Renewables-Induced Displacement of Fossil Fuel Power Generation and Employment Effects

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Preliminary Version

Abstract

Renewable energy sources can reduce global dependence on fossil fuels for electricity production, but they may also adversely impact the labor market in regions reliant on fossil fuel industries. We estimate these effects during a period of substantial growth in wind and solar generation in Brazil from 2015 to 2019. By examining the exogenous hourly variation in solar and wind generation, we find that intermittent renewables partially displace coal and natural gas generation. Using aggregated annual and monthly labor market data at the municipal level, our findings indicate that the increased share of renewables reduces employment and wages, particularly in municipalities with gas-fired power plants. This effect can be explained by increased involuntary dismissals and the end of temporary contracts. Our results provide quantitative evidence of the local adverse effects of fossil fuel displacement on the labor market, offering valuable insights into the policy debate on supporting a fair and just energy transition.

Keywords: Renewable energy, fossil fuel power generation, local employment.

JEL Codes: Q42, O13, C33

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1 Introduction

The increasing adoption of renewable energy sources is reshaping the global energy matrix. The rise in renewables can significantly reduce global dependence on fossil fuels for electricity generation (IEA, 2023). This energy transition promotes environmental sustainability and offers opportunities for local economic growth by expanding green jobs (IRENA, 2022). However, shifting away from fossil fuel-based electricity generation poses economic challenges, particularly for regions heavily reliant on fossil fuel industries. Consequently, some municipalities may face issues such as reduced revenue, job losses, and the need for economic restructuring to adapt to the new energy landscape.

The primary renewable energy sources on the rise worldwide are wind and solar. Solar and wind power are intermittent, meaning their power generation depends on weather conditions such as sunlight and wind speed, and the plants cannot be turned on and off to meet demand. In contrast, fossil fuel-based power plants are dispatchable and can be controlled and adjusted to meet electricity demand as needed. Typically, contracts for dispatched power plants follow a model involving remuneration for both availability and actual energy generation. In this sense, thermal power plants receive a fixed revenue to cover the plant's fixed costs, such as maintenance, personnel, and other operational expenses. When the plant is actually generating energy, it receives additional revenue based on the amount of energy produced.

In this paper, we aim to examine how changes in fossil fuel generation, induced by solar and wind, impact the local labor market. First, we assess how solar and wind power impact the displacement or ramp-up of coal and natural gas generation. For this, we use hourly electricity generation data from the National System Operator (ONS) at the plant level, covering the period from 2006 to 2019. We consider different spatial aggregation levels of the hourly fossil fuel generation data and rely on exogenous variation in solar and wind generation to identify changes in coal and natural gas generation.

After estimating the changes in fossil fuel generation induced by renewable energy sources, we then assess the impact on the labor market in municipalities with thermal power plants. First, using microdata from the Annual Social Information Report (RAIS), we construct an annual panel at the municipality level. We employ a Difference-in-Differences (DID) strategy, along with the Synthetic Control Difference-in-Differences (SDID) extension of DID, to investigate whether the number of jobs, the number of firms, and the average wage were affected during the period of substantial wind and solar generation growth in Brazil from 2015 to 2019. For a cleaner identification strategy, using microdata from the General Register of Employed and Unemployed (CAGED), we construct a monthly panel at the municipality level. Utilizing the predicted changes in fossil fuel generation by municipality, we estimate how renewable energy generation affects the number of hirings and dismissals.

Our findings indicate that solar and wind energy displace coal and natural gas generation. Considering the aggregated data at the national level, a 100 MWh increase in wind generation leads to a reduction of 2.5 MWh in coal generation and 5.3 MWh in natural gas generation. This effect is primarily driven by the reduction in fossil fuel generation in the Northeast region, which boasts the highest wind and solar generation potential. In this region, for every 100 MWh increase in wind generation, coal generation decreases by 3.9 MWh and gas generation by 3.1 MWh. Additionally, a 100 MWh increase in solar generation decreases gas generation by 5.9 MWh, whereas the effect on coal is 3.7 MWh. These results suggest that, given the generation and demand profile, solar energy has a greater potential to displace fossil fuel generation.

Regarding labor market impacts, our findings indicate that, during the period of decreased fossil fuel generation in the country, average wages in municipalities with coal-fired power plants decreased by 12%. In municipalities with natural gas power plants, employment numbers fell by 8.4%, and average wages declined by 2.5%. To improve our identification strategy, we utilized monthly data, which revealed a modest decline in hiring one month after the renewable-induced reductions in fossil fuel generation in municipalities with coal power plants. Conversely, municipalities with natural gas power plants experienced a significant increase in dismissals. Specifically, a 1,000 kWh increase in solar generation leads to a 9.5% rise in dismissals in municipalities with natural gas power plants.

This paper contributes to two main areas of literature. Firstly, it advances the empirical research on the displacement of fossil fuel electricity generation resulting from the expansion of renewable energy sources. Previous studies have explored this topic, including those by (Kaffine et al., 2013; Cullen, 2013; Novan, 2015; Callaway et al., 2018; Fell et al., 2021; Bushnell and Novan, 2021; Rivera et al., 2024). Our study builds upon the approaches of Bushnell and Novan (2021) and Rivera et al. (2024), which utilized linear models of hourly generation to estimate the impact of new renewable capacity on fossil fuel generation. However, considering the hydrothermal characteristics of the Brazilian electricity system, we extend these models by incorporating parameters related to precipitation volume. This inclusion allows us to account for the dispatch cost associated with hydroelectric power plants, thereby enhancing the accuracy of our estimates.

Secondly, we contribute to the empirical literature on the local effects of electricity generation. A growing body of literature examines the impact of solar and wind energy on the labor market (Gonçalves et al., 2020; Fabra et al., 2023). Additionally, several studies have investigated the employment effects of fossil fuel activities (Feyrer et al., 2017; Allcott and Keniston, 2018; Bartik et al., 2019). Specifically, some studies have focused on the impact of thermal power plants after closures (Burke et al., 2019; Black et al., 2005). Our study is more closely related to the latter literature. However, we do not assess the local effects following plant closures but rather during the reduction of electricity generation. Although the plant remains operational, reduced fossil fuel generation may affect the supply chain, leading to a decrease in input usage and potentially generating indirect effects on the local economy.

The remainder of this paper is structured as follows. Section 2 provides the institutional background, presenting the National Interconnected System and discussing the role of fossil fuel power plants in Brazil. Section 3 describes the datasets utilized in this study, including the hourly electricity generation data and the annual and monthly labor panel dataset, which encompasses information on the labor market and economic and demographic characteristics of Brazilian municipalities. Section 4 details the empirical strategy, including the fossil fuel displacement model and the various strategies employed to evaluate the effects on the local labor market. Section 5 presents the results, including robustness checks. Finally, Section 6 offers concluding remarks and discussions.

2 The Brazilian power sector

Brazil has the largest power sector in Latin America, with 200 GW of installed capacity in 2022. Hydroelectric power is the primary energy source, contributing approximately 63% of electricity generation capacity. Solar and wind power, renewable energy sources that have seen significant growth in the past decade, together represent 20% of the installed capacity. Meanwhile, coal and natural gas, important fossil fuels for ensuring the country's energy security, account for 11% of the installed capacity (EPE, 2023).

Over the past decades, hydropower exploration in Brazil has faced significant limitations. Hydropower generation depends on climatic conditions affecting reservoir energy storage. During drought periods, reservoir levels can reach critical points, leading to uncertainty regarding water availability and the need to reduce energy generation. The environmental impacts associated with the construction of hydroelectric plants, such as the flooding of large areas, the construction of transmission lines in protected territories, and the displacement of traditional communities, limit their expansion in the country (Juárez et al., 2014; De Lucena et al., 2009; Schaeffer et al., 2012).

Dependence on a single energy source may lead to energy insecurity, meaning there is a risk of insufficient energy to meet the population's needs. One measure to enhance supply security is to have a diversified electricity mix (da Silva et al., 2016; Pao and Fu, 2013). Generally, dispatchable energy sources fulfill this requirement. A dispatchable energy source is one whose electricity production can be controlled and adjusted according to the demand of the electrical system. In other words, the generation can be increased or decreased in response to real-time consumption needs. In Brazil, this generation flexibility is achieved with fossil-based thermal power plants, particularly those using natural gas, coal, and oil.

2.1 The National Interconnected System

The Brazilian electrical system is grounded in the National Interconnected System (SIN), a network that interconnects most power plants and electricity distribution systems nationwide. The system covers almost the entire national territory, encompassing 99.7% of the Brazilian population[1]. Operating as an integrated electricity transmission network, the SIN facilitates the generation, transmission, and distribution of electricity nationwide. This integration allows energy generated in one part of Brazil to be utilized by consumers in distant regions (Ferreira et al., 2015).

