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WIND ENERGY AND LOCAL FINANCES: A SYNTHETIC CONTROL APPROACH TO ECONOMIC IMPACT IN THE MUNICIPALITY OF JOÃO CÂMARA/RN

Energia eólica e finanças locais: uma abordagem de controle sintético do impacto econômico no município de João Câmara/RN

Energía eólica y finanzas locales: un enfoque de control sintético del impacto económico en el municipio de João Câmara/RN

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ABSTRACT

In view of the scenario of expanding renewable energy production, academics and public and private entities have dedicated themselves to assessing the impact of the installation and use of these sources on the economy, both nationally (Simas, 2012; Rintzel, 2017; Martini, Jordão, & Grimaldi, 2018; Rodrigues; Gonçalves; Chagas, 2019; Rodrigues et al., 2019; Gonçalves; Rodrigues; Chagas, 2020) and internationally (Lantz, 2008; Reategui; Hendrickson, 2011; IRINA, 2016a, 2016b; ICF International, 2015; Böhringer et al., 2013; Inglesi-Lotz, 2016; Brown et al., 2012; De Silva et al., 2016). In this sense, this study aims to identify the impact on the Gross Domestic Product (GDP) per capita of the municipality of João Câmara during the period from 2012 to 2020, resulting from the implementation of wind farms. For this purpose, a panel database was constructed, including information on GDP, GDP per capita, population, and the year of installation. The data covers the period from 2001 to 2020, obtained from the Brazilian Institute of Geography and Statistics (IBGE) and the National Electric Energy Agency (ANEEL). The synthetic control method, proposed by Abadie and Gardeazabal (2003) and Abadie, Diamond, and Hainmueller (2010), was employed to achieve the objective. Robustness analyses were conducted through placebo testing and the synthetic difference-in-differences method. The results indicate that the installation of wind farms in João Câmara resulted in a statistically significant increase of R$ 11,942.09 in GDP per capita. That is, wind energy has the potential to drive economic growth in municipalities where it is implemented.

Keywords: Wind farms; GDP per capita; João Câmara; Synthetic control; Economic growth.

RESUMO

Frente ao cenário de expansão da produção de energia renovável, acadêmicos e entidades públicas e privadas dedicaram-se a avaliar o impacto da instalação e uso dessas fontes na economia, tanto nacional (Simas, 2012; Rintzel, 2017; Martini, Jordão e Grimaldi, 2018; Rodrigues; Gonçalves; Chagas, 2019; Rodrigues et al., 2019; Gonçalves; Rodrigues; Chagas, 2020) quanto internacionalmente (Lantz, 2008; Reategui; Hendrickson, 2011; IRINA, 2016a, 2016b; ICF International, 2015; Böhringer et al., 2013; Inglesi-Lotz, 2016; Brown et al., 2012; De Silva et al., 2016). Nesse sentido, este estudo objetiva identificar o impacto no Produto Interno Bruto per capita do município de João Câmara durante o período de 2012 a 2020, resultante da implementação de parques eólicos. Para isso, uma base de dados em painel foi construída, incluindo informações sobre PIB, PIB per capita, população e o ano de instalação. Os dados abrangem o período de 2001 a 2020, sendo obtidos do Instituto Brasileiro de Geografia e Estatística (IBGE) e da Agência Nacional de Energia Elétrica (ANEEL). O método de controle sintético, proposto por Abadie e Gardeazabal (2003) e Abadie, Diamond e Hainmueller (2010), foi empregado para atingir o objetivo. Análises de robustez foram conduzidas por meio do teste de placebo e do método de Diferença em Diferenças sintético. Os resultados apontam que a instalação de parques eólicos em João Câmara resultou em um aumento estatisticamente significativo de R$ 11.942,09 no PIB per capita. Isto é, a energia eólica tem o potencial de impulsionar o crescimento econômico em municípios onde é implementada.

Palavras-chave: Parques eólicos; PIB per capita; João Câmara; Controle sintético; Crescimento econômico.

ABSTRACT

In view of the scenario of expanding renewable energy production, academics and public and private entities have dedicated themselves to assessing the impact of the installation and use of these sources on the economy, both nationally (Simas, 2012; Rintzel, 2017; Martini, Jordão, & Grimaldi, 2018; Rodrigues; Gonçalves; Chagas, 2019; Rodrigues et al., 2019; Gonçalves; Rodrigues; Chagas, 2020) and internationally (Lantz, 2008; Reategui; Hendrickson, 2011; IRINA, 2016a, 2016b; ICF International, 2015; Böhringer et al., 2013; Inglesi-Lotz, 2016; Brown et al., 2012; De Silva et al., 2016). In this sense, this study aims to identify the impact on the Gross Domestic Product (GDP) per capita of the municipality of João Câmara during the period from 2012 to 2020, resulting from the implementation of wind farms. For this purpose, a panel database was constructed, including information on GDP, GDP per capita, population, and the year of installation. The data covers the period from 2001 to 2020, obtained from the Brazilian Institute of Geography and Statistics (IBGE) and the National Electric Energy Agency (ANEEL). The synthetic control method, proposed by Abadie and Gardeazabal (2003) and Abadie, Diamond, and Hainmueller (2010), was employed to achieve the objective. Robustness analyses were conducted through placebo testing and the synthetic Difference-in-Differences method. The results indicate that the installation of wind farms in João Câmara resulted in a statistically significant increase of R$ 11,942.09 in GDP per capita. That is, wind energy has the potential to drive economic growth in municipalities where it is implemented.

