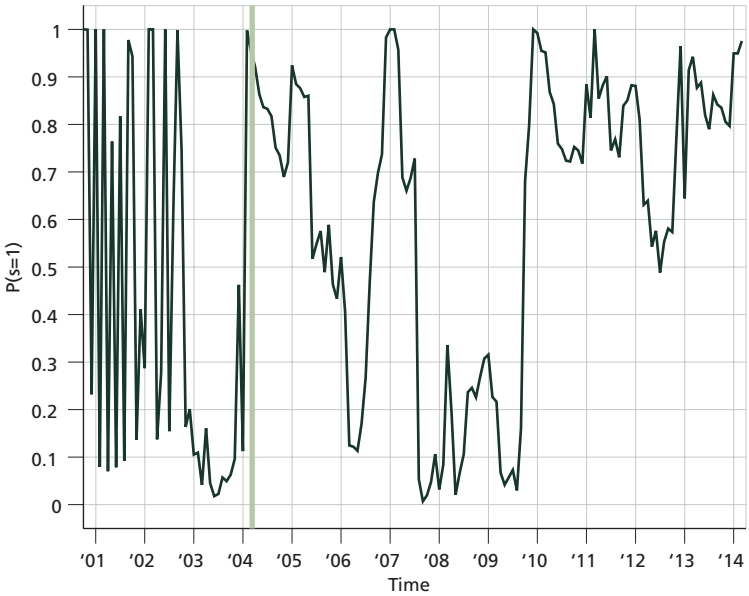
Volatility changed post-reform: in state 2 the reform increased mean log volatility by 0.4435, leaving a mean volatility of $e^{-1.6107+0.4453} = 0.3112$. In state 1, on average, reform decreased log volatility by 0.9147, leaving a mean volatility of $e^{-0.3493-0.9147} = 0.2825$. Thus, post-reform, state 2 is now the state with the higher mean level of volatility, but there is less disparity between the states.[6] Graph 8 shows that pre-reform, the series likely spent a longer stint in state 2 (the lower volatility state) in the lead up to the reform, then post-reform (where state 1 has a higher volatility) there are extended periods spent in both states

Examination of volatility must, however, include consideration of hydrological variables. EAR positively impacts log price changes in both states, to a small degree, while ENA has a large negative effect on log price changes in both states. We note that in terms of volatility, effects on state 1 are low for both ENA and EAR. However, for state 2, the ENA effect is quite pronounced. Post-reform, state 2 is the more volatile state due to this effect. Pre-reform, the baseline volatility effect dominates, leaving state 1 more volatile.

6. This is analogous to our finding when excluding covariate effects on transition probabilities (see column 5 of table 3 and section 4.1).

GRAPH 8

Probability of persisting in state 1, over time from the final model, in which we include the binary variable reform, EAR (the deseasonalised stored energy), and ENA (the deseasonalised natural hydropower) in all three equations: mean, volatility and state persistence



Note: The solid vertical line represents the reform. In this case, pre- reform state 1 has the lower baseline volatility, whereas post-reform state 2 has the lower baseline volatility.
Elaborated by the authors

The probability equations in this case also yield interesting results. The gamma coefficients tell us what increases and decreases the likelihood of persisting in one or other of the states. The reforms lead to decreased state 2 persistence, coupled with increased state 1 persistence (a good outcome, since post-reform, state 1 is the more benign state). Higher levels of EAR increase persistence. ENA, in contrast, increases persistence of state 1, but has a strong *negative* effect on state 2 persistence.

In summary, pre-reform, state 2 was characterised by lower volatility, and state 1 by higher volatility. Post-reform, the two states have closer levels of volatility, but state 2 became the more risky state. EAR and ENA have strong impacts on transition probabilities between the two states. A reasonable question to then pose is: which combinations of EAR and ENA lead to high persistence of the volatile state?

4.3 Hydro management

We now discuss the effect that the EAR to ENA ratio has on the electricity market's stability. Specifically: which combinations of EAR and ENA place the system at risk of spending protracted time in the volatile state 1 (pre-reform) or state 2 (post-reform). To answer this, we consider ranges of EAR and ENA that would cause $P11$ or $P22$ to lie above a certain level, computed separately pre- and post- reform. In the pre-reform period, by considering EAR/ENA combinations that result in high $P11$, we consider situations that could result in a prolonged period in state 1 (a crisis). However, this concern would be mitigated by a high $P22$ since this would mean that if the market was already in state 2, the probability of moving to state 1 is low in the first place. The analysis of the post-reform period reverses the roles of the states, so that one would be concerned if $P22$ is high and $P11$ is low.