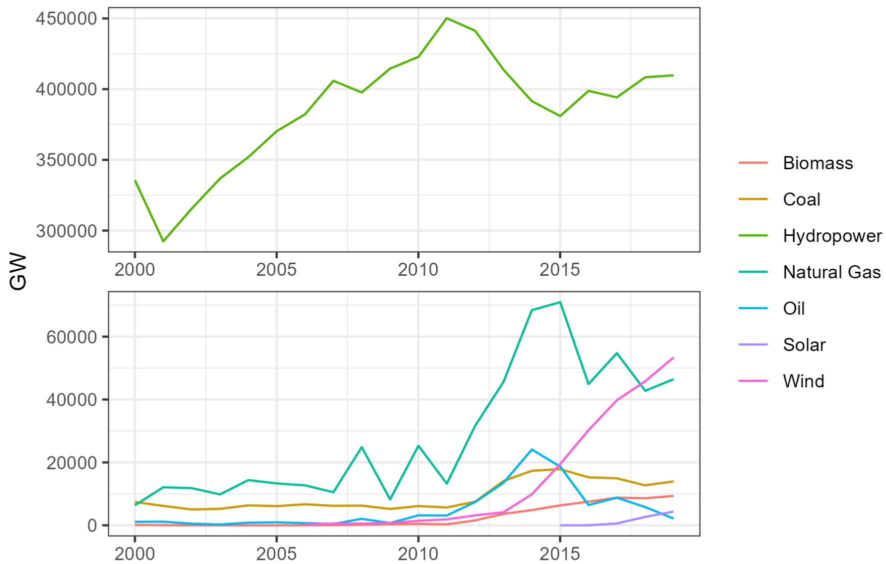
The Brazilian National Interconnected System (SIN) is divided into four subsystems: South, Southeast/Central-West, Northeast, and North. The South subsystem includes states like Rio Grande do Sul and Paraná, which are known for their significant hydropower capacity. The Southeast/Central-West subsystem, the largest, covers states such as São Paulo and Minas Gerais and has a diverse energy mix. The Northeast subsystem includes states like Bahia and Ceará, which are noted for their growing wind and solar power capacity. Lastly, the North subsystem, encompassing states like Amazonas and Pará, relies heavily on hydropower from the Amazon Basin.

The growth of hydroelectric power in Brazil's National Interconnected System (SIN) was mainly driven by the abundance of water resources and the potential for clean and renewable electricity generation. Until the 2000s, there was a significant increase in the construction of new hydroelectric plants, harnessing major rivers in the Amazon region. However, in response to the 2002 energy crisis, there was a growing diversification of Brazil's energy matrix, with a substantial rise in thermal power generation from natural gas and coal. This shift was motivated by the need to complement hydroelectric generation, especially during years of lower water availability due to adverse climatic conditions. From 2015 onwards, fossil fuel generation declined, partly due to improved hydrological conditions and the continued growth of renewable energies such as solar and wind (Figure 1).

Solar and wind energy are intermittent and non-dispatchable energy sources. Intermittent means their availability fluctuates based on weather conditions, such as sunlight for solar panels and wind speed for wind turbines. Unlike dispatchable sources like natural gas or coal-fired plants that can adjust output according to demand, solar and wind generation cannot be controlled or scheduled to meet specific demand patterns. Solar photovoltaic energy began to gain prominence from 2015 onward due to declining technology costs and incentive policies, leading

[1]The SIN covers the entire country, except the state of Roraima, located in the Amazon region bordering Venezuela.

Figure 1: Electricity generation energy source



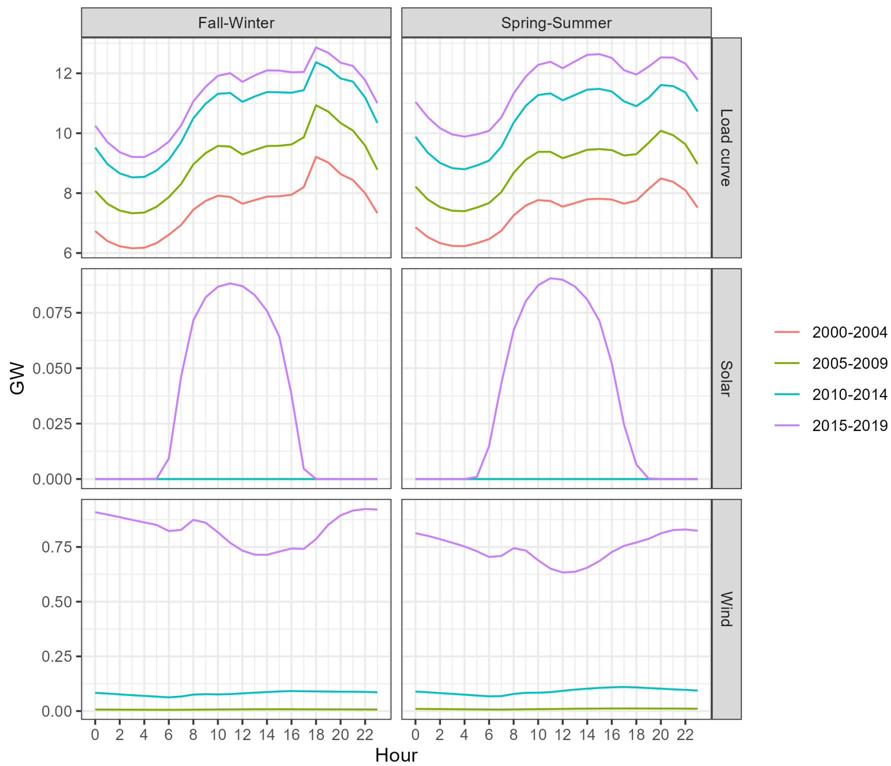
Source: Author's own prepared from the ONS data.
Notes: This figure shows the electricity generation by selected energy sources. The generation corresponds to the electricity injected into the National Interconnected System (SIN) annually from 2000 to 2019.

to a significant increase in installed capacity nationwide. On the other hand, wind energy has seen significant growth since around 2008, driven by investments in large wind farms primarily in Brazil's Northeast region, where winds are more favorable (Juárez et al., 2014; Martins et al., 2017).

The National Electric System Operator (ONS) operates the SIN, dispatching power plants according to the merit order. This determines the sequence in which different electricity generation units connected to the grid are dispatched to meet the load curve profile. The dispatch process considers several factors, including each power plant's generation cost, energy availability, real-time electricity demand, subsystem characteristics, and operational constraints of the transmission network. This approach ensures an efficient and reliable supply of electricity across the interconnected grid.

The operations of the National Electric System Operator (ONS) aim to meet the country's electricity demand, or load curve, at any given moment. The load profile has shifted in recent years, as shown in Figure 2. Peak demand has moved from 8 p.m. to 3 p.m., notably during the spring-summer seasons, driven by increased energy demand for cooling (EPE, 2018). Despite being non-dispatchable, solar and wind energy generation profiles can complement peak demand periods traditionally served by thermal power plants. Solar energy production typically aligns well with daytime peaks in electricity demand due to abundant sunlight. Similarly, wind energy tends to peak during the late afternoon and evening hours, coinciding with periods of high electricity consumption.

Figure 2: Hourly load curve and generation by period



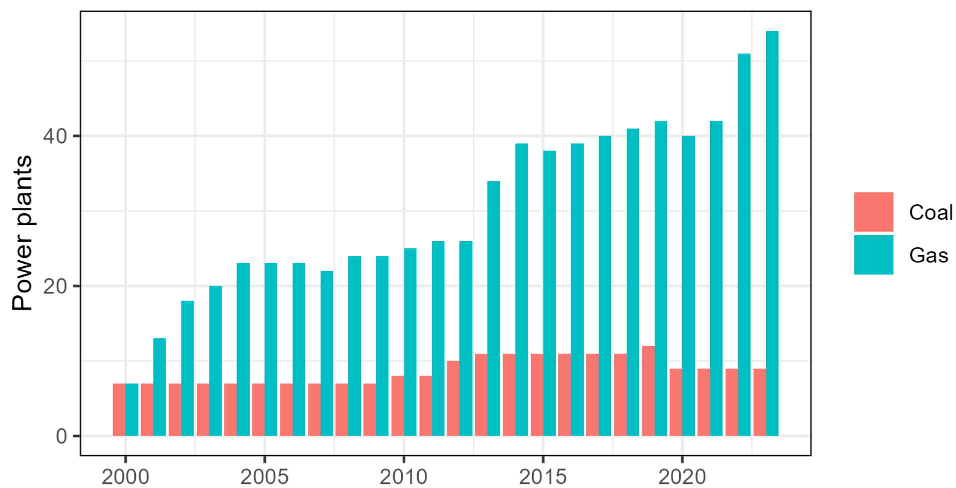
Source: Author's own prepared from the ONS data.
Notes: This figure displays the annual average hourly load curve, as well as solar and wind generation, in gigawatts (GW). The curves represent the demand supplied by the National Interconnected System (SIN) throughout the year.

2.2 The thermal power plants in Brazil

Between 2001 and 2002, Brazil experienced a period of severe electricity supply constraints. This crisis was precipitated by a prolonged drought that significantly reduced the water levels in hydroelectric reservoirs, coupled with rapid economic growth that increased electricity demand. Faced with the need for energy supply, the Brazilian government implemented measures, including incentives for constructing thermal power plants. The investment in thermal power plants during this period aimed not only to mitigate the immediate effects of the energy crisis but also to strengthen the country's long-term energy security by diversifying generation sources and enhancing capacity to respond to fluctuations in water availability (Hunt et al., 2018).

In 2002, the country had seven coal-fired power plants and 18 natural gas power plants producing electricity in the SIN. By 2019, the number of coal-fired power plants had increased to 12, while the number of natural gas power plants totaled 51. However, the number of fossil fuel plants in the SIN remained constant between 2015 and 2019 (Figure 3), a period marked by the recovery of hydroelectric reservoirs after the drought that began in 2013.

Figure 3: Number of fossil fuel power plants generating energy in the SIN

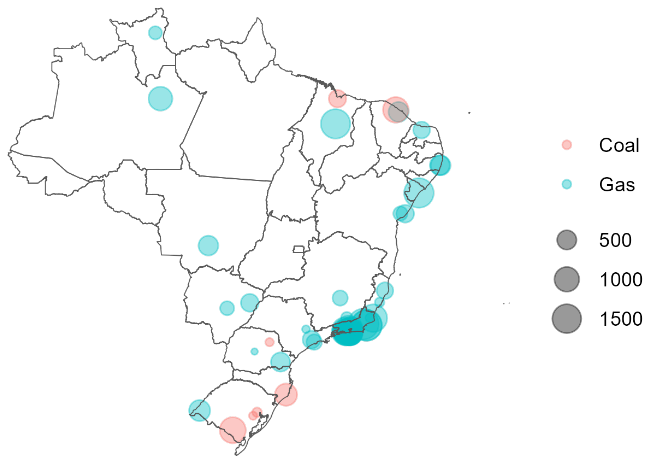


Source: Author's own prepared from the IBGE and ANEEL data.
Notes: This figure displays the number of coal and gas natural power plants generating energy in the SIN.

