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Does Self-Generating Energy Technology Adoption Increase Residential Electricity Consumption Inequality in an Emerging Country? Evidence From Brazil

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We identified the impact of adopting self-generating energy technologies on electricity demand in Brazil. Using the Household Budget Survey database and the unconditional quantile treatment effect estimator to analyze heterogeneous treatment effects, we find that adopting self-generating energy technologies leads to an increase in residential electricity consumption, mainly in the highest quantiles of consumption distribution, thereby imposing inequality in residential electricity consumption.

I. Introduction

Initiatives promoting renewable energy technologies have expanded alternative energy sources in developing nations such as Brazil (Benevit et al., 2023). In Brazil, since the enactment of the Normative Resolution No. 482 in 2012, consumers have been afforded the option to generate and compensate for their level of electricity consumption. The proliferation of renewable generation technologies, alongside rising electricity tariffs, has prompted many consumers to adopt these technologies as a cost-saving measure and for the generation of clean energy.

However, inequalities in energy consumption may arise due to disparities in access to these advanced technologies and the financial ability to invest in them (Carley et al., 2021; Jenkins et al., 2016). In this context, this research aims to contribute to the literature by testing if adopting self-generating energy technology impacts (i) the population's electricity consumption and (ii) the population's inequality in electricity consumption in Brazil.

This is the first study to examine the relationship between self-generating energy technology adoption and Brazil's unconditional distribution of residential electricity consumption. This research innovates by utilizing micro-data from the Family Budget Survey (POF/2017-2018) conducted by Brazil's main research institute, *Instituto Brasileiro de Geografia e Estatística* (Brazilian Institute of Geography and Statistics - IBGE). The POF sample weight

allows inferences for the Brazilian population. We examine the underlying relationship using the Unconditional Quantile Treatment Effect estimator - UQTE (Firpo et al., 2009).

II. Data

The Family Budget Survey analyzes the expenditure structures, income, and part of the wealth variation of families, providing a profile of the population's living conditions by observing household budgets.¹ The construction of the variables follows Marques et al. (2024). The outcome variable is the electricity consumed per kilowatts per hour (kW/h). The treatment variable indicates whether the household has alternative energy sources. We created a variable based on the residential electricity tariffs defined by the National Electric Energy Agency (ANEEL) for each federation state to adjust the household's sensitivity to residential power costs. To control the sensitivity of the home to income, we constructed a variable that considers the total monthly gross income of the family unit. Moreover, the value of the electricity tariff and the household income were deflated to January 15, 2018 values. Finally, we apply the natural logarithm to the three variables.

We performed the analysis for two different samples. We analyzed the full sample (General Sample) and the ordinary consumers sample (Ordinary Consumers). [Table 1](#) presents the descriptive statistics. The study employs four groups of covariates. The first group aims to control the architec-

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tural characteristics of the household. The second group controls specific demand characteristics through the number of electronic devices in the home. The third group comprises binary variables aimed at maintaining the status of the property and its classification. The fourth group aims to control the characteristics of the household's inhabitants.

Table 1 shows that high-intensity consumers tend to have a significantly higher income and more electronic devices. These factors can contribute to greater adoption of self-generating technologies due to the greater return on investment and financial capacity to bear the initial costs, as argued by the energy justice and energy inequality theory (Jenkins et al., 2016).

III. Method

The objective is to test whether adopting self-generating energy technologies impacts: (i) the population's electricity consumption and (ii) the population's inequality in electricity consumption. It is possible to model the demand for residential electricity as follows:

$$\ln C_{isy} = \alpha_0 + \beta T_{isy} + \alpha_1 \ln P_{isy} + \alpha_2 \ln I_{isy} + \text{Cov}'_{isy} \delta + \mu_s + \theta_y + u_{isy} \quad (1)$$

