Bringing to light a new energy path: the case of the state of Minas Gerais, Brazil

Trazendo à luz um novo caminho energético: o caso de Minas Gerais, Brasil

Ana Pimenta Ribeiro [1]

[1] *PhD in Environmental Planning, Postdoctoral Researcher, PPGSAT (Associated Master's Program of UFMG/Unimontes in the field of Society, Environment, and Territory), Montes Claros, MG, Brazil*
E-mail: piperaceae@gmail.com

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ABSTRACT

In Brazil, more than 55% of the energy comes from hydroelectricity, making the system highly vulnerable in the context of global climate change, with precipitation and temperature shifts over the years. Characterised by its multiple opportunities in sources and conversion technologies for energy, biomass has a high potential to become responsible for a relevant share of the renewable energy supply. Previous studies on biomass energy production in Brazil confirm promising results. This paper highlights possibilities for biomass power generation in Minas Gerais State. To estimate energy productivity, a Sustainable Technical Coefficient was adopted: a conservative index that considers the portion of residues that could be used to maintain the integrity of the soil. This index was applied with the data on silviculture and selected crop yields. The local energy demand was also calculated and compared to the potential energy production. Results show that 78% of the municipalities could have their basic energy needs and 18% of the demand for productive uses met by crop residues and silviculture production. For the state of Minas Gerais, with its tradition of agriculture, biomass residual energy is viable and should be considered by policymakers.

Keywords: Biomass energy. Sustainable development. Renewable energy. Energy potential.

RESUMO

No Brasil, mais de 55% da energia provém de hidroeletricidade, tornando o sistema altamente vulnerável no contexto das mudanças climáticas globais, com alterações na precipitação e temperatura ao longo dos anos. Caracterizada por suas múltiplas possibilidades de fontes e tecnologias de conversão para energia, a biomassa possui um alto potencial para se tornar responsável por uma parcela relevante no fornecimento de energia renovável. Estudos anteriores sobre a produção de energia a partir de biomassa no Brasil confirmam resultados promissores. Este artigo destaca as possibilidades para geração de energia a partir de biomassa no estado de Minas Gerais. Para estimar a produtividade energética, adotou-se um Coeficiente Técnico Sustentável: um índice conservador que considera a porção de resíduos que poderia ser utilizada mantendo a integridade do solo. Esse índice foi aplicado juntamente com os dados de silvicultura e rendimento de culturas selecionadas. A demanda local de energia também foi calculada e comparada com o potencial de produção desta. Os resultados mostram que 78% dos municípios poderiam suprir suas necessidades básicas de energia e que 18% da demanda

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para usos produtivos poderia ser atendida pelos resíduos da produção agrícola e da silvicultura. Para o estado de Minas Gerais, com sua tradição agrícola, a energia residual proveniente da biomassa é viável e deve ser considerada pelos formuladores de políticas públicas.

Palavras-chave: *Energia de biomassa. Desenvolvimento sustentável. Energia renovável. Potencial energético.*

1 INTRODUCTION

Brazil presents a unique model for the energy sector's structural development: having advanced in hydropower technology since the 19th century, which has dominated the country's energy matrix since the 1970s. During this period, several supply crises were faced. The most severe occurred in 2001 when general blackouts began. This marked a turning point in the country, with the resumption of energy projects to guarantee the supply of energy to the population. Interestingly, the source of most of this energy remained the same: hydroelectricity (GOMES *et al*., 2002). The two biomes with the highest levels of species endangerment and fragmentation, the Cerrado and Amazon (OLIVEIRA *et al*., 2017; VEDOVATO *et al*., 2016), contain about 70% of the potential for hydropower production (FERREIRA *et al*., 2014). The negative impacts of the projects on the way of life of local communities on the river's surroundings and nature are hard to avoid. Regardless of the Brazilian Environment Agency requiring specific conditions and limitations for the execution of such projects, the dam's construction continued to defy these restrictions and create irreparable impacts on the environment and social areas (ABRAMOVAY, 2014; FEARNSIDE, 2009; FEARNSIDE; PUEYO, 2012; FUCHS, 2016; WINEMILLER *et al*., 2016). Moran *et al*. (2018) point out that without considering the real social, environmental and cultural costs involved in the water dams construction, it cannot be considered a sustainable energy source. Dávalos, Rodrigues Filho and Litre (2021) offered a comprehensive discussion not only on how the dams have impacted the way of life of indigenous communities but also on the necessity of considering their knowledge when formulating public policies.

In a country such as Brazil, where hydro energy represents not only the highest share in the energy matrix but also a fragile energy source in a climate change context, the assessment of alternatives that minimise environmental impacts, promote the sustainable development of the population, and guarantee the energy security should be seriously considered. According to (RIBEIRO; RODE, 2016), the state of Minas Gerais in Brazil presents favourable characteristics for developing biomass energy initiatives. The authors conducted an analysis to find ideal regions to develop new biomass energy initiatives, considering the local demand, transmission lines, existing energy sources and environmental constraints (land use and environmental preservation factors). The state of Minas Gerais presented a higher potential to develop a biomass energy initiative, respecting the environmental fragilities and its regulations.

This paper assesses an estimation of the regional potential from Minas Gerais state for energy production from biomass residues; recommendations from literature for how much residue could be removed without damaging the soil are also considered. This potential energy production is compared to the local energy demand. We aimed to answer the following questions: 1) How much energy from residues can be produced sustainably without compromising the soil? And 2) Can sustainable potential meet the local energy demand?

2 BACKGROUND

Brazil has experienced precipitation and temperature shifts in the context of global climate change over recent years. Considering the lack of seasonality in Brazil, the impact of these shifts on electricity generation has been massive and has negatively impacted the population's quality of life. More than 55% of the energy for the whole country comes from hydroelectricity, obtained from a mix of energy sources that makes the system highly vulnerable (Figure 1) (EPE, 2022). Without investment in the sector, the necessary amount of water, and alternative sources of clean energy, the country is more dependent than ever on natural gas thermoelectric energy generation as an alternative to meet its demand (WELFLE, 2017). This makes the system expensive and harmful to the environment (GOMES, 2014).