The distribution of natural gas power plants spans all regions of Brazil, with the majority of installed capacity located in the Southeast near coastal natural gas production regions. In contrast, coal-fired power plants are primarily concentrated in the northern and southern regions, as depicted in Figure 4. In the southern region, these plants are strategically located near coal-producing areas. Conversely, coal-fired plants in northeastern municipalities predominantly rely on higher-quality coal imported from Colombia for their operations (Lucena et al., 2016).

The contracts for coal or natural gas power plants that can be dispatched by the ONS typically follow a model involving remuneration for both availability and actual energy generation. Thermal power plants receive fixed compensation for being able to supply energy. This means

Figure 4: Capacity sizes of coal-fired and gas power plants



Source: Author's own prepared from the IBGE and ANEEL data.
Notes: This figure displays the capacity sizes of coal-fired and gas power plants by municipality, measured in megawatts (MW).

the plant is paid to be ready to generate electricity when needed, even if it is not actively generating power all the time. This fixed income is intended to cover the plant's fixed costs, such as maintenance, personnel, and other operational expenses. When the plant is actually dispatched and begins generating energy, it receives additional compensation based on the amount of energy produced. This variable income covers the variable costs of generation, such as fuel.

Coal plants, in particular, receive subsidies averaging over R$ 1,000 million per year between 2013 and 2023 (see Figure A1 in the Appendix). Additionally, the proposed legislation seeks to extend the contracts of coal-fired power plants until 2050. According to the bill, contract renewal is necessary for *"ensuring electricity supply security during the energy transition period, as well as making a significant social contribution by preventing the collapse of coal-dependent regional economies"*.[2]

3 Data

For our empirical analysis, we created three databases. The first dataset covers hourly data from 2006 to 2019, including energy generation by source. We use these data to estimate the

[2]https://www.cnnbrasil.com.br/economia/em-meio-a-cop28-camara-tenta-prorrogar-contratos-de-energia-a-carvao-mineral-ate-2050/

displacement of wind and solar generation on fossil fuel sources, specifically coal and natural gas. To study the effect on the labor market, we constructed two additional databases. We compiled municipality-level yearly panel data covering 2015 to 2019, a period of wind generation growth, and the introduction of solar generation. We also constructed a municipality-level monthly panel dataset with information on hiring and dismissals to study the short-term effects on the labor market. These two datasets incorporate data on power plants, economic indicators, and demographic characteristics of the municipalities under study.

3.1 Plant-level data

The plant-level data are extracted from ONS and ANEEL from 2006 to 2019. ONS provides detailed hourly generation data in the SIN, while ANEEL offers administrative information on all the power plants. Specifically, we use ONS data on hourly generation per plant and the hourly load curve by the SIN subsystem. The generation dataset includes the reference date (hour, day, month, and year), power plant identification, energy source, average hourly energy generation, and location. The ONS hourly load curve dataset also contains the reference date and the energy load in average megawatts (MW) by subsystem.

Table 1 shows that wind plants, on average, generate more energy than solar plants between 2015 and 2019, though solar generation variance is higher. Wind plants operated 95.40% of the time after starting operations in the SIN, while solar plants generated energy slightly over 50% of the time due to daylight limitations. Among fossil fuels, coal plants are generally larger than gas plants, which show more variability. Both coal and gas plants generated energy about 65% of the time. Small-scale oil-burning plants were the least utilized in the SIN.

Table 1: Hourly power generation metrics

	Renewables		Fossil fuels		
	Wind	Solar	Gas	Coal	Oil
Mean (MWh)	42.91	21.33	148.94	162.34	15.12
Standard Deviation (MWh)	52.80	44.79	203.93	188.37	42.61
Hours of Generation (%)	95.40	50.86	65.32	67.63	23.03
Power Plants	71	4	42	12	59

Notes: This table displays the hourly power generation metrics for power plants operating between 2015 and 2019.

ANEEL provides administrative data on plants, including those that participate and do not participate in the SIN. The administrative data on power plants are sourced from the ANEEL Generation Information Database. This database includes information on large-scale power plants, such as the energy source, project stage details, operation start date (day, month, and year), geographic coordinates, and installed capacity.

Using plant identification, we merged the ONS data with the ANEEL data. We aggregated the data at the country level, SIN subsystem, and municipality. The dataset is aggregated at the hourly level, allowing us to identify the energy source and hour-date for each type of geographical aggregation. With this, we constructed panel datasets that enable us to obtain hourly energy generation, hourly load curve, and daily installed capacity introduced into SIN from 2006 to 2019.

3.2 Labor market

The labor market outcomes are derived from the Annual Social Information Report (RAIS) and the General Register of Employed and Unemployed (CAGED) provided by the Ministry of Labor and Employment (MLE). RAIS and CAGED data only cover the formal labor market sector since formal firms report it.

RAIS is a data collection instrument for gathering information on employers and workers in Brazil. Private companies and public agencies must provide this information annually to the MLE. The collected information includes data on the number of employees, wages, occupations, and employment relationships, among other variables. CAGED is a data collection system and database maintained by the MLE that records information on the hiring and dismissals of employees in the formal labor market. Companies are required to report all hires and dismissals to CAGED monthly.

Using the annual RAIS microdata and monthly CAGED microdata, we aggregated employment outcomes at the municipal level, both in total and by economic sectors such as industry, construction, services, and agriculture. These sector categories are defined according to the groups prescribed by the National Classification of Economic Activities (CNAE). We select municipalities with a population of fewer than 300,000 inhabitants, which comprise 95% of all municipalities in Brazil. This population threshold was chosen because the majority of the power plants included in our study are located within these municipalities. Additionally, larger cities exhibit different labor market dynamics compared to medium and small-sized cities, which justifies focusing on smaller municipalities for a more consistent analysis.

Figure 5 illustrates the average number of jobs, firms, and wages in municipalities with coal, natural gas, or no power plants from 2002 to 2019. It is evident that all labor outcomes exhibit a general increase over the years, with a notable decline around 2015. Part of this decline in labor outcomes can be attributed to the economic crisis of 2015[3]. However, the decline is particularly pronounced in municipalities with coal and natural gas power plants.

3.3 Geo-climatic data

We utilized precipitation as a measure of the opportunity cost of hydroelectric generation. We used daily precipitation data provided by Saldanha et al. (2024). The authors used grid files with different spatial and time resolutions to construct daily climate indicators compatible with administrative boundaries. As a result, they provide datasets with zonal statistics of climate indicators with municipality daily data, covering the period from 1950 to 2022.

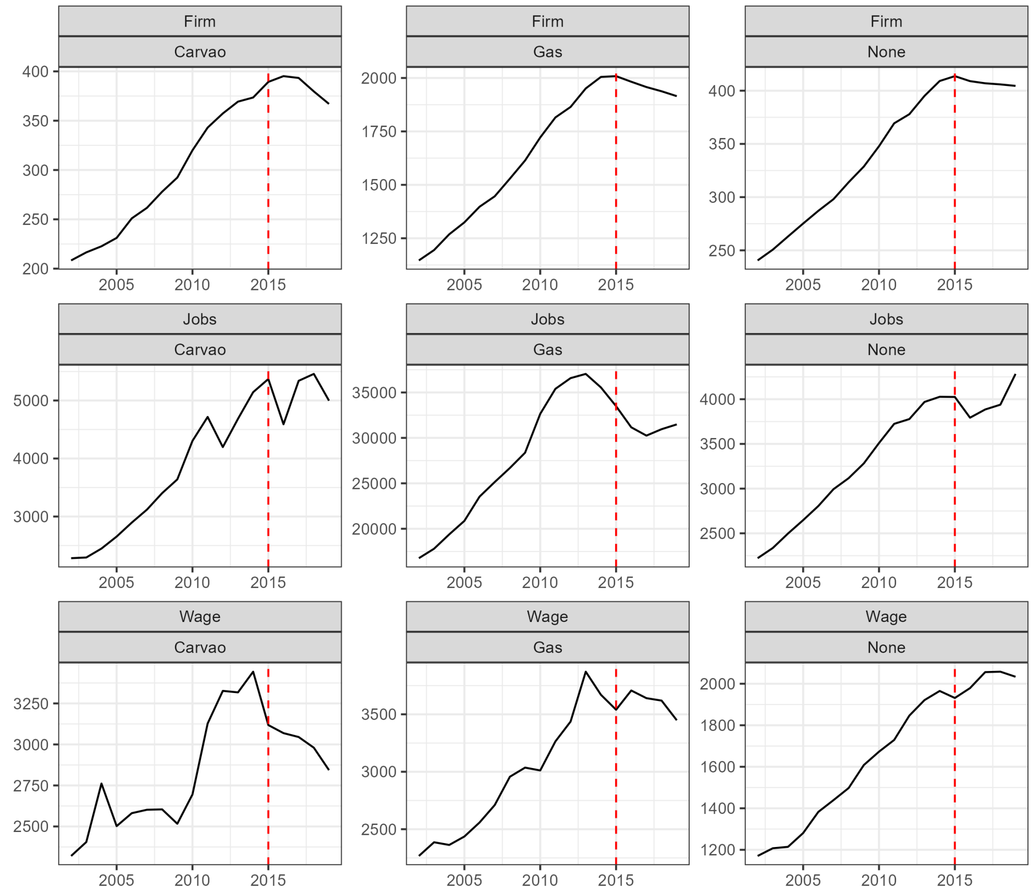
Based on the data from ONS and ANEEL, we identified the municipalities with hydroelectric plants and aggregated the daily precipitation data by month. Our measure of the opportunity cost of hydroelectric generation is the three-month lagged average of monthly precipitation. This precipitation information is combined with the generation data.