Keywords: Wind farms; GDP per capita; João Câmara; Synthetic control; Economic growth.

1 INTRODUÇÃO

The scarcity of resources and climate change have created a conducive context for the debate on the importance of renewable energy sources. In response, the United Nations Summit on Sustainable Development took place in New York in 2015 and established the 2030 Agenda with the support of 193 world leaders. This agenda focuses on the Sustainable Development Goals (SDGs), which include combating poverty, promoting prosperity and well-being, protecting the environment, and addressing climate change. In this context, there was discussion on replacing the energy matrix, emphasizing the need to use clean and accessible energy to ensure cheap, reliable, sustainable, and renewable energy.

Another favorable factor for adopting a clean energy matrix is the reduction of greenhouse gas emissions associated with energy production from primary sources. As a result, renewable energy sources accounted for 25% of global generation in 2018, becoming the third largest source of energy (Koebrich; Bowen; Sharpe, 2018). Wind energy stands out in this scenario due to advantages such as (i) not producing waste in electricity generation, (ii) being considered practically inexhaustible compared to other sources, (iii) not incurring costs related to raw material acquisition, (iv) low environmental risks in the construction of its facilities; and (v) having one of the best cost-benefit ratios among renewable energies (Martini; Jordão; Grimaldi, 2018).

Given this scenario of expanding renewable energy production, academics and public and private entities have dedicated themselves to assessing the impact of the installation and use of these sources on the local, regional, and national economy (Lantz, 2008; Reategui; Hendrickson, 2011; IRINA, 2016a, 2016b; ICF International, 2015; Böhringer et al., 2013; Inglesi-Lotz, 2016; Brown et al., 2012; De Silva et al., 2016). In the Brazilian context, some have focused on studies on developing Brazil's renewable energy matrix and its economic impacts. However, most of these studies are conducted at the national or regional level, with fiscal and labor market variables predominantly as variables of interest (Simas, 2012; Rintzel, 2017; Martini; Jordão; Grimaldi, 2018; Rodrigues; Gonçalves; Chagas, 2019; Rodrigues et al., 2019; Gonçalves; Rodrigues; Chagas, 2020).

In the context of expanding renewable energy generation, especially wind energy, both globally and in Brazil, the Northeast region stands out in wind energy production, accounting for over 90% of Brazil's onshore wind energy installed capacity. The state of Rio Grande do Norte (RN), in particular, is notable, contributing 32.4% of the total capacity in the region, thus becoming the country's largest producer of wind energy (Macedo; Melo;

Silva, 2023). Due to its climatic and territorial characteristics, it can be said that the state has the best wind conditions for wind farm installations in Brazil. The regions of Mato Grande, Litoral Norte (Costa Branca Pole), and Serra de Santana concentrate wind energy generation in the state (Dantas et al., 2021; Da Silva; De Azevedo, 2020).

Located in Litoral Norte (Costa Branca Pole), the city of Macau, in Rio Grande do Norte (RN), was the first to receive a wind farm with an installed capacity of 1.8 MW generated by three wind turbines, each with a capacity of 600 kW. Petrobras constructed the wind farm to produce energy for self-consumption. The municipality of Rio do Fogo was the second to host a wind energy project in the state in 2006. The park consisted of 62 turbines, each with a capacity of 800 kW, totaling 49.6 MW of installed capacity (Azevedo; Araújo; Silva, 2015).

However, wind energy production in the state became significant from the auctions, the 1st Reserve Energy Auction A-3, and Free Agents Auction - ACL, held in 2009. In addition to these two auctions, between 2010 and 2013, other auctions were held, allowing for the signing of 75 commercial agreements to install new wind farms in Rio Grande do Norte, generating new investments and transformations in the wind energy generation sector. By 2010, the Alegria I wind farm in Guamaré/RN had begun operating. The wind farm consists of 31 wind turbines with an installed capacity of 51.0 MW. Thus, by 2010, Rio Grande do Norte had three wind farms in operation, totaling an installed capacity of approximately 102.4 MW (Dantas et al., 2021; Azevedo; Araújo; Silva, 2015).

The municipality of João Câmara/RN, located in the Mato Grande region, saw wind energy projects emerge in its territory following federal auctions held between 2009 and 2013. These auctions resulted in a total investment of over R$ 2.8 billion in the municipality. Between 2012, the year of the installation of the first wind farm in the municipality, and 2020, João Câmara gained prominence in the state scenario, becoming the largest wind energy producer in 2020 with an installed capacity of 741.6 MW and having the highest number of wind farms (twenty-nine) in the state of Rio Grande do Norte (ANEEL, 2020).