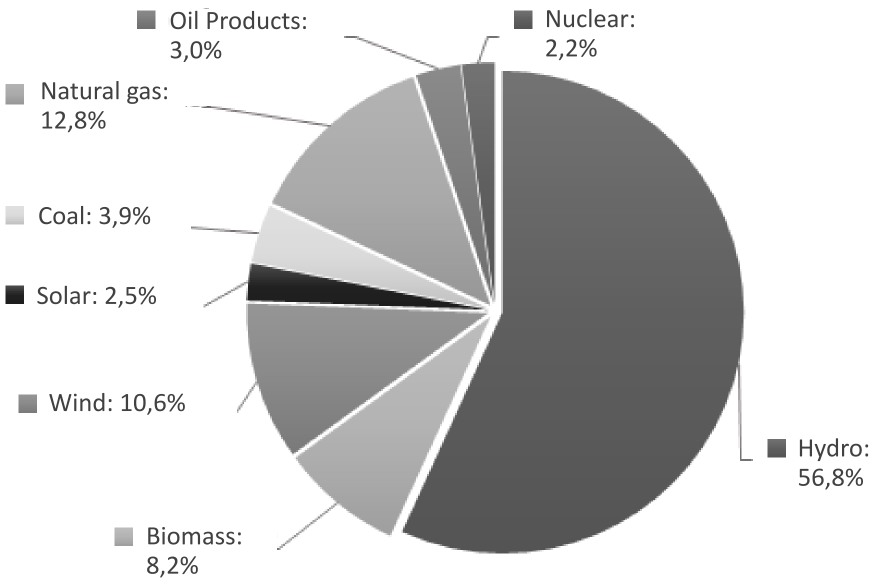

Figure 1 | Domestic electric supply by source

Source: (EPE, 2022).

A relevant change in the energy sector requires investment, legislative and organisational changes, combining environmental considerations and a set of multi-criteria local planning and public participation (HAAREN *et al*., 2012). According to Abramovay (2014), despite being responsible for a small share of the world's energy matrix (3%), the increasing use of modern renewable energy sources (solar, wind, geothermal and modern biomass) lean towards exponentially lowering their costs and thus, make them more generally accessible. A distributed energy production system from renewable technologies would be able to provide a central source of renewable environmental-friendly energy.

Biomass energy is characterised by its diverse sources and conversion technologies for energy, presenting a relevant potential for supply through renewable energy. Biomass includes plant material produced through photosynthesis and all its by-products, such as cultivated crops, forest wood, animal manures, and organic matter (VIDAL; HORA, 2011). A considerable amount of research has already been developed on the topic of cleaner, cheaper and accessible energy sources in a diverse sort of regions such as Peru (LILLO *et al*., 2015), Spain (DÍAZ-CUEVAS; DOMÍNGUEZ-BRAVO; PRIETO-CAMPOS, 2019), Italy (PALMAS *et al*., 2012), Saudi Arabia (ABDEL DAIEM; SAID, 2022), Greece (SKOULOU *et al*., 2011), Germany (PALMAS; SIEWERT; VON HAAREN, 2015), China (SHAPIRO-BENGTSEN *et al*., 2022), South Africa (BATIDZIRAI *et al*., 2016) and Southern Asia (BHATTACHARYYA, 2014), as some examples of the many researches present different methods to explore the best opportunities for renewable energy generation. Responsible for 8,2% of the energy supply in Brazil (EPE, 2022), previous studies on biomass energy production conclude that it is an option that should be considered in developing the country's energy sector. A national-wide methodology was presented in the Brazilian Atlas of Bioenergy (COELHO; MONTEIRO; KARNIOL, 2012). There, it was considered residual energy production from agriculture and silviculture activities, liquid swine sewage and solid urban waste in sanitary landfills. Maps were used to present the results to each region of the country, considering different conversion efficiency scenarios.

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The Brazilian Energy Research Office produced the Rural Residues Energetic Inventory (EPE, 2014) to explore the potential as an energy source from agriculture, agroindustry and livestock residues. A summary of different sources was presented, detailing the agriculture production and the estimation of its residues. Considering different conversion technologies, a potential of 48 million tonnes for agriculture and livestock waste was estimated regarding the technical potential for biomethane and energy production.

Another example of biomass energy potential assessment in Brazil is the Biomass Residues as Energy Source to Improve Energy Access and Local Economic Activity in low HDI regions of Brazil and Colombia (BREA Project) (GBIO *et al*., 2015). A cooperative effort between Brazilian and Colombian scientists presented a complete data set on energy generation from residues. The target of the study was to "develop a better knowledge of energy requirements for productive purposes among poor households in urban and rural areas of Brazil and Colombia (many of them in isolated regions), which could allow inputs for targeted policy interventions" (GBIO *et al*., 2015). The methodology encompassed an assessment of different conversion technologies, potentials, policies, scenarios, and barriers to the development of bioenergy for 32 municipalities in the Brazilian Amazonian region.

Regarding other renewable energy sources, biomass energy requires needs the major area per produced energy unit (BLASCHKE *et al*., 2013b), and it could be related to a potential conflict with other land uses (SÖDERBERG; ECKERBERG, 2013). Without considering careful planning, the competition between biomass energy, conservation, agriculture, and forestry is inevitable (BLASCHKE *et al*., 2013a). Concerning sustainability, any enterprise that seeks biomass as a source of power must guarantee soil health, biodiversity and the water cycle, lowering the negative impacts in the long term.

One alternative for minimising the negative environmental impacts of biomass use and ensuring sustainability is to produce energy from cultivation residues, thereby bringing more opportunities to the local population. Several agricultural systems base their natural cycle on nutrient recycling, where part or certain residue of the main crop is left on the soil to protect it physically from rain, sun, and wind and to nurture soil biota. Crop residue retention is, in fact, one of the three pillars of Conservation Agriculture (HOBBS; SAYRE; GUPTA, 2008; SOMMER *et al*., 2018). This measure can avoid the necessity of fertiliser input, protect against soil degradation, and increase carbon sequestration in the soil. However, some studies point out there is no need to place all the residues on the soil. In some cases, a proportion can be removed without causing harm to the integrity of the soil (DIAS *et al*., 2012; EPE, 2014; FOELKEL, 2016).

