BRINGING TO LIGHT A NEW ENERGY PATH:

BIOMASS RESIDUES AS A CONTRIBUTION TO A SUSTAINABLE AND INCLUSIVE ENERGY SOURCE IN BRAZIL

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Bringing to light a new energy path: biomass residues as a contribution to a sustainable and inclusive energy source in Brazil

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Abstract

Keywords: Biomass potential, Renewable energy, Spatial planning, Sustainable development

In 2015, the United Nations released a set of 17 goals as part of a new sustainable development agenda. The agenda focused on ending poverty, protecting the environment, and ensuring prosperity for all by 2030. The objective was to reinforce the urgency of acting in order to change the status quo. The topic of renewable energy is mentioned in goal 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all.

The opportunity for renewable energy production in developing countries is a highly relevant topic. In Brazil, more than 60% 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. Hydroelectricity also dominates the energetic sector expansions, although great dams do not bring in a return proportional to their costs, and those that have been planned most recently present disastrous social, economic, and environmental consequences. Previous studies on biomass as a renewable source for energy production in Brazil have shown promising results. Biomass is characterized as plant material generated through photosynthesis and all its by-products: forest-wood, cultivated crops, animal droppings, organic matter. Characterized by its diverse possibilities of sources and conversion technologies for energy products, biomass has a high potential for renewable energy supply. Sustainable power generation through biomass should guarantee the soil health, water, and biodiversity cycle.

This research is dedicated to exploring alternative future pathways for the electricity sector in Brazil that unite the respect for people and the environment, advance nature conservation as well as the lives of the people and communities involved, and thereby contribute to more sustainable development. The use of residual biomass as a source for decentralized and clean energy production that does not affect food security is the most promising option. It comes without the enormous impact of the large-scale hydroelectric dams, can be applied virtually anywhere and does not rely on a connection to the central grid, and does not compete with food supply.

The aim of this thesis is to investigate the role that biomass can play in the Brazilian electricity matrix. The hypothesis is that residual biomass as an energy source could play a significant role in transforming the Brazilian energy matrix towards a sustainable path. To attain the overall goal, four general steps were defined: (1) to explore the potential areas for sustainable biomass energy production; (2) to evaluate the perspectives for biomass energy production in peripheral areas; (3) to identify the potential of biomass

energy production in one entire state and (4) to evaluate the costs and social acceptance for biomass enterprises.

On the First Step, the potentials areas for energy production were identified, in which the use of biomass for a sustainable power production can have a particularly high significance for the energy supply of the population: 1. areas with higher energy demand, 2. areas that were more remote of an installed transmission line, 3. areas far from already installed hydroelectric and thermoelectric power plants, 4. areas with an anthropic land use, and 5. areas of relevance for environment preservation. The main findings of this step were that there is an area of approximately seven million hectares with the potential to produce energy through biomass meeting local demand, favoring areas with fewer power connections, avoiding changes in land use, and maintaining priority areas for environmental conservation. On this basis, a new concept for energy supply could be built.

The Second Step had the objective to assess potential areas where the energy could have a positive social impact in an example region. The region chosen for the study is a supplier of eucalyptus charcoal for the iron industries in the west of the state of Minas Gerais. By combining the Human Development Index, the yearly permanent crop production, the yearly silviculture production, and the yearly temporary crop production in a GIS system, it was possible to select three municipalities to study. The results indicate a potential for each of the three investigated small municipalities to be self-sustainable in energy production by using silviculture and agricultural waste, and also that the success of biomass energy generation through agriculture residue enterprises depends on more than energy efficiency.

The Third Step focuses on the investigation of the possibilities to sustainably attend the demand on a larger scale. Opportunities for power generation from biomass residues in the whole Minas Gerais State were assessed, considering the silviculture and crop yield and applying a conservative index that considerers the portion of residues that should be used maintaining the soil health. The chosen crops were coffee, corn, beans, manioc, and sugarcane. The assessment of production data is vital to estimate the amount of residue generated in the production process. For all the crops, literature indicates a percentage of rests remaining from harvesting or primary processing. For the estimation of residues from forestry, data were selected on 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. Data were generated per municipality to them be joined at the state level. The primary outcomes were that in a state with the tradition of agriculture, 78% of the municipalities could have their basic energy needs attended. This would relieve pressures placed on the construction of new hydroelectric plants, which have negative impacts on the environment. In addition, a cooperative production system among farmers can reduce costs and may allow the partial improvement of their agricultural raw material.

Finally, on the fourth Step, the implementation costs were investigated. In a region were many initiatives have been carried out in order to create new opportunities for people affected by a dam rupture with very negative consequences for land use, it was pursued innovative initiatives for agriculture in the municipalities surrounding the Doce River State Park. There was an interest from the communities to increase the cultivation of certain crops and one possibility proposed to the locals was to use agricultural waste for electricity production. Ensuring the sustainability and development of clean technologies, this step sought to evaluate the potential of energy production through agricultural waste, the ideal allocation of the energy production unit, and the costs involved in the enterprise. The demand of the municipalities was considered as the monthly average consumption per resident (150 kW.h/month) and the market prices of October 2018 were applied for the calculation of the implementation costs, which was conducted by a company that works on the area and applied the potentials and the transportation distances to estimate the costs and the allocation of the power plants accordingly. The calculations of the costs involve collection logistics, transport of materials, purchase, installation, and operation of a power generating unit and team training. From a total of 16, 13 municipalities presented a production capable of meeting about 20% of local demand. Based on the residual potential, transportation costs and current market prices, the most efficient arrangement found would be to build two power plants. This step shows that a significant investment is required. But, the enterprise could be viable and pay itself in a short amount of time. This statement is even more applicable in a scenario where the agricultural area is increased, growing the power generation capacity of the power plant. Further studies should explore the spatial limitations for the agricultural expansion, modeling scenarios where the environmental constraints are respected. Over all, the input of the population on the matter is also fundamental for the continuity of such a project, but working together, municipalities can generate energy and create better power availability, jobs, income, and more opportunities for energy decentralization.

The overall outcomes of this thesis show that residual biomass presented the potential to be integrated in the Brazilian energy matrix more intensively. The availability of residues was spatially assessed on different scales and could positively impact populations away from large centers and outside of development initiatives. Conservation of native vegetation areas and soil health were considered as critical points in the analyses so that a part of the agricultural residues could be left in the soil to ensure agricultural sustainability and still have a significant energy production.

This work is the first of its kind and is a crucial step in the direction of a cleaner and safer energy matrix, also the first to put together a public set of data with this objective. Even adopting less efficient technologies, the availability of agricultural and silvicultural residues for energy generation was enough to be relevant to the local energy mix. The focus on improving life for populations in marginal areas, isolated from large centers, also showed that there is a lack of studies on the use of biomass residues as a contribution to a decentralized, sustainable, and socially acceptable power supply in Brazil. For developing countries, the adoption of cleaner technologies at an early stage has the potential to save a lot of effort, money, and natural resources.

The effectiveness of these initiatives still relies on the engagement of rural producers, which could not be ascertained during the development of this study. The acceptance from the communities involved in bioenergy projects is essential for the implementation of successful residual biomass initiatives.

The results also generated the recommendation that a more in-depth evaluation of people's knowledge of bioenergy unveils exciting insights into the development of public policies aimed at achieving different energy sources in Brazil. They can be used as a basis for further studies observing the local characteristics and be a relevant tool for municipalities to know their potentials and seeking investments. These methods could lead to local arrangements, depending on their potentials and affinities, in order to promote biomass energy or be used by public or private initiative, as a basis for projects aimed at sustainable energy development, as basis for planning of energy generation from biomass, reducing dependence of hydro energy. The methods also could provide a basis for promoting decentralizing generation of energy, creating better conditions of social and economic development. In a large and disparate country such as Brazil, with a population quota of 54.8 million people (26.5% of the population) living below the poverty line, such efforts are even more urgent. Following the current trends of global warming, the most impoverished strata of society will be the first to suffer its adverse effects: droughts, diseases, lack of potable water and food. A cooperative energy production system from agricultural and forestry residues among rural producers can offer an alternative here. It may allow to reduce production costs and the partial improvement of agricultural raw material, adding value to the final product. In this sense, the study method can be used as a tool to organize the information on possibilities of generation of energy.

Zusammenfassung

Schlagworte: Biomassepotenziale, Erneuerbare Energien, Räumliche Planung, Nachhaltige Entwicklung

Die Vereinten Nationen haben 2015 eine 17 Ziele umfassende neuen Agenda für nachhaltige Entwicklung veröffentlicht. Die Agenda konzentrierte sich auf die Beendigung der Armut, den Schutz der Umwelt und die Sicherung des Wohlstands für alle bis 2030. Das übergeordnete Ziel bestand darin, die Dringlichkeit des Handelns zu bekräftigen, um den Status quo zu ändern. Dem Thema der erneuerbaren Energien widmet sich Ziel 7, das darauf abzielt, den Zugang zu bezahlbarer, zuverlässiger, umweltverträglicher und nachhaltiger Energie für alle zu gewährleisten.

Die Möglichkeit der Produktion erneuerbarer Energie in Entwicklungsländern ist ein hoch relevantes Thema. In Brasilien stammen mehr als 60% der Energie aus Wasserkraft, was das System vor dem Hintergrund des globalen Klimawandels mit Niederschlags- und Temperaturverschiebungen im Laufe der Jahre sehr anfällig macht. Wasserkraft dominiert auch weiterhin den Ausbau des Energiesektors, trotz ihres fragwürdigen Kosten-Nutzen-Verhältnisses. Die in jüngster Zeit geplanten Staudämme haben katastrophale soziale, wirtschaftliche und ökologische Folgen. Frühere Studien über Biomasse als erneuerbare Quelle für die Energieerzeugung in Brasilien haben vielversprechende Ergebnisse gezeigt. Biomasse ist der Oberbegriff für durch Photosynthese erzeugtes Pflanzenmaterial sowie seine Nebenprodukte: Waldholz, Kulturpflanzen, Tierdung, organische Substanz. Charakterisiert durch ihre vielfältigen Quellen und Konversionstechnologien für Energieprodukte hat Biomasse ein hohes Potenzial für die Versorgung mit erneuerbarer Energie. Eine nachhaltige Energieerzeugung durch Biomasse muss zudem Bodengesundheit, Wasserkreislauf und Biodiversität berücksichtigen.