From 2012 to 2019, according to data from the Brazilian Institute of Geography and Statistics (IBGE), the municipality of João Câmara experienced an approximate growth in its per capita GDP (GDPpc) of about 177.17%, rising from R$ 9,603.50 in 2012 to R$ 26,617.73 in 2019. This increase caused João Câmara to jump from the 40th to the 14th position in the state ranking of GDPpc (IBGE, 2010[1]).

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[1] Os dados da série revisada têm como referência o ano de 2010, seguindo a nova referência das Contas Nacionais.

Given this context, it is necessary to measure how the installation of wind farms has affected the per capita GDP of the municipality of João Câmara. Therefore, this study aims to estimate the impacts on the per capita GDP of João Câmara from 2012 to 2020 resulting from the installation of wind farms. A panel dataset was constructed with information on GDP, GDP per capita, population, and year of wind farm installation in municipalities of Rio Grande do Norte. All this information will be available for municipalities in Rio Grande do Norte from 2001 to 2020, obtained from the Brazilian Institute of Geography and Statistics (IBGE) and the National Electric Energy Agency (ANEEL).

Methodologically, the work will use the synthetic control method approach proposed by Abadie and Gardeazabal (2003) and Abadie, Diamond, and Hainmueller (2010).

This methodology seeks to compare each treated unit with a synthetic control unit, which consists of a weighted average of all eligible units available for comparison in the database. Placebo testing and the Synthetic Differences-in-Differences method (Arkhangelsky et al., 2021) were conducted for robust analyses.

This paper is structured as follows: following this introduction, a literature review describes how the implementation of wind energy has impacted the economy in the locations where it has been installed. Next, the details of the consolidated database and key information from its sources are presented. The following section outlines the methodology, which employs an approach using the synthetic control method proposed by Abadie and Gardeazabal (2003) and Abadie, Diamond, and Hainmueller (2010); this section also discusses the theoretical models for estimating the proposed method. Subsequently, the results of the estimates are presented, followed by the study's concluding remarks and potential policy implications and future developments in this line of research.

2 THE ECONOMIC IMPACT OF WIND ENERGY IMPLEMENTATION

The rationale that implementing renewable energy sources can drive economic growth has consistently been used to justify government support. Numerous studies have been conducted addressing the economic impact of increased use of renewable energies at different geographical scales. For example, IRINA (2016a, 2016b) simulated, using a macroeconometric model (E3ME), a scenario that doubles the share of renewable energy in the global final energy matrix by 2030, resulting in a global GDP increase between 0.6% and 1.1%. Economies such as the United States (ICF International, 2015), the European Union (European Commission, 2014), Germany, OECD countries, among others (Böhringer et al., 2013; Inglesi-Lotz, 2016), also show positive effects.

De Silva et al. (2016) argue that wind resources are often abundant in economically less developed regions, making the impact of wind energy development in these economies of particular interest. Thus, encouraging electricity generation from wind energy while simultaneously stimulating local economies appears advantageous. However, it is important to carefully assess whether wind energy implementation can indeed positively contribute to local economies.

Several methods have been employed to assess the local economic impact of wind energy development. A common method is the input-output approach, which categorizes these impacts as direct, indirect, and induced. Direct impacts include increased income from investments in wind farm development, construction, and operation. Indirect impacts stem from multiplier effects driven by demand for goods and services from those involved in the projects. Finally, induced impacts result from reinvestment and consumption by direct and indirect beneficiaries.

For example, Lantz (2008), using the Wind Economic Development Impact (JEDI) model from the National Renewable Energy Laboratory (NREL), which incorporates direct, indirect, and induced impacts, estimated the economic impacts for Nebraska resulting from the installation of 1000 MW of wind energy. The analysis revealed that between 264 and 515 full-time jobs would be sustained during the operational phase, contributing to economic activity ranging from 30 to 57 million dollars. The author also estimated land lease payments ranging from 3.5 to 4.1 million dollars annually and local property tax revenues of 3.7 million annually.

Using the JEDI model, Reategui and Hendrickson (2011) prepared a report analyzing the jobs and economic impacts of installing 1,000 MW of wind energy in Texas. During the construction phase, this scenario sustained approximately 240 permanent jobs, generated nearly 260 million dollars in economic activity, over 7 million dollars in annual property taxes, and almost 5 million dollars annually in landowner income, among other benefits. Similar benefits are observed by Torgerson et al. (2006), Lantz and Tegen (2008, 2009), and Reategui and Tegen (2008).

It is pertinent to emphasize that wind energy development can impact local economies positively and negatively. In this regard, the input-output method, adopted by many studies, analyzes only the positive impact, neglecting the opportunity costs associated with wind energy implementation. Two types of opportunity costs should be considered: (i) costs related to replacing other energy sources or land uses and (ii) costs of public funds invested in wind energy development at the expense of other industries (Xia; Song, 2017).

