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The impact of biomass power plants on Brazilian workers' income: a synthetic difference-in-differences approach

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Abstract

Purpose – This research assesses the economic impact of biomass plant installations on Brazilian municipalities, focusing on (1) labor income, (2) sectoral labor income and (3) income inequality.

Design/methodology/approach – Municipal data from the Annual Social Information Report, the National Electric Energy Agency and the National Institute of Meteorology spanning 2002 to 2020 are utilized. The Synthetic Difference-in-Differences methodology is employed for empirical analysis, and robustness checks are conducted using the Doubly Robust Difference in Differences and the Double/Debiased Machine Learning methods.

Findings – The findings reveal that biomass plant installations lead to an average annual increase of approximately R$688.00 in formal workers' wages and reduce formal income inequality, with notable benefits observed for workers in the industry and agriculture sectors. The robustness tests support and validate the primary results, highlighting the positive implications of renewable energy integration on economic development in the studied municipalities.

Originality/value – This article represents a groundbreaking contribution to the existing literature as it pioneers the identification of the impact of biomass plant installation on formal employment income and local economic development in Brazil. To the best of our knowledge, this study is the first to uncover such effects. Moreover, the authors comprehensively examine sectoral implications and formal income inequality.

Keywords Biomass power plants, Brazilian workers, Income

Paper type Research paper

1. Introduction

Renewable electricity must be expanded more rapidly to achieve the milestones outlined in the Net Zero Emissions by 2050 Scenario (IEA, 2022). Biomass represents a renewable energy

JEL Classification — C21, O13, Q42

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source with the potential to significantly contribute to attaining zero-emission targets (Awosusi *et al.*, 2022; Börjesson, Gustavsson, Christersson, & Linder, 1997; Yang *et al.*, 2021). It supports circular bioeconomies (Girard, 2022; Gregg *et al.*, 2020) and stands out as one of the most promising alternatives to replace fossil fuels (Cherubini, 2010; Kumar, Adamopoulos, Jones, & Amiandamhen, 2021). The energy generation from biomass is part of an intricate production chain (Lo *et al.*, 2021; Nunes, Casau, Dias, Matias, & Teixeira, 2023) that can generate numerous socioeconomic benefits for local communities (Esmaeili & Rafei, 2021; Situmorang, Zhao, Yoshida, Abudula, & Guan, 2020). In this context, it becomes imperative to study the implementation of biomass power plants and their local effects, as it bears significant implications for the economic development of municipalities (Awosusi *et al.*, 2022; Gyamfi, Ozturk, Bein, & Bekun, 2021; Shahbaz, Balsalobre-Lorente, & Sinha, 2019; Umar, Ji, Kirikkaleli, & Alola, 2021). Furthermore, understanding and forecasting future energy supply patterns (Umar *et al.*, 2021) and assessing relevant public policies (Young, Anderson, Naughton, & Mullan, 2018) are essential to this exploration. Such policies encompass various aspects, such as infrastructure provisions, energy production and distribution, to foster greater social welfare (Guo, Sun, & Grebner, 2007; Yu, Lu, Hu, Liu, & Wei, 2021).

This research aims to investigate the impact of the installation of biomass power plants on the formal income of Brazilian workers. We employ a rigorous approach to assess the effects of biomass power plant installation and operation on (1) labor income, (2) sectorial labor income and (3) income inequality among workers. To achieve this, we utilized municipal data from various sources, including the Annual Report of Social Information (RAIS) from the Ministry of Labor and Social Security, the National Electric Energy Agency (ANEEL) under the Ministry of Mines and Energy and the National Institute of Meteorology (INMET). The dataset covers 2002 to 2020 and follows a panel data structure.

We employ the Synthetic Difference-in-Differences methodology proposed by Arkhangelsky, Athey, Hirshberg, Imbens, and Wager (2021) to conduct the empirical analysis. We also stratified the treatment variable into four groups based on the potential energy production to explore the heterogeneous treatment effects. To ensure the robustness of the findings, we employ the Doubly Robust Difference-in-Differences estimator (Callaway & Sant'Anna, 2021) and the Double/Debiased Machine Learning (DDML) estimator (Chernozhukov *et al.*, 2018) as supplementary tests. We seek to provide valuable insights into the consequences of biomass power plant establishment on formal income for Brazilian workers. By utilizing a comprehensive dataset and employing advanced methodologies, we contribute to understanding the potential implications on labor income, sectorial labor income and income inequality.

Our findings indicate that installing a biomass plant in a municipality yields an average annual impact of approximately R$687.99 on income. Contextualizing the magnitude of the impact, it is approximately equivalent to an increase of 11.44% on average income. This positive impact predominantly emanates from the industrial and agricultural sectors. The average effects vary significantly based on the energy production potential, ranging from R$595.82 to R$1,310.00. Furthermore, the outcomes derived from the Synthetic Difference-in Differences and Doubly Robust Difference-in-Differences methodologies suggest that installing biomass power plants improves income distribution across the population.

This paper has seven sections in addition to this introduction. In the following section, we review the literature addressing the energy matrix, the regulation of biomass plants in Brazil and the possible impacts of installing a biomass plant. Next, we present the data. Subsequently, we discuss the synthetic Difference-in-Differences methodology. In the fifth section, we show and discuss the results. Robustness analysis is in the subsequent section. The seventh section addresses a cost–benefit analysis of installing biomass power plants. Finally, we present final considerations.

2. Literature review

2.1 Energy matrix and biomass plants

A country's energy matrix can combine various energy generation sources. Among the possible sources, the following stand out: (1) Hydroelectric energy, (2) Nuclear energy, (3) Wind energy, (4) Solar energy, (5) Geothermal energy, (6) Biomass energy, (7) Thermal energy.

Hydroelectric energy generation occurs through the falling water from dammed rivers, which moves turbines connected to generators. Hydroelectric energy is a renewable source widely used in many countries. Nuclear energy generation occurs through nuclear reactions, where the nuclei of atoms are split (nuclear fission) or combined (nuclear fusion). Nuclear energy is considered non-renewable and involves specific risks and challenges, such as the safe management of radioactive waste. Wind energy generation relies on the force of the wind, which moves the blades of wind turbines, converting kinetic energy into electrical energy. Wind energy is a renewable source that has been expanding worldwide. Solar energy is generated from sunlight captured by solar panels that convert solar energy into electricity. Solar energy is a renewable source, and its adoption has increased due to decreased solar panel costs. In recent years, wind and solar energy generation have played a prominent role in Brazil, mainly due to government incentives to stimulate small-scale energy production. Geothermal energy is generated from the heat originating from the Earth's interior. Geothermal energy is harnessed through geothermal power plants, which utilize underground steam or hot water to drive turbines and generate electricity.