Diese Arbeit widmet sich der Erforschung alternativer Zukunftspfade für den Elektrizitätssektor in Brasilien, die den Respekt für Mensch und Umwelt vereinen, den Naturschutz sowie das Leben der beteiligten Menschen und Gemeinden fördern und damit zu einer nachhaltigeren Entwicklung beitragen. Die Nutzung von Restbiomasse als Quelle für eine dezentralisierte und saubere Energieproduktion, die die Ernährungssicherheit nicht beeinträchtigt, ist die vielversprechendste Option. Sie kommt ohne die enormen Auswirkungen der großen Wasserkraft-Staudämme aus, kann praktisch überall eingesetzt werden, ist nicht auf einen Anschluss an das zentrale Netz angewiesen und steht nicht in Konkurrenz zur Nahrungsmittelversorgung.

Das Ziel dieser Arbeit ist es, die mögliche Rolle der Biomasse im brasilianischen Elektrizitätssektor zu untersuchen. Die Hypothese ist, dass Restbiomasse als Energiequelle eine bedeutende Rolle bei der

Transformation der brasilianischen Energiemixes in Richtung eines nachhaltigeren Pfades spielen könnte. Um das Gesamtziel zu erreichen, wurden vier Schritte definiert: (1) Untersuchung potenzieller Gebiete für eine nachhaltige Energieproduktion aus Biomasse; (2) Bewertung der Perspektiven für die Energieproduktion aus Biomasse in peripheren Räumen; (3) Identifizierung des Potenzials der Energieproduktion aus Biomasse in einem ganzen Bundesstaat und (4) Bewertung der Kosten und der sozialen Akzeptanz von Biomasseunternehmen.

Im ersten Schritt wurden Potenzialgebiete identifiziert, in denen nachhaltige Energieerzeugung aus Biomasse eine besonders hohe Bedeutung für die Energieversorgung der Bevölkerung haben kann. Folgende Kriterien wurden betrachtet: 1. Gebiete mit höherem Energiebedarf, 2. Gebiete, die von einer installierten Übertragungsleitung weiter entfernt sind, 3. weit von bereits installierten Wasser- und Wärmekraftwerken entfernte Gebiete, 4. Gebiete mit überwiegend anthropischer Landnutzung und 5. für den Naturschutz relevante Gebiete. Die Hauptergebnisse dieses Schrittes waren, dass es in Brasilien etwa sieben Millionen Hektar Fläche gibt, die das Potenzial hat, Energie aus Biomasse zu erzeugen um die lokale Nachfrage zu decken, und dabei weniger gut an das Stromnetz angeschlossene Gebiete zu begünstigen, Landnutzungsänderungen zu vermeiden und für den Naturschutz bedeutsame Gebiete zu erhalten. Auf dieser Grundlage ließe sich ein neues Konzept für die Energieversorgung aufbauen.

Der zweite Schritt hatte zum Ziel, potenzielle Gebiete zu untersuchen, in denen die Energie in einer Beispielregion eine positive soziale Wirkung haben könnte. Die für die Studie ausgewählte Region ist ein Lieferant von Eukalyptusholzkohle für die Eisenindustrie im Westen des Bundesstaates Minas Gerais. Durch die Kombination des Human Development Index, der jährlichen Dauerkulturproduktion, der jährlichen Waldbau-Produktion und der jährlichen temporären Pflanzenproduktion in einem GIS-System war es möglich, drei Gemeinden für die Studie auszuwählen. Die Ergebnisse deuten darauf hin, dass jede der drei untersuchten kleinen Gemeinden das Potenzial hat, sich durch die Nutzung von Abfällen aus Waldbau und Landwirtschaft für die Energieproduktion selbst zu versorgen, und dass der Erfolg der Energieerzeugung aus Biomasse durch landwirtschaftliche Reststoffe nicht nur von der Energieeffizienz abhängt.

Der dritte Schritt konzentriert sich auf die Untersuchung der Möglichkeiten, den Energiebedarf in einem größeren Maßstab nachhaltig zu bedienen. Die Möglichkeiten zur Energieerzeugung aus Biomasse-Reststoffen im gesamten Bundesstaat Minas Gerais wurden unter Berücksichtigung des Waldbau- und Ernteertrags und unter Anwendung eines konservativen Indexes bewertet, der den Anteil der Reststoffe berücksichtigt, der zur Erhaltung der Bodengesundheit eingesetzt werden sollte. Die ausgewählten

Kulturen waren Kaffee, Mais, Bohnen, Maniok und Zuckerrohr. Die Auswertung der Produktionsdaten ist von entscheidender Bedeutung, um die Menge der im Produktionsprozess anfallenden Reststoffe abzuschätzen. Für alle Kulturen wird in der Literatur ein Prozentsatz der bei der Ernte oder Erstverarbeitung verbleibenden Restmengen angegeben. Für die Schätzung der forstwirtschaftlichen Reststoffe wurden Daten über die Produktion von Eukalyptusholzkohle, Brennholz und Holz im Jahr 2016 herangezogen. Um die Nachhaltigkeit des Prozesses zu gewährleisten, wurden Daten zu Holzprodukten aus der heimischen Vegetation in dieser Studie nicht berücksichtigt. Die Daten wurden pro Gemeinde generiert, um sie auf Bundesstaatsebene zusammenzuführen. Die Hauptergebnisse waren, dass in einem Bundesstaat mit Landwirtschaftstradition 78% der Gemeinden ihren grundlegenden Energiebedarf decken konnten. Dies würde den Druck zum Bau neuer Wasserkraftwerke, die negative Auswirkungen auf die Umwelt haben, mindern. Darüber hinaus kann ein kooperatives Produktionssystem unter den Landwirten die Kosten senken und eine teilweise Veredelung ihrer landwirtschaftlichen Rohstoffe ermöglichen.

Im vierten Schritt wurden schließlich die Implementierungskosten untersucht. In den Gemeinden rund um den Doce River State Park, einer Region, in der viele Initiativen durchgeführt wurden, um neue Möglichkeiten für die von einem Dammbruch mit sehr negativen Folgen für die Bodennutzung betroffenen Menschen zu schaffen, wurden innovative Initiativen für die Landwirtschaft entwickelt. Die Gemeinden waren daran interessiert, den Anbau bestimmter Feldfrüchte zu steigern, und eine Möglichkeit, die den Einheimischen vorgeschlagen wurde, war die Verwendung von landwirtschaftlichen Reststoffen zur Stromerzeugung. Um die Nachhaltigkeit und die Entwicklung sauberer Technologien zu gewährleisten, wurde in diesem Schritt versucht, das Potenzial der Energieerzeugung durch landwirtschaftliche Reststoffe, die ideale Allokation der Energieproduktionsanlage und die mit dem Vorhaben verbundenen Kosten zu bewerten. Die Nachfrage der Gemeinden wurde als monatlicher Durchschnittsverbrauch pro Einwohner (150 kW.h/Monat) betrachtet und die Marktpreise vom Oktober 2018 wurden für die Berechnung der Implementierungskosten herangezogen, die von einem Unternehmen durchgeführt wurde, das auf dem Gebiet arbeitet und die Potentiale und die Transportentfernungen verwendete, um die Kosten und die Allokation der Stromerzeugungsanlagen entsprechend abzuschätzen. Die Kostenberechnungen umfassen die Sammellogistik, den Materialtransport, den Kauf, die Installation und den Betrieb einer Energieerzeugungsanlage sowie die Ausbildung der Arbeitskräfte. Von insgesamt 16 Gemeinden wiesen 13 eine Produktion auf, die etwa 20% des lokalen Bedarfs decken kann. Auf der Grundlage des Reststoffpotenzials, der Transportkosten und der aktuellen Marktpreise wäre der Bau von zwei Kraftwerken die effizienteste Anordnung, die gefunden wurde. Dieser Schritt zeigt, dass eine erhebliche Investition erforderlich ist. Das Vorhaben könnte jedoch tragfähig sein und sich in kurzer Zeit amortisieren. Diese Aussage gilt umso mehr in einem Szenario, in dem die landwirtschaftliche Fläche vergrößert wird und die Stromerzeugungskapazität des Kraftwerks wächst. Weitere Studien sollten die räumlichen Beschränkungen für die landwirtschaftliche Expansion untersuchen und Szenarien modellieren, in denen Naturschutzauflagen eingehalten werden. Insgesamt ist auch der Beitrag der Bevölkerung zu diesem Thema von grundlegender Bedeutung für die Durchführbarkeit eines solchen Projekts, aber wenn die Gemeinden zusammenarbeiten, können sie Energie erzeugen und eine bessere Stromversorgung, Arbeitsplätze, Einkommen und mehr Möglichkeiten zur dezentralen Energieerzeugung schaffen.

Die Gesamtergebnisse dieser Arbeit zeigen, dass die Restbiomasse das Potenzial hat, intensiver in die brasilianische Energiematrix integriert zu werden. Die Verfügbarkeit von Reststoffen wurde räumlich auf verschiedenen Skalen bewertet und könnte sich positiv auf die Bevölkerungsgruppen außerhalb der großen Zentren und außerhalb von Entwicklungsinitiativen auswirken. Die Erhaltung der einheimischen Vegetationsflächen und die Bodengesundheit wurden in den Analysen als kritische Punkte betrachtet, so dass ein Teil der landwirtschaftlichen Residuen im Boden belassen werden konnte, um die nachhaltige Landwirtschaft zu sichern und dennoch eine signifikante Energieproduktion zu ermöglichen.

Diese Arbeit ist die erste ihrer Art und ein entscheidender Schritt auf dem Weg zu einer saubereren und sichereren Energieversorgung, auch die erste, die einen öffentlichen Datensatz mit diesem Ziel zusammengestellt hat. Selbst beim Einsatz weniger effizienter Technologien reichte die Verfügbarkeit von land- und forstwirtschaftlichen Reststoffen für die Energieerzeugung aus, um für den lokalen Energiemix relevant zu sein. Die Konzentration auf die Verbesserung des Lebens der Bevölkerung in peripheren Räumen, die von großen Zentren isoliert sind, zeigte auch, dass es an Studien über die Nutzung von Biomasse-Reststoffen als Beitrag zu einer dezentralisierten, nachhaltigen und sozialverträglichen Energieversorgung in Brasilien mangelt. Für Entwicklungsländer hat die frühzeitige Einführung sauberer Technologien das Potenzial, viel Mühe, Geld und natürliche Ressourcen einzusparen.

Die Wirksamkeit dieser Initiativen hängt nach wie vor vom Engagement ländlicher Produzenten ab, was während der Durchführung dieser Studie nicht feststellbar war. Die Akzeptanz der an Bioenergieprojekten beteiligten Gemeinden ist für die Umsetzung erfolgreicher Initiativen zur energetischen Restbiomassenutzung unerlässlich.