3.4 Additional data

We integrate generation data with exogenous fuel price data to proxy for the opportunity cost associated with dispatching thermal plants. This includes incorporating the Henry Hub Natural Gas Spot Price and Brent Crude Oil Future Price. The Henry Hub Natural Gas price, expressed in dollars per million British thermal units (MMBtu), serves as a benchmark in the U.S. natural gas market and is widely utilized as an indicator for both domestic and global

[3]The 2015 economic crisis in Brazil was marked by a severe recession characterized by a sharp decline in GDP, high unemployment rates, and elevated inflation. This period also saw a fiscal crisis, with increased public deficits and deterioration of government accounts.

Figure 5: Average number of jobs, firms, and wages by municipality type



Source: Author's own prepared from the RAIS data.
Notes: This figure shows the average number of jobs, firms, and wages for municipalities with coal, natural gas, or no power plants between 2002 and 2019. The average wage is adjusted for inflation and corresponds to values in January 2020. The municipalities included have a population of fewer than 300,000 inhabitants. The dashed line corresponds to the year 2015.

natural gas prices. The Brent Crude Oil price is extensively used as a reference for oil prices in futures contracts and for assessing the cost of crude oil in international markets.

Regarding the labor market panel data at the municipal level, we combine them with economic and demographic information. Census population data from the Brazilian Institute of Geography and Statistics (IBGE) provide demographic insights every ten years, specifically for 2000, 2010, and 2022. For the years in between, we interpolate population figures for each municipality and year using spline interpolation. Additionally, we utilize other demographic details from the 2010 Census, such as urban population, population density, average family income, education levels, and racial composition.

For the monthly labor market panel data, we rely on IBGE's monthly population estimates for the entire month of July. To obtain monthly population data, we interpolate population estimates for each municipality and year using spline interpolation.

4 Empirical strategy

In our empirical strategy, we first estimate the effect of wind and solar generation on coal and gas using a linear energy displacement model. Once we identify the reduction in fossil fuel generation, we assess the effects on the local labor market in municipalities affected by this reduction.

4.1 Fossil fuel displacement

We aim to identify how solar and wind generation affect coal and gas generation. To achieve this, we rely on the fact that seasonal and hourly variations in solar and wind generation are driven almost entirely by exogenous factors (e.g., solar irradiation and wind speed). Consequently, we do not need to be concerned that short-term variations in solar and wind production are endogenously caused by changes in fossil fuel generation.

Although short-term changes in solar and wind output are exogenous, they are not random. Seasonal patterns in solar and wind output can be correlated with seasonal variations in electricity demand. Additionally, weather conditions influence hourly variations in both renewable output and demand. Therefore, we include exogenous control variables in our model.

Following Bushnell and Novan (2021), we employ a linear model to identify whether the introduction of large-scale solar and wind plants into the SIN has led to changes in the generation of dispatchable fossil fuels. We utilize hourly-level variations in power generation to identify the effects of the dispatch of these energy sources as follows:

$$G_h = \beta_0 + \beta_1 S_h + \beta_2 W_h + \beta_4 L_h + \beta_3 \mathbf{P}_d + \beta_5 \mathbf{X}_d + \theta_t + \varepsilon_h \tag{1}$$

where G_h is the generation of fossil (coal or gas) during hour h in GW, $\mathbf{P}$ is the vector with daily Henry Hub Natural Gas Spot Price and Brent Crude Oil Future Price as a measure of the opportunity cost associated with dispatching thermal plants, L_h represents the system's load curve during hour h to control for increases in demand over time, $\mathbf{X}$ is a matrix with daily weather covariates, including the three-month lagged average of monthly precipitation, which serves as a measure of the opportunity cost of hydropower, θ_t is a vector of time-fixed effects (year, month, weekend, and hour).

The variables of interest are S_h and W_h, which denote the generation of solar and wind power during hour h, respectively. The idea behind Equation 1 is that, after controlling for system-specific covariates, weather, and time-fixed effects, residual hourly variation in fossil fuel generation can be explained by hourly variation in the system's total solar and wind power. Thus, the parameters β_1 and β_2 reflect whether solar or wind generation induces changes in the hourly generation of other sources j.

We estimate Equation 1 using an ordinary least squares (OLS) estimator with Newey-West standard errors to account for potential heteroskedasticity and autocorrelation in our hourly generation data.

After estimating the overall impact of solar and wind power on the system's fossil fuel generation using Equations 1, we conduct a municipal-level analysis to assess whether renewable generation displaces fossil fuel in each municipality i with a thermal power plant, individually. A negative β_{i1} or β_{i2} indicates a solar or wind-induced displacement of fossil power units. Conversely, a positive sign of the parameters indicates a ramp-up in fossil fuel generation.

4.2 Impacts on local labor market

After identifying the municipalities affected by displacement, we proceed to estimate the impact on the local labor market resulting from reduced power plant revenue and expenditures. Initially, we employ a DID and SDID approach using annual labor market data. Subsequently, we analyze monthly data along with predicted fossil fuel displacement to determine when the reduction in fossil fuel generation impacts hiring and dismissals.

Annual labor market outcomes. To estimate the impacts on local labor outcomes, we implement a two-stage strategy to address differences in pre-treatment characteristics of municipalities with and without fossil fuel power plants and then compare the two groups to infer the effect brought by the introduction of solar and wind energy into the SIN.

In the first stage, we regress the treatment indicator on the municipalities' characteristics and obtain the propensity score. We use a probit regression to bound the probability of treatment in the range of [0, 1] following the approach of Caliendo and Kopeinig (2008). The model specification is:

$$\Pr\left(D_i = 1 \mid X_i\right) = \Phi\left(X_i'\theta\right), \tag{2}$$

where D is a dummy variable equal to one if the municipality is treated and zero; otherwise, X represents a matrix of municipality characteristics at the baseline, including population, average family income, and education. With the estimated propensity score, we match the municipalities using k-nearest neighbors (kNN) with replacement. This method matches k untreated municipalities to each treated one with similar propensity scores. Thus, we create a subset of comparable municipalities in size and baseline treatment.

In the second stage, considering the increase in wind generation and the introduction of solar generation in the SIN in 2015, we apply a DID approach:

$$\ln Y_{it} = \delta_1 \cdot \mathbb{1}\{\hat{\beta}_{in} \neq 0\} + \delta_2 \cdot T_t + \delta_3 \cdot \mathbb{1}\{\hat{\beta}_{in} \neq 0\} \cdot T_t + \alpha_i + \lambda_t + \varepsilon_{it} \tag{3}$$

where Y_{it} is the labor outcome for municipality i in year t; T_t identifies the treatment period, which is post-2015; α_i is the municipality fixed effect, and λ_t is the year fixed effect. The treated municipalities are those where β_{i1} or β_{i2} are statistically significant at conventional levels as estimated by Equation 1, indicated by the indicator function $\mathbb{1}\{\hat{\beta}_{in} \neq 0\}$ where $n \in \{1, 2\}$.

The two-way fixed effects model (TWFE) represented by Equation 3 is estimated by OLS, and the treatment effect is given by the parameter δ_3 associated with the interaction term $\mathbb{1}\{\hat{\beta}_{in} \neq 0\} \cdot T_t$. A negative sign of δ_3 indicates that during the analyzed period, there was a reduction in the labor outcome (e.g., number of jobs, number of firms, or wages).

As discussed above, the primary dispatchable fossil fuel sources in Brazil are natural gas and coal, with power plants concentrated in a few municipalities. The small number of treated units may limit the validity of the assumption of parallel trends. To mitigate these issues, we use the Synthetic Differences-in-Differences (SDID) strategy proposed by Arkhangelsky et al. (2021), which combines re-weighting and matching pre-intervention trends to weaken the reliance on the parallel trends assumption of Synthetic Control (Abadie et al., 2015). For inference, since we potentially have few treated units and possibly only one unit, we use placebo inference (see Arkhangelsky et al. (2021)).

Monthly labor market outcomes. Based on Rivera et al. (2024), using the Equation 1 estimate of the municipal-level displacement parameter $\hat{\beta}_{i1}$ and $\hat{\beta}_{i2}$, and only for those municipalities for which the parameters are statistically significant at the 10% level, we compute solar and wind-induced municipal-level displaced fossil fuel generation at the monthly level as follows:

$$\hat{G}^S_{im} = \sum_m \left[\sum_{h=1}^{24} \hat{\beta}_i \cdot S_h \right], \quad \text{and} \quad \hat{G}^W_{im} = \sum_m \left[\sum_{h=1}^{24} \hat{\beta}_i \cdot W_h \right]$$

where $\hat{G}^S_{im}$ and $\hat{G}^W_{im}$ represent the predicted displacement, corresponding to the sum displaced fossil fuel generation across each month m of the year for each municipality i.