The Brazilian electrical distribution sector is mainly divided by state. Until the early 1990s, most state governments owned companies that provided the local operations on the energy distribution system (TOVAR; RAMOS-REAL; ALMEIDA, 2010). This condition changed with the privatisations that came along to reduce the debt of a system that experienced rapid growth during the 1960s and 1970s and culminated in a profound crisis in the 1980s (ALMEIDA; PINTO JÚNIOR, 2000; LORENZO, 2002; TOVAR; RAMOS-REAL; ALMEIDA, 2010). The privatisation wave did not reach the state of Minas Gerais, where the same company, Cemig (Minas Gerais Energy Company), is responsible for the concessions of 96% of the state. Cemig also figures as one of the few companies in the country that join the tasks of generation, distribution, transmission, and commercialisation of energy (CEMIG, 2012).

Considering the necessity of choosing a study area, the state unit appears as the most appropriate option since, besides having uniformity in the electric system, it also presents a political management unit that facilitates the creation and application of policies. The state of Minas Gerais has favourable environmental and economic characteristics for the development of this study. Therefore, it has been elected as the focus area of this paper.

Given the context of climate change and the fragility of Brazil's energy matrix in the face of these changes, it is important to analyse the self-sufficiency in sustainable bioenergy of a federative unit with the fourth-largest territorial area in the country, the second-highest population, and the largest number of municipalities in the country (IBGE, 2023) This analysis aims to shed light on potential new directions that can guide decision-making regarding the sustainable diversification of the Brazilian energy matrix.

3 MATERIAL AND METHODS

3.1 DEFINITION OF THE STUDY AREA

Drawing from the findings Ribeiro and Rode (2016, 2019) presented, a focal area for conducting the study needed to be selected. Among the options, the state of Minas Gerais (Figure 2) exhibited the highest potential in the country for establishing the groundwork for a biomass energy initiative while adhering to environmental regulations.

Figure 2 | The state of Minas Gerais

Source: (IBGE, 2019, 2023).

Minas Gerais gained importance during colonial times, mainly from the wealth coming from its abundance of gold. With the exhaustion of these sources and the decline of the mining industry in the early nineteenth century, agriculture emerged as an important economic activity of the region. Considered by some authors as a period of stagnation and decay, the exhaustion of the gold mining activity left society more diverse and one which demanded different agricultural products. This led to the structuring of a productive and commercial sector that aimed to meet these internal demands (SOUZA, 2013).

The industrial sector is the second largest in the Minas Gerais economy, accounting for about 29.5% of the state's GDP (IBGE, 2017a), with the iron mining industry leading this economic sector. The state also stands out in producing automobiles, steel products, cement, chemicals, and food. Minas Gerais also presents the third-largest economy in Brazil, participating with approximately 8.7% of the Brazilian GDP, behind only the states of São Paulo and Rio de Janeiro (IBGE, 2017a). The primary agricultural goods produced are coffee, sugar, milk, various types of meats, soy, corn, and beans. In 2022, agribusiness exports reached US$ 15,3 billion, corresponding to 9,6% of Brazilian agribusiness exports (MAPA, 2023; SEAPA, 2023). In this mineral and agricultural wealth context, the state presents an average Human Development Index higher than the country's total average (Table 1).

Table 1 | HDIs from Brazil and Minas Gerais compared

	Brazil	*Minas Gerais*
HDI (Total)	0,761	0,769
HDI Income	0,729	0,731
HDI Longevity	0,841	0,866
Life expectancy at birth (years)	75,44	76,97

Source: FJP (2018).

In the environmental area, Minas Gerais has three of the six Brazilian biomes: the Cerrado (Brazilian savannah), the Atlantic Forest and a small portion of the Caatinga (dry forest). This encounter of different environments creates transition areas that are extremely rich in biodiversity and environmental specificities.

The selection of the state of Minas Gerais as the focal point of this paper is grounded in identifying ideal conditions characterised by uniformity in administrative aspects (e.g., consistent laws, financial conditions, taxes, and support agencies) and in the electricity sector (uniform regulations). An evaluation of the potential, as outlined by Ribeiro and Rode (2016), solidified the state of Minas Gerais as the optimal choice for this investigation due to its favourable conditions. The analyses were conducted considering municipal-level data, as this is the format in which data are presented in the national database. Nonetheless, certain regions within the state are referenced in the analyses due to their potential. However, it is not the aim of this research to delve into the historical economic development of the state or explore its potential.

3.2 PRODUCTIVITY DATA ANALYSIS

In order to assess the distribution of biomass residues in the state of Minas Gerais from annual crops, permanent crops, and silviculture production was downloaded from the governmental Sidra (SIDRA; IBGE, 2015a) platform. For annual and permanent crops, data was collected considering the crops produced in the entire state area, some predominantly in a large-scale agricultural model (corn, sugarcane, and coffee) and others more commonly in a family production model (manioc). Municipalities that had a biomass production rate (selected crops and silviculture) higher than 1,000 tonnes per year in the last agriculture census were selected to be analysed. This intended to calculate the potential for municipalities where the yield would make installing an energy production unit worthwhile. The chosen crops were coffee, corn, beans, manioc, and sugarcane. The assessment of production data is important for estimating the amount of residues generated during the production process. The literature indicates a percentage of the remainings from harvesting or primary processing for all the crops.

For the silviculture, we selected data pertaining to the production of eucalyptus charcoal, firewood and wood in 2016. To ensure the sustainability of the process, data regarding wood products from native vegetation was not considered in this study. Of 853 municipalities in the state of Minas Gerais, 804 met the conditions and were analysed.