Die Ergebnisse führten auch zu der Empfehlung, dass eine eingehendere Bewertung des Wissens der Menschen über Bioenergie spannende Einblicke in die Entwicklung der öffentlichen Politik zur Erreichung verschiedener Energiequellen in Brasilien enthüllt. Sie können als Grundlage für weitere Studien zur

Beobachtung der lokalen Besonderheiten verwendet werden und ein relevantes Instrument für Gemeinden sein, um ihre Potenziale zu kennen und Investitionen zu realisieren. Diese Methoden könnten je nach ihren Potentialen und Affinitäten zu lokalen Vereinbarungen führen, um Biomasseenergie zu fördern oder durch öffentliche oder private Initiative als Grundlage für Projekte zur nachhaltigen Energieentwicklung, als Grundlage für die Planung der Energieerzeugung aus Biomasse und zur Verringerung der Abhängigkeit von Wasserkraft genutzt werden. Die Methoden könnten auch als Grundlage für die Förderung der dezentralen Energieerzeugung dienen, um bessere Bedingungen für die soziale und wirtschaftliche Entwicklung zu schaffen. In einem großen und uneinheitlichen Land wie Brasilien mit einer unter der Armutsgrenze lebenden Bevölkerungsgruppe von 54,8 Millionen Menschen (26,5% der Bevölkerung) sind solche Bemühungen noch dringlicher. Nach den aktuellen Trends der globalen Erwärmung werden die am stärksten verarmten Schichten der Gesellschaft die ersten sein, die unter deren negativen Auswirkungen leiden: Dürren, Krankheiten, Mangel an Trinkwasser und Nahrungsmitteln. Ein kooperatives Energieproduktionssystem aus land- und forstwirtschaftlichen Reststoffen durch ländliche Erzeuger kann hier eine Alternative bieten. Es kann die Senkung der Produktionskosten und die teilweise Veredelung von landwirtschaftlichen Rohstoffen ermöglichen, wodurch das Endprodukt einen Mehrwert erhält. In diesem Sinne kann die Untersuchungsmethode als Instrument zur Organisation der Informationen über die Möglichkeiten der Energieerzeugung genutzt werden.

1. Introduction

1.1 Background

1.1.1 A timeline of Brazilian environmental scenario

With occupation characterized by the irrational exploitation of the natural resources, the history of Brazil, after the arrival of the Portuguese (1500), was dominated by the belief that the environment exists to be exploited and that the natural resources were endless (Borges et al. 2009). The Atlantic Forest was the first biome to be reached by the Europeans. It is a coastal forest that originally covered circa 150 million hectares and was characterized by high diversity and endemism, including more than 20,000 plants species, 261 species of mammals, 688 birds species, 200 species of reptiles, 280 species of amphibians (Ribeiro et al. 2009). It is estimated that the Atlantic Forest flora and fauna may include from 1 to 8% of the world's total species (da Silva and Casteleti 2003). The interiorization of the country's occupation began at first after the scarcity of resources on the coast. With the discovery of gold in the interior, both the establishment of settlements and the decimation of the indigenous population were consolidated (Borges et al. 2009).

During colonial times and at the beginning of the Brazilian Republic (1889), not much was done to protect the environment (Borges et al. 2009). The authorities maintained certain blindness to the predatory actions of large landowners and, even with the establishment of the republic, continued to make biased concessions to powerful groups that held political influence (Drummond and Barros-Platiau 2005). One of the many consequences of this approach is the high concentration of land and wealth. This is still present today in Brazilian society: Brazil is positioned 98th on the UN Inequality-adjusted HDI, out of a total of 189 countries (UNDP 2017a).

Concerning environmental laws, in 1934 the first Forest Code was created. This was later altered in 1965, after seventeen years of discussion in the Congress (Drummond and Barros-Platiau 2005). Even though it was a protective legislation, since its inception, it has never been appropriately obeyed and implemented. A presumption of impunity due to an absence of enforcement bodies has made it economically advantageous to circumvent environmental laws (Borges et al. 2009).

In 1972, Brazil's participation in the Stockholm Conference was with the mentality of defending national sovereignty and the idea that developing countries should not be 'sacrificed' for environmental restrictions (Magalhães De Moura 2016). As absurd as this may sound, defending the right to destroy the environment, 47 years later this is still a vision commonly observed in parts of society. The 'Developmentalism' idea, present during the dictatorship, was that Brazil should become a world leader at any cost: at the cost of social justice, of natural resources or even of political freedom (Drummond and Barros-Platiau 2005).

With the growth of global environmental awareness in the 1980s, the developmentalism model began to be questioned, as faith in authoritarian governments and in dirty growth also began to fade. The end of the Brazilian military dictatorship in 1985 led to a new National Constitution, issued in 1988, where the environment was addressed with more attention (Drummond and Barros-Platiau 2005; Borges et al. 2009; Magalhães De Moura 2016). In 1992, the Rio Summit (United Nations Conference on Environment and Development) is not only marked in the history of Brazil but in the whole world in terms of discussions on global environmental policy and sustainability.

Following on from the 1992 Rio Summit, the Environmental Crimes Law was created in 1998, where environmental crimes were finally specified and enforced by law. Penalties were standardized and offenses were clearly defined (Magalhães De Moura 2016). Unlike in the past, the law established the liability of corporations, allowing large companies to be held criminally liable for any harm that their ventures may cause to the environment (Drummond and Barros-Platiau 2005; Borges et al. 2009). Despite the fact that, presently, Brazil presents a modern, extensive and innovative environmental legislation, the legal support for compliance remains weak, being completely ignored in some cases (Drummond and Barros-Platiau 2005).

It is worth briefly mentioning Oliveira and Cunha's (2017) study that addresses the culture of disrespecting laws in Brazil, or laws that commonly *stick* or *don't stick*. According to the study, Brazilians generally consider their chances of being punished for breaking a law as low. Stemming from the immense social inequality present in the country, the popular concept that the law is for the poor and that the rich are above the law, was proven in the aforementioned work. One of the results showed that the richer the person is, the greater their propensity is to disobey laws. In the eyes of individuals and institutions, social inequality can cause the extreme poor to be invisible, the demonization of those who challenge the system and the protection of the privileged, thus destroying the impartiality of laws.

The Environmental Code is a clear example of a law that *didn't stick*. As explained by Brancalion et al. (2016), in 2009, pressures from agribusiness to change environmental legislation increased, with the argument that the law was old and needed to be modernized. Among important advances on environmental protection, the academic community promptly pointed out serious setbacks that were being implemented, but their suggestions were not incorporated into the final version of the law text. The logic that the environment should be adapted to suit agricultural production prevailed, placing the long-term success of the agriculture activity at risk. An amnesty was granted to those who had previously disrespected the law, generating not only a sense of impunity but also economic advantages to those who do not comply with the law.

Also explained by the authors, many areas that were in non-conformity with the old environmental legislation were destined for large-scale agribusiness, a sector that has extensive financial power. Food for the Brazilian population is mostly produced by family farming, an activity that was eventually displaced to areas of lower agricultural aptitude and/or degraded (Brancalion et al. 2016). Public and social policies that meet the needs and create more possibilities for this section of the population emerged as a way to ensure the longevity of an activity and guarantee the supply of food to the country.

1.1.2 Inequality in Brazil

Inequality has always been part of the Brazilian social structure. As well explained by Suarez Dillon Soares (2006) "Brazil is internationally known for being a five-time world champion in football, home to much of the world's largest rainforest, and for being a country of extreme inequality. An extensive bibliography deals with the permanence of this inequality through events as different as the economic miracle, the return of democracy, the hyperinflation and the several stabilization plans, the trade opening, the economic stabilization, and the diverse valorizations and exchange devaluations".

In the most recent UN Human Development Report, Brazil was in the 79th position in the development ranking, out of a total of 189 countries (UNDP 2017a). However, when the index considers social inequality, Brazil is 19 positions lower. This is below the average for Latin America and the Caribbean, starkly illustrating the development issues facing Brazil. Also used to measure inequality, the GINI index does not improve the Brazilian situation: the country is ranked among the ten worst inequality grades in the world at the 146th position, the worst performance from any Latin American country (UNDP 2017b). Inequality reduction in Brazil has stopped. The distribution of income has stagnated, poverty has returned, and the equalization of income between men and women, and blacks and whites has receded. These are undesirable setbacks for a country whose majority is made up of the poor, blacks and women (Oxfam Brasil 2018).

Less developed areas are often forgotten by national politics in regard to development measures. Growth and funding continually go to the same regions and people. To direct innovative research possibilities to this social stratum could figure as a way to positively impact the lives of people with great needs and help to move in the direction of an equal society.

1.1.3 An overview of Brazilian power sector

According to Lorenzo (2002), with the founding of the Brazilian republic, the consumption of electricity in the country began, concentrated in major urban centers and in areas of industrial production. Power generation and distribution in the 1930s began to be consolidated in the country, mainly owned by foreign firms and focusing exclusively on hydroelectricity. Also, within this decade, regulation of the electricity sector began. Concurrently, the federal government commenced control of the watercourses and waterfalls in Brazil, requiring the granting of any kind of use. It also began to regulate energy tariffs, which reduced the profits of foreign companies and, consequently, investments and expansion of the system. In the 1940s, state-owned energy companies began to emerge with great strength in the market.

In the 1960s the Rio de Janeiro-Sao Paulo axis was faced with an exhaustion of hydroelectric possibilities. This was a region with the largest population and industrial concentration and resulted in the expansion of the hydroelectric system out of this axis. State companies became more and more important, creating large hydroelectric power generation plants and almost completely dominating energy generation in the country. Later, military dictatorship in the country (1964-1985) supported these companies and invested in a unified and centralized national system (Lorenzo 2002).

The 1990s were also marked by privatizations in the energy sector, which aimed to pay off the debt of the sector that had enjoyed rapid growth in the 1960s and 1970s and subsequently went bankrupt in the 1980s (Fagundes de Almeida and Queiroz Pinto Junior 2000; Tovar et al. 2010).

The Brazilian electricity sector went through a serious crisis in 2001 when lack of planning in the sector was demonstrated by widespread blackouts throughout the country (Javier Ramos-Real et al. 2008). Caused by a period of drought, the situation caused a nationwide power outage until it was circumvented two years later (Fagundes de Almeida and Queiroz Pinto Junior 2000).