In our following analysis, we take a potential crisis period to mean that probability of persisting in the "good" state is less than 95% (meaning that there is a probability of at least 5% of transitioning into the "bad" state), while probability of persisting in the bad state is more than 50% (meaning that if the market transitions to the bad state, we would expect to spend at least two months there).

We plot these two regions in graph 9. The dotted line shows the locus of EAR/ENA points that would lead to a persistence probability for state 1 of 0.5 in the pre-reform period or 0.95 in the post-reform period. Below this line, state 1 has over a 50% (95%) chance of persisting. In contrast, the dash-dotted line shows points where state 2 has a 95% chance of persisting in the pre-reform period, or 50% after it. Below this line, $P22 > 0.95$ (0.5).

These two lines divide the region into quadrants. The "dangerous" quadrant for the pre-reform market lies *above* the dotted line, but *below* the dash-dotted line: a persistent state 1, and a non-persistent state 2. This lies on the right hand side of the first graph in 9 (see shaded region), and we note that a number of data points lie in this region. During the post-reform period, the dangerous quadrant is the region *below* the dotted line, but *above* the dash-dotted line: a region on the left hand side of the second graph (again shaded). In this case, we note that the majority of data-points lie in this region.

We next perform a cointegration analysis on the two covariates to analyse their behaviour in relation to one another. We perform the analysis on the pre- and post-reform periods separately, to yield a pre-reform relationship of

$$\mathrm{EAR}_t = \underset{(0.4959)}{-2.072} + \underset{(0.5543)}{2.131}\,\mathrm{ENA}_t + \epsilon_t \tag{11}$$

$$\Delta\epsilon_t = \underset{(0.0865)}{-0.1735}\epsilon_{t-1}, \tag{12}$$

and a post-reform relationship of:

$$\mathrm{EAR}_t = \underset{(0.1480)}{1.0072} + \underset{(0.1525)}{1.0615}\mathrm{ENA}_t + \epsilon_t \tag{13}$$

$$\Delta\epsilon_t = \underset{(0.0499)}{-0.0981}\epsilon_{t-1}. \tag{14}$$

In both cases, parenthetical numbers indicate standard errors. The intercepts and coefficients on ENA in the equations (11) and (13) shown above describe the ratios of EAR to ENA tending to occur in the model. The negative coefficients on *Et*-1 in equations (12) and (14) show that, both pre- and post- reform, there is statistically significant mean reversion. These critical mean-reverting ratios are also plotted in graph 9, as a solid line.

There are several key results apparent from these graphs. Firstly, from the scatter of points it is evident that deseasonalised EAR and deseasonalised ENA are positively correlated. This makes intuitive sense: how generators react to unseasonal rainfall levels is likely to depend largely on how much water is already in their reservoirs or water sheds. For example, if deseasonalised ENA is low, indicating that the season is drier than would be expected, it is natural that the amount of water allowed to sit in the reservoirs (not generating electricity) would fall. This is due to the demand for electricity generation still being present, leading to the generators running reserves through the system. This would, in turn, lead to a deseasonalised EAR lower than zero based on the severity or duration of the drought. In contrast, a generator could be excused for storing water during times of high rainfall.

Comparing the shaded areas of graph 9 pre- and post- reform shows that the "danger zone" post-reform encompasses a lot of the observed data. Although per state volatility fell post reform (see section 4.2), the market has often been in a position to spend protracted time in state 2. Graph 10 illustrates the transition probabilities as a time series.