Brown et al. (2012) highlight that an ex-post economic analysis can better address outcomes, considering both the economic costs and benefits of local wind energy development, reflecting measurable changes in outcomes such as employment and income. Thus, it measures the positive impact, as modeled in input-output methods, and any substitution and displacement effects that may affect overall economic performance.

However, few studies assess overall economic effects using ex-post economic analyses. Noteworthy are the studies conducted by Brown et al. (2012) and De Silva et al. (2016). Brown et al. (2012) conducted an ex-post economic analysis of the economic impacts at the county level resulting from wind energy installations from 2000 to 2008 in the wind-rich Great Plains region of the USA, considering the influence of turbine locations. The results showed an aggregate increase in personal income and employment in counties with installed wind energy.

De Silva et al. (2016) investigated the localized economic impacts of the rapid increase in county-level wind energy capacity in Texas. They used traditional economic methods to estimate direct and indirect impacts on employment, personal income, tax base, and public school spending levels. The results revealed modest increases in employment, significant increases in per capita income, and substantial benefits in local property and school taxes.

Xia and Song (2017) conducted an ex-post economic assessment of the impact of wind energy installation on the local economy in China, using national county-level data from 2005 to 2011. They found that installed wind energy capacity has a small yet statistically significant positive effect on GDP but also negatively affects local fiscal income.

In the Brazilian context, studies such as those by Simas (2012), Rintzel (2017), Martini, Jordão, and Grimaldi (2018), Rodrigues, Gonçalves, and Chagas (2019), Rodrigues et al. (2019), and Gonçalves, Rodrigues, and Chagas (2020) assess the economic impact of wind energy on Brazilian municipalities.

Simas (2012) sought to quantify the job generation potential of wind energy in Brazil, considering not only direct employment but also indirect jobs generated in the economy due to demand for inputs. They used tools such as life cycle assessment, semi-structured interviews, input-output matrices, and scenario development, and the results indicate that up to 330,000 job-years could be created by 2020, with approximately 70% of these being direct jobs.

Rintzel (2017), using the Differential Structural Method and employing data on employment, tax revenue, and value-added for municipalities with installed wind farms in

Brazil from 1998 to 2012, aimed to observe the economic impact of wind farm installations on Brazilian municipalities. The results indicated that municipalities with wind farms experienced a greater increase in employment, with less significant variations in tax revenue and value-added.

Martini, Jordão, and Grimaldi (2018) examined the impacts on per capita GDP of municipalities that received investments in wind farm construction from 2008 to 2014. Using a consolidated municipal database and the adaLASSO methodology to reduce parameter space dimensionality, they applied the synthetic control method. The results showed that the effects, with a median estimate between 7.1% and 9.4%, were more pronounced for relatively poorer municipalities or those that received larger wind farms between 2 and 3 years after construction began.

Rodrigues, Gonçalves, and Chagas (2019) analyzed the relationship between the presence of wind farms and labor market outcomes in municipalities in the Northeast region of Brazil. They used a combination of methodologies, including propensity score matching and estimating the average treatment effect. Considering the spatial dependence of municipalities, the results suggest increases in payroll in municipalities with wind farms.

Rodrigues et al. (2019) sought to identify the economic and fiscal impact following the operation of wind farms in Brazilian municipalities using the Differences-in-Differences method. The results showed significant effects on agriculture's gross value added (GVA) but negative effects on GVA in industry, services, and taxes.

Gonçalves, Rodrigues, and Chagas (2020) estimated the impact of wind farms on employment and wages, considering economic sectors, educational levels, business sizes, and types of jobs - whether direct or indirect employment. Using a Differences-in-Differences approach with multiple periods, time-varying treatment, and dynamic treatment effects, the results suggest significant social impacts through the labor market, contributing to local development and increasing social welfare in developing economies.

3 METHODOLOGY

A dataset at the municipal level was compiled, encompassing information on Gross Domestic Product (GDP), GDP per capita, population, and identification of the start of wind farm installations in João Câmara. These data cover the period from 2001 to 2020 in Rio Grande do Norte. The identification of the implementation year was obtained from the Brazilian Electricity Regulatory Agency (ANEEL).

Meanwhile, GDP, GDP per capita, and population data were acquired from the Brazilian Institute of Geography and Statistics (IBGE). It is crucial to emphasize that GDP per capita was used as the response variable. GDP per capita and GDP were adjusted for inflation to the 2020 base year using the National Consumer Price Index (IPCA).

The sample was restricted to municipalities in Rio Grande do Norte that did not install wind farms during the analyzed period, except João Câmara. Therefore, the final sample consists of 148 municipalities, with one municipality installing wind farms between 2012 and 2020 (treatment group), while the other 147 did not install wind farms (control group).

This study employs the synthetic control method proposed by Abadie and Gardeazabal (2003) and Abadie, Diamond, and Hainmueller (2010) to assess the impact of wind farm installation on the income of João Câmara municipality, Rio Grande do Norte, using a "counterfactual" approach. The synthetic control method offers notable advantages compared to other policy evaluation methods.