A major milestone in the 2000s was the creation of the program *Light for All* (Luz para Todos – LPT) in 2003, which aimed at providing electricity to the 12 million Brazilians who lived in non-illuminated areas, 10 million of these people were located in rural areas (Gómez and Silveira 2015). The program had impressive results: focusing mainly on the extension of the grid. The LPT brought electricity to 14 million people, 42.3% of these people being rural workers and 60% living from, at most, a minimum wage (MME 2009). The LPT made improvements to households and communities with electricity, especially with regard to life quality (91.2%) and living conditions (88.1%) (MDA 2013). According to a quantitative survey of the program's results (MME 2009), 9 out of 10 respondents stated that their quality of life improved after electricity. Income improved for 35.6% of the beneficiaries and 40.7% were able start school activities at night. The availability of medical care improved to 22.1%. The arrival of electricity also encouraged small producers to unite. Another interesting result was the return of people to the countryside: Out of 2 million families, 96,000 families returned to live in the countryside, which is equivalent to 480,000 people leaving the cities. The success of the program did have a limitation, isolated areas could not be provided with electric power. Especially in the Amazon region, the extension of the grid proved impossible to achieve (Gómez and Silveira 2015).

Another severe water supply crisis occurred, one that began in 2014 and for which there was no effective mitigation measure. In a context in which hydropower still represents more than 65% of the country's total energy supply (EPE 2018), there remains no significant investment in improving the system to make it safer and cleaner. We also find that the country is still dominated by an impoverished population that is repeatedly losing its social guarantees. It is a country with inestimable environmental wealth, where sustainability measures are still considered by its leaders as delays to progress.

There is a consensus in the scientific community about the damages caused to the environment and riverine communities by major hydroelectric projects (Oliveira et al. 2016; Winemiller et al. 2016; Nobre et al. 2016; Voivodic and Nobre 2018; Castro-Diaz et al. 2018; Moran et al. 2018), it continues to be the primary energy source for expansion of the country's electric system. The main geographical foci for this development are the Amazon and the Cerrado (Brazilian Savannah) (Ferreira et al. 2014a), two large megadiverse biomes that suffer high pressure from agriculture, livestock farming and logging. Recent corruption scandals involving the construction of hydroelectric plants raise the question of whether the motivation for such construction is actually the generation of energy for the population or only a way to divert public money and to attend particular financial interests (Voivodic and Nobre 2018; Moran et al. 2018).

Moran et al. (2018) point that without considering the real social, environmental, and cultural costs involved in the water dams construction, it cannot be considered a sustainable source of energy. Another impact of large hydroelectric dams is related to the displacement of a large number of workers for their construction, causing a significant imbalance in the local social dynamics (Fearnside 2016). Nobre et al. (2019) highlights that in dryer regions, water from dams is coveted for use with irrigation. Since energy generation is the priority, conflict over the resource often occurs. One way to minimize this dispute for water in cases of scarcity is to plan multiple sources of renewable energy generation, preferably taking advantage of the opportunities of each location.

The purpose of this project is to think about possible alternatives for the electricity sector, where a union can be found between the respect for people and the environment, bringing advances in environmental areas but also on the lives of the people and communities involved. In order to access sustainable possibilities that could improve life in the country, the generation of clean decentralized energy and the guarantee of food security in Brazil led to the investigation of residual biomass energy: an activity that has the potential to generate clean energy, without the impact of large scale hydroelectric dams, that do not rely on a connection to the central grid and that do not compete with food supply.

As detailed during the study, relying on one single technology without a clean and sustainable alternative may condemn Brazil to scenarios of water and energy scarcity and may cause an abrupt raise on GHG emissions. The water crisis in 2013-2015 exposed the fragility of the system, aggravated by bad conditions of natural gas thermoelectricity (Corrêa da Silva et al. 2016). Having faced cyclical periods of drought, it is to be expected that similar problems occur in the near future, even more within the context of climate change. There is an urgent need for investigation and direct application of new possibilities for electrical energy generation that promotes environmental sustainability.

1.2 OBJECTIVES AND RESEARCH QUESTIONS

It is necessary to explore alternative energy sources that are sustainable and would guarantee a safe energy system for Brazil in the coming years. Hence, the aim of this thesis is to investigate the role that biomass can play in the Brazilian electricity matrix. The hypothesis is that residual biomass as an energy source could play a major role in transforming the Brazilian energy matrix towards a sustainable path: renewable, reliable, with a small negative social and environmental impact, that could bring social and economic benefits to the producer communities and promote the decentralization. To attain the overall goal, four general steps were defined: (1) to explore the potential areas for sustainable biomass energy production; (2) to evaluate the perspectives for biomass energy production in peripheral areas; (3) to identify the potential of biomass energy production in one entire state and (4) to evaluate the costs and social acceptance for biomass enterprises. More specifically, the following research questions were formulated to narrow the research gaps:

1. How are the potential areas for sustainable biomass energy production spatially distributed in Brazil in relation to power demands?
2. Is there potential to develop the biomass energy sector to meet the demand of peripheral areas?
3. How much energy from residues can be produced sustainably without compromising the soil?
4. Can the sustainable potential meet the energy demand of an entire state?

5. What is the potential of energy production from agricultural waste, the ideal allocation of the energy production unit and the costs involved in the enterprise?

1.3 Approach and structure of the thesis

To answer the aforementioned research questions, a GIS assessment was conducted, overlaying data on demand for energy, existing transmission lines, existing power plants units, and data on the environmental restrictions. It resulted in a ranked map with indications of areas with high potential for biomass production, not demanding land use change. One of the regions illustrated on the map, with high potential for energy production by biomass, was selected for an estimation of its local potential. Municipalities with low Human Development Index (HDI) values and which were not well connected to the central grid, were chosen and their agricultural and forest production accessed. This resulted in an estimation of agricultural and forest residue production. Existing formulas were applied, resulting in the regional potential of energy production by waste. These results were compared with the local demand for electricity, showing a picture of energy self-sufficiency for basic uses. In order to map opportunities for power generation from biomass residues in a different scale, the energy potential was estimated adopting a Sustainable Technical Coefficient, a conservative index that considers the portion of residues that could be used to maintain the integrity of the soil. This index was applied, together with the data on the silviculture and selected crops yield. The local energy demand was also calculated and compared to the potential energy production. The same methodology was tested in a different area, where calculation regarding the ideal location for biomass energy producing units needs to be established, as well as the costs involved in the operation. In addition to a current production scenario, the cost for a scenario where the production is increased was assessed, giving data for the local communities to evaluate the viability of the proposal.

The research approaches and methods, as well as the answers to the research questions are presented in four papers. The thesis is structured as follows:

Paper #1 (Chapter 2.1): Addresses the research question 1, regarding the sustainable potentials of the energy sector in Brazil.

Definition of the study area (Chapter 2.2): This section briefly explains the criteria used to choose the study area on the next paper.

Paper #2 (Chapter 2.3): Addresses the research question 2, presenting the opportunities for power generation in a Brazilian peripheral region. The main objective of this paper was to evaluate the regional potential of energy generation in municipalities with a low HDI, where it could positively impact people's lives.

Paper #3 (Chapter 2.4): Addresses the research questions 3 and 4, assessing how much energy from residues could be produced sustainably without compromising the soil and if the sustainable potential meets the local demand for energy.

Paper #4 (Chapter 2.5): Addresses the research question 5, evaluating the potential of energy production through agricultural waste, the ideal allocation of the energy production unit and the costs involved in the enterprise.

Chapter 3 presents the synthesis of the results, describing the overall achievements and listing the research questions. Incorporated in Chapter 4 is a discussion on how the results are useful for Brazil and a synthetizes of what was discussed in each of the papers, as well as any research gaps. In Chapter 5, a synthesis of the conclusions is presented, together with an overall conclusion and an indication of next steps.

2. Publications

2.1 PAPER #1: SPATIALIZED POTENTIAL FOR BIOMASS ENERGY PRODUCTION IN BRAZIL: AN OVERVIEW

Ribeiro, Ana Pimenta; Rode, Michael (2016) Spatialized potential for biomass energy production in Brazil: an overview. *Brazilian Journal of Science and Technology* 3:13. https://doi.org/10.1186/s40552-016-0037-0

Authors' contributions: the research was conceived by APR and MR, conducted and written by APR under supervision of MR. Both authors read and approved the final manuscript.

Paper purpose

On this first step of the work, the main objective was to identify potential areas for sustainable biomass energy production within the entire country. A unique approach was used for that, where five premises were adopted:

1. To locate regions with higher energy demand, directing than the energy to places where it would be more necessary;
2. To identify areas that would be further from an installed transmission line, considering it as a sign of greater need and potential for decentralization initiatives;
3. To generate new energy production areas, avoiding locations with existing hydro or thermoelectric power plants;
4. To focus on areas with anthropic land use (agriculture or silviculture), as a way to guarantee the conservation of native vegetation;
5. To exclude critical areas for environmental conservation.

This step was necessary to have an overview of the scenarios on the country and, based on that, to select the area with the desired characteristics to further develop the next steps.

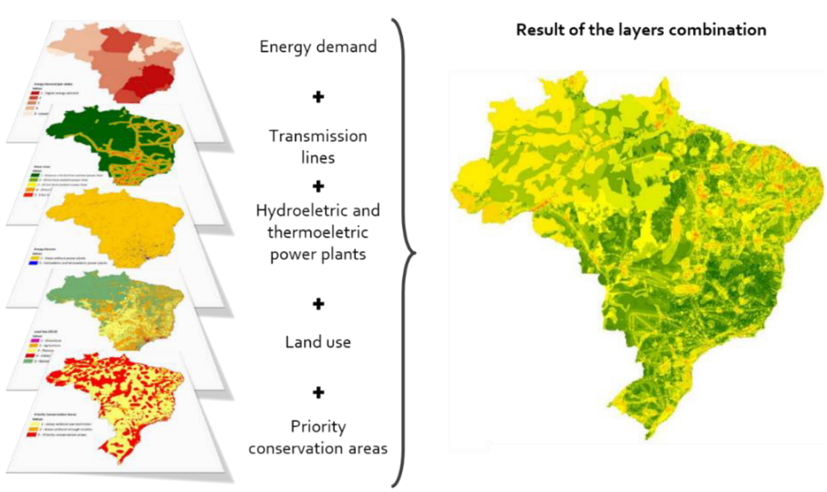

Figure 1: Graphical abstract of the first step.

Ribeiro and Rode *Braz J Sci Technol (2016) 3:23*
DOI 10.1186/s40552-016-0037-0

Brazilian Journal of Science and Technology

RESEARCH Open Access

Spatialized potential for biomass energy production in Brazil: an overview

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Abstract

The opportunity for renewable energy production in developing countries is a theme of high relevance within the context of climate change. In this paper we explore the production of electricity in Brazil and investigate the potential for sustainable biomass energy production. This is explored in a GIS system (1) establishing the demand centers or regions (energy demand factor), (2) checking if they can be served by existing capacity and transmission (transmission lines factor), (3) deciding on new generation and whether it will an island or the main grid connection (power plants factor), (4) locating the power plant subject to the potential biomass supply accepting the environmental constraints (land use and environmental preservation factors). Results show that even though large areas have a potential for biomass energy production, the lack of investments in technological improvements and changes in the system *status quo* result in a system that does not progress towards of becoming a cleaner, safer and less dependent on climatic factors. We conclude that biomass has the potential to grow as a source of renewable and clean energy. This potential can be explored by conserving respecting the environment and encouraging the creation of decentralized systems, thereby making Brazil a key player in the climate change targets in the coming years.