After identifying the affected municipalities and computing the predicted displacement, we estimate the impact on hiring and dismissing employment. We define our employment equation as follows:

$$\ln Y_{im} = \delta_0 + \delta_1 \hat{G}^S_{i,m-1} + \delta_2 \hat{G}^W_{i,m-1} + \ln(P_{im}) + \alpha_i + \lambda_t + \varepsilon_{im}, \tag{4}$$

where Y_{im} denotes the count of hiring or dismissing employment in municipality i in month m, $\hat{G}^S_{i,m-1}$ is the amount of solar-induced coal displacement in month $m-1$, and $\hat{G}^W_{i,m-1}$ is the amount of wind-induced coal displacement in month $m-1$. We use a one-month lag in predicted displacement to account for the delayed effects of reduction on revenue from fossil fuel generation. The variable P denotes the population in municipality i in month m, α_i is a vector of municipal-level fixed effects, λ_t is a vector of time fixed effects, and ε_{im} is the idiosyncratic error term.

We employ Poisson regression to estimate the parameters. Equation 4 represents counts of monthly movements in the local labor market, which present a substantial number of zeros. Finally, we cluster standard errors at the municipal level.

4.3 Identification

A fundamental assumption used to identify the parameters specified in Equation 1 is that hourly wind and solar output varies exogenously concerning fossil fuel generation. There are two threats to this assumption: i) renewable capacity can change in response to shifts in fossil fuel capacity, and ii) renewable output can be curtailed.

Regarding the potential for renewable capacity to change in response to shifts in fossil fuel capacity, this concern is mitigated in our setting. Firstly, the planning and approval processes for new power plants in Brazil involve significant regulatory oversight and long lead times, discouraging short-term adjustments to capacity in response to market changes. Additionally, the development of renewable energy projects in Brazil is primarily driven by government incentives and long-term contracts through energy auctions, ensuring stability and predictability in capacity planning. Secondly, the integration of renewable energy into the Brazilian electricity grid is influenced by natural resource availability, such as sunlight and wind speeds, which are independent of fossil fuel dynamics. The geographic distribution of renewable resources further ensures that variations in solar and wind output are largely unaffected by changes in fossil fuel capacity.

Curtailments are implemented to reduce system-wide oversupply or mitigate grid congestion. From the SIN, we observe wind and solar curtailments for the period after 2020. These curtailments can distort the relationship between renewable generation and fossil fuel displacement, as renewable output is intentionally reduced to manage grid operations. However, in our context, the extent of these curtailments is relatively limited. Brazil's electricity grid, with its significant reliance on hydropower, possesses greater flexibility to integrate variable renewable energy sources. Hydroelectric plants can quickly adjust their output to balance fluctuations in wind and solar generation, minimizing the need for curtailments. Moreover, the widespread distribution of renewable energy projects across different regions helps mitigate the impact of localized grid congestion.

5 Results

This section presents the results of estimating fossil fuel displacement due to solar and wind energy generation. We begin by employing a DID and SDID approach with annual data to evaluate the impact of generation reduction on employment numbers, firm counts, and wages during periods of increased solar and wind generation. Subsequently, using monthly data, we examine when the reduction in fossil fuel generation affects hiring and dismissals.

5.1 Fossil fuel displacement

Table 2 presents the results of the impact of solar and wind generation on coal and gas outcomes. The table displays the aggregated results for the SIN. Columns 1 and 2 show the results for the period from 2006 to 2014. As discussed in Section 2, this period is characterized by the growth of fossil fuels and the entry of wind power into the SIN. Columns 3 and 4 present the results for the period from 2015 to 2019, which is the focus of our study. This latter period is marked by the growth of wind power and the introduction of solar power into the system.

Table 2: The impact of renewable energy on fossil fuel generation

	2006-2014		2015-2019	
	Coal (1)	Gas (2)	Coal (3)	Gas (4)
Wind	-0.118	0.353	-0.025**	-0.053*
	(0.078)	(0.335)	(0.006)	(0.021)
Solar			-0.013	-0.071
			(0.026)	(0.047)
Adjusted R^2	0.827	0.803	0.435	0.622
Num.Obs.	76,767	76,767	39,260	39,260

Notes: The table presents the effect of solar and wind on coal and natural gas electricity generation. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

Between 2006 and 2014, the estimated parameters for coal are negative and gas are positive, but neither is statistically significant. This result suggests that during the initial introduction of wind energy, this source could not replace fossil fuels but rather met additional electricity demand. For the period between 2015 and 2019, the estimated parameters are negative for both wind and PV. However, only the parameters for wind generation are statistically significant, indicating that at least wind generation is capable of displacing electricity generation from fossil fuels. Although not the focus of this study, Table A2 in the Appendix includes estimations for oil sources. The results indicate that solar and wind primarily displace oil electricity generation.

The results indicate that an increase of 100 MW in wind generation reduces coal generation by 2.5 MW and natural gas generation by 5.3 MW. This suggests that the wind generation profile may have a greater impact on displacing gas than coal when considering the overall generation in SIN. Although not statistically significant, the parameters for solar generation have magnitudes similar to those of wind generation, suggesting some heterogeneity between subsystems or municipalities.

To optimize the system, in addition to the merit order, ONS considers the context of the subsystems when dispatching plants. The results for each subsystem of the SIN from 2015 to 2019 are shown in Table 3, based on the specification in Equation 1. Columns 1 and 2 present the results for the North (N) subsystem, columns 3 and 4 for the Northeast (NE) subsystem, columns 5 and 6 for the Southeast (SE) subsystem—which includes the states in the Southeast, Center-West, and two states from the North region (Rondônia and Acre)—and columns 7 and 8 for the South (S) subsystem. Each subsystem contains at least one coal and natural gas plant, except for the SE subsystem, which does not have coal plants.

Table 3: The impact of renewable energy on fossil fuel generation by SIN subsystems

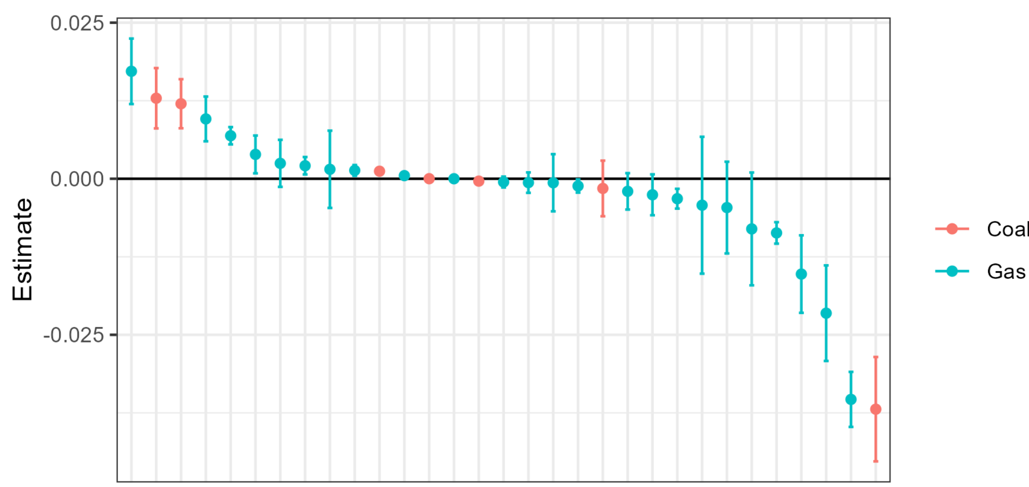
	N		NE		SE		S	
	Coal	Gas	Coal	Gas	Coal	Gas	Coal	Gas
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Wind	0.000	0.005	-0.039**	-0.031**	–	-0.022	0.014	-0.005
	(0.005)	(0.013)	(0.009)	(0.008)	–	(0.023)	(0.009)	(0.003)
Solar	0.012	0.002	-0.037*	-0.059*	–	-0.018	0.011	0.004
	(0.008)	(0.017)	(0.014)	(0.024)	–	(0.041)	(0.009)	(0.010)
Adjusted R^2	0.515	0.725	0.320	0.301	–	0.565	0.347	0.207
Num.Obs.	39,260	39,260	39,260	39,260	–	39,260	39,260	39,260

Notes: The table presents the effect of solar and wind on coal and natural gas electricity generation. The columns represent the SIN subsystems: North (N), Northeast (NE), Southeast (SE), and South (S). The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

The point estimates for wind and solar generation predominantly show a negative sign. The parameters for the N, SE, and S subsystems are not statistically significant, and the magnitude of the point estimates is small. This indicates that, on average, the effect of wind and solar on fossil fuel generation is not different from zero. On the other hand, the estimated parameters for the NE region are statistically significant. In this subsystem, wind displaces coal and gas by almost the same magnitude: for every 100 MW increase in wind generation, coal generation is reduced by 3.9 MW and gas generation by 3.1 MW. Conversely, the effect of solar in the NE subsystem is more pronounced on gas: for every 100 MW increase in solar generation, gas generation is reduced by 5.9 MW, while the effect on coal is about 60% smaller, reducing it by 3.7 MW.

Our data allow us to analyze the heterogeneity of effects at the municipal level. Figures 6 and 7 display the estimated parameters for solar and wind generation, respectively, for the seven municipalities with coal power plants and the 24 municipalities with natural gas power plants participating in the SIN. The figures show the parameters' point estimates and the confidence intervals corresponding to a significance level of 10%.