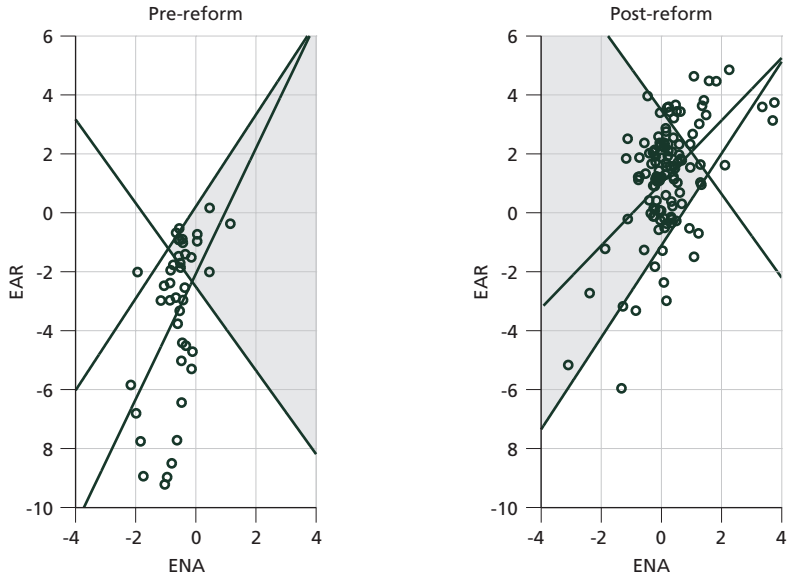
Lastly, by examining the locus of steady-state levels for EAR-ENA (the solid line) that in the pre-reform market, dangerous steady states were generally those with high EAR/ENA, while those post-reform were characterised by low EAR/ENA. We conclude that the market did a better job of managing droughts (low EAR/ENA), whereas the new regime handled deluge periods (high EAR/ENA) better.

4.4 Other regions

Finally, we extend our analysis to the other regions of Brazil: the South, North, and North-East. Table 4 contains the results of estimating the model from section 4.2 applied to the other regions. The Seco region is the major production region for electricity, and has strong transmission connections to the other regions, while connections between the other regions are sparser. For this reason, we extend the model from section 4.2 by including the effects of EAR and ENA in the Seco region as covariates to explain state transitions for the other regions. In this way, a water shortage in Seco can translate into a crisis in other regions.

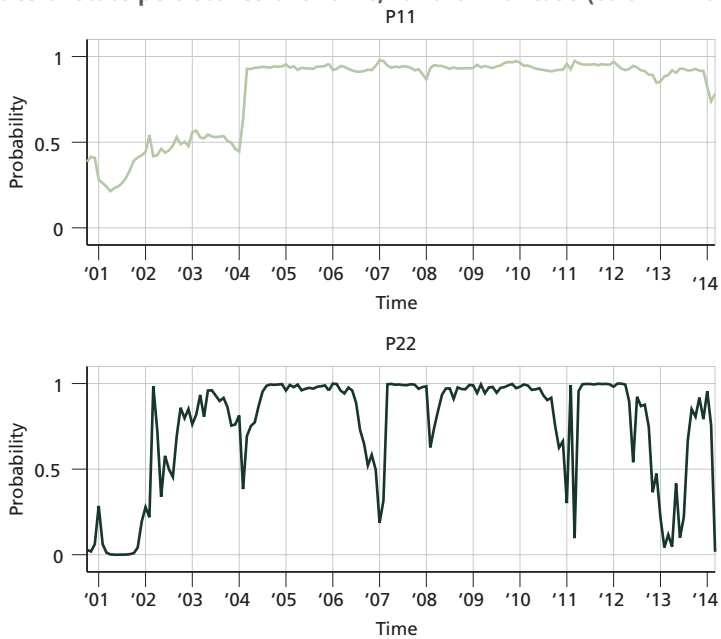
Volatility effects from the reforms in the Northeast and North were marked.

GRAPH 9
The solid line represents the locus of levels for EAR and ENA that the system mean-reverts to pre- and post- reform



Elaborated by the authors

GRAPH 10
Probabilities of state persistence over time, for the final case (column 7 of table 3)



Note: we include all three covariates (the binary variable reform: equalling one after March 2004, EAR: the deseasonalised stored energy measure, and ENA: the deseasonalised natural hydropower measure) in all three equations: mean, volatility and probability.
Elaborated by the authors

Prior to the reforms, both markets experienced very high volatility in state 1; post- reform, this declined considerably. While state 2 volatility increased post-reform, the overall effect was that the market becomes considerably less prone to extreme price movements. The South similarly saw a decline in state 1 volatility, and a rise in state 2 volatility; however, in this case, the end result was a market more prone to extreme events.[7]

All regions' volatility is positively affected by local EAR, and negatively affected by local ENA, with the exceptions of the Northeast in state 2 (where EAR has a negative effect and ENA has a positive effect on volatility) and the South in state 1 (where ENA has a positive effect on volatility). The EAR effect is particularly strong in state 1, resulting in this state potentially being very volatile during high EAR periods.