The energy derived from biomass power plants involves the controlled burning or decomposition of organic materials, such as agricultural residues, forest waste or energy crops. Specifically, examples of biomass materials include firewood, sugarcane bagasse, used paper and cardboard, sawdust, tree branches and leaves, rice husks and sludge from wastewater treatment plants. Furthermore, biomass energy is considered renewable, but it is crucial to ensure sustainable production. It is worth noting that thermal energy generation occurs through the combustion of fossil fuels such as coal, oil or natural gas in thermal power plants. However, thermal energy can also be obtained through the burning of biomass.

The energy generation process in a biomass power plant revolves around biomass combustion within a boiler to produce steam. This steam is then directed to rotate a turbine connected to a generator, generating electricity. Regarding their generation potential, smaller-scale biomass plants, including bioenergy plants or cogeneration plants, typically possess capacities ranging from 1 MW to 10 MW. These smaller-scale plants are commonly utilized to cater to specific areas such as industries, rural communities or agro-industrial complexes, meeting the demand for electricity and heat in industrial processes or heating systems. On the contrary, larger-scale biomass plants, also called biomass thermal power plants, boast significantly higher capacities ranging from tens of megawatts (MW) to hundreds of megawatts (MW). The primary purpose of these larger-scale plants is to supply electricity to the broader power grid of the country or region.

The generation of energy from biomass power plants offers several advantages. For instance, biomass is a renewable energy source because organic materials such as agricultural residues, forest waste and energy crops can be continuously produced or collected, unlike fossil fuels, which have limited availability and do not replenish in the short term. Thus, biomass energy generation can be a sustainable alternative. Furthermore, biomass production in biomass power plants can involve the local communities surrounding the plant, creating employment opportunities and fostering economic development. It creates local jobs, reduces migration and strengthens regional economies.

2.2 The regulation for installing biomass plants in Brazil

The regulation for installing biomass power plants in Brazil involves different legal and normative aspects. Some of the main regulatory and institutional milestones are as follows: having (1) Environmental Licensing, complying with the general norms of the (2) National Electric Energy Agency (ANEEL); in case of receiving governmental support, such as the Program for the Incentive of Alternative Electric Energy Sources (PROINFA), it must observe the contract and comply with its specific norms; moreover, it is worth highlighting the specific norms and regulations for the installation and operation of biomass power plants. These regulations include technical standards for safety, air quality, emissions control, waste management, and other relevant aspects for these plants' safe and sustainable operation.

Federal Law No. 6,938/1981 instituted the National Environmental Policy [1]. This law establishes the general guidelines for environmental licensing, applicable to several undertakings, including biomass plants. Moreover, environmental licensing is regulated by the Resolution [2] of the National Council for the Environment (CONAMA) nº 237/1997, which provides for the environmental licensing procedure. This resolution establishes the steps and documents necessary to obtain environmental licenses, such as the Preliminary License (L.P.), the Installation License (LI) and the Operation License (L.O.), and, when required, the Environmental Impact Study (E.I.A.) and the Environmental Impact Report (RIMA). It should be noted that environmental licensing may also be subject to specific regulations in each Brazilian state, as state environmental agencies are responsible for conducting the environmental licensing process in their respective territory.

ANEEL is responsible for regulating and supervising the electricity sector in Brazil. Although no specific ANEEL regulations exist exclusively for installing biomass plants, the agency establishes general regulations for all energy generation sources. We highlight the Normative Resolution [3] ANEEL nº 1059/2023. This resolution establishes the general conditions for microgeneration and distributed generation access to Brazil's electric power distribution systems. It elaborates on installing biomass power plants on properties for self-generation of electricity, with the possibility of compensating for excess energy injected into the grid. In addition to establishing the conditions for the procurement of energy from incentivized generation projects, including biomass, it defines the guidelines for entering into contracts for the purchase and sale of electric power between biomass power plant developers and distribution or commercialization agents of electric power. The Normative Resolution [4] ANEEL nº 1000/2021 establishes the guidelines for classifying electric energy generation projects. Furthermore, this applies to biomass generation projects that seek to establish bilateral contracts for purchasing and selling electricity. In addition to these resolutions, ANEEL also issues ordinances, normative instructions and other regulations that may address technical requirements, energy auction procedures and tariffs for the use of the electrical system, among other aspects relevant to the generation of electrical energy by biomass plants.

The Brazilian federal government instituted the Program to Incentive Alternative Sources of Electric Energy (PROINFA) [5] in 2002 to encourage the generation of electricity from renewable sources. Although PROINFA was terminated in 2011, its norms and guidelines are still relevant for installing biomass power plants. In general terms, the program established criteria for selecting electricity generation projects using biomass. These criteria were required to encompass technical, economic, social and environmental aspects. After project selection, the ventures entered into power purchase agreements with Eletrobras, the state-owned energy company. These contracts ensured the purchase of energy generated by the biomass power plant under defined financial and time conditions. The program itself established targets for the participation of each renewable energy source, including biomass. PROINFA was terminated in 2011, so the program's specific regulations are no longer in force. However, the program significantly impacted the development of Brazil's biomass energy sector, encouraging investments and adopting this renewable source for electricity generation.

Lastly, the power plant installation must comply with specific technical standards related to safety, environmental quality, waste management and other relevant aspects. Such standards are dictated by the Brazilian Association of Technical Standards [6] (*Associação Brasileira de Normas Técnicas* - ABNT), which establishes relevant technical standards for installing and operating biomass power plants. For example, the ABNT NBR 16401–1 standard addresses air conditioning and ventilation systems in buildings and may apply to aspects of air quality.