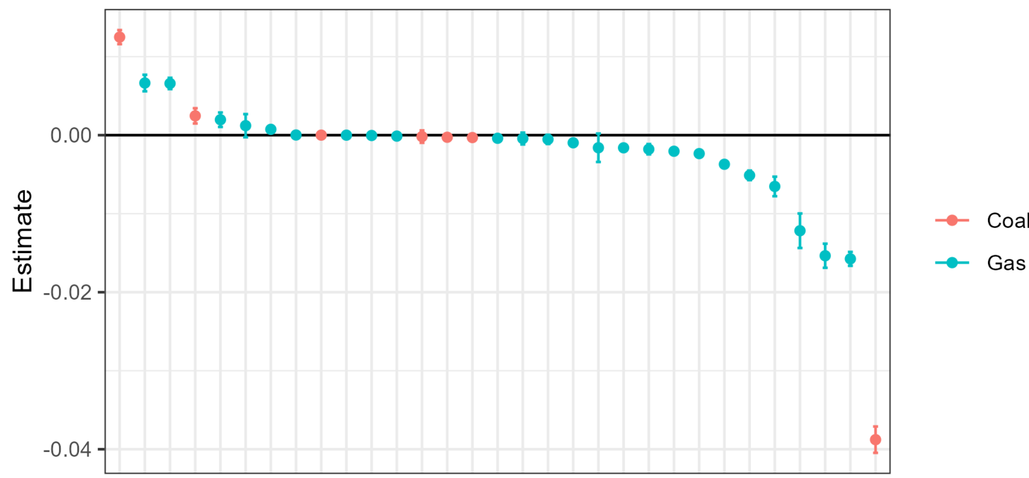
Figure 6: The effect of solar on fossil fuels generation by municipality



Source: Author's own prepared from the IBGE and ANEEL data.
Notes: These figures display the estimated parameters for solar generation for the seven municipalities with coal power plants and the 24 municipalities with natural gas power plants participating in the SIN. The figures show the parameters' point estimates and the confidence intervals corresponding to a significance level of 10%.

Despite some modest effects, the figure shows that wind generation displaces fossil fuel gener-

Figure 7: The effect of wind on fossil fuels generation by municipality



These figures display the estimated parameters for wind generation for the seven municipalities with coal power plants and the 24 municipalities with natural gas power plants participating in the SIN. The figures show the parameters' point estimates and the confidence intervals corresponding to a significance level of 10%.

ation in most municipalities. For the solar parameter, 71% of the municipalities have statistically significant estimates, with 68% showing a negative sign. Conversely, the solar parameter is statistically significant for 64% of the municipalities, and among these, only 40% have a negative sign. Municipalities with gas plants experience a higher proportion of generation displacement for both wind and solar. These results corroborate the findings in Table 2, indicating that wind is the primary renewable source displacing fossil fuels, with natural gas being the most impacted.

However, according to Figure 6, the most significant displacement indicates that an additional 100 MW of solar generation results in 3.9 MWh of avoided coal generation during a particular hour, while the most significant displacement for wind generation results in 3.7 MWh of avoided coal generation during a particular hour in the same municipality.

5.2 Impacts on Local Economies

Between 2015 and 2019, the overall estimation indicates that wind generation substantially reduced both coal and natural gas generation, while solar generation, though impactful, had more modest effects. Municipal-level analysis corroborates these findings, showing that wind generation displaces fossil fuels in most municipalities, with a higher proportion of gas plants affected. Therefore, in this section, we investigate the effects of local labor on municipalities associated with coal and gas thermal generation.

Annual labor market outcomes. Table 4 presents the results of DID and SDID specifications for labor market outcomes. Panel A displays the average effects observed in municipalities with coal power plants, while Panel B shows those for municipalities with gas power plants. Columns (1) to (3) present the results for DID, and columns (4) to (6) present the results for SDID. The latter models combines re-weighting and matching pre-intervention trends to weaken the reliance on the parallel trends assumption and, therefore, represent our preferred specification. Columns (1) and (4) present results for jobs per capita, columns (2) and (5) for firms per capita, and columns (3) and (6) for average monthly wage. All dependent variables are presented in logarithmic form.

Table 4: The impact on annual labor outcomes

	DID			SDID		
	Jobs (1)	Firms (2)	Wage (3)	Jobs (4)	Firms (5)	Wage (6)
Panel A. Coal						
Treatment	0.059	0.070	-0.137	0.015	0.033	-0.123***
	(0.141)	(0.120)	(0.120)	(0.035)	(0.023)	(0.018)
Treated Units	6	6	6	6	6	6
Control Units	120	120	120	120	120	120
Observations	2,268	2,268	2,268	2,268	2,268	2,268
Panel B. Gas						
Treated	-0.027	0.031	-0.039	-0.088***	-0.016	-0.033***
	(0.056)	(0.034)	(0.036)	(0.023)	(0.013)	(0.012)
Treated Units	15	15	15	15	15	15
Control Units	300	300	300	300	300	300
Observations	5,670	5,670	5,670	5,670	5,670	5,670

Notes: The table presents the effect of solar and wind generation on labor market outcomes. The variables are transformed into logarithms. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

For both coal and gas, the magnitudes of the parameters estimated by DID and SDID are similar, and the signs of the parameters are consistent. This suggests that the adjustments made by SDID to align pre-exposure trends in outcomes between unexposed and exposed units, as well as balancing pre-exposure and post-exposure periods, have minimal impact on estimating the average treatment effect. This implies that the assumption of parallel trends may hold for the DID estimator. Additionally, according to the table, SDID generates smaller standard errors, indicating that its estimates are less variable than the DID estimator.

Considering the results from the SDID estimation, for municipalities with coal power plants, we find no effects on the number of jobs or the number of firms but significant negative parameters for average monthly wage. According to the table, from 2015 to 2019, the average monthly wage in municipalities with coal power plants decreased by approximately 12%. For municipalities with natural gas, we observe a reduction of 8.4% in the number of jobs and 2.5% in average monthly wage. This result suggests that electricity generation through intermittent renewable sources may negatively impact the labor market in municipalities with fossil fuel power plants, even when the power plant is still in operation.

The results above indicate some impact on labor market dynamics in regions with fossil fuel power plants competing with renewable energy sources. Municipalities with coal power plants experience significant wage decreases without changes in job numbers or firm counts, suggesting shifts in job types or wage structures. Conversely, municipalities with natural gas power plants face job and wage declines, indicating more severe local employment impacts. The expansion of wind and solar energy affects the local economy differently, with gas plant municipalities showing pronounced negative impacts on commerce and services sectors and unexpected overall wage increases, suggesting the need for targeted economic policies to support local workforce adaptation during the renewable energy transition.

Monthly labor market outcomes. After evaluating the effects on the labor market during the wind and solar growth years, we now examine the short-term impact on affected municipalities. In this set of models, we incorporate the wind- and solar-induced predicted changes in fossil fuel electricity generation for each municipality. Using these exogenous variations in the model allows us to improve our identification strategy and compare the separate effects of solar and wind on affected municipalities.

Table 5 presents the effects of renewables-induced fossil fuel electricity generation on hiring and dismissals. Panel A shows the results for municipalities with coal plants, while Panel B presents the results for municipalities with gas plants. The dependent variable for Columns (1) to (3) is the logarithm of the number of hirings, and for Columns (4) to (6), it is the logarithm of the number of dismissals. We present Poisson estimates with clustered standard errors at the municipal level. The regression models in Columns (1) and (4) include municipality-level fixed effects, the models in Columns (2) and (5) add month-level fixed effects, and the models in Columns (3) and (6) add municipality-year fixed effects. The latter models are robust to unobserved variation in hiring and dismissal at a more granular spatiotemporal level and, therefore, represent our preferred specification.

The results in Table 5 indicate that renewables-induced fossil fuel changes affect local labor market dynamics in the short term. In our preferred specification, for municipalities with coal power plants (Panel A), we find a modest but negative effect on hiring (Column (3)). An increase of 1 GWh in wind generation reduces hirings by 0.2% one month later. Although the point estimate is not statistically significant at the 10% level, the table suggests a 5.1% drop in hirings one month after a 1 GWh increase in solar generation. On the other hand, we do not find statistically significant parameters for dismissals in these municipalities (Column (6)).

Conversely, the results in Table 5 show no statistically significant parameters for solar or wind generation affecting hirings (Column (3)) in municipalities with natural gas power plants (Panel B), in our preferred specification. However, we find a significant and positive effect on dismissals (Column (6)). The results indicate that a 1 GWh increase in solar generation leads to a 9.5% increase in dismissals in the following month. On the other hand, we do not find statistically significant parameters associated with wind energy.

Table A3 in the Appendix shows the results for the same specifications as above, but considering the contemporaneous effect of wind- and solar-induced predicted changes in fossil fuel electricity generation. In this case, we find weaker evidence of the impact of wind generation on dismissals in municipalities with gas power plants. This result corroborates the lagged effect of reduced generation on the labor market.

Table 5: The impact on monthly hiring and dismissal

	Hiring			Dismissal		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Coal						
$\hat{W}_{t-1}$	0.004	0.004	-0.002*	0.007	0.007	0.000
	(0.002)	(0.003)	(0.001)	(0.006)	(0.006)	(0.001)
$\hat{S}_{t-1}$	0.009	0.011	-0.051	-0.006	-0.004	-0.028
	(0.020)	(0.023)	(0.038)	(0.044)	(0.047)	(0.019)
Municipalities	6	6	6	6	6	6
Num.Obs.	334	334	334	334	334	334
Panel A. Gas						
$\hat{W}_{t-1}$	-0.009	-0.010	-0.011	0.003	-0.001	-0.003
	(0.007)	(0.007)	(0.008)	(0.004)	(0.003)	(0.003)
$\hat{S}_{t-1}$	0.055*	0.056*	0.041	0.051	0.055	0.095**
	(0.028)	(0.028)	(0.116)	(0.047)	(0.045)	(0.040)
Municipalities	15	15	15	15	15	15
Num.Obs.	804	804	804	804	804	804
Municipality FE	X	X	X	X	X	X
Month FE		X	X		X	X
Municipality × Year FE			X			X

Notes: The table presents the effect of solar and wind generation on labor market outcomes. The variables are transformed into logarithms. The results refer to Poisson estimates with clustered standard errors at the municipal level. All regression models include municipality-year fixed effects. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

Table 5 suggests that the main effect of renewables-induced displacement of fossil fuel electricity generation is an increase in dismissals. Our dataset enables us to explore this effect by type of labor movement. Table 6 presents the effects by job termination type. Panel A shows the results for municipalities with coal plants, while Panel B presents the results for municipalities with gas plants. Columns (1) to (3) show the results for types of hiring: first formal job, new formal job, and temporary job. Columns (4) to (6) show the results for types of dismissal: voluntary, involuntary, and temporary. The model specifications align with our preferred specification reported in column (6) of Table 5.