Keywords: Renewable energy, Sustainable development, Biomass, New technologies, Energy matrix, Energy security

Background

Satisfying the demand for energy supply is a persistent issue in the world today. To meet the requirements of a growing population, this demand will continue to increase in the coming years (IPCC 2007). In the second half of the 20th century, a number of research has pointed to the endangerment of the life on earth due to the effects of the climate change (Socolow et al. 2004; IPCC 2007; Kates 2010; IPCC 2011; Abramovay 2014). This is a direct consequence of the higher concentration of greenhouse gases in the atmosphere, mostly CO_2 originating from fossil fuels. Non-renewable sources of energy—mostly fossil fuels—are still responsible for 85 % of the energy supply in the world (IEA 2010; IPCC 2011), an exceptionally unsustainable aspect of human society.

The first concept of Sustainable Development—"Meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations 1987)—emerges from the necessity of finding alternative forms of development. The demand for renewable energy is a direct consequence of the global movement to decrease CO_2 emissions in the atmosphere and to retard the consequences of global warming, providing greener ways of living. In 2004, 48GtCO_2-eq were emitted to the atmosphere, and approximately 26 % of this amount was released during the process of power generation and heat supply (Sims et al. 2007). Therefore, an important step to reduce the effects of greenhouse gases is to change the way in which energy is generated, focusing on a planned, intelligent, and efficient chain of power production.

The installation and use of large-scale decentralized renewable energy technologies requires significant monetary investment and relevant changes in all sectors of energy consumption, plus organizational and legislative changes, the integration of environmental considerations, and the setting of multi-criterial regional planning and public participation (von Haaren et al. 2012). According to Abramovay (2014), despite being responsible for only 3 % of the energy matrix in the world, the increasing use of *Modern Renewable Energy Sources* (solar, eolic, geotermic, and biomass) tends to exponentially lower their price and thus, make them more accessible.

Distributed energy production from renewable technologies can provide an important source of renewable environmental-friendly energy. According to Blaschke et al. (2013), around 30–45 million hectares of land would need to be converted to meet European targets for biomass supply. The same authors point out that without adequate planning competition between bioenergy, conservation, traditional agriculture, and forestry, is inevitable.

Characterized by its diverse possibilities of sources and conversion technologies for energy products, biomass has a high potential for renewable energy supply. The term biomass encompasses plant material generated through photosynthesis and all its by-products, such as forest-wood, cultivated crops, animal droppings, and organic matter (Vidal and da Hora 2011). However, of all renewable energy technologies, biomass needs the greatest area per produced unit of energy (Blaschke et al. 2013), and is associated with a high conflict potential with other spatial uses (Söderberg and Eckerberg 2013). Regarding environmental sustainability, power generation through biomass should guarantee the quality of soil, water and biodiversity cycle, lowering externalities in the long term.

Brazilian case

Brazil has a peculiar source of power generation, where hydropower is a source of almost 80 % of the total energy supply in an extremely centralized system (EPE 2014). When a risk of blackouts is eminent, thermoelectric plants become the government guarantee that the energy system is safe. In 2014, they were responsible for 27 % of Brazil's energy (EPE 2014). About 70 % of the country's hydropower potential is located in the Amazon and Cerrado (Ferreira et al. 2014) (Fig. 1), the two biggest Brazilian biomes, both with high levels of species endangerment. The impact of those projects, both on nature and on the way of life of the local communities around the rivers, is impossible to avoid. Even with the Brazilian Environment Ministry imposing a series of conditions for the licensing of the projects, it is not uncommon to see the continued construction of dams, which defy these constraints and consequently create irreversible social and environmental impact (Fearnside 2009; Abramovay 2014).

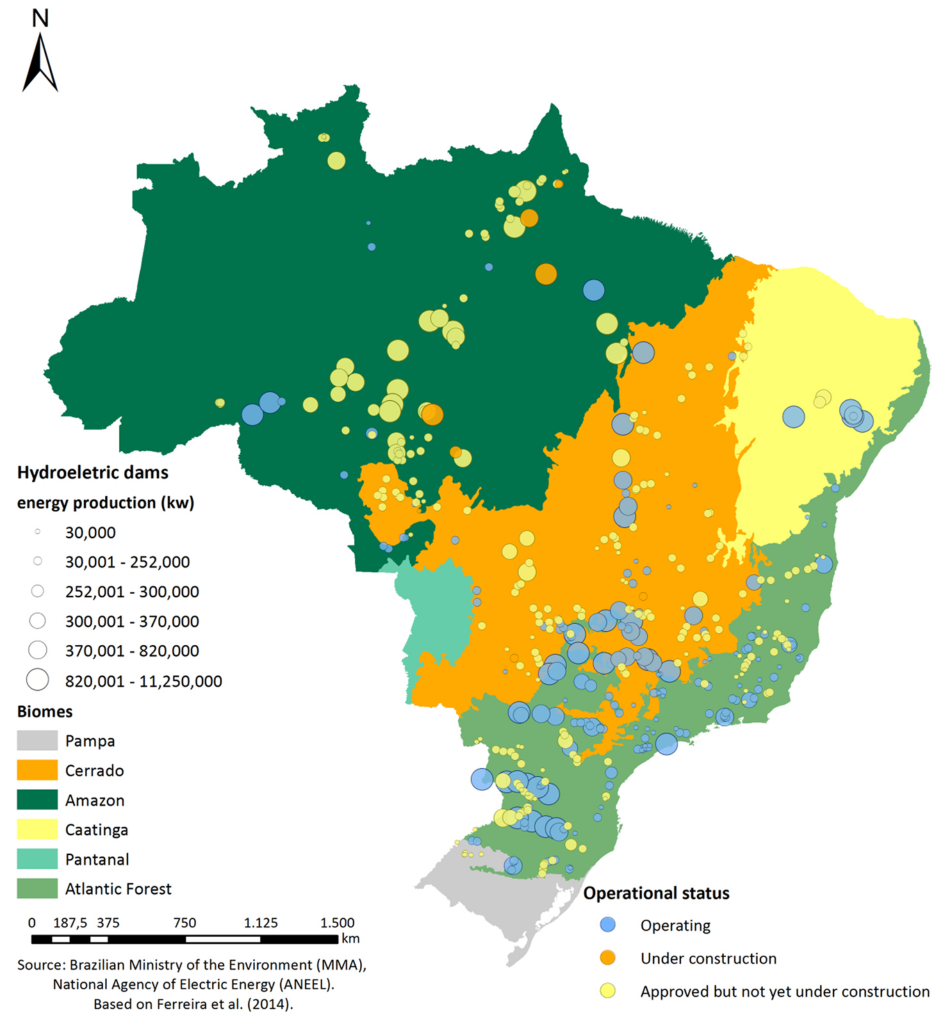

Fig. 1 Panorama of hydroelectric dams in Brazil

Having experienced an unexpectedly weak rainy season in 2013–2015, with a low amount of rainfall, the Brazilian population has had to deal with the consequences of an electrical system that is highly dependent on only one technology and the associated effects of water and energy rationing in the country's largest cities and its regions (Escobar 2015; Brasileiro 2014; Corrêa 2014). Without proper investment in the sector, which currently focuses on a few *capacity* increases and not *efficiency* increases, without the necessary water quantity, and without an alternative source of clean energy, the country is appealing as never before to thermoelectric energy to meet its demand, making the system more expensive and environmentally dirty (Gomes 2014).

Being a pioneer in the use of biofuels (Goldemberg 2008), biomass currently contributes to only 7 % of the total share of electricity in Brazil. According to the trend of decarbonizing energy production, based on the 2050 reduction targets of CO_2 emissions and the recent target of a 20 % increase in the share of renewable energy (other than hydropower) in electricity generation in the country by 2030 (Mason and Volcovici 2015; Plaisant 2015), the prospect of potential energy production through biomass in Brazil has become an important factor for the country's decision-makers. Even though it is currently an expensive source of energy, the increased use of biomass tends to lower the production costs.

In Brazil, the generation of energy from biomass is chiefly sourced from sugarcane bagasse, eucalyptus, and wood byproducts (Tolmasquim et al. 2007). The sugarcane production is a traditional activity in the country since the colonial period (Santos et al. 2015) and is the main responsible for the biomass energy production. The bagasse, a byproduct of sugarcane beneficiation, is commonly used to generate energy for self-supply in sugar-ethanol companies (Dantas et al. 2013). In addition, eucalyptus, planted on a large scale throughout the country for cellulose, paper and wood production, has recently begun to be used also for energy production. For this purpose, fast cycle plantations of eucalyptus have been established and are achieving good results (Cortez et al. 2009).

A commonality between the two main crops used for energy production in the country, are the major environmental impacts caused by their monocultures. Both eucalyptus and sugarcane tend to be cultivated in large-scales by large-scale companies. This results in a loss of biodiversity and impacts on the communities in the region and their way of life (Muñoz 2007).

Some cases of biomass energy production are also carried out on smaller scales (Agostinho and Ortega 2012). One example of such a project is implemented in the Brazilian Amazon by a small community. Using byproducts from the timber industry and other local crops, they generated electricity for approximately 400 people who previously had no access to it (Velázquez et al. 2010). Despite the existence of legislative programs, the high short term cost always appears to be the main issue limiting the application of new technologies in the country (Lampreia et al. 2011).

In this context, this study aims to explore Brazilian electricity production and investigate the spatial potential of biomass energy production in the country. To address this target, we answered the following questions: What are the struggles and the potentials of the energy sector in Brazil? Which are the spatial possibilities for biomass energy production? Considering the existing resources of each region, where the production of biomass for power generation in Brazil could be viable?

Methods

With the aim of achieving sustainability in electricity generation, five factors were determined for analysis: energy demand factor, transmission lines factor, power plants factor, land use factor, and preservation factor (Table 1). The database used in the research was selected in regard to the relevant aspects important for investigation of locations with high potential for power production.

The energy factor focuses on the energy demand in the country per state. This factor was chosen in order to highlight the spatial potential in areas where the energy is most needed. The energy demand from 2013, in each state, was divided by its population to be able to show the demand *per capita*. This factor was generated adding the data from the Brazilian Energetic Agency with the country vector. The state scale was chosen considering that this data is not available for all the 5.570 municipalities in the country.