The maintenance of current land use was presupposed for all the energy sources. Considering that the state of Minas Gerais has around 30% of its original vegetation cover (CARVALHO *et al*., 2008), this research estimates an energy production that excludes the conversion of preserved areas into agriculture or silviculture areas. Another principle followed was to guarantee that the competition of uses between energy and food would not occur, ensuring productivity and sustainability (RIBEIRO; RODE, 2016).

Considering soil integrity as a main necessity for the continuation of production activities for crops and silviculture, the recommendations in the literature regarding the percentage of the residues that should be left in the field for soil recovery were followed. To estimate energy productivity, a Sustainable Technical Coefficient (TCS) was adopted (see Table 2). The Traditional Technical Coefficient (TCT) represents the proportion of residues within the total yield (COELHO *et al*., 2015). For each of the crops and wood, literature was found indicating how much could be used to maintain the integrity of the soil. For most of the sources, a percentage indicated by studies in Brazil as Dias *et al*. (2012), EPE (2014) and Foelkel (2016), adequate for tropical conditions, was adopted. Only for the case of coffee, as no specific literature was present, a generalist recommendation of leaving 70% in the soil was assumed. Even though it may be considered a conservative value, removing a minor amount of residues aims to avoid solving one problem by creating another (soil degradation). Conservation tillage has proven effective for soil and environment conservation (BUSARI *et al*., 2018). In this paper, it was considered that the guarantee of supply for bioenergy production depends directly on soil productivity. A lower amount of organic matter in the soil can be more damaging to productivity than its excess. Thus, a more conservative coefficient was adopted in order to guarantee sustainability. Table 2 represents the values of TCS used in the calculation.

Table 2 | Traditional Technical Coefficient and Sustainable Technical Coefficient

Source	*Type of residue*	*Traditional Technical Coefficient (TC_T)*	*Percentage left on the soil*	*Sustainable Technical Coefficient (TC_S)*
Coffee	Husk	1.00	70%	0.30
Sugarcane	Straw	0.20	50%	0.10
Beans	Husk	1.16	60%	0.45
Manioc	Aerial	0.65	60%	0.25
Corn	Stover	1.68	60%	0.65
Eucalyptus	Primary processing	0.25	20%	0.20

Source: Dias et al. (2012), EPE (2014), Foelkel (2016) and authors' calculations

The TC_T and TC_S for beans, manioc and corn, were found on (EPE, 2014). For sugarcane, the coefficients adopted were from (Dias *et al*., 2012). For the eucalyptus, less literature was found regarding the use of residues. A relevant portion of the residues corresponds to the litter, representing an important share of the nutrient cycling process. Foelkel (2016) recommends that litter, leaves, and small branches are indispensable for maintaining soil fertility. Therefore, only the residues from the harvests (primary processing) were considered. Specific data on the availability of each source and its proportion to be considered in the calculation can be seen in Table 3.

Table 3 | Availability of each source and sustainable proportion considered for energy conversion

Source	*Total yield (ton/year)*	*Sustainable Technical Coefficient(TC_S)*	*Available residues (ton/year)*
Coffee	1,303,681	0.30	391,104
Sugarcane	71,080,882	0.10	7,108,088
Beans	569,466	0.45	256,260

Source	Total yield (ton/year)	Sustainable Technical Coefficient(TC_S)	Available residues (ton/year)
Manioc	844,122	0.25	211,031
Corn	6,947,837	0.65	4,516,094
Wood	12,388,720	0.20	2,477,744

Source: Sidra e IBGE (2015a, 2015b) and authors' calculations

We applied different formulas to different sources to calculate the potential for energy production from biomass residues in the state of Minas Gerais or the amount of energy that could be produced considering losses in the process. All the formulas were used by Coelho *et al*. (2012) for the Brazilian Bioenergy Atlas. These calculations show how biomass energy is distributed in the state per source.

- **Crops:** the conversion efficiency adopted for the residues was 15% of the low thermodynamic yield - 20 bar boiler compound systems, atmospheric condenser turbine (COELHO; MONTEIRO; KARNIOL, 2012).

$$Potential\ (MW/year) = \frac{[(Crops_{tons} \times TC) \times LHV_{kcal/kg}\ \times 0.15]}{(860 \times 8{,}322_{hours})}$$

Where:

- Cropstons: total of harvested crops in a year
- TC: technical coefficient
- LHV: lower heating value
- 0.15: 15% conversion efficiency
- 860: conversion factor from kcal/kg to kWh/kg
- 8,322: working hours per year (considering that the energy would be produced in 95% of the year hours. This factor converts the results from Megawatt hour to Megawatts per year).

- **Sugarcane:** as the calculation was made for simple systems, the lower energetic yield of 30 kW/sugarcane tons was considered.

$$Potential\ (MW/year) = \frac{(Sugarcane_{tons} \times 30_{kWh/ton}\ )}{(1{,}000 \times 5{,}563_{hours})}$$

Where:

- $Sugarcane_{tons}$: total of harvested sugarcane in a year
- $30_{kWh/ton}$: energetic yield of sugarcane in cogeneration systems
- 1,000: conversion from kW to MW
- 5,563: working hours from April to November (considering the harvesting time). This factor is important to convert the results from Megawatt hour to Megawatts per year)

- **Wood:** the calculation of the potential considered for a conventional steam turbine system (Rankine cycle) with yields of 15%, considering a small-sized system.

$$Potential\ (MW/year) = \frac{\left[(Wood_{tons} \times TC) \times LHV_{kcal/kg} \ \times 0.15\right]}{(860 \times 8{,}322_{hours})}$$

Where:

- $Wood_{tons}$: total of harvested wood in a year
- TC: technical coefficient, proportion of residues in the total yield
- LHV: lower heating value
- 0.15: 15% conversion efficiency
- 860: conversion factor from kcal/kg to kWh/kg
- 8,322: working hours per year (considering that the energy would be produced in 95% of the year hours. This factor converts the results from Megawatt hour to Megawatts per year)

All the calculations were made considering a viable technology: a cheap technology with low conversion efficiency (15%). Considering that investing in sustainable energy to improve people's lives is not necessarily an attractive business, even more in the context of economic crisis. A modern and expensive technology with a higher conversion coefficient would be unlikely to be financed.