In municipalities with coal plants, we do not find statistically significant effects on types of labor movement. However, for municipalities with natural gas plants, we find that solar

Table 6: The impact on monthly hiring and dismissal by type

	Hiring			Dismissal		
	First Job (1)	New Job (2)	Temporary (3)	Voluntary (4)	Involuntary (5)	Temporary (6)
Panel A. Coal						
$\hat{W}_{t-1}$	-0.002	-0.002	0.001	-0.002	0.003	-0.008
	(0.002)	(0.001)	(0.004)	(0.002)	(0.003)	(0.004)
$\hat{S}_{t-1}$	-0.055	-0.041	0.032	0.015	-0.068	0.052
	(0.036)	(0.039)	(0.124)	(0.044)	(0.063)	(0.078)
Municipalities	6	6	6	6	6	6
Num.Obs.	334	334	334	334	334	334
Panel A. Gas						
$\hat{W}_{t-1}$	-0.007	-0.009	-0.017	-0.004	-0.002	-0.001
	(0.004)	(0.007)	(0.016)	(0.003)	(0.003)	(0.005)
$\hat{S}_{t-1}$	-0.226***	0.123	-0.325**	0.024	0.077*	0.148***
	(0.059)	(0.116)	(0.135)	(0.058)	(0.039)	(0.046)
Municipalities	15	15	15	15	15	15
Num.Obs.	804	804	804	804	804	804

Notes: The table presents the effect of solar and wind generation on labor market outcomes. The variables are transformed into logarithms. The results refer to Poisson estimates with clustered standard errors at the municipal level. All regression models include municipality-year fixed effects. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

generation reduces the hiring of first jobs and temporary jobs. Specifically, the results indicate that a 1 GWh increase in solar generation leads to a 22.6% reduction in the hiring of first jobs (Column (1)) and a 32.5% reduction in temporary contracts in the following month. For types of dismissal, we find an increase in involuntary and temporary dismissals. A 1 GWh increase in solar generation leads to a 7.7% increase in involuntary dismissals (Column (5)) and a 14.8% increase in the end of temporary contracts. It is worth noting that we do not find an effect on voluntary dismissals, where the dismissal is initiated by the worker. This suggests that the increase in solar generation may be associated with greater job instability in the short term, particularly affecting workers with less secure employment.

The results emphasize the differences between municipalities with coal and natural gas power plants regarding the labor market effects of renewable energy generation. In coal-dependent municipalities, the impact of solar and wind generation on hiring is more pronounced. Meanwhile, the significant increase in dismissals following solar generation in natural gas-dependent municipalities indicates more volatile labor market dynamics, with potential increases in unemployment. These findings highlight the need for tailored economic policies to mitigate adverse labor market impacts and support local economies during the transition to renewable energy sources.

5.2.1 Robustness

Our primary finding regarding local labor market impacts indicates that during periods of reduced fossil fuel generation nationwide, average wages significantly decreased in municipalities with coal-fired power plants, as did both employment and wages in municipalities with natural gas power plants (Table 4). Additionally, the estimates suggest a modest decline in hiring one month after renewable-induced changes in fossil fuel generation in municipalities with coal plants but a significant increase in dismissals in municipalities with natural gas power plants due to solar (Table 5). We conducted robustness checks to ensure the reliability of these results, examining sensitivity related to sample selection, treated units, and control groups. Detailed tables with results are provided in the Appendix.

Sample selection. The main results were estimated considering a sample of municipalities with up to 300,000 inhabitants, which account for 95% of Brazil's municipalities. We imposed this sample selection because medium and small-sized cities may exhibit distinct labor market dynamics compared to large cities. To assess the effect of including large cities, we estimated the effects considering all municipalities with coal and gas power plants. In this case, our sample of municipalities with coal-fired power plants increase from 6 to 7, and those with natural gas plants increase from 15 to 24.

For the annual data specification, including a large municipality does not significantly alter the results. Using our preferred SDID estimation method, for municipalities with coal-fired power plants, we find that the average monthly wage decreased by 11.3% (Table A5), only one percentage point less than the result in Table 4. For municipalities with natural gas power plants, we observe a decrease of 8.0% in employment, which is 0.8 percentage points less than the results in Table 4, but we find no statistically significant effect on average monthly wage.

For the monthly outcomes data specification, including a large municipality does not significantly alter the results for municipalities with coal (Table A6). According to our preferred specification, which includes municipality, month, and municipality-year fixed effects, we find that a 1 GWh increase in wind generation reduces hirings by 0.3% one month later (0.1 percentage point higher than the result in Table 5). On the other hand, the effect of an increase in solar generation does not significantly affect dismissals in gas municipalities, unlike the 9.5% increase in dismissals shown in Table 5.

Therefore, including large municipalities diminishes the effect of the policy or renders it statistically insignificant. Thus, the results suggest that economic and energy transition policies may need to be tailored more specifically for different municipality sizes to mitigate adverse impacts on local economies while adopting renewable energy sources.

Treated units. In our main results, the treatment groups consist of municipalities with coal and natural gas power plants installed in their territory. However, alternatively, we can define the treated municipalities based on the distance between the power plants and the urban areas of the municipalities. In this analysis, we are concerned with spillover effects, which is the possibility of the impacts extending beyond the boundaries of municipalities where the power plant is located. For this, we used the power plants' geographic coordinates and the municipalities' administrative centers to select the municipalities contained in buffers of 10, 20, and 30 km.

When using distance to define the treatment group, all parameters present negative signs, although not all are significant at the 10% level. The negative effect on the average wage is statistically significant for most DID and SDID estimates. Furthermore, the magnitude of the wage parameter decreases with increasing distance. This result corroborates the findings in Table 4 and suggests a spillover effect, potentially encompassing municipalities beyond those with power plants. Unlike the estimates in Table 4, some job and firm parameters are statistically significant. It suggests that other labor market outcomes, besides wages, may negatively affect the local labor market of coal-fired municipalities.

6 Conclusion

This study aims to examine how changes in fossil fuel generation, induced by the rise of renewable energy sources, impact the local labor market. First, we assess how solar and wind induce displacement or ramp-up of coal and natural gas generation. To achieve this, we utilize the hourly variation in renewable generation to identify changes in fossil fuel generation. We estimate the effect of aggregated generation at the national level, SIN subsystem levels, and municipalities with thermal power plants. Despite the modest effect, the results indicate that solar and wind displace coal and natural gas generation, especially in the Northeast subsystem, a region with the highest wind and solar generation potential.

After estimating the changes in fossil fuel generation induced by renewable energy sources, we then assess the impact on the labor market in municipalities with thermal power plants. First, we use annual data in a Difference-in-Differences (DID) strategy, along with the Synthetic Control Difference-in-Differences (SDID) extension of DID, to investigate whether the number of jobs, the number of firms, and the average wage in the affected municipalities change relative to a control group during the period of decreased fossil fuel generation in the country. Subsequently, considering various levels of fixed effects and utilizing the predicted changes in fossil fuel generation, we estimate how renewable energy generation affects the monthly number of hirings and dismissals in these municipalities.

After estimating the changes in fossil fuel generation induced by renewable energy sources, we then assess the impact on the labor market in municipalities with thermal power plants. Initially, we employ annual data and utilize a Difference-in-Differences (DID) strategy, along with the Synthetic Control Difference-in-Differences (SDID) extension of DID, to examine whether the number of jobs, the number of firms, and the average wage in the affected municipalities change relative to a control group during the period of decreased fossil fuel generation in the country. Subsequently, by considering various levels of fixed effects and utilizing the predicted changes in fossil fuel generation, we estimate the effects of renewable energy generation on the monthly number of hirings and dismissals in these municipalities.

The results indicate that during the period of decreased fossil fuel generation in the country, average wages in municipalities with coal-fired power plants significantly decreased, as did both employment and wages in municipalities with natural gas power plants. Additionally, the estimates suggest a modest decline in the number of hirings one month after the renewable-induced changes in fossil fuel generation in these municipalities with coal plants but a significant increase in the number of dismissals in municipalities with natural gas power plants.

The findings suggest that municipalities with natural gas power plants are the most affected by intermittent renewable energy generation. The effect difference between municipalities with coal-fired plants and those with natural gas plants can be explained by counter-cyclical subsidy policies for coal, a factor that can be further explored in future studies. These findings may hold significant implications for public policy formulation. Understanding the localized effects of the energy transition is essential for fostering sustainable regional development and creating policies that support a fair and just energy transition.

An improvement to the paper could involve considering the effect on municipalities with oil power plants, i.e., municipalities with plants that burn fuel oil and diesel—more polluting fuels and higher emitters of CO_2 than natural gas.

Depending on data availability and following Rivera et al. (2024), we can improve these estimations of renewables-induced changes in fossil fuel generation in future paper versions by considering two aspects. First, given that solar and wind generation depends on solar irradiation, wind speed, and installed capacity, we can adopt an instrumental variables specification to test the validity of the exogeneity hypothesis of intermittent solar and wind energy generation. Second, we can consider the capacity factor as the dependent variable, defined as the system's hourly generation divided by net capacity, which provides a better basis for comparing changes in generation relative to total installed capacity.