Table 1 Criterias adopted for the area selection

	Factors	Criteria	Goal
1	Energy demand factor (Download in March of 2015 from http://goo.gl/iMiMzO)	Areas with greater demand for energy/inhabitant will have a greater need energy production	Locate places with higher demand
2	Transmission lines factor (Download in March of 2015 from http://goo.gl/6vBU0n)	More remote area is of a installed transmission line, greater is the need	Encourage a decentralized system
3	Power plants factor (Download in March of 2015 from http://goo.gl/iMiMzO)	The lower energy production density in the region, the greater is its need	Generate new production areas
4	Land use factor (Download in March of 2015 from http://goo.gl/xcscy)	Areas with an anthropic land use will have a greater need	Conservation of native vegetation
5	Preservation factor (Download in March of 2015 from http://goo.gl/4khjso)	Areas of relevance for environment preservation present less need for energy production	Preservation of key areas for environmental conservation

The transmission lines and the power plants factors are connected by the issue of supply availability. These factors should comprise of areas that are not well connected with existing lines in the country, encouraging a new connection or importantly, indicating a potential area for a decentralized system. The transmission lines factor was included in the analysis with five different buffers: 5, 10, 20, 50, and more than 51 km. With this, we planned to scale the effort of new connections, as the area extends far from existing transmission lines. For the power plants factor, a simple point was given for areas with hydroelectric or thermoelectric power source, locating areas without any power source.

Finally, the two last factors, land use and preservation, aim to avoid the use of native vegetation for energy production and locate areas with the most suitable potential sources. Both were chosen considering that to base a study only in the land use or the priority areas for conservation would let a gap between places with remains of native vegetation and places with a great relevance for the biodiversity in the country. The classification of the land use areas assigned a greater potential to disturbed areas, to save the native vegetation. The energy should be generated through the capacity already installed in the area, not being necessary to open new areas or change the local main activity. The preservation factor is based on a detailed study conducted by the Brazilian Environment Ministry, involving scientists from universities, the government, and NGO's. This study collected data about biodiversity, resulting in a map of areas showing where usage would endanger the ecosystem in the given region.

Database

The database was used in vector format and was acquired from official Brazilian government websites. The scale of the data is 1:5.000.000, the default scale from the official website database for the entire country.

The organization of the database was based on the criteria adopted for the selection of the ideal areas. For every factor, values were assigned on a scale of 1–5, with the lowest value (1) for the ideal feature for selection and the highest value, 5, to the less suitable areas. To calculate the demand for energy, for example, the value 1 was allocated to the states with the highest demand for electricity. This value increased gradually until the states with the lowest demand for energy were reached, which had the designated value 5. This logic was applied for the five vectors used in the analysis.

The analyzed layers were combined through a simple layer math in the software ArcGis 10.3, generating a file with values ranging from 5 to 25 (Fig. 2). In the resulting map, areas with the value 5 were considered extremely suitable, according to the chosen criteria. Areas with the value 25 were considered extremely unsuitable (Fig. 2).

Results

The description focuses on the areas that have a final score between 5 and 7. We considered that the areas with results above 7 would bring too many adverse characteristics to the final investigation. The grouping system sought to separate the results into relevant classes. The first group (5–7) indicates the most significant areas for the study, where the characteristics fit with the desired goals. The second and the third group (8–14 and 15–21) contain intermediate areas of equal intervals. While the second group is positioned more closely to the suitable areas, the other is more associated with the less suitable. Finally, the last group (22–25) comprises of the worst areas, where the features were less favorable for power generation through biomass.

Figure 3 shows that this demand is concentrated in the Southeast region, an area with 42 % of the country's population (85.115.623 people) (IBGE 2014).

The supply availability is represented in Fig. 4. The centralized system is evident in both the transmissions lines (Fig. 4a) and in the energy sources (Fig. 4b). By overlaying both images from Fig. 4, it is possible to notice that the incidence of the transmission lines is concentrated in the locations with power sources. Another possible association is the connection between the distribution of power plants (Fig. 4b) and the agriculture areas, illustrated in the land use figure (Fig. 5a).

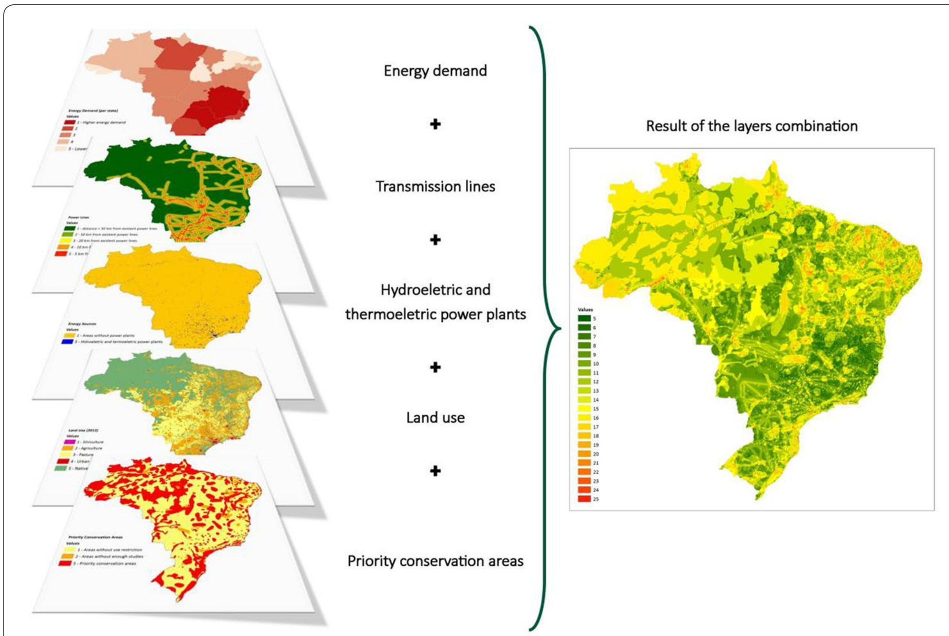

Fig. 2 Layers math scheme

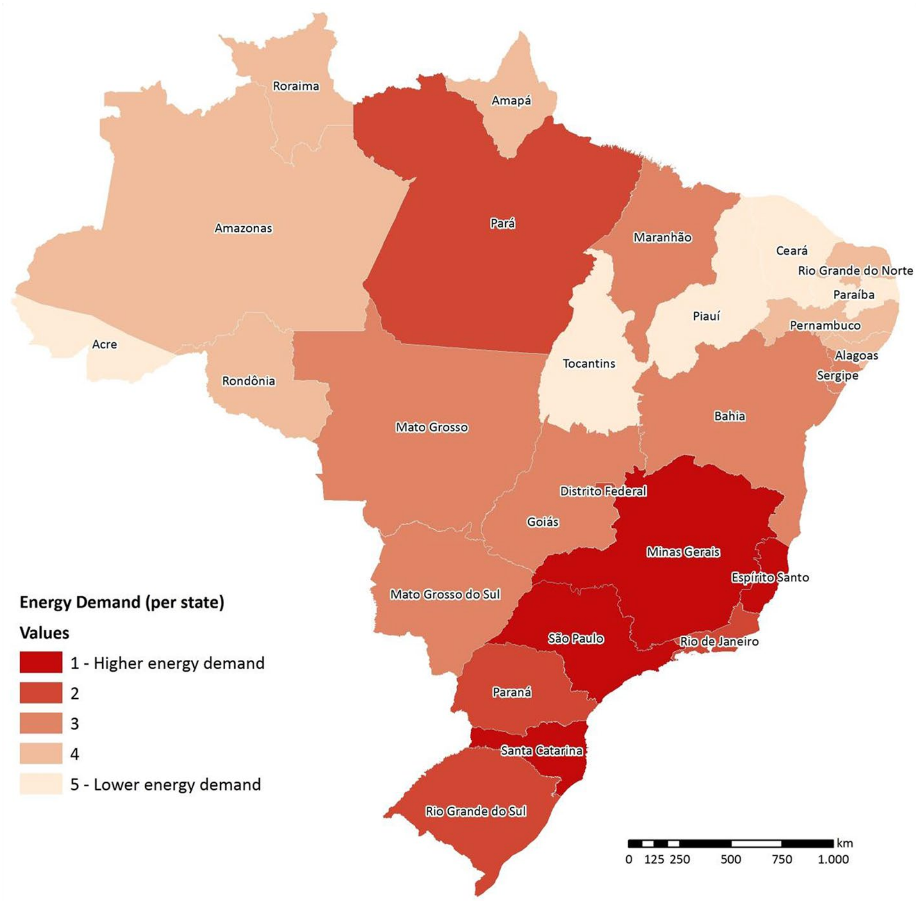

Fig. 3 Energy demand in Brazil (*Source* National Agency of Electric Energy—ANEEL)

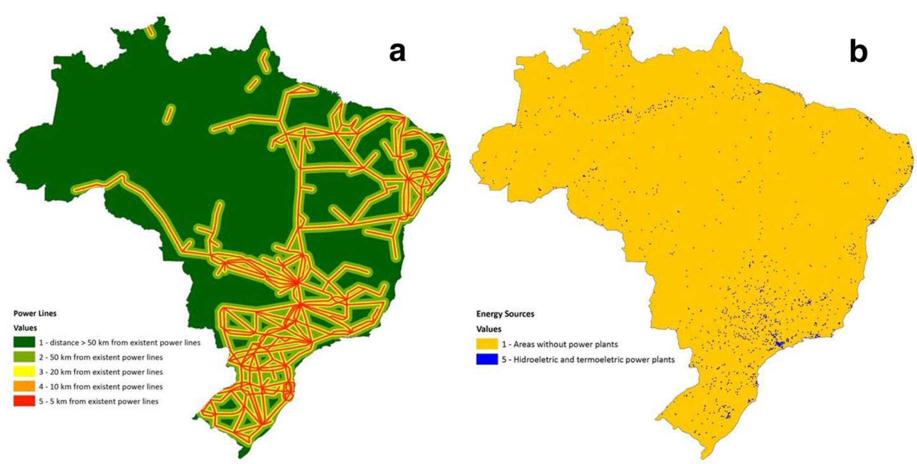

Fig. 4 **a** Transmission lines; **b** hydroelectric and thermoelectric power plants (*Source* National Agency of Electric Energy—ANEEL)

In Fig. 5, the potential availability of biomass is shown. The land use (Fig. 5a) shows that the remnant native vegetation is highly concentrated in the Northern region, where the Amazon Forest is located. The figure illustrating the priority conservation areas