2.3 The socioeconomic impacts and hypotheses

Installing a biomass power plant can generate positive and negative socioeconomic effects, depending on the specific characteristics of the local context. Firstly, installing and operating the biomass plant create direct and indirect employment opportunities in the region. The plant construction may require local labor and hiring services such as transportation and construction. Additionally, the plant's ongoing operation requires workers for maintenance, monitoring and management. Thus, the presence of the biomass power plant in the municipality can contribute to local economic development by reducing unemployment rates and improving the quality of life for people in the region. It can be achieved through an increase in the average income level of the municipality, an increase in formal income and, eventually, a reduction in income inequality. However, it is important to note that if the municipality does not have a sufficient labor force in all economic sectors, some form of worker transfer between sectors may decrease income in specific sub-sectors.

It is also important to emphasize that installing a biomass power plant can improve local infrastructure and public and private services. It is because meeting the needs of the plant and the local population may require improvements in roads, water supply, electrical networks and communication networks. These potential investments can benefit not only the power plant but also the community as a whole. Additionally, the operation of the biomass plant can generate fiscal revenues for local and state governments through taxes and fees. Through a virtuous cycle, these additional revenues can be redirected toward social investments such as education, healthcare, social infrastructure and local development programs, benefiting the community.

So, to measure the impact of installing biomass plants, we propose the following hypotheses:

H1. Installing biomass power plants increases the average salary of formal municipal workers.

H2. Installing biomass power plants affects the average salary of formal workers in different sectors (Agriculture, Industry, Construction, Services, Business and Others);

H3. Installing biomass power plants improves income distribution.

3. Data

The data is from multiple reputable institutions, namely the Annual Report of Social Information (RAIS) from the Ministry of Labor and Social Security, the National Electric Energy Agency (ANEEL) under the Ministry of Mines and Energy and the National Institute of Meteorology (INMET). This dataset covers a municipal panel data structure spanning from 2002 to 2020. The selection of the initial year, 2002, was purposeful as it coincides with the commencement of the government incentive program to expand the Brazilian energy matrix, known as PROINFA. This program's initiation represents a significant milestone, thus justifying its selection as the starting point for data collection. The choice of 2020 as the final year is attributed to the fact that it was the last available year for all the variables utilized in this study. By employing this latest available data, we ensure the currency and relevance of our analysis. The careful selection of the data sources and the period from 2002 to 2020 has led to the constructing of a balanced panel of information. This balanced panel enhances the robustness of our empirical analysis, enabling us to draw meaningful and reliable conclusions based on a comprehensive dataset covering a significant period.

To empirically test the hypotheses formulated in this study, we propose employing various outcome variables sourced from the Annual Report of Social Information (RAIS). These variables encompass essential aspects of income and economic sectors within the municipality. Specifically, we intend to use the following outcome variables: (1) Average wage income in the municipality, (2) average wage income in the agricultural sector in the municipality, (3) average wage income in the industrial sector in the municipality, (4) average wage income in the construction sector in the municipality, (5) average wage income in the services sector in the municipality, (6) average wage income in the business sector in the municipality, (7) average wage income in other sectors in the municipality and (8) municipal income distribution (Gini index). Additionally, we will consider average covariates related to the level of education, categorized by different types of workers: Illiterate, Elementary School, High School and University Education. The sectors of the economy have been classified based on the CNAE 2.0 codes (Agriculture [7], Industry [8], Construction [9], Services [10], Business [11] and Others [12]). It is essential to specify that the "Others" sector in the analysis comprises diverse activities, such as administrative activities and complementary services, public administration, defense and social security, arts, culture, sport and recreation, and international organizations. Including these varied activities in the analysis ensures a comprehensive evaluation of income and economic sectors within the municipality. Moreover, to account for inflation and maintain the accuracy of the data, all variables were deflated using the Brazilian official inflation index IPCA (*Índice Nacional de Preços ao Consumidor Amplo*), which is conducted by the Brazilian Institute of Geography and Statistics (IBGE). The base year for this inflation index is 2020, ensuring that the data is adjusted to reflect the purchasing power and real income value across the study period (Table 1).

The treatment variable is crucial in identifying whether a municipality received a biomass plant, allowing for a comparative analysis between treated and control groups. Biomass power plants are categorized into four groups based on their energy generation potential, enabling a more nuanced examination of the effects of different plant capacities on the outcome variables. The four groups are defined as follows: (1) up to 10 MW: biomass power plants with an energy generation potential of up to 10 megawatts; (2) Between 10 and 50 MW: biomass power plants with an energy generation potential ranging from 10 to 50 megawatts. (3) Between 50 and 100 MW: biomass power plants with an energy generation potential ranging from 50 to 100 megawatts. (4) Between 100 and 500 MW: biomass power plants with an energy generation potential ranging from 100 to 500 megawatts. By stratifying the treatment variable into these distinct groups, the research aims to explore potential variations in the impact of biomass power plant installation on the outcome variables across different plant capacities. Additionally, including average environmental covariates from INMET, such as solar radiation, temperature, relative humidity, gust of wind and wind speed, serves to characterize the municipality's environment. These environmental factors can influence the performance and efficiency of biomass power plants and may also have implications for the local economy and workforce (Table 1).

Figure 1 depicts the chronological evolution of biomass power plant installations in Brazil. It is important to clarify that the data presented in the figure includes only those biomass power plants installed after 2002. Furthermore, to isolate the effect of installing only one plant in each municipality, the analysis focuses solely on municipalities that received one biomass power plant within the specified installation period.