3.4 DEMAND CALCULATION

The energy ladder from Coelho and Goldemberg (2013) was adopted to estimate the potential energy demand in the municipalities for two distinctive phases: (1) First phase: basic energy needs (lighting, cooking, and heating), which would necessitate about 50 - 100 kWh per person per year, (2) Second phase: productive uses (water pumping, irrigation, agricultural processes, heating, and cooking), which would necessitate about 500 – 1,000 kWh per person per year.

As presented by Coelho *et al*. (2015), low and high electricity requirements were calculated based on the following formulas:

- First phase (basic human needs)

$$Electricity\ demand_{(low)} = number\ of\ inhabitants \times access\ rate_{(\%)} \times 50\ kWh$$

$$Electricity\ demand_{(high)} = number\ of\ inhabitants \times access\ rate_{(\%)} \times 100\ kWh$$

- Second phase (productive uses)

$$Electricity\ demand_{(low)} = number\ of\ inhabitants \times 500\ kWh$$

$$Electricity\ demand_{(high)} = number\ of\ inhabitants \times 1{,}000\ kWh$$

For both phases, an average value of electricity demand was measured for the results. This was calculated by taking the mean of the low and high values:

$$Electricity\ demand_{(average)} = \frac{\left(Electricity\ demand_{(low)} + Electricity\ demand_{(high)}\right)}{2}$$

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As presented by Coelho *et al*. (2015) and applied by Ribeiro and Rode (2019), low and high electricity requirements were calculated.

4 RESULTS

Of 853 municipalities in the Minas Gerais state, only 49 did not reach the minimum production rate of 1,000 tonnes per year in the last agriculture census to integrate the analysis. As a result, the analysis focuses on 804 municipalities that reached the stipulated value.

4.1 ENERGY POTENTIAL

Minas Gerais is a state where agriculture represents one of the strongest local activities, ranging from large-scale monoculture farms to traditional family subsistence farming (IBGE, 2009). The energy potential from annual crop residues (Figure 3) had the highest results from all the sources, reaching values up to 60 MW with the yearly harvesting per municipality. The west sub-region, Triângulo Mineiro, had the best result due to the dominance of modern large-scale agribusiness. This sub-region is the state's main producer of sugarcane and corn (BASTOS; GOMES, 2011).

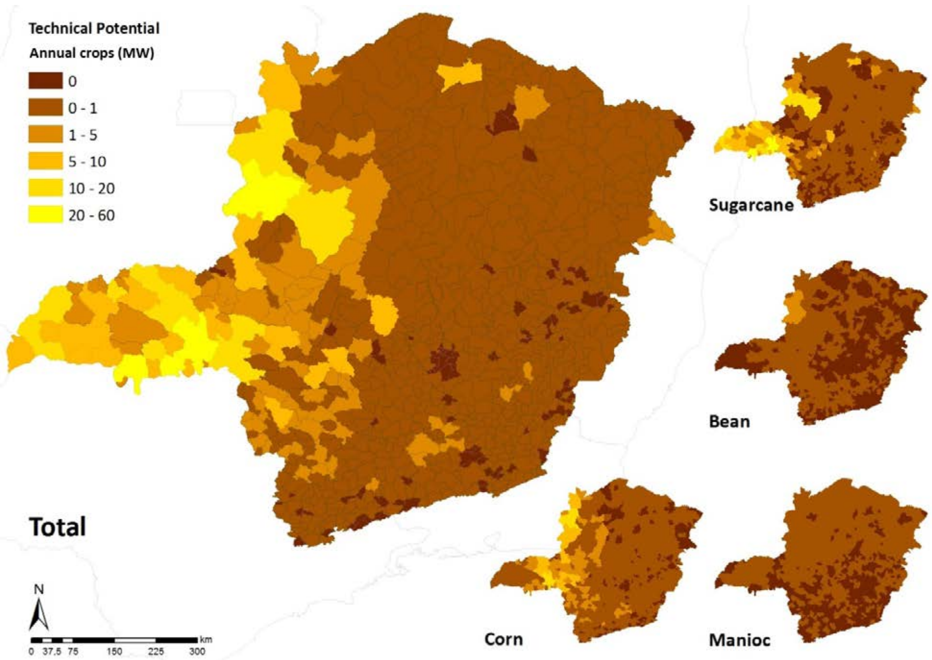

Figure 3 | Sustainable technical potential of energy production from annual crop residues with the yearly harvest per municipality

Source: IBGE (2009), IBGE (2019), Sidra (2015) and authors' calculations

Standing out as Brazil's largest producer and exporter of coffee, the state of Minas Gerais is responsible for more than 50% of the country's production. Even though the residues of coffee production alone show results varying from 0.1 to 1.5 MW (Figure 4), the results are considerably lower than those of energy production from annual crop residues.

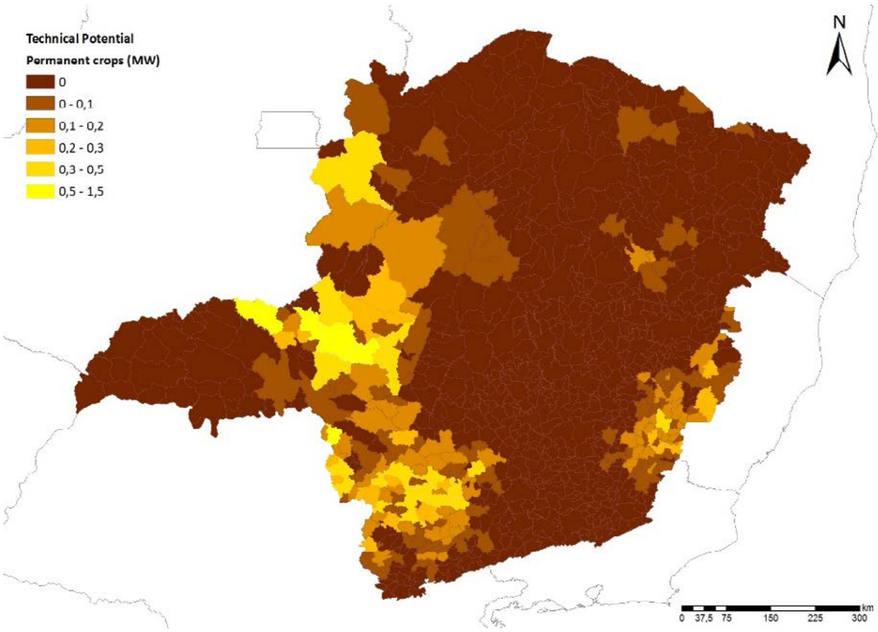

Figure 4 | Sustainable ttechnical potential of energy production from coffee residues with the yearly harvest per municipality