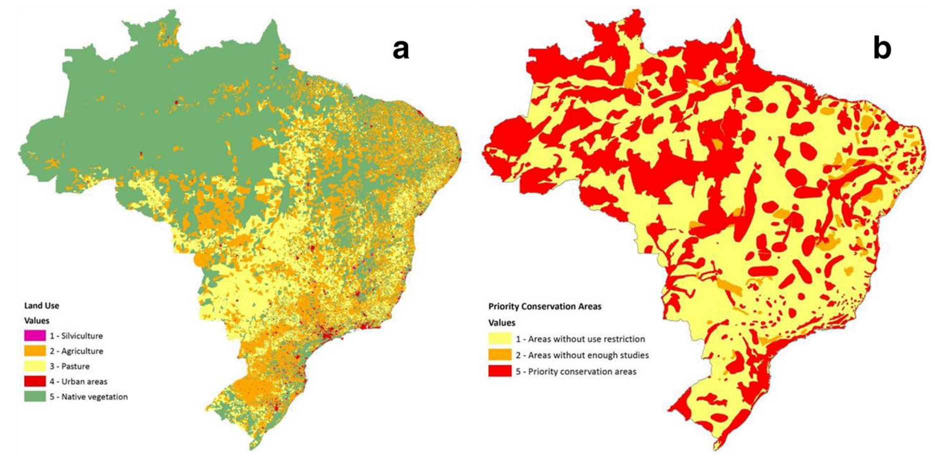

Fig. 5 **a** Land use; **b** priority conservation areas (*Source* Environment Ministry—MMA)

(Fig. 5b), similarly shows that there are a greater quantity of priority areas in the northern region, demonstrating the large relevance of these natural areas. On the other hand, conservation areas in places with high human disturbance can be extremely vulnerable, reinforcing the significance of this factor.

The results are presented in Fig. 6 and were analyzed per state, with the computed areas showing the greatest potential for energy production through biomass. The Southeast, Midwest, and Southern regions had the greatest number of areas with a potential for energy production.

Summarizing the results by state, only two states, when combined, held about 52 % of the best areas for energy production (Table 2).

Discussion

In other country-scale research, conducted for instance in Uganda and Thailand (Okello et al. 2013; Jenjariyakosoln et al. 2014), unexplored potential for biomass energy production is presented. Brazil does not show any contrary results when compared to such studies, even when examining large areas with potentials for production. One of the main reasons is that the lack of investments in technological improvements and changes in the system *status quo* result in a stationary system, which does not advance in the direction of becoming a cleaner, safer and less dependent on climatic factors. For the Brazilian case, Abramovay (2014) highlights that the country is following the path of the developed countries, investing first in polluting technologies (thermoelectric) and to only later make the shift to renewable energy. Over the past decades, Germany has been directing its efforts to change the way energy is produced in the country: primarily due to increased concerns about the environment, followed by environmental conventions and treaties on global scale (i.e. ECO 92 and Kyoto Protocol). Fighting climate change, reducing energy imports, stimulating technology innovation and a green economy, reducing or eliminating the risks of nuclear power, energy security, strengthening local economies, and providing social justice are some of the reasons why the country

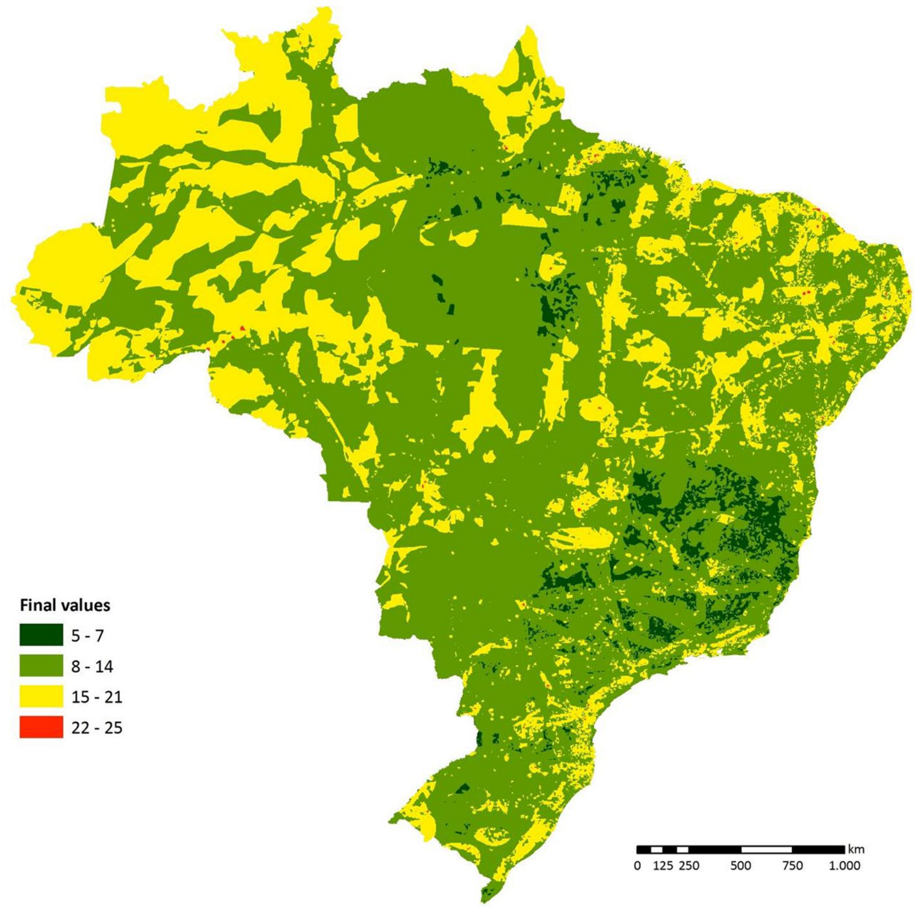

Fig. 6 Grouped results of the analyzed layers combination

Table 2 States with the best results

	State	Value	Frequency	Hectares	Sum hectares	HA total/state	% state area
1	Minas Gerais	5	8	86.709,72	18.249.606,78	65.231.313,67	27.98
		6	243	6.294.118,88			
		7	457	11.868.778,18			
2	Espírito Santo	5	3	46.471,54	1.288.300,00	5.187.497,70	24.83
		6	19	376.927,24			
		7	49	864.901,22			
3	São Paulo	5	1	2.418,17	2.329.327,23	28.926.735,36	8.05
		6	23	131.138,88			
		7	155	2.195.770,18			
4	Santa Catarina	6	4	6.620,87	615.695,36	11.996.020,69	5.13
		7	32	609.074,49			
5	Pará	7	128	5.724.936,48	5.724.936,48	125.727.312,64	4.55
6	Rio Grande do Sul	7	22	373.113,90	373.113,90	37.374.972,22	1.00

is investing in clean energy (Runci 2005; Morris and Pehnt 2012). For developing countries, the adoption of cleaner technologies at an early stage has the potential to save a lot of effort, money, and natural resources.

Even not being well connected to the national power grid, according to our results, most of Brazil's Northern region did not have favorable grades for energy production through biomass power plants. This region encompasses most of the Brazilian Amazon Forest, a factor that adds a high relevance concerning land use change and environmental preservation. Nevertheless, according to Fuso Nerini et al. (2014), the region has a potential for energy production from the residues of local agricultural production activities. This is a topic not yet well included in the country's energy agenda, one that could create a good scenario for decentralized renewable energy production.

Since 2003, the Brazilian government has been investing in multiplying the population's access to energy through the large scale program *Luz para Todos* (Light for all). In the last 10 years, the program has suceeded in supplying electricity to over 15 million people in the country (MDA 2013). Even with these advances, most of the new connections were based on a grid extension approach (Gómez and Silveira 2012), which still excludes around 200 thousand households in isolated communities. In some of these communities, an off grid solution would be the only way for people to have energy. These offgrid systems exist in some places but are mostly based on diesel generator technology, which is a very unsustainable power source that has an enormous dependency on informal sellers. Decentralized biomass energy may be a viable sustainable alternative.

The three states with the best scores—Minas Gerais, Espírito Santo, and São Paulo—are part of the Southeast region. This region is responsible for 55 % of the total Brazilian GDP (IBGE 2012), a consequence of the large amount of industries, commerce, the larger share of the country's population and energy connections. Even though the region contains many deforested areas, the higher demand for energy and its history of intensive agricultural use has contributed to the regions good grade. The Atlantic Forest biome that used to cover most of São Paulo state, for example, today occupies only 15 % of its original area (Fundação SOS Mata Atlântica et al. 2015). This region is the most vulnerable to blackouts, due to its higher energy demand as from its empty water reservoirs during the 2013–2015 water crisis. In this context, biomass energy could act as a complementary source of energy, bringing together source opportunities with the energy demand. This would make the region system safer as it would help to reduce the water usage for power production, thereby enhancing the sustainability of the system.

Considering the environmental impact caused by large scale biomass production, a mixed system between biomass and other renewables would contribute to attend the region's demand in a sustainable way. Also, the country has a large amount of degraded and unused areas, lacking of aptitude to produce food, but with no obstacles to produce biomass. So, with the proper investments, planning and an adequate range of sources, mixed systems of energy could be a reliable solution (Ambec and Crampes 2012), making possible relevant economies of scale for energy generation and storage (Elliott 2016). The modernization of the transmission system, not based in large connections but more focused on the local production-consume, could also help the country to meet the demand in a secure and reliable way. According to Armstrong et al. (2016), the future of the energy networks relies in a distributed, multi-source and multidirectional system. The biomass energy can fit those conditions, becoming a promising clean source.

The state of Minas Gerais, which had the best score, was where the first hydropower plant was located in the country. Even though it is a state with a high level of biodiversity, mostly caused by the different biomes found in its area (Klink and Machado 2005)—Savanna, Atlantic forest and Dry forest—the areas historic land use of agriculture and mining has removed a big portion of native vegetation. The state has the third highest GDP in the country, mainly due to the mining industry and activities related to it (FJP 2012). The development of a robust and sustainable system of renewable energy would lower the pressure and dependency on the hydropower system, allowing the region to develop socially and economically in an environmentally friendly way.

Conclusions

The domination of hydropower as an energy source in the country acts as an inhibiting factor for the emergence of newer technologies. The water crisis in 2013–2015 exposed the fragility of a system that relies only on one source. This article shows that, even with an energy source with a low rate of use in the country, biomass has a potential to grow as a renewable and cleaner supplier of energy in the coming years. This potential can be explored with respect to the environment and can encourage the creation of mixed and decentralized systems, placing Brazil as a key player in the climate change targets in the coming years.