The dependent variable $\ln C_{isy}$ is the natural logarithm of electricity consumption at the household level. The variable T_i identifies those households that have adopted self-generating energy technologies. The treatment variable assumes the value 1 when using alternative energy sources (generator, solar, and wind board) and zero otherwise. The price and income elasticities of domestic demand for electricity associated with the variables $\ln P_{isy}$ and $\ln I_{isy}$ are, respectively, α_1 and α_2 . The second is the natural logarithm of the residential electricity tariff, and the third is the natural logarithm of the real household income. The indicator X'_{ify} represents the vector of covariates. The parameter vector identifies the effects of covariates on electricity consumption. Finally, u_{isy} represents the random perturbation. The terms μ_s and θ_y are the unobserved fixed effects (or fixed confounders). We assume that macroeconomic shocks in the electricity market that have some effect on electricity consumption are controlled by the fixed-year effect (θ_y) and that the effects of seasonality and those eventual consumption characteristics and the substitutability of energy goods derived from family preferences due to differences in regional cultures are controlled by the state-fixed effect (μ_s).

Firpo, Fortin, and Lemieux (2009) introduced a new type of regression, a particular case of recentered influence functions regression. According to Firpo and Pinto (2016), under the hypotheses of un-confoundedness and common support, treated groups and controls are comparable in terms of covariates X_i . The first hypothesis assumes that the vector of observable variables X_i contains all the information about the potential outcome. The second hypothesis assumes that each household in the treatment group is comparable to those in the control group. Thus, the inequality treatment effects are identifiable from the data.

We applied the UQTE using the propensity score framework analysis for the mean, the quantile Q90, and the in-

equality measures: inter-quantile ratios Q90/Q01, Q90/05, Q95/Q10; Atkin inequality index, Gini inequality index, and Lorenz inequality index. All regressions fit the survey sampling plan.

IV. Results

Table 2 presents the balances of the covariates after the weighting by the propensity scores. All covariates are statistically comparable between the treated and control groups.

Table 3 presents the results. The first column shows how adopting self-generating energy technology affects the unconditional average. The second column shows the effect on the 90th quantile. We present inter-quantile residential electricity consumption from columns (3) to (5). From column (6) to column (9), we present the results for the inequality measures of Gini, Absolute Gini, Atkinson, General Entropy, and Lorenz.

Panel A applies the analysis to the entire sample. In the first column, the results show that an increase in self-generating energy technology adoption by a percentage point does not affect the average unconditional consumption distribution. We corroborate the hypothesis that adopting self-generating renewable energy technologies does not affect the population's electricity consumption. In the second column, the 1% increase in adoption generates an increase of approximately 0.34% in residential energy consumption at the 90th quantile. This result indicates an increase in consumption in the upper tail of the unconditional distribution. Columns (3) to (5) show an increase in the gap between the tails of the distribution of unconditional energy consumption. Finally, all the inequality measures show that adopting self-generating energy technologies increases the concentration of residential electricity consumption. Thus, we corroborate the hypothesis that adopting self-generating energy technologies in Brazil generated inequality in residential electricity consumption.

In Panel B, the one percentage point increase in the adoption of self-generating residential energy technologies generates an increase of approximately 0.14%. In economic terms, it is possible to argue that households with higher electricity consumption adopt modern self-generating energy technologies as a strategy to increase electricity consumption. On the other hand, adopting self-generating technologies for households with lower consumption may indicate replacing the electricity source by maintaining the same level of consumption.

In the second column of Panel B, the 1% increase in adoption generates an increase of approximately 0.28% in residential energy consumption at the 90th quantile. Columns (3) to (5) follow the same pattern of increasing the distance between the distribution's tails presented in Panel A. All concentration measures generally follow the same pattern as in the previous panel.

V. Conclusion

This research pioneered the study of the impact of renewable energy technology adoption on the unconditional