Source: IBGE (2009), IBGE (2019), Sidra (2015) and authors' calculations

The state of Minas Gerais also has a strong silviculture sector. Having its origins in the steel and iron industries' stimulation in the 1970s by the military dictatorship (1964-1985), the lack of coal to fire the sector was presented as an impediment. An incentive project was created, giving a 50% tax reduction to private owners and companies willing to invest in silviculture (CALIXTO *et al*., 2009). This marked the beginning of the development of the eucalyptus sector in the country. By 2016, more than 2 million tonnes of wood were produced yearly in Minas Gerais (SIDRA; IBGE, 2015b). In the more productive areas, the estimation of the potential energy production from silviculture residues (Figure 5) could reach up to 8 MW with the annual yearly harvest per municipality.

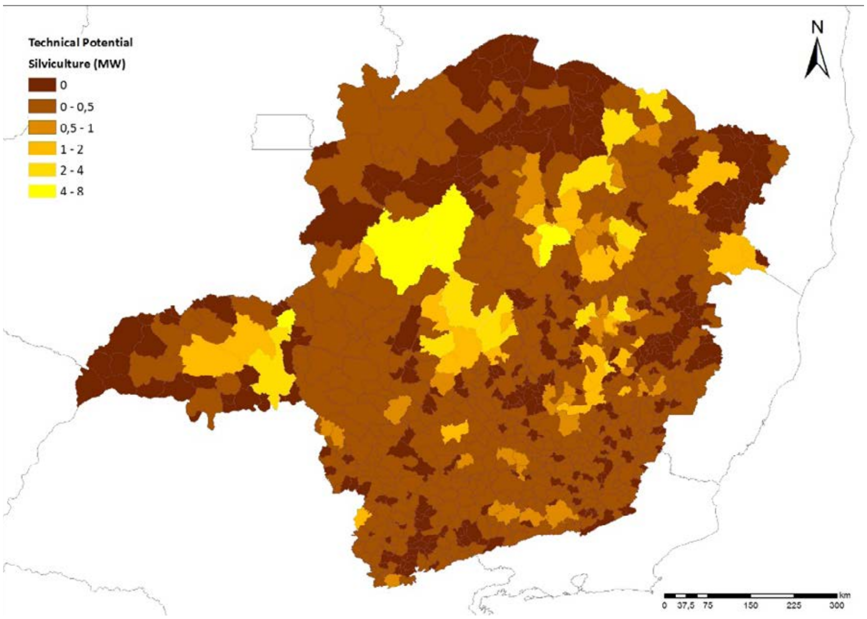

Figure 5 | Sustainable technical potential of energy production from silviculture residues with the yearly harvesting per municipality

Source: IBGE (2009), IBGE (2019), Sidra (2015) and authors' calculations

The combination of the values presented in the scenario generated above, where the most fruitful areas of the state would reach a value of the total sustainable technical potential for energy production of up to 65 MW with the yearly harvest per municipality (Figure 6).

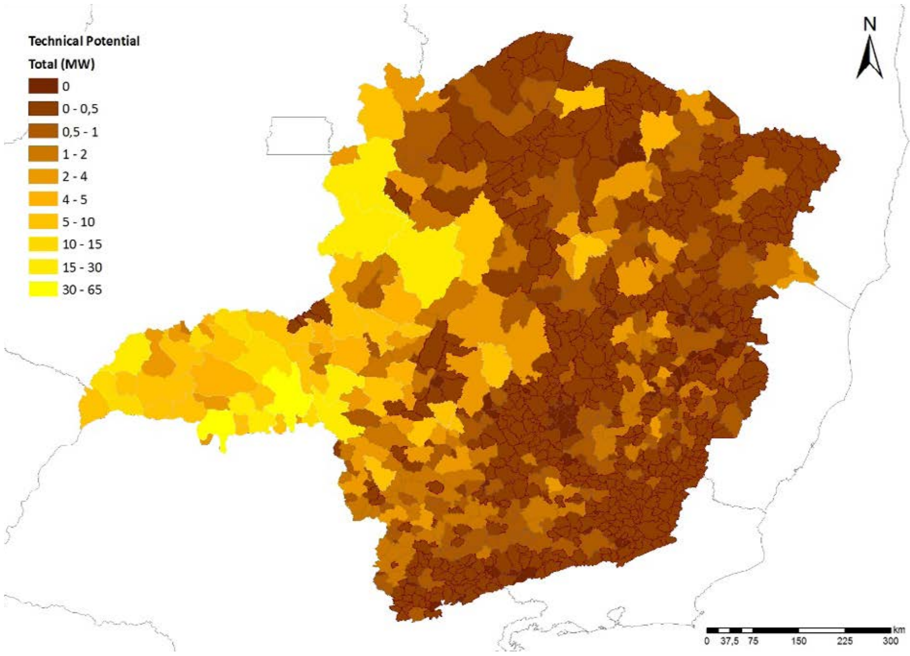

Figure 6 | Sustainable technical potential of energy production from all agriculture residues with the yearly harvest per municipality

Source: IBGE (2009), IBGE (2019), Sidra (2015) and authors' calculations

In total, within all the accessed sources, the annual crops show the highest potential in the state of Minas Gerais, reaching a total of 6,495 GWh/year. This reflects the consolidated agriculture industry in the state, mainly in the West. The permanent crops have the smallest value: 259 GWh/year. The results are interesting because the only permanent crop type accessed was coffee. The silviculture potential shows a more distributed result, with no concentration in one specific state region and reaching 1,409 GWh/year.