7. State 2 post-reform volatility in the South is $e^{0.5340+0.0174} = 1.7357$.

The transition equations, however, show the most striking results for the regions. The South is characterized by extremely high state persistence. However this is strongly affected by hydrological factors. Low reserves in Seco reduce state 1 persistence, while low local reserves increase persistence. In contrast, in state 2, low EAR locally or in the Seco region can significantly reduce state persistence? The net result of these effects is that the Southern region faces high volatility only if both itself and Seco have high EAR. If EAR is low in the South, then state 1 is unlikely to be volatile, while if EAR is low in Seco, then state 1 is unlikely to persist. A possible explanation for this is that given persistence of states in the Seco region in response to high EAR, and the dependence of the Southern region on Seco electricity exports, modest changes in the Seco region's volatility can have much larger effects on the Southern region. However, if the South is not running a high EAR level (and therefore is less prone to mis-management; see section 4.3), then this can buffer the region against Seco shocks.

For the South, ENA shows different effects in state 1 and 2. In state 1, Seco ENA increases persistence, while local ENA lowers persistence. In contrast, state 2 has the opposite effect (local ENA increases persistence, while Seco ENA lowers persistence). Lastly, the reforms have increased state 2 persistence and decreased state 1 persistence. Given the sensitivity of state 1 to EAR, we suspect that while baseline volatility in state 2 post-reform was higher, this change in persistence has probably reduced Southern volatility.

The Northeast region, in contrast, has very low baseline persistence pre-reform. Post-reform, state 2 becomes highly persistent, and state 1 becomes almost completely transitory. Local EAR and ENA both have positive effects on both states' persistence, while Seco EAR has a negative effect. High Seco ENA makes state 2 even more persistent, and state 1 less so. In particular, state 1 is strongly affected by local hydrological variables, so that even post-reform, this state can linger if rainfall is high or water reserves are high. Hence, the Northeast is prone to persistent high volatility when EAR and ENA are high. This can be mitigated by a high ENA in the Seco region (or exacerbated by a low ENA in Seco).

TABLE 4
Model for electricity market shocks: all regions.

	Southeast/Central West		South		Northeast		North	
	coeff.	se.	coeff.	se.	coeff.	se.	coeff.	se.
μ_1	-0.2823	0.1820	-0.5193***	0.0001	1.5218***	0.0014	1.4920***	0.0352
μ_2	-0.1315	0.0925	0.0874*	0.0525	-0.0149	0.0728	0.0594	0.0655
$\beta_{1reform}$	0.3353*	0.1919	1.0684***	0.0001	-0.9850***	0.0010	-0.4539***	0.0189
β_{1EAR}	0.0442*	0.0251	-0.3001***	0.0001	1.0341***	0.0008	8.8387***	0.1155
β_{1ENA}	-0.2682***	0.0683	-0.8582***	0.0000	-2.3059***	0.0008	-0.8306***	0.0055
$\beta_{2reform}$	0.1252	0.1506	-0.0680	0.0669	-0.0004	0.0979	-0.1068	0.0886
β_{2EAR}	0.0235	0.0188	0.2004	0.1671	0.0564	0.0466	0.1254	0.2514
β_{2ENA}	-0.5403***	0.1154	-0.2827***	0.1063	-0.8556***	0.1245	-0.0206*	0.0107
$\delta_{1intercept}$	-0.3493	0.2228	-1.0544*	0.5777	4.9821***	0.3158	5.7924	7.7733
$\delta_{2intercept}$	-1.6107***	0.3843	-1.2884***	0.1224	-1.7969***	0.1828	-1.2608***	0.2905
$\delta_{1reform}$	-0.9147***	0.2692	-9.6517***	0.1626	-11.4971***	0.5608	-11.7220	9.8503
δ_{1EAR}	0.0280	0.0433	8.6451***	0.6831	5.7195***	0.2861	28.5836	27.2703
δ_{1ENA}	-0.0134	0.0846	0.0174	1.3970	-1.2378*	0.6419	-1.0245	0.9384
$\delta_{2reform}$	0.4435	0.5250	0.5340***	0.1458	0.8346***	0.2137	0.2956	0.3700
δ_{2EAR}	0.0965	0.0793	0.3719	0.2575	-0.2367**	0.1039	0.2425	0.8176
δ_{2ENA}	-0.2259	0.3823	-0.3155*	0.1859	0.9173***	0.2371	-0.1037**	0.0408
$\gamma_{1intercept}$	0.3670	1.3817	16.7266***	1.9672	-0.1563	1.0661	-0.0309	1.9417
$\gamma_{1reform}$	2.0685	1.6444	-3.0322	2.0459	-19.1304	12.4075	-20.8059**	8.4671
γ_{1EAR}	0.1462	0.2933	-7.0638***	1.4856	5.4430*	3.0165	11.0768**	4.7336
γ_{1ENA}	0.2076	0.6498	-8.6209***	1.5793	12.8409	10.6817	-0.8697	0.9258
$\gamma_{1SecoEAR}$			9.6423***	1.2437	-0.7449	0.4721	2.8030	1.7343
$\gamma_{1SecoENA}$			2.0412	1.2467	-5.2007	5.1470	-9.4331*	5.1663
$\gamma_{2intercept}$	2.6837**	1.2347	18.9856***	2.1068	-0.3841	0.6212	8.3149***	1.6505
$\gamma_{2reform}$	-1.0618	1.8066	5.2022***	0.7527	6.6999***	0.8658	0.5565	4.1434
γ_{2EAR}	1.4577**	0.6624	14.1364***	1.8581	1.9527**	0.8314	30.0586***	4.3291
γ_{2ENA}	-2.2741*	1.2692	2.3251***	0.8395	1.9920**	1.0155	-1.2491***	0.2276
$\gamma_{2SecoEAR}$			8.1040***	0.6933	-1.3858***	0.2793	-1.3361***	0.2775
$\gamma_{2SecoENA}$			-7.5049***	1.1701	4.2744***	0.7186	7.9950***	1.5594
$P0$	0.0000	1.0081	0.0000	0.9922	0.0000	1.0035	1.0000	1.4976