Table 1. Descriptive Statistics and Balance of Variables

	Sample		General Consumers			Ordinary Consumers		
	Mean	S.D.	Treated Mean	Non-treated Mean	p-val.	Treated Mean	Non-Treated Mean	p-val
Treatment	0.027	0.161	-	-	-	-	-	-
kw/h	342.90	150.10	362.76	186.70	0.000	526.87	339.32	0.000
Tariff	0.52	0.06	0.54	0.51	0.000	0.55	0.51	0.000
Income	8615.96	12584.88	14292.99	5811.02	0.000	14766.01	8445.41	0.000
Group 1								
# Rooms	6.66	2.58	7.80	6.08	0.000	7.94	6.63	0.000
# Bathrooms	1.63	0.96	2.06	1.36	0.000	2.12	1.62	0.001
Group 2								
# Air conditioning	0.62	1.09	0.95	0.32	0.000	1.14	0.61	0.000
# Dishwasher	0.05	0.22	0.13	0.02	0.000	0.13	0.05	0.002
# Washing machine	0.80	0.48	0.77	0.67	0.004	0.78	0.80	0.743
# Iron	0.88	0.57	0.80	0.80	0.778	0.76	0.89	0.048
# Stereo	0.35	0.55	0.37	0.34	0.425	0.37	0.35	0.698
# TV's	1.64	0.97	1.88	1.40	0.000	1.96	1.64	0.023
# Fans	1.72	1.40	1.25	1.46	0.018	1.22	1.74	0.000
# Computers	0.85	1.00	1.15	0.60	0.000	1.21	0.84	0.019
# Microwave	0.68	0.49	0.56	0.55	0.971	0.56	0.68	0.005
# Freezer's	1.05	0.33	0.86	1.02	0.000	0.83	1.05	0.000
# Shower	1.04	0.92	0.99	0.82	0.081	1.04	1.04	0.986
Group 3								
Own	0.67	0.47	0.73	0.67	0.043	0.74	0.67	0.072
Rented	0.14	0.35	0.06	0.17	0.000	0.05	0.15	0.000
Funded	0.07	0.25	0.10	0.07	0.148	0.08	0.07	0.613
Given	0.12	0.32	0.11	0.95	0.573	0.13	0.11	0.581
Another condition.	0.01	0.09	0.01	0.01	0.827	0.01	0.01	0.635
House	0.88	0.33	0.79	0.89	0.009	0.83	0.88	0.230
Apartment.	0.12	0.33	0.21	0.11	0.009	0.17	0.12	0.228

Another type	Sample		General Consumers			Ordinary Consumers		
	0.0008	0.03	0.001	0.001	0.351	0.0007	0.0008	0.810
Group 4								
Age average of residence	34.36	14.31	35.53	35.27	0.787	34.89	34.34	0.647
Head's average age	48.75	14.16	49.33	48.53	0.278	48.85	48.74	0.904
Couple's average age	47.86	13.86	48.17	47.68	0.501	47.69	47.66	0.834
Race	0.55	0.01	0.44	0.55	0.000	0.43	0.48	0.221
Head's education	9.83	4.73	9.82	8.79	0.021	9.68	9.83	0.768
Couple's education	9.87	4.40	10.01	8.85	0.006	9.87	9.87	0.994
Head's Formal Work	0.95	0.22	0.97	0.96	0.342	0.94	0.95	0.762
Couple's formal work	0.87	0.23	0.90	0.90	0.551	0.87	0.87	0.823
# Number of children	1.67	1.31	1.70	1.48	0.036	1.81	1.66	0.282
SocialTariff1	0.19	0.003	0.20	0.19	0.595	0.22	0.14	0.013
SocialTariff2	0.05	0.001	0.05	0.05	0.611	0.05	0.03	0.116

Source: Family Budget Survey 2017-2018, IBGE. The descriptive statistics of the federative units were not reported due to space limitations.

Notes: This table presents the descriptive statistics of the variables and samples used for the empirical analysis.

Table 2. Balance of Covariates

	General Consumers			Ordinary Consumers		
	Treated Mean	Control Mean	p-value	Treated Mean	Control Mean	p-value
Tariff	0.54	0.54	0.862	0.55	0.54	0.669
Income	14292.99	14067.65	0.896	14756.83	14242.92	0.794
Group 1						
# Rooms	7.80	7.35	0.151	7.94	7.49	0.229
# Bathrooms	2.06	1.85	0.104	2.12	1.89	0.151
Group 2						
# Air-conditioners.	0.95	0.86	0.435	1.14	0.98	0.281
# Dishwashers	0.13	0.15	0.299	0.13	0.15	0.517
# Washing Machines	0.77	0.74	0.368	0.78	0.74	0.341
# Iron	0.80	0.77	0.684	0.76	0.74	0.750
# Stereo	0.37	0.36	0.865	0.37	0.34	0.549
# TV's	1.88	1.76	0.297	1.96	1.82	0.356
# Fans	1.25	1.19	0.550	1.22	1.15	0.540
# Computers	1.15	1.00	0.250	1.21	1.03	0.245
# Microwaves	0.56	0.57	0.694	0.55	0.57	0.724
# Freezers	0.86	0.85	0.803	0.83	0.83	0.998
# Showers	0.99	0.94	0.656	1.04	1.03	0.530
Group 3						
Owned	0.73	0.72	0.875	0.74	0.73	0.870
Rented	0.06	0.05	0.411	0.05	0.04	0.922
Financed	0.10	0.09	0.610	0.08	0.07	0.789
Ceded	0.11	0.14	0.295	0.13	0.14	0.675
Other cond.	0.004	0.003	0.899	0.005	0.004	0.887
House	0.79	0.81	0.530	0.83	0.85	0.653
Apartment	0.21	0.19	0.520	0.17	0.15	0.637
Other type	0.001	0.001	0.317	0.001	0.002	0.385
Group 4						