Variables	Treated Mean	Treated S.D.	Controls Mean	Controls S.D.	Sample Mean	Sample S.D.
Outcome variables						
Income	7591.52	3435.13	5971.91	3097.95	6011.83	3114.89
Agriculture	1080.82	573.493	786.29	520.46	793.56	523.60
Industry	1394.24	830.351	898.10	817.04	909.92	820.74
Construction	1070.63	715.792	741.36	729.32	749.81	731.87
Services	1396.11	648.945	1368.61	758.20	1,369.73	756.15
Business	1002.27	450.882	870.84	436.10	874.09	436.64
Others	1647.45	921.879	1306.72	761.54	1,314.72	767.38
Gini	0.33670	0.06304	0.3019	0.07106	0.30269	0.0711
Treatment variables						
Biomass power plant	0.54	0.499	0	0	0.019	0.1365
Biomass P. Plant – 10 MW	0.26	0.439	0	0	0.009	0.0956
Biomass P. Plant – 10–50 MW	0.17	0.373	0	0	0.006	0.0768
Biomass P. Plant – 50–100 MW	0.08	0.272	0	0	0.003	0.0533
Biomass P. Plant – 100–500 MW	0.03	0.165	0	0	0.001	0.0315
Covariates						
Illiterate	0.017	0.039	0.012	0.025	0.012	0.025
Elementary school	0.432	0.169	0.375	0.169	0.377	0.169
High school	0.430	0.143	0.454	0.146	0.454	0.147
University education	0.121	0.060	0.159	0.101	0.158	0.100
Solar radiation	1547.50	1685.19	1552.42	1633.69	1553.28	1641.14
Temperature	23.47	3.030	23.86	3.54	23.84	3.53
Relative humidity	74.04	7.275	74.14	9.12	74.15	9.09
Gust of Wind	4.90	1.291	4.99	1.43	4.99	1.43
Wind speed	2.07	0.893	2.07	0.90	2.07	0.90

Note(s): This table reports descriptive statistics of treated group, control group and complete sample (means and standard deviation - S.D.)
Source(s): Table by authors

Table 1.
Descriptive statistics

4. Method

Arkhangelsky *et al.* (2021) propose the Synthetic Difference-in-Differences (SDD) estimator, which combines the strengths of the Difference-in-Differences (DD) method and the Synthetic Control Method (SCM). Like DD models, SDD allows treated and control units to have distinct pre-intervention trends. Moreover, like SCM, SDD aims to generate a corresponding control unit optimally that substantially reduces the need for parallel trend assumptions. On the other hand, SDD avoids the common pitfalls of DD and SCM In the case of DD, the inability to estimate causal relationships if the parallel trends assumption is not met in aggregate data and the requirement that the treated unit be allocated within a "convex combination" of the control units in the case of SCM.

The objective of SDD is to consistently estimate the causal effect of receiving the treatment variable D_{it} (average treatment effect on the treated – ATT). The ATT estimate proceeds as follows:

$$\left(\widehat{\beta}^{sdd}, \widehat{\mu}, \widehat{\alpha}, \widehat{\tau}\right) = argmin \sum_{i=1}^{N} \sum_{t=1}^{T} \left(Y_{it} - \mu - \alpha_i - \tau_t - D_{it}\beta\right)^2 \widehat{w}_i^{sdd} \widehat{\gamma}_t^{sdd} \quad (1)$$

Estimated by two-way fixed-effects (TWFE), with optimal weights [13] ($\widehat{w}_i^{sdd}$ e $\widehat{\gamma}_t^{sdd}$). Individual fixed effects imply that the SDD will seek to match treated and control units in pretreatment trends and not necessarily in pretreatment trends and levels, allowing for a constant difference between treatment and control units.

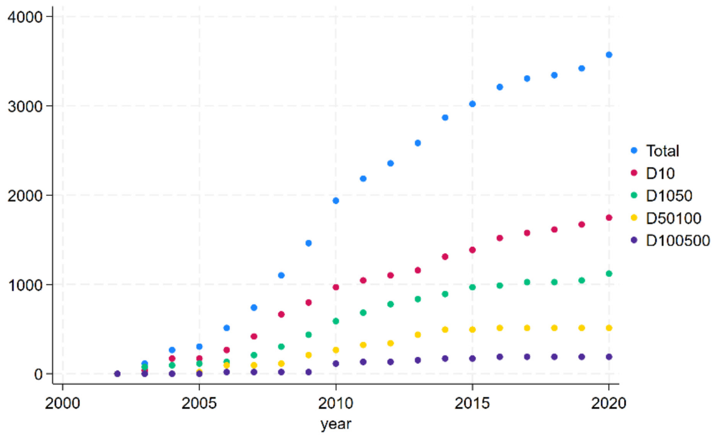

Figure 1.
Biomass power plants evolution in Brazil

Source(s): Figure by authors

To identify the impact of biomass power plant installation on the economic development of Brazilian municipalities, D_{it} takes a value of one when the treated municipality has a functioning biomass power plant and zero otherwise. Specifically, the variable identifies only the municipalities that received the installation of a single plant (we disregard from the analysis the municipalities always treated or those municipalities with more than one plant installed). In addition, for a heterogeneous analysis, we created four other treatment variables (D10 MW, D10-50 MW, D50-100 MW and D100-500 MW) to identify the specific effect due to plant size. The outcome variable Y_{it} will encompass different measures of income. Lastly, α_i controls for municipality fixed effects and τ_t captures temporal fixed effects.

SDD does not require the use of covariates. On the contrary, when using covariates, the model changes, and the estimator is calculated on the residuals of the dependent variable. Thus, the use of covariates can be understood as a preprocessing task, which removes the impact of changes in the covariates on the outcome Y_{it} before calculating the synthetic control, we performed the SDD without covariates as an adequate identification and comparison with the models proposed in the robustness analysis.

5. Results and discussion

Table 2 presents the average formal employment income (column 1), followed by columns 2 to 7, which display sectoral wages (Agriculture, Industry, Construction, Services, Commerce and Others). The table presents five panels. In panel A, we present the results for the treatment variable that identifies the installation of the plant in the municipality, regardless of its energy generation potential. In panels B to E, we present the results considering the size of the plants.

Panel A shows that installing the biomass power plant in the municipality increases workers' income by approximately R$688.00 (column 1). This increase is distributed among all sectors at a significance level of 1%, except for the services sector. It is approximately equivalent to an increase of 11.44% on average income. Notably, there is a significant increase in income in the industry sector (column 3), which represents approximately 35% of the total, followed by the agriculture sector (21%), construction sector (19%) and others