4.2 DEMAND VS PRODUCTION

To evaluate if the sustainable energy potential could meet the local energy demand, the potential future energy demand for basic needs and productive uses was calculated and compared to the sustainable technical potential (Figures 7 and 8).

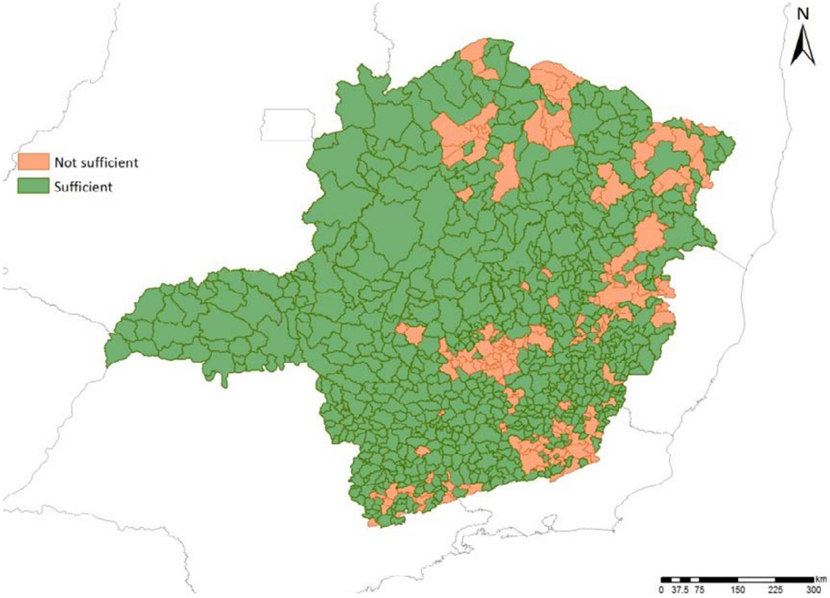

Figure 7 | Demand vs. production in a scenario of basic needs

Source: IBGE (2009), IBGE (2019), Sidra (2015) and authors' calculations

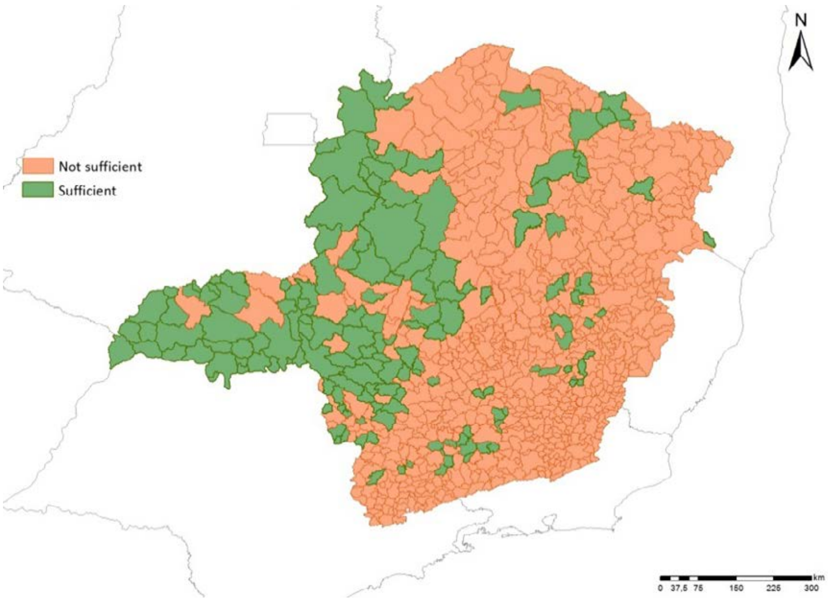

Figure 8 | Demand vs. production in scenario of productive uses

Source: IBGE (2009), IBGE (2019), Sidra (2015) and authors' calculations

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The municipalities where the demand was met in the basic needs scenario reached 79% of the total (Table 4) and 83% of the analysed municipalities. Most places where the results were insufficient represent large metropoles with no space for agriculture and high energy demand. The large municipalities that could meet the energy demand in a productive use scenario are those with the greatest yield in the state. Many of them are in the municipalities where the agribusiness is concentrated and the highest GDP in the state is located.

Table 4 | Synthesis of the results of demand vs. production

		Basic Needs		*Productive Uses*	
Municipalities	Sufficient	670	78%	157	18%
	Not sufficient	134	16%	647	80%
	Not analysed	49	6%	49	6%

Source: Authors' calculations

5 DISCUSSION

For the scenario of basic needs for the whole state, a surplus of 6,704 GWh/year was estimated. One possibility for optimisation is the exportation of residues from regions with energy surplus to places where the agricultural and silviculture residues cannot cover the demand. Another option to be exploited is the transformation of the surplus into pellets: a dry, compact and small portion of biomass that is easily stored and transported. This alternative could be a solution to meet the demand for areas with lower residues and generate income for the places with additional residues. A Brazilian law resolution from 2015 (National Electricity Agency – Aneel 687/15) began to facilitate the process of decentralised energy production, regulating the distribution of micro and mini energy generation. Therefore, creating an ideal context for developing small energy generation units.

According to the Brazilian Institute of Geography and Statistics (IBGE), Minas Gerais is a state with the fourth biggest territory in the country and the second largest in terms of inhabitant numbers, with a population of 20,538,718 inhabitants in 2022 (IBGE, 2023). Of the 853 municipalities, 32 have large cities (more than 100 thousand inhabitants) and hold 45% of the state's population. Those populated municipalities have more capacity to increase the energy demand and less area to produce agriculture and residues. These municipalities are responsible for 12% of the energy potential and, as calculated based on the population, 45% of the energy demand. This unbalanced relation means 11 of those 32 municipalities meet the demand on a basic needs scenario and only one on a productive uses scenario. (PALMAS *et al.*, 2015) investigated the regional potential for the ideal renewable energy mix in Germany. Such research has not been carried out yet in Brazil and could be the next step to creating a sustainable energy system for Minas Gerais. As assessed in this paper, biomass could supply 78% of the demand for basic needs and 18% of the energy in a scenario of productive uses (Table 5). An ideal sustainable energy mix, including other sources such as solar and wind energy or even biomass from urban solid waste, could reduce the risk of energy shortages and blackouts and contribute to a clean and safe energy matrix.