Firstly, according to Athey and Imbens (2017), it is a non-parametric method that extends the traditional Differences-in-Differences approach. Secondly, the control group's weight is data-driven, thus avoiding issues of policy endogeneity. Thirdly, it simulates the situation of treatment groups before policy implementation by weighting multiple control groups, which can influence the contribution of each control group to construct the "counterfactual."

Furthermore, it provides more reliable evaluation results, avoiding biases caused by excessive extrapolation since the weight constraint is positive and the sum of all weights equals 1. Lastly, a corresponding control group for each treatment group is constructed to avoid an average assessment. It allows different policy adoption times in each area to depict their outcomes, thereby avoiding biases caused by subjective selection.

The central idea behind the synthetic control method is to consider the municipality under analysis as the treatment group and find the appropriate weight using predictor variables, weighting the average value of municipalities that did not install wind farms to establish the "counterfactual" control group.

Subsequently, the income difference between the treatment group and its synthetic control group is compared after policy implementation, i.e., the effect of wind farm installation. Formally, considering $J+1$ units (municipalities), the first unit undergoes treatment, while the remaining J units serve as controls since they were not exposed to the treatment. These units constitute the donor pools.

Let Y_{it}^{N} denote the annual per capita income for each municipality i at time t in the absence of intervention, for units $i = 1, \dots, J+1$, and periods $t = 1, \dots, T$. Let T_0 be the number of periods before the intervention, where $1 \leq T_0 < T$. Now, let Y_{it}^{I} be the per capita GDP that would be observed for municipality i at time t, given that unit i was treated, i.e., exposed to the intervention during periods $T_0 + 1$ to T.

Assuming the installation of the wind farm in João Câmara had no anticipated effect on the outcome before implementation. Therefore, the effect of the wind farm installation on the municipality's per capita income is given by:

$$\alpha_{1t} = Y_{it}^{I} - Y_{it}^{N} = Y_{1t} - Y_{it}^{N} \quad (01)$$

Once Y_{it}^{I} is observed, the task now is to estimate Y_{it}^{N}, which will be done using a vector of covariates unaffected by the intervention. Considering a $(J+1)$ dimensional weight vector $W = (w_2, \dots, w_{j+1})'$ such that $w_j \geq 0$ for $j = 2, \dots, J+1$ and $\sum_{j=2}^{j+1} w_j = 1$, the estimated effect of the intervention for $t \in \{T_0 + 1, \dots, T\}$ would be $\widehat{\alpha_{1t}} = Y_{1t} - \sum_{j=2}^{j+1} w_j^{*} Y_{jt}$, where Y_{jt} represents the observed per capita GDP for the municipalities that comprise the donor groups after the intervention.

The idea is to estimate the per capita GDP of João Câmara in the absence of intervention, represented by Y_{it}^{N}, through a weighted average of the per capita GDP of similar municipalities during the pre-intervention period in terms of the $(k \text{ x } J + 1)$ covariate matrix X.

The weights for an unbiased estimator of Y_{it}^{N} will be provided by the synthetic control. Even in cases where data is available for only a single pre-treatment period, the synthetic control estimator is unbiased (Abadie, Diamond, Hainmueller, 2010). Each value assigned to W represents a weighted average of available control municipalities. Thus, if we define X_1 as a vector of pre-intervention characteristics for João Câmara and X_0 as a matrix $(k \text{ x } J)$ containing the same variables for untreated municipalities, the optimal weight vector W^{*} is chosen to minimize the Root Mean Squared Prediction Error (RMSPE), given by $||X_1 - X_0 W||$, subject to $w_2 \geq 0, \dots, w_{J+1} \geq 0$ and $w_2 + \dots + w_{J+1} = 1$.

Abadie, Diamond, and Hainmueller (2010) provide all the steps to perform this minimization and a comprehensive description and derivations of the synthetic control method. This methodology aims to compare each treated unit with a synthetic control unit, which consists of a weighted average of all eligible units available for comparison in the database. For robust analyses, placebo tests and the Synthetic Differences-in-Differences method (Arkhangelsky et al., 2021) will be conducted.

4 RESULTS AND DISCUSSION

Table 01 presents the weighted coefficients assigned to each municipality composing the donor pool responsible for generating the synthetic João Câmara. The reported coefficients indicate that the per capita Gross Domestic Product (GDPpc) trajectories of João Câmara, prior to the implementation of wind farms, are accurately replicated by a combination predominantly of Nova Cruz (76.3%), São Miguel (9.8%), and other municipalities (13.9%).

Table 01 – Optimal Weights by Donor Municipality

Municipalities	Weights per municipality
Nova Cruz	0,7630
São Miguel	0,0980
Other municipalities	0,1390

Font: Developed by the authors (2023).
Note: For space reasons, municipalities with weights of 0.0030 (2 municipalities), 0.0020 (6 municipalities), and 0.0010 (137 municipalities) were combined.