Table 2. Synthetic difference in differences

	(1) Income	(2) Agriculture	(3) Industry	(4) Construction	(5) Services	(6) Business	(7) Others	(8) Gini
A. Average								
Effect	687.99***	143.21***	239.10***	129.63***	17.30	41.94***	110.49***	−0.01065***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.232)	(0.000)	(0.000)	(0.000)
Std. Error	67.18	17.57	13.46	32.31	14.49	10.06	24.11	0.00211
t-stat	10.24	8.15	17.76	4.01	1.19	4.17	4.58	−5.04
B. 10 MW								
Effect	595.82***	113.99***	188.51***	116.04***	46.10***	41.99***	108.92***	−0.0085***
p-value	(0.000)	(0.000)	(0.000)	(0.002)	(0.004)	(0.008)	(0.004)	(0.008)
Std. Error	92.61	19.67	26.50	37.44	15.82	15.78	37.35	0.00318
t-stat	6.43	5.79	7.11	3.10	2.92	2.66	2.92	−2.66
C. 10–50 MW								
Effect	618.47***	154.70***	184.24***	171.45***	−42.46	36.55***	137.31***	−0.0103**
p-value	(0.000)	(0.000)	(0.000)	(0.002)	(0.144)	(0.007)	(0.000)	(0.020)
Std. Error	111.24	29.97	33.09	54.46	29.07	13.65	35.62	0.00442
t-stat	5.56	5.16	5.57	3.15	−1.46	2.68	3.86	−2.32
D. 50-100 MW								
Effect	1,060***	237.44***	396.62***	293.93***	77.56	50.26***	58.63***	−0.01389**
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.215)	(0.000)	(0.001)	(0.011)
Std. Error	84.39	34.27	30.69	47.67	62.62	8.58	16.98	0.00545
t-stat	12.61	6.93	12.92	6.17	1.24	5.86	3.45	−2.55
E. 100-500 MW								
Effect	1,310***	213.98*	636.31***	169.80***	106.34***	84.16***	111.12**	−0.01091*
p-value	(0.000)	(0.063)	(0.000)	(0.001)	(0.010)	(0.000)	(0.035)	(0.050)
Std. Error	262.64	115.10	112.00	53.03	41.16	20.89	52.62	0.00558
t-stat	4.97	1.86	5.68	3.20	2.58	4.03	2.11	−1.96

Note(s): This table reports estimates of the effect of biomass power plant installation on average income salary for Brazilian municipalities. The estimates consider bootstrap standard errors. The symbols *, ** and *** represent statistical significance of 10, 5 and 1%, respectively

Source(s): Table by authors

(16%). In addition to the overall income increase, it is important to highlight that the results show improved income distribution. The Gini index of municipal income demonstrates a significant negative effect (column 8). Therefore, it can be concluded that installing biomass power plants reduces formal income inequality in the beneficiary municipalities.

Panel B shows the heterogeneous effect for plants of up to 10 MW. Installing the biomass power plant in the municipality affects workers' income by approximately R$595.82 (column 1). This increase is distributed among all sectors at a significance level of 1%. Again, the most affected sectors are the industry sector (column 3), which represents approximately 32% of the total, followed by the agriculture sector (19%) and the others (18%). The Gini index shows that the installation of biomass plants leads to a reduction in formal income inequality.

Panel C shows the heterogeneous effect for plants between 10 and 50 MW. The biomass plant increased income by approximately R$618.47 (column 1). This increase is distributed among all sectors at a significance level of 1%, except for the services sector. The Gini index shows that installing biomass power plants reduces income inequality. Again, the industry sector was most affected.

Panel D shows the heterogeneous effect for plants between 50 and 100 MW. The treatment leads to an average increase in income of approximately R$1,060 (column 1). Again, industry is the economic sector that receives the greatest effect, followed by the construction and agriculture sectors. The Gini index shows a reduction in income inequality. Finally, Panel E presents slightly different results from the others. On the one hand, the industry sector continues to be the most positively affected, followed by agricultural and construction sectors. However, the services sector has statistical significance.

Regarding the hypotheses raised (section 2.3.), the results corroborate the hypothesis that installing biomass power plants affects the average wages of formal workers in the beneficiary municipality (Hypothesis 1). It is possible to verify that the average effect was approximately R$688.00 annually. However, these values vary between R$595.00 and R$1,310.00, depending on the production capacity of the installed plant. The results also corroborate hypothesis 2, that the effect is different between sectors of the economy. It is important because it enables a better understanding of income distribution mechanisms in the beneficiary economy.

Let us evaluate this hypothesis 3 in more depth. Considering the magnitude of the effects and the average Gini index of the municipalities (Table 2), we can see a reduction of approximately 3.26% in income inequality (Table 3). From the results, it is possible to state that installing biomass power plants generated a better formal income distribution in the local economy (Hypothesis 3).

6. Robustness analysis

This section examines whether the findings remain robust to a different empirical method. First, we propose using the doubly robust differences-in-differences estimator proposed by

	(1) Average	(2) 10 MW	(3) 10–50 MW	(4) 50–100 MW	(5) 100–500 MW
Effect	−0.01065	−0.0085	−0.0103	−0.01389	−0.01091
Gini mean	0.32673	0.3237901	0.3208633	0.3254311	0.3893516
Difference	0.31608	0.3152901	0.3105633	0.3115411	0.3784416
Var. (%)	−3.26	−2.63	−3.21	−4.27	−2.80

Note(s): This table reports estimates of the effect of biomass power plant installation on municipalities Gini
Source(s): Table by authors

Table 3.
Impact on Gini index

Callaway and Sant'Anna (2021). Subsequently, we propose the DDML and Chernozhukov *et al.* (2018) estimators.

6.1 Doubly robust difference in differences

Callaway and Sant'Anna (2021) proposed a robust difference-in-differences estimator (CSDD) for cases with treatments occurring at different points in time. The authors' approach to this problem involves disaggregating the staggered treatment DD into multiple 2×2 canonical DDs. They aim to identify the specific timing of treatment for certain individuals and separate the analysis into specific blocks or "building blocks." Under the assumptions of (1) conditional parallel trends, (2) non-anticipation of treatment effects, (3) overlap in covariates and (4) the vector of outcome variables and treatment status being i.i.d. with distribution F that satisfies parallel trends. This estimation procedure is called doubly robust by combining the outcome regression approaches (Heckman, Ichimura, & Todd, 1997, 1998) with the propensity score (Abadie, 2005) to obtain a DD configuration with multiple periods.