	General Consumers			Ordinary Consumers		
Average age	35.53	33.93	0.112	34.88	33.10	0.161
Head's average age	49.33	48.61	0.348	48.84	48.20	0.471
Couple's average age	48.17	47.27	0.239	47.68	46.85	0.350
Race	0.44	0.43	0.895	0.43	0.44	0.777
Head's education	9.82	9.40	0.359	9.67	9.04	0.245
Couple's education	10.01	9.63	0.377	9.86	9.28	0.255
Head's formal work	0.97	0.98	0.699	0.97	0.98	0.460
Couple's formal work	0.90	0.89	0.352	0.90	0.90	0.914
# Number of children	1.70	1.81	0.375	1.82	1.95	0.382
SocialTariff1	0.20	0.20	0.928	0.22	0.22	0.876
SocialTariff2	0.05	0.04	0.492	0.05	0.04	0.834

Sources: POF2017-2018 (IBGE).

Notes: This table presents the balance of variables after propensity score matching.

Table 3. The Adoption of Self-Generating Energy Technologies

	(1) Mean	(2) Q90	(3) Q90/01	(4) Q90/05	(5) Q90/10	(6) Atkin	(7) Entropy	(8) Gini	(9) Lorenz
Panel A. General Consumers									
<i>Effect</i>	0.018 (0.066)	0.336*** (0.107)	0.580*** (0.1293)	0.628*** (0.192)	0.502*** (0.161)	0.004*** (0.001)	0.004*** (0.001)	0.017*** (0.005)	-0.011*** (0.004)
R-squared	0.5285	0.3333	0.0720	0.2017	0.2823	0.2415	0.2498	0.2666	0.2769
N	177,800	177,800	177,800	177,800	177,800	177,800	177,800	177,800	177,800
Panel B. Ordinary Consumers									
<i>Effect</i>	0.137*** (0.053)	0.278* (0.144)	0.266** (0.134)	0.281** (0.133)	0.239* (0.138)	0.002*** (0.001)	0.002*** (0.001)	0.011*** (0.004)	-0.008*** (0.003)
R-squared	0.4340	0.2331	0.2450	0.1721	0.1599	0.1978	0.1954	0.2059	0.202
N	61,018	61,018	61,018	61,018	61,018	61,018	61,018	61,018	61,018

Notes: This table presents the results of the effect of adopting self-generation energy technologies on electricity consumption. Covariables were omitted by space considerations. The symbols *, **, and *** represent statistical significance of 10%, 5%, and 1%, respectively. The values in parentheses are bootstrapped standard errors with 50 reps. Population sizes: Panel A: 206,768,839; Panel B: 70,791,312.

distribution of residential electricity consumption in Brazil. The study was innovative, using microdata from the 2017-2018 POF/IBGE Survey and methodologies that had not previously been used in the literature. The results provided reliable estimates of the adoption of self-generating energy technologies on the residential electricity demand of the Brazilian population. In strict terms, the results indicated that adopting self-generating energy technologies increased the average energy consumption of ordinary consumers. However, it was consumers with higher consumption that shifted the average. The results suggested that adopting energy transition technologies can increase the inequality of residential electricity consumption. Public managers must pay particular attention to the potential mechanisms for generating electricity inequality and in-

come concentration within the current socio-economic context.

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