Table 02 provides the predictor values for João Câmara, both in the actual and synthetic scenarios, during the pre-intervention period. It can be observed that the covariate values for real João Câmara are close to the covariate values for synthetic João Câmara in the period before the intervention. This similarity indicates that the synthetic control method provides a suitable approximation between the actual municipality of João Câmara and its synthetic counterpart.

Table 02 – Predictor balance in the pre-treatment period

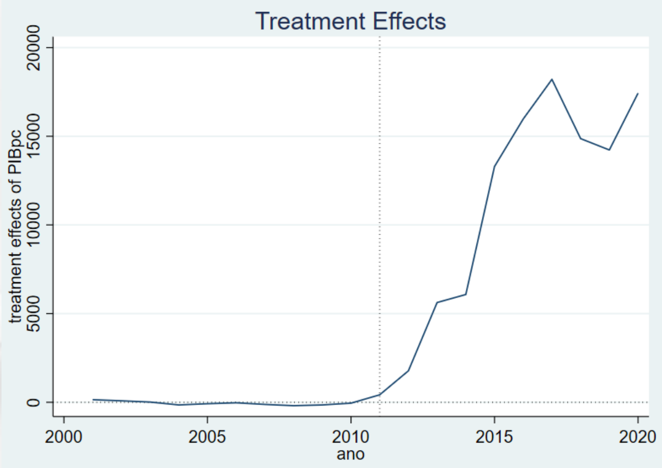
Variable	João Câmara	Synthetic João Câmara
GDPpc (2002)	1.910,86	1.908,41
GDPpc (2003)	2.042,14	2.042,32
GDPpc (2004)	2.054,30	2.056,12
GDPpc (2005)	2.798,83	2.796,46
GDPpc (2006)	3.209,81	3.210,14
GDPpc (2007)	3.798,44	3.798,90
GDPpc (2008)	3.927,14	3.927,46
GDPpc (2009)	4.646,29	4.642,67
GDPpc (2010)	6.475,95	6.476,58
GDPpc (2011)	7.232,10	7.237,02

Font: Developed by the authors (2023).

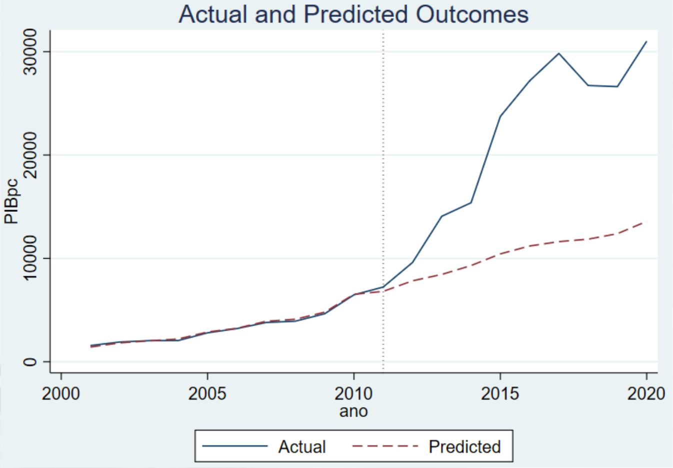
Figure 01 illustrates the effect of the treatment, the actual and predicted trajectories, and the p-values for the Gross Domestic Product per capita (GDPpc) of the municipality of João Câmara and its synthetic equivalent, resulting from the installation of wind farms in the area. Figure 01(A) represents the impact on João Câmara's GDPpc generated by the implementation of wind farms since 2012.

Figure 01 – Gross Domestic Product per capita of João Câmara and synthetic João Câmara

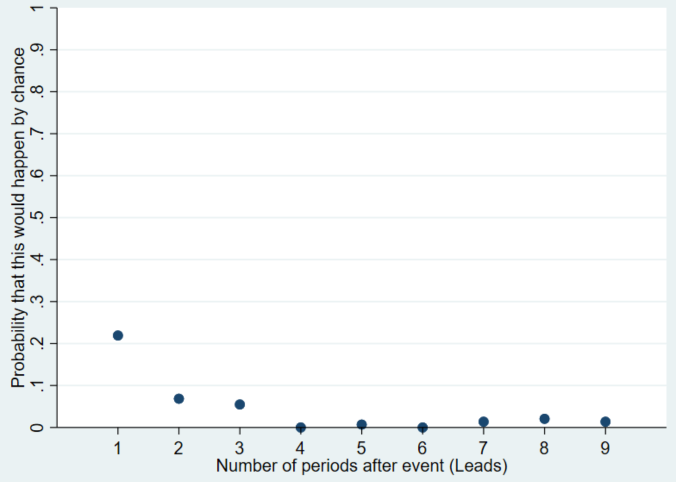
(A) Treatment Effect



(B) Real versus predicted outcome



(C) P-value



Font: Developed by the authors (2023).

In turn, Figure 01(B) presents the GDP per capita trajectories for the municipality of João Câmara and its synthetic equivalent from 2001 to 2020. Figure 01(C) expresses the significance (p-value) of the results presented in Table 03.