The average effect of treatment on the treated (ATT) for group (g) in period (t) is estimated semi-parametrically by the following equation:

$$ATT(g,t) = E\left[\left(\frac{G_g}{E[G_g]} - \frac{\frac{p_g(X)C}{1-p_g(X)}}{E\left[\frac{p_g(X)}{1-p_g(X)}\right]}\right)\left(Y_t - Y_{g-1} - \mu_{g,t}(X)\right)\right] \tag{2}$$

where $p_g(X)$ (the propensity score) represents the probability of belonging to the treated group (g) or control group (C), and $\mu_{g,t}(X) = E[Y_t - Y_{g-1}|X, C = 1]$. Unlike a traditional DD approach, the main parameter of causal interest here is an average group treatment effect, given by $ATT(g,t)$, being a function of treatment group (g) and period (t).

Table 4 presents the effects of the robustness analysis. Overall, the Doubly Robust Difference in Differences corroborated the effects found previously. Here, we see that the average effects on wages are lower than previously. That is, wages increased between R$454.78 and R$826.25, with an average of R$579.29. However, again, the distribution of this income occurs mainly in the industry, followed by agriculture and others. It should be noted that in all analyses, the installation of the plant led to a better income distribution for workers in the treated municipalities.

6.2 Double/debiased machine learning

Chernozhukov *et al.* (2018) proposed an estimator to estimate the causal effect between variables using machine learning (ML), which was named DDML. The algorithm proposed by the authors seeks to carry out an orthogonalization process based on the Frisch–Waugh–Lovell (FWL) theorem. The estimator seeks to mitigate selection bias and treatment bias in the data, which can skew causality estimates. Generally, the estimator procedure takes place in two steps that combine selection bias correction with treatment bias correction. It uses ML models to predict selection and outcome, and it fits those models using the residuals to estimate corrected causal effects.

The DDML algorithm allows the use of five different models (Partial, Interactive, IV, IVF and LATE). For the research problem of this article, the models: Partial and Interactive are the most adequate. The partially linear model is represented as follows:

$$Y_{it} = \alpha D_{it} + X_{it}\beta + \varepsilon_{it} \tag{3}$$

Table 4. Callaway and Sant'Anna difference in differences (CSDD)

	(1) Income	(2) Agriculture	(3) Industry	(4) Construction	(5) Services	(6) Business	(7) Others	(8) Gini
A. Average								
Effect	579.29***	120.09***	247.74***	49.03	16.22	31.35***	114.86***	−0.01352***
p-value	(0.000)	(0.000)	(0.000)	(0.117)	(0.379)	(0.000)	(0.000)	(0.000)
Std. Error	56.96	17.92	28.34	31.32	18.45	8.19	22.04	0.0031
z-stat	10.17	6.70	8.74	1.57	0.88	3.83	5.21	−4.35
B. 10 MW								
Effect	454.78***	81.40***	177.92***	40.42	22.16	30.81**	102.07***	−0.0125***
p-value	(0.000)	(0.001)	(0.000)	(0.343)	(0.290)	(0.017)	(0.004)	(0.006)
Std. Error	85.32	23.75	44.10	42.60	20.96	12.87	35.72	0.0046
z-stat	5.33	3.43	4.03	0.95	1.06	2.39	2.86	−2.75
C. 10–50 MW								
Effect	585.42***	143.65***	232.73***	86.97*	−49.21	29.26**	142.01***	−0.0154***
p-value	(0.000)	(0.000)	(0.000)	(0.055)	(0.198)	(0.021)	(0.000)	(0.005)
Std. Error	95.96	29.84	47.02	45.25	38.26	12.69	39.14	0.00545
z-stat	6.10	4.81	4.95	1.92	−1.29	2.31	3.63	−2.83
D. 50–100 MW								
Effect	826.25***	184.76***	374.44***	105.72	57.02	28.82*	75.48**	−0.01338**
p-value	(0.000)	(0.000)	(0.000)	(0.340)	(0.206)	(0.086)	(0.015)	(0.046)
Std. Error	121.96	48.87	55.81	110.82	45.07	16.78	30.92	0.0067
z-stat	6.77	3.78	6.71	0.95	1.27	1.72	2.44	−1.99
E. 100–500 MW								
Effect	707.08***	199.97	490.34***	−180.02	52.98	44.78*	99.03*	−0.02899**
p-value	(0.007)	(0.118)	(0.000)	(0.276)	(0.490)	(0.073)	(0.064)	(0.023)
Std. Error	262.97	127.82	126.92	165.18	76.78	24.97	53.48	0.0127
z-stat	2.69	1.56	3.86	−1.09	0.69	1.79	1.85	−2.28

Note(s): This table reports estimates of biomass power plant installation's effect on Brazilian municipalities' average income salary. The estimates consider wild bootstrap standard errors. The symbols *, ** and *** represent statistical significance of 10, 5 and 1%, respectively. Control group "never treated" outcome model: least squares; Treatment model: inverse probability
Source(s): Table by authors

$$D_{it} = m(X_{it}) + v_{it} \tag{4}$$

where D_{it} is a treatment binary variable. The objective is to estimate "α" controlling for the covariates X_{it}. To that end, we estimate the conditional expectations $E[Y|X]$ and $E[D|X]$ using supervised ML. The interactive model is represented as follows:

$$Y_{it} = g(D_{it}, X_{it}) + \varepsilon_{it} \tag{5}$$

$$D_{it} = m(X_{it}) + v_{it} \tag{6}$$

It relaxes the assumption that X_{it} and D_{it} are separable. For this second model, the conditional expectations $E[D|X]$, and $E[Y|X, D]$ are estimated using ML. We propose two learners for each conditional expectation (first with linear regression with fixed effects controls for time and individuals, and the second with the Random Forest method). Furthermore, we consider the number of cross-fitting folds of four, with two repetitions.

Table 5 presents the results with the linearly partial model described in (3) and (4). This model is quite intuitive and resembles traditional differences-in-differences analyses.

Table 6 presents the results found with the interactive model. In this model, the algorithm considers the most flexible relation for causal identification, as described in (5) and (6). The results follow the same presentation as the previous ones. It should be noted that all estimates obtained statistically significant relationships at a significance level of 1%, except for the services sector in the heterogeneous analysis with the installation of a power plant with a potential between 10 and 50 MW.