Note: The model estimated here is identical to the full model for the Seco region. However, for the other regions, Seco EAR and ENA are allowed to affect transition probabilities. This allows a water shortfall in the Seco region to translate into a crisis in other areas dependent on electricity imports. *, **, and *** denote statistically significant difference from zero at the 10%, 5%, and 1% significance levels, respectively.
Elaborated by the authors

Lastly, the North has (pre-reform) a highly persistent state 2, and a mildly persistent state 1. The reforms (as in the North-East) reduced state 1 to a transitory condition. Here, local EAR is the dominant factor in determining state transitions. High EAR results in both states' persistence rising considerably. The other important factor is Seco's ENA, which reduces state 1 persistence, but raises state 2 persistence. Moreover, local ENA has a small negative effect on both states' persistence, while Seco EAR increases state 1 persistence and lowers state 2 persistence. As in the Northeast, high EAR can cause high and persistent volatility, which can be offset by high ENA in the Seco region.

5 CONCLUSION

In the context of the Brazilian electricity market, this paper introduces the empirical debate about the potential virtues and drawbacks of a single buyer market versus a free market. Brazil, having implemented both market structures, allows us to compare them without biases linked to geographical, technological, and political differences. Specifically, starting from 1996, purchase of electricity was left to free contracting. However, following the market reform in March 2004, and the creation of the RCE, the reformed market became a single-buyer market.

Starting from monthly log price changes spanning 2000-2014, we analyse the effect of 2004 reform through a two-state Markov switching model. We find that between September 2000 and February 2004 (that is, pre-reform), the South-Eastern/Central Western region of the Brazilian electricity market is characterised by periods of volatility when the market enters state 1. Post reform, although baseline volatility declined, hydrological variable fluctuation (specifically ENA) could still cause volatility in state 2.

We find that the combination of EAR to ENA is instrumental in determining the persistence of states. We show that post-reform, many combinations of EAR and ENA developed that could lead to protracted energy crises.

Examining the other regions of Brazil, we find strong effects of the Seco market, particularly for the South, where high local and Seco combinations of EAR can cause persistent periods of high volatility. In contrast, the North and Northeast regions have less

influence from Seco (consistent with their more isolated status on the transmission grid). They, however, are also prone to high volatility when their local EAR levels are high.

In conclusion, we find mixed evidence for the merits of the two regimes. On the one hand, a more centralised model can lead to some mitigation of price fluctuations. However, difficulties in efficiently managing hydrological resources can result in protracted periods of high volatility. This "tail risk" can partially or wholly offset the gains from lower price volatility through eliminating market-driven wholesale price fluctuations.

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