It is important to remark that the demand calculation is based on the essential needs of a household, so the amount of energy estimated does not reflect the modern patterns of energy consumption. The energy from residues could be directed to the low-income population, focusing on the rural area where it is produced, improving locally produced goods, andaising attractiveness for new local businesses (VENGHAUS; ACOSTA, 2018). Investments in education and infrastructure can come from a more accessible energy system, as well as better possibilities for savings, entrepreneurism and new agricultural activities. The impact of energy generation is not purely related to income increment. It could also significantly improve education, health, and gender equality, considering that improving electricity access usually has a larger effect on female employment (COOK, 2011). Considering the environmental and social risks involved with new hydropower projects (DÁVALOS; RODRIGUES FILHO; LITRE, 2021; FERREIRA *et al*., 2014), the development of technologies and programs that support the propagation of the use of biomass residues for energy production can play an important role on future sustainable development in Brazil.

Taking a step back to consider `why does it matter' for Minas Gerais to be self-sustainable with biomass residual energy highlights that this importance relies on the historical and economic relevance of the state. A highly populated state can fulfil part of its energy demand with an available resource without requiring land use change or competition with other established markets. This is an important finding concerning the energy matrix change. It means that if it works there, it could also work in other states or regions. This could lead to local arrangements (between states, municipalities or even small communities), depending on their potentials and affinities, in order to promote biomass energy. This could provide a promising new path for the state of Minas Gerais and other parts of the country. A cooperative production system among rural producers is also an alternative to reduce production costs and may allow the partial improvement of agricultural raw materials, adding value to the final product.

Among the production means existing in the state, family farming is the main responsible for the food supply for the state population. Characterised by small properties managed essentially by the family, it presents a larger amount of properties (79% of the farms in the state (IBGE, 2017b)), with greater work and income generation per cultivated area (ABRAMOVAY, 1997). Those small farmers are commonly organised in cooperatives production systems and associations to increase their product's competitiveness and market insertion (COSTA *et al*., 2015). As previously mentioned, since these farmers are already employing this model for other objectives, organising biomass energy production cooperatives using their crop residues could enhance the efficiency of logistics for residue collection and processing, along with the distribution of the generated energy.

One concept that could be applied to developing energy production through biomass residues is the so-called Social Technology. According to (DAGNINO, 2014), a Social Technology is any method, process, product, or technique shaped to solve some social problem that meets the necessities of simplicity, low cost, easy applicability, replicability and proven social impact. An exemplary instance in Brazil is the P1MC program (One Million Rural Cisterns Program), which involved the construction of cisterns as a proactive water policy in the Brazilian semiarid region (ANDRADE; CORDEIRO NETO, 2016). Creating a model for energy production that works for lower income communities and is simple to replicate with minor adaptations could improve the local and regional development without impacting the environment and improving the local economy, as demonstrated by Shukla (2022).

Recent studies, including Casau *et al*. (2022) and Nunes *et al*. (2023), examine the significance of energy generation from biomass waste in effectively realising the foundational principles of a circular and sustainable economy. With an emphasis on agroforestry residues, these studies contribute to the research results by highlighting potential possibilities and making progress in identifying gaps within the energy generation supply chain.

It is important to note that this paper does not address calculations pertaining to collection logistics, material transportation, procurement, power unit installation and operation, or training. Applying this methodology to a sample area, Pimenta and Dalmolin (2021) highlighted that not only financial factors and land availability could impede the implementation of such an enterprise but also the willingness of the local population. While the results of this study were presented, they did not align with the community's preferences for their future development. A more comprehensive investigation should involve the local populace, specifically focusing on biomass energy and its potential applications. Such an approach might yield valuable insights to advance the continuation of this research area in Brazil.

6 CONCLUSIONS

This paper aimed to explore the alternatives for renewable energy generation in Brazil, investigating specifically the case of residual biomass from agriculture and silviculture. The chosen study area was the state of Minas Gerais; a region pointed out by previous research as promising for this type of assessment. A Sustainable Technical Coefficient was developed, taking into consideration that part of the residues would be left on the soil to maintain nutrient cycling and soil health, ensuring sustainability in the long term. The technology chosen for the calculations has low efficiency in energy conversion. Being a cheaper option, easily found in the national market, it was selected as the most viable. The energy demand was estimated and compared with the energy potential results.

In a country where hydro energy represents not only the highest share of the energy matrix but also a fragile energy source, the results of this study reveal a promising new path. For the state of Minas Gerais, with its tradition of agriculture, 78% of the municipalities could meet their basic energy needs through crop residues and silviculture production. When more elaborated uses are considered, there is a drop where 18% of the municipalities could be self-sufficient in energy supply. Even with a significant reduction in the percentage, this would relieve pressures placed on the construction of new hydroelectric plants, which have substantial negative impacts on the environment and the way of life of the communities in the surroundings of the flooded areas. A cooperative production system among rural producers is also presented as an alternative to reduce production costs and may allow the partial improvement of agricultural raw material, adding value to the final product. An energy mix where other renewable energy sources are considered can also increase the chances of success of an enterprise focused on renewable energy.

Since 2015, Brazil has faced an economic downturn that tends to decrease the attractiveness of an investment. Other relevant aspects for consideration are the lack of policies that encourage the deployment of new renewable energies and the questionable environmental agenda adopted by the government from 2018-2022. The results obtained here can be used to empower the local population or stakeholders to seek renewable energy projects, creating the ground for changes in the country's energy system.

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