Regarding the estimations of effects on local labor markets, power plants are located in a limited number of municipalities and states, particularly in the case of coal. To enhance the identification of local effects, in future versions of this paper, we can adopt the strategy proposed by Ferman (2021) and Alvarez and Ferman (2020), which addresses the estimation of policy effects in contexts with few treated units and spatial correlation. Additionally, we can incorporate recent advancements in the literature to analyze dynamic effects within the

Synthetic Control Difference-in-Differences (SDID) framework, as proposed by Ciccia (2024).

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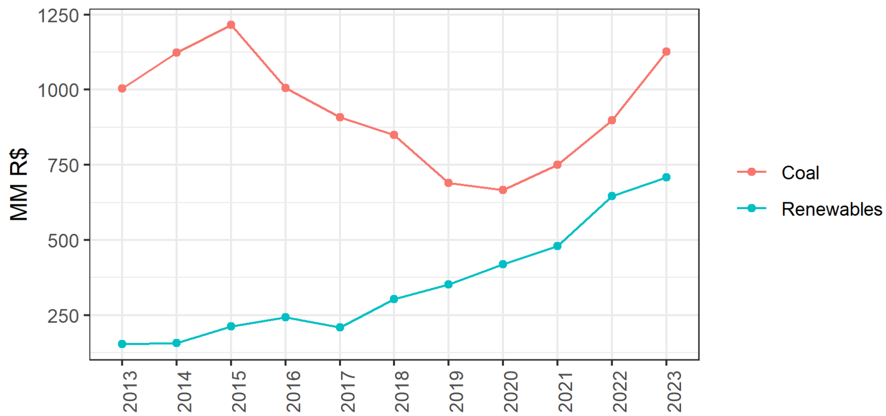
Appendix

Figure A1: Subsidies for coal and renewable energy sources encouraged



Source: Author's own prepared from the ONS data.

Table A1: Coal production and coal-fired power plants capacity

State	Municipality	Production (Kton)	Capacity (MW)
CE	São Gonçalo do Amarante	0	1,085
MA	São Luís	0	360
PR	Figueira	284	20
RS	Arroio dos Ratos	901	0
RS	Butiá	118	0
RS	Cachoeira do Sul	209	0
RS	Candiota	3,449	1,141
RS	Charqueadas	0	36
RS	São Jerônimo	0	20
SC	Capivari de Baixo	0	740
SC	Içara	828	0
SC	Lauro Müller	2,555	0
SC	Treviso	2,254	0
SC	Urussanga	166	0

Source: Author's own prepared from the AMN and ANEEL data.
Notes: This table displays coal production and the installed capacity of coal-fired power plants by municipality. Coal production corresponds to the year 2022. Installed capacity corresponds to the total installed capacity of coal-fired power plants that injected energy into the SIN between 2005 and 2020.

Table A2: The impact of renewable energy on coal, gas and oil generation

	2006-2014			2015-2019		
	Coal	Gas	Oil	Coal	Gas	Oil
	(1)	(2)	(3)	(4)	(5)	(6)
Wind	-0.118	0.353	0.509***	-0.025**	-0.053*	-0.096***
	(0.078)	(0.335)	(0.147)	(0.006)	(0.021)	(0.014)
Solar				-0.013	-0.071	-0.202**
				(0.026)	(0.047)	(0.046)
Adjusted R^2	0.827	0.803	0.742	0.435	0.622	0.498
Num.Obs.	76,767	76,767	76,767	39,260	39,260	39,260

Notes: The table presents the effect of solar and wind on coal and natural gas electricity generation. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

Table A3: The impact on monthly hiring and dismissal: contemporaneous effect

	Hiring			Dismissal		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Coal						
$\hat{W}_t$	0.003	0.003	-0.003	0.007	0.006	-0.002***
	(0.002)	(0.002)	(0.002)	(0.006)	(0.006)	(0.000)
$\hat{S}_t$	0.014	0.015	-0.031	-0.001	0.001	0.011
	(0.019)	(0.020)	(0.035)	(0.042)	(0.045)	(0.007)
Municipalities	6	6	6	6	6	6
Num.Obs.	338	338	338	338	338	338
Panel A. Gas						
$\hat{W}_t$	-0.008	-0.007	-0.006	0.004	0.000	-0.001
	(0.007)	(0.006)	(0.007)	(0.006)	(0.005)	(0.006)
$\hat{S}_t$	0.048*	0.046*	0.004	0.055	0.058	0.092*
	(0.025)	(0.026)	(0.121)	(0.047)	(0.044)	(0.046)
Municipalities	15	15	15	15	15	15
Num.Obs.	819	819	819	819	819	819
Municipality FE	X	X	X	X	X	X
Month FE		X	X		X	X
Municipality × Year FE			X			X

Notes: The table presents the effect of solar and wind generation on labor market outcomes. The variables are transformed into logarithms. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

Table A4: The impact on monthly hiring and dismissal by gender

	Hiring			Dismissal		
	Total	Males	Females	Total	Males	Females
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Coal						
$\hat{W}_{t-1}$	-0.002*	-0.002**	-0.003***	0.000	0.000	-0.002***
	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)
$\hat{S}_{t-1}$	-0.051	-0.065	0.013	-0.028	-0.049	0.059***
	(0.038)	(0.036)	(0.017)	(0.019)	(0.025)	(0.009)
Municipalities	6	6	6	6	6	6
Num.Obs.	334	334	334	334	334	334
Panel A. Gas						
$\hat{W}_{t-1}$	-0.011	-0.011	-0.009*	-0.003	-0.004	-0.001
	(0.008)	(0.009)	(0.005)	(0.003)	(0.004)	(0.002)
$\hat{S}_{t-1}$	0.041	0.032	0.080	0.095**	0.080	0.057
	(0.116)	(0.106)	(0.153)	(0.040)	(0.058)	(0.051)
Municipalities	15	15	15	15	15	15
Num.Obs.	804	804	804	804	804	804

Notes: The table presents the effect of solar and wind generation on labor market outcomes. The variables are transformed into logarithms. The results refer to Poisson estimates with clustered standard errors at the municipal level. All regression models include municipality-year fixed effects. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

Table A5: The impact on the annual labor outcomes: sample selection

	DID			SDID		
	Jobs (1)	Firms (2)	Wage (3)	Jobs (4)	Firms (5)	Wage (6)
Panel A. Coal						
Treated	0.063	0.065	-0.123	0.005	0.027	-0.113***
	(0.120)	(0.103)	(0.103)	(0.047)	(0.025)	(0.021)
Treated Units	7	7	7	7	7	7
Control Units	140	140	140	140	140	140
Observations	2,646	2,646	2,646	2,646	2,646	2,646
Panel B. Gas						
Treated	-0.048	-0.006	-0.047*	-0.08***	-0.013	-0.012
	(0.039)	(0.029)	(0.025)	(0.018)	(0.01)	(0.009)
Treated Units	24	24	24	24	24	24
Control Units	480	480	480	480	480	480
Observations	10,584	10,584	10,584	10,584	10,584	10,584

Notes: The table presents the effect of solar and wind generation on labor market outcomes. The variables are transformed into logarithms. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

Table A6: The impact on monthly hiring and dismissal: sample selection

	Hiring			Dismissal		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Coal						
$\hat{W}_{t-1}$	0.004*	0.004	-0.003*	0.008	0.008	0.000
	(0.002)	(0.003)	(0.001)	(0.006)	(0.006)	(0.001)
$\hat{S}_{t-1}$	0.006	0.009	-0.004	-0.017	-0.015	-0.020
	(0.019)	(0.021)	(0.060)	(0.046)	(0.048)	(0.018)
Municipalities	7	7	7	7	7	7
Num.Obs.	393	393	393	393	393	393
Panel A. Gas						
$\hat{W}_{t-1}$	-0.002	-0.003	-0.003	0.002	0.000	-0.001
	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.001)
$\hat{S}_{t-1}$	0.019	0.022*	0.013	0.019*	0.024**	0.036
	(0.013)	(0.012)	(0.028)	(0.011)	(0.011)	(0.022)
Municipalities	24	24	24	24	24	24
Num.Obs.	1,325	1,325	1,325	1,325	1,325	1,325
Municipality FE	X	X	X	X	X	X
Month FE		X	X		X	X
Municipality $\times$ Year FE			X			X

Notes: The table presents the effect of solar and wind generation on labor market outcomes. The variables are transformed into logarithms. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.

Table A7: The impact on the local labor market by distance

	DID			SDID		
	Jobs	Firms	Wage	Jobs	Firms	Wage
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. 10 km						
RE Generation	-0.082	-0.100**	-0.189***	-0.048	-0.01	-0.136***
	(0.059)	(0.048)	(0.053)	(0.04)	(0.027)	(0.015)
Treated Units	9	9	9	9	9	9
Control Units	90	90	90	90	90	90
Observations	1,980	1,980	1,980	1,980	1,980	1,980
Panel B. 20 km						
RE Generation	-0.048	-0.070	-0.104*	-0.056*	-0.011	-0.091***
	(0.073)	(0.061)	(0.057)	(0.033)	(0.021)	(0.012)
Treated Units	14	14	14	14	14	14
Control Units	140	140	140	140	140	140
Observations	3,080	3,080	3,080	3,080	3,080	3,080
Panel C. 30 km						
RE Generation	-0.022	-0.043	-0.040	-0.001	-0.002	-0.046***
	(0.043)	(0.036)	(0.030)	(0.023)	(0.013)	(0.008)
Treated Units	30	30	30	30	30	30
Control Units	300	300	300	300	300	300
Observations	6,600	6,600	6,600	6,600	6,600	6,600

Notes: The table presents the effect of solar and wind generation on labor market outcomes. The variables are transformed into logarithms. The significance level is denoted as * for the 10% level, ** for the 5% level, and *** for the 1% level.