Although the results for average and sectoral incomes (Columns 1 to 7, Panel A) are relatively close, in terms of impact magnitude and significance level, to those found by the SDD (Table 2, Panel A). It is noticed that the results through the DDML-interactive present a greater variability of the effects when we consider the heterogeneous effects (Panel B to E). For example, installing a plant of up to 10 MW increases income by approximately R$470.00. A plant between 100 and 500 MW increases the municipality's workers' income by approximately R$2,210.00. This greater variability of the analysis discords than the interval found by the SDD. Regarding sectorial propagation of the effect, the main benefited sector is industry. However, in the DDML analysis, the construction, services and business sectors gained statistical relevance and consistency in the heterogeneous analyses.

A curious result to be highlighted is that in both analyses using the DDML (Tables 5 and 6), the Gini index (Column 8) showed the opposite sign of those found by the SDD and CSDD. That is, through the DDML method, the installation of biomass power plants increases the concentration of workers' income.

7. Cost and benefits analysis

This section presents a simulation of the installation costs for four potential biomass power plant projects with varying production capacities: 5 MW, 50 MW, 100 MW and 500 MW. We are considering constant values from 2020. The financial analysis provided here is for illustrative purposes and is a straightforward representation of the costs of setting up these biomass power plants. The first column of Table 7 displays the estimated installation costs for each plant capacity. Notably, these costs represent only a portion of the total investment in a biomass power plant. Other significant expenses include ongoing operation and maintenance costs, including biomass acquisition, fuel costs, equipment operation, personnel expenses and other factors. In the analysis, we assume that, on average, one ton of biomass can generate 1 MW/h of electricity, valued at R$ 60. Considering eight hours of daily operation and 20 days per month, the annual inputs (biomass) costs are presented in column 4. The annual revenue generated by the plants is displayed in column 5 (assuming

Table 5. Double/debiased machine learning – partial

	(1) Income	(2) Agriculture	(3) Industry	(4) Construction	(5) Services	(6) Business	(7) Others	(8) Gini
A. Average								
Effect	879.28***	116.38***	333.66***	161.51***	37.98***	59.23***	180.53***	0.0229***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Std. Error	24.50	5.04	12.38	10.31	9.70	3.27	6.59	0.0010
z-stat	35.89	23.08	26.94	15.67	3.92	18.13	27.41	22.95
B. 10 MW								
Effect	450.72***	74.39***	133.99***	72.30***	27.76**	33.28***	128.47***	0.01575***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.033)	(0.000)	(0.000)	(0.000)
Std. Error	32.82	7.13	14.94	13.95	13.00	4.61	8.95	0.0014
z-stat	13.73	10.44	8.97	5.18	2.14	7.22	14.35	11.68
C. 10–50 MW								
Effect	852.01***	97.43***	332.53***	184.51***	8.75	64.34***	185.01***	0.02098***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.594)	(0.000)	(0.000)	(0.000)
Std. Error	41.72	8.33	20.18	17.80	16.40	5.36	10.51	0.00164
z-stat	20.42	11.69	16.48	10.37	0.53	12.00	17.60	12.78
D. 50–100 MW								
Effect	1628.03***	269.32***	578.12***	241.27***	187.95***	75.83***	209.94***	0.02173***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Std. Error	64.97	13.91	28.77	27.97	25.66	8.68	17.41	0.00265
z-stat	25.06	19.36	20.09	8.62	7.32	8.74	12.06	8.20
E. 100-500 MW								
Effect	2054.93***	131.93***	1065.84***	343.89***	69.38*	147.88***	300.45***	0.06515***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.070)	(0.000)	(0.000)	(0.000)
Std. Error	93.90	20.44	40.92	39.08	38.27	13.50	28.82	0.00377
z-stat	21.88	6.45	26.05	8.80	1.81	10.96	10.43	17.30

Note(s): This table reports estimates of biomass power plant installation's effect on Brazilian municipalities' average income salary. The estimates consider bootstrap standard errors. The symbols *, ** and *** represent statistical significance of 10, 5 and 1%, respectively
Source(s): Table by authors

Table 6. Double/debiased machine learning – interactive

	(1) Income	(2) Agriculture	(3) Industry	(4) Construction	(5) Services	(6) Business	(7) Others	(8) Gini
A. Average								
Effect	812.84***	106.59***	310.95***	159.30***	35.41***	52.87***	166.88***	0.0219***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Std. Error	30.25	5.77	13.97	11.62	8.51	4.23	9.02	0.00099
z-stat	26.87	18.48	22.25	13.70	4.16	12.49	18.49	22.22
B. 10 MW								
Effect	469.64***	78.19***	136.98***	72.08***	40.76***	35.89***	134.10***	0.01642***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
Std. Error	35.76	8.43	17.07	17.37	12.19	5.30	12.13	0.00151
z-stat	13.13	9.28	8.02	4.15	3.34	6.78	11.06	10.87
C. 10–50 MW								
Effect	776.58***	87.01***	313.01***	178.58***	16.08	59.34***	167.72***	0.02134***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.279)	(0.000)	(0.000)	(0.000)
Std. Error	51.78	8.60	23.93	17.11	14.86	7.54	16.46	0.00159
z-stat	15.00	10.12	13.08	10.44	1.08	7.87	10.19	13.40
D. 50–100 MW								
Effect	1739.18***	278.22***	649.03***	272.04***	214.24***	86.36***	235.80***	0.02448***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Std. Error	64.38	18.95	29.96	25.48	25.83	7.16	17.73	0.00197
z-stat	27.02	14.68	21.67	10.68	8.29	12.07	13.30	12.43
E. 100–500 MW								
Effect	2209.86***	149.03***	1149.53***	404.55***	138.18***	179.78***	339.96***	0.0699***
p-value	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Std. Error	115.42	24.15	57.59	38.80	22.88	25.94	42.72	0.003668
z-stat	19.15	6.17	19.96	10.43	6.04	6.93	7.96	19.06

Note(s): This table reports estimates of biomass power plant installation's effect on Brazilian municipalities' average income salary. The estimates consider bootstrap standard errors. The symbols *, ** and *** represent statistical significance of 10, 5 and 1%, respectively
Source(s): Table by authors

Table 7.
Cost and benefits analysis

	(1) Installation costs (R$)	(2) Program interest (10%)	(3) Energy production capacity	(4) Inputs annual costs	(5) Annual generation revenue	(6) 20-Year cash flow
Biomass plant A	20 million	2 million	5 MW	576,000	3.360.000	24533671.81
Biomass plant B	200 million	20 million	50 MW	5,760,000	33,600,000	245336718.13
Biomass plant C	400 million	40 million	100 MW	11,520,000	67,200,000	490673436.27
Biomass plant D	2 billion	200 million	500 MW	57,600,000	336,000,000	2453367181.33

Note(s): This table reports projections of costs and revenues for biomass plant installation

R$350,00/MWh price). Moreover, the table provides a 20-year cash flow for each of the four biomass power plants (assuming 9.5% annual discount rate). Based on the analysis, it is estimated that the investments made in these plants can potentially be paid off within a period ranging from 15 to 20 years. It is essential to emphasize that this financial simulation is for illustrative purposes only and may not represent the actual costs and revenues of specific biomass power plant projects. Actual investment returns and payback periods may vary depending on real-world factors, market conditions and operational efficiencies.