This result means that it delineates the actual trajectory of GDP per capita influenced by the installation of wind farms between 2012 and 2020, as well as the predicted trajectory, representing how GDP per capita would have evolved if such installations had not occurred in the municipality in question.

As observed in Figure 01(B), if the wind farms had not been installed, the GDP per capita would have been lower than that recorded during the analyzed period. Figure 01(C) displays the p-values of the GDP per capita results during the period following the installation of the wind farms in the municipality. It is noted that from the second year after the installation of these farms, the effect is statistically significant in all subsequent years, at a significance level of 10% ($p < 0.10$).

Table 03 presents the average heterogeneous effects on Gross Domestic Product per capita (GDPpc) resulting from the installation of wind farms in the municipality of João Câmara during the post-treatment period. The second column shows the average effect on GDPpc due to the implementation of wind farms in João Câmara. The third column displays the effect on GDPpc for the entire post-treatment period, considering the hypothesis that wind farms would not have been installed in the municipality.

Table 03 – Forecast results in post-treatment periods

Year	Actual Outcome	Predicted Outcome	Treatment Effect
2012	9.603,50	7.830,47	1.773,03
2013	14.076,08	8.451,65	5.624,43
2014	15.383,55	9.306,48	6.077,07

2015	23.731,50	10.436,44	13.295,06
2016	27.173,83	11.200,35	15.973,48
2017	29.829,03	11.620,25	18.208,78
2018	26.726,17	11.859,66	14.866,51
2019	26.617,73	12.391,38	14.226,35
2020	31.013,55	13.579,48	17.434,07
Average	22.683,88	10.741,79	11.942,09

Font: Developed by the authors (2023).
Note: all values (R$) are constant for the base year 2020 and have been rounded to the nearest second decimal place.

The fourth column presents the average annual heterogeneous effects of wind farm installation in João Câmara. Finally, in the last row, we find the actual average effects (occurrence of wind farm installation), predicted effects (without the occurrence of wind farms), and the total effect of installing these farms in the municipality. Heterogeneous analysis is crucial for understanding how this average effect has evolved.

As observed in Table 03, the treatment effect varies over the years, all being positive. In the year of the first wind farm installation in 2012, the effect on the municipality's GDP per capita was R$ 1,773.03. From 2013 onward, despite fluctuations, the economic effects of installing wind farms demonstrate a substantial increase, reaching R$ 5,624.43. 2014, the increase was lower than the previous year's at R$ 6,077.07. After the initial three years of wind farm installation, there is a significant annual increase, culminating in an overall average effect of R$ 11,942.09. This pattern is consistent with the literature, suggesting more favorable effects two years after the installation of wind farms (Martini, Jordão, & Grimaldi, 2018).

Considering the results from Table 03 regarding heterogeneous effects, it is imperative to observe a shift in the scenario over the years as investments in the sector intensified. Thus, it can be seen that following the implementation of wind farms, the Gross Domestic Product per capita (GDPpc) showed growth, resulting in an average effect for the analyzed period of approximately R$ 11,942.09. Overall, we conclude that the installation of wind farms consistently promoted a long-term increase in GDPpc in João Câmara compared to the counterfactual scenario.

The results obtained in our analysis are aligned with the findings presented in the literature (Martini; Jordão; Grimaldi, 2018; Xia; Song, 2017; Brown et al., 2012; De Silva et al., 2016), which argue for a positive impact on municipal income from wind farms. These studies attribute the income increase to these wind farms, reinforcing the consistency of the results.

4.1 Robustness Analysis

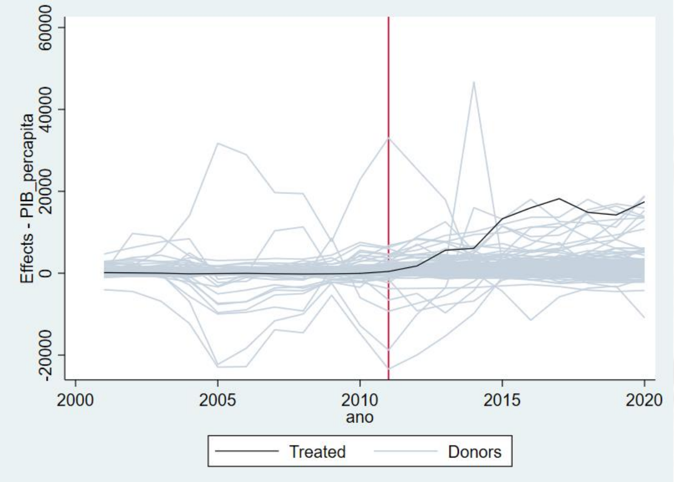
In this subsection, two analyses are outlined to assess the robustness of the results. Initially, we present the placebo test. Additionally, we introduce the synthetic Difference-in-Differences estimator (Arkhangelsky et al., 2021).