The additional analysis incorporating potential socioeconomic gains presents compelling results that further reinforce the attractiveness of investing in biomass power plants. For a city with 50,000 inhabitants, the estimated average increase in formal employment income amounts to R$34,399,500 per year. Over 20 years, this translates to a substantial total of R$687,990,000. Furthermore, when considering the heterogeneous effects across different biomass power plant capacities, the results highlight even more promising outcomes: (1) For a plant with a production capacity of up to 10 MW, the average effect per year is R$29,791,000, resulting in a cumulative effect of R$595,820,000 in 20 years. (2) For a plant with a production capacity between 10 and 50 MW, the average annual effect is R$40,923,500, leading to a cumulative effect of R$760,570,000 in 20 years. (3) For a plant with a production capacity between 50 and 100 MW, the average effect per year is R$53,000,000, resulting in a cumulative effect of R$1,060,000,000 in 20 years. (4) For a plant with a production capacity between 100 and 500 MW, the average annual effect is R$65,500,000, leading to a cumulative effect of R$1,310,000,000 in 20 years.

From a financial standpoint, it is evident that the investment in biomass power plants is likely to pay off in approximately 20 years. However, the economic perspective reveals an even more favorable outlook, with the investment potentially paying off in a shorter time frame. It is primarily due to the positive effects triggered by installing the power plant, which includes increasing the average income of formal employment, stimulating local economic sectors and reducing local income inequality. These significant socioeconomic benefits add further weight to the case for investing in biomass power plants. The interplay between financial viability and economic development underscores the potential positive impact such projects can have on the overall welfare and prosperity of the municipality and its residents.

8. Final remarks

This article represents a groundbreaking contribution to the existing literature as it pioneers the identification of the impact of biomass power plant installation on formal employment income and local economic development in Brazil. To the best of our knowledge, this study is the first to uncover such effects. Moreover, we undertake a comprehensive examination of sectoral implications and income inequality. The outcomes indicate a significant average salary increase of approximately R$688.00, providing direct benefits to workers. Contextualizing the magnitude of the impact, it is approximately equivalent to an increase of 11.44% on average income. Notably, the primary income generation mechanisms are observed in the industry and agriculture sectors. Furthermore, the effects display heterogeneity, varying between R$595.82 and R$1310.00 based on the plant's energy production potential. Additionally, our SDD and Doubly Robust Difference in Differences results reveal a noteworthy improvement in income distribution following biomass power plant installation. The empirical evidence successfully corroborates the three hypotheses proposed in this study: (1) installation of biomass power plants lead to an increase in the average salary of formal municipal workers, (2) the impact on the average salary of formal workers varies across different sectors and (3) biomass plant installation positively influences income distribution. The SDD methodology effectively addresses potential endogeneity concerns associated with the treatment by constructing a synthetic control group for each treated municipality. Nevertheless, it is imperative to acknowledge that this method does not offer a comprehensive solution. The existence of unobserved variables introduces an ongoing risk to the internal validity of the findings. Furthermore, the validity of the methods employed in robustness analyses hinges upon fulfilling all their assumptions. Consequently, prudent interpretation of the results derived from these methodologies is essential, accompanied by a discerning consideration of the inherent limitations associated with each approach.

The cost–benefit analysis indicates that investment in biomass power plants will become profitable in approximately 15 and 20 years. However, from an economic standpoint, this investment yields returns even sooner. The positive impacts emanate from rising average formal employment income, fostering dynamism among local economic sectors and mitigating local income inequality.

These findings hold significant implications for the Brazilian economy and other developing countries. At the local level, the increase in income and the more equitable distribution of resources strengthen communities affected by power plant installation. Additionally, the observed gains in the industry sector underscore the importance of diversifying the energy matrix and investing in renewable sources to stimulate regional economic growth.

This research presents a valuable contribution in the international arena, addressing an unexplored gap and enriching discussions on sustainable energy and economic development. By highlighting the socioeconomic benefits of biomass power plant installations, our results promote public policies and investments that facilitate the transition to clean energy sources across various countries. Consequently, this research provides empirical evidence to inform decision-making, drive progress and foster positive impacts locally and globally.

Notes

1. https://www.planalto.gov.br/ccivil_03/leis/l6938.htm
2. http://conama.mma.gov.br/?option=com_sisconama&task=arquivo.download&id=237
3. http://www2.aneel.gov.br/cedoc/ren20231059.pdf
4. http://www2.aneel.gov.br/cedoc/ren20211000.pdf
5. https://www.planalto.gov.br/ccivil_03/leis/2002/l10438.htm
6. https://www.abnt.org.br/
7. CNAE 2.0 codes: 01, 02, and 03.

8. CNAE 2.0 codes: 05 to 39.
9. CNAE 2.0 codes: 41, 42 and 43.
10. CNAE 2.0 codes: 49, 50, 51, 52, 53, 55, 56, 58, 59, 60, 61, 62, 63, 64, 65, 66, 68, 69, 70, 71, 72, 73, 74, 75, 94, 95, 96, and 97.
11. CNAE 2.0 codes: 45, 46, and 47.
12. CNAE 2.0 codes: 77, 78, 79, 80, 81, 82, 84, 85, 86, 87, 88, 90, 91, 92, 93, and 99.
13. The procedure to identify the optimal weights can be found in Arkhangelsky *et al.* (2021), pages 4091 and 4092.

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