4.1.1 Placebo Tests

The placebo test involves estimating the same model for each municipality in the donor group, considering the hypothesis that they underwent the treatment experienced by the municipality of João Câmara. In other words, the test simulates the fictitious installation of wind farms in the donor municipalities. Subsequently, differences between the GDPpc of these municipalities and their respective synthetic counterparts are calculated. The expectation is that there would be no program effect in the other municipalities; therefore, we anticipate that the differences between these municipalities and their synthetics will approach zero. Only João Câmara shows a notable difference between its actual GDPpc and its synthetic (counterfactual) counterpart.

Figure 02 illustrates the result of the placebo test conducted on the considered sample, composed of 148 municipalities. In other words, the figure represents the placebo simulation for the sample covering 148 municipalities. The gray lines highlight GDP per capita performance discrepancies between each municipality in the donor group and their corresponding synthetic versions. The black line overlaid on the graph represents the estimated difference for João Câmara. Through visual analysis, it is observed that João Câmara stands out from most other municipalities.

Figure 02 – Placebo Tests



Font: Developed by the authors (2023).

Therefore, considering the placebo test, we perceive that the results found in the previous section are robust. Thus, the GDP per capita of the municipality of João Câmara, according to the adopted synthetic control, was positively affected by the installation of wind farms.

4.1.2 Synthetic Difference-in-Differences Method

The Synthetic Difference-in-Differences (SDD) method, proposed by Arkhangelsky et al. (2021), combines elements of the Synthetic Control (SC) method and the Difference-in-Differences (DD) method. In other words, SDD relaxes the assumption of parallel trends and assigns weights both in the time dimension and for untreated sample units, aiming to construct a synthetic trajectory for the treated unit in the pre-intervention period. The results obtained through SDD demonstrate robustness. Table 04 presents the average effects resulting from the installation of wind farms on the GDP per capita of the municipality of João Câmara, considering the presence or absence of covariates.

Table 04 – Average effect of the installation of wind farms on João Câmara's GDP per capita

	(1)	(2)	(3)	(4)
Effect	11.951,18***	11.832,50***	11.923,78***	11.853,03***
Statistic t	(2,76)	(3,29)	(3,21)	(3,15)
GDP	No	Yes	No	Yes
Population	No	No	Yes	Yes

Font: Developed by the authors (2023).
Note: It is noteworthy that all estimates for the SDD estimator present a statistical significance level of 1%.

We propose four Synthetic Difference-in-Differences (SDD) models to assess the robustness of the previously obtained results. The first model (column (1)) does not incorporate any covariate. The second model (column (2)) includes only the GDP covariate. The third model (column (3)) incorporates only the Population covariate. Finally, the fourth model (column (4)) includes GDP and Population covariates.

In terms of the economic significance of the model, it is observed that the estimated GDP per capita closely aligns with the results obtained by the SC method. In other words, the economic outcomes support those found in the previously applied synthetic control model, maintaining a statistical significance level of 1%.

5 FINAL CONSIDERATIONS

Political decisions to boost economic development have increasingly encouraged investments in wind energy as a growth strategy. However, a nuanced understanding of these investments' impact remains incomplete. This study contributes to the existing literature by empirically evaluating the effects of wind farm installations on the Gross Domestic Product (GDP) per capita of João Câmara/RN municipality. Using data from the Brazilian Institute of Geography and Statistics (IBGE) and the National Agency of Electric Energy (ANEEL) from 2001 to 2020, the synthetic control method (Abadie; Gardeazabal, 2003; Abadie; Diamond; Hainmueller, 2010) was applied to assess the impact of wind farm installations on the municipality's GDP per capita.

The results highlight a long-term positive and statistically significant increase in João Câmara's GDP per capita due to the installation of wind farms. The robustness of these findings was validated through the placebo test and the Synthetic Difference-in-Differences (SDD) method (Arkhangelsky et al., 2021), confirming the positive impact of wind farm installations on the municipality's long-term economic indicators. An average aggregate increase of approximately R$ 11,942.09 in GDP per capita suggests that wind energy serves as a sustainable source and has the potential to drive economic growth in municipalities where it is implemented. It is important to note that our results indicate that the positive impacts of wind energy on municipal GDP per capita become more pronounced after the second year of project implementation.

These findings have significant implications for policymakers. Firstly, amidst the persistent economic challenges many Brazilian municipalities face, our results advocate that investments in wind energy can act as a catalyst to diversify and strengthen local economies. Secondly, the study underscores that the economic benefits of wind energy increase with installed capacity, highlighting that municipalities with multiple installations and higher generation capacities experience substantial economic advantages. Consequently, policymakers involved in economic development should consider wind farm installations as a viable strategy to stimulate local economic growth, especially in municipalities conducive to this form of energy generation. However, further research is needed on both the positive and negative impacts generated by wind farm installations to comprehensively contribute to municipal, state, regional, and national economic development.

In conclusion, this study not only adds empirical insights into the impact of wind energy on economic development but also underscores the need for ongoing research to inform strategic policy formulation.

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