The scale of the data used in the analysis may incorporate a factor uncertainty in the study due to the scale 1:5.000.000 being used, which is not ideal for exact accuracy. However, considering the country's size, this is the finest scale with available homogeny data that can be used. Further studies with a more accurate scale should be conducted in the areas with the higher potential, creating the possibility to develop a regional plan for biomass use. An assessment on the potential of using marginal, unused and contaminated areas to cultivate biomass plants should also be led, as a possible alternative that aims to save the native vegetation and not threat the country's food security.

Authors' contributions
The research was conceived by APR and MR, conducted and written by APR under supervision of MR. Both authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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2.2 DEFINITION OF THE STUDY AREA

Based on the results presented in section 2.1, an area to develop the study had to be chosen. The state of Minas Gerais (figure 2) showed the best potential in the country for proving the bases to the development of a biomass energy initiative, respecting the environment and its regulations.

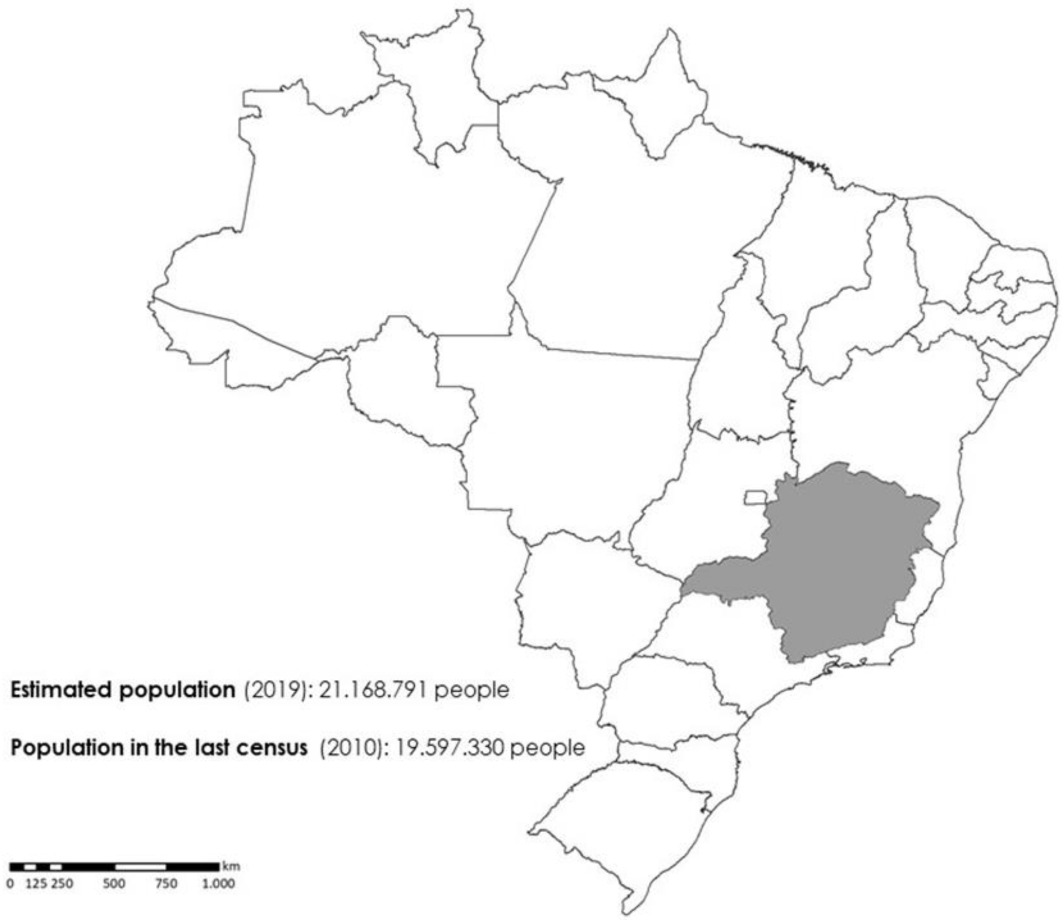


Figure 2: The state of Minas Gerais. Source: IBGE (2019).

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 the production of 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 2008, the exportation from the agribusiness reached US$ 5.9 billion, corresponding to 8.2% of Brazilian agribusiness exports that year (Bastos and Gomes 2011). In this context of mineral and agriculture wealth, 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. Source: FJP (2018)

	Brazil	Minas Gerais
	2015	2015
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

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) (table 2, figure 3). This encounter of different environments creates transition areas that are extremely rich in biodiversity and environmental specificities.

Table 2: 2017's land use on the state of Minas Gerais. Source: MapBiomas (2018)

Classes	**Coverage and land use (thousand ha)**	**Percentage of coverage and land use in relation to the total area of the State (%)**
Natural Forest	18.639,70	31,78
Planted forest	1.623,18	2,77
Pasture	20.342,37	34,68
Annual and perennial crops	2.355,20	4,02
Semi-Perennial crops	746,58	1,27
Agriculture or grassland mosaic	9.996,86	17,04
Urban infrastructure	268,62	0,46
Other non-vegetated areas	67,12	0,11
Outcrop	151,76	0,26
Mining	6,07	0,01
Grasslands	3.899,72	6,65

Other non-forestry areas	0,09	0,00
Not observed	1,53	0,00
Water	553,27	0,94

Figure 3: Brazilian Biomes overview. Source: IBGE 2006. Photos: Ana Pimenta Ribeiro (Atlantic Forest and Cerrado), Cristiano Lanza (Atlantic Forest) and Patrícia Mesquita (Caatinga).

The choice of the state of Minas Gerais as a focus of the study for Paper #3 (chapter 2.4), this state was considered ideal as there is uniformity in both the administration level (for example: same laws, financial conditions, taxes, support agencies) and electricity company (same regulations on the sector). After an overview of the potentialities (Paper #1), the state of Minas Gerais was considered as having the best conditions for this investigation and was therefore chosen. The research steps and the different analyzed scales within the state are represented on the figure 4.

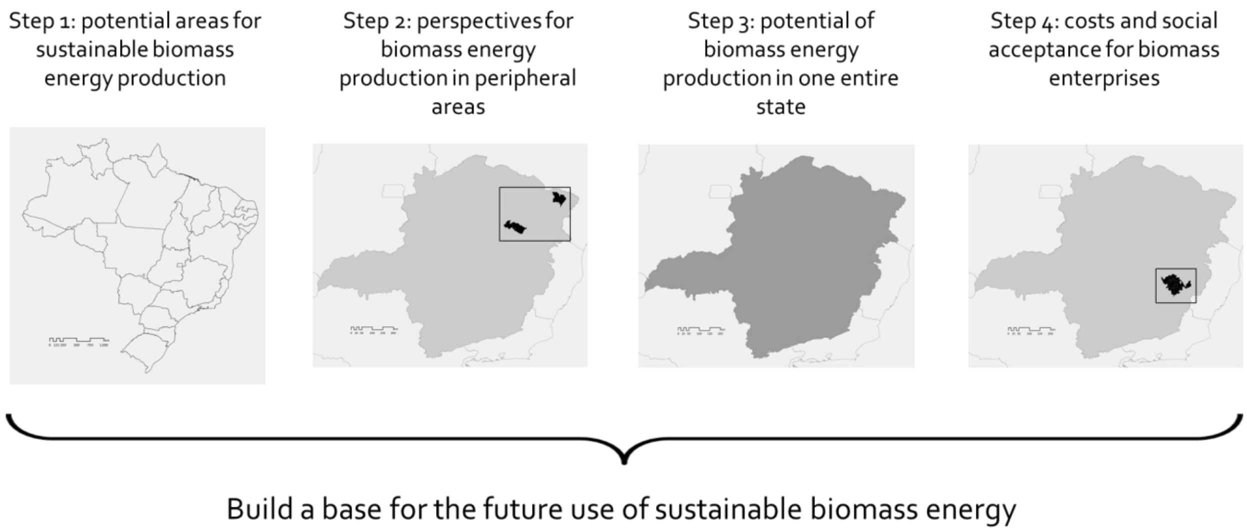


Figure 4: Research steps

2.3 Paper #2: Residual biomass energy potential: perspectives in a peripheral region in Brazil

Ribeiro, Ana Pimenta; Rode, Michael (2019) Residual biomass energy potential: perspectives in a peripheral region in Brazil. *Clean Technologies and Environmental Policy* 1:3. https://doi.org/10.1007/s10098-019-01675-3

Authors' contributions: the research was conceived by APR and MR, conducted and written by APR under supervision of MR. Both authors read and approved the final manuscript. The final publication is available at https://link.springer.com/article/10.1007/s10098-019-01675-3.

Paper purpose

After identifying areas in the country where there was a higher potential for biomass energy production, a second step was developed, with the objective of assessing potential areas where the sustainable energy could have a positive social impact on the municipality level.

Aiming at the investigation the perspectives for biomass energy production in peripheral areas, the methodological approach was divided into four phases:

1. The selection of the municipalities to be studied;
2. An assessment based on the production data from the selected municipalities;
3. The calculation of energy demand;
4. A comparison of the biomass energy potential and demand.

The relevance of this step relies on the possibility of going more in-depth on the investigation of the biomass energy potentials, using this time data on a more accurate level: for the crop and silviculture production and the relevant social-economic aspect.

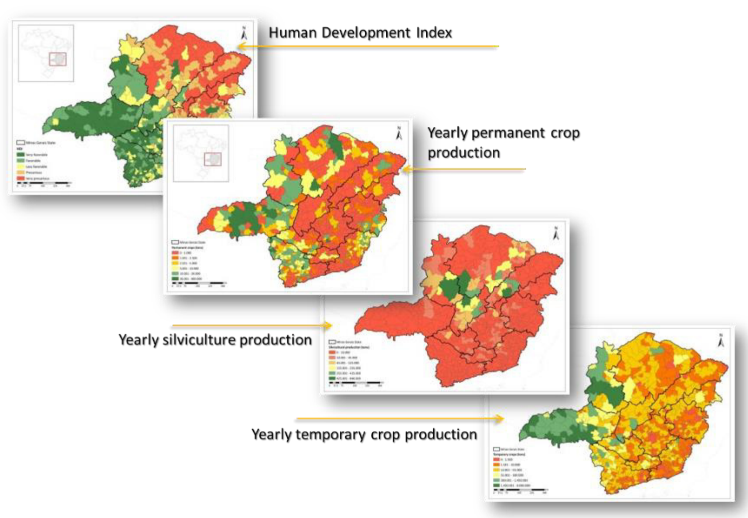


Figure 5: Graphical abstract of the second step.

Clean Technologies and Environmental Policy
https://doi.org/10.1007/s10098-019-01675-3

ORIGINAL PAPER

Residual biomass energy potential: perspectives in a peripheral region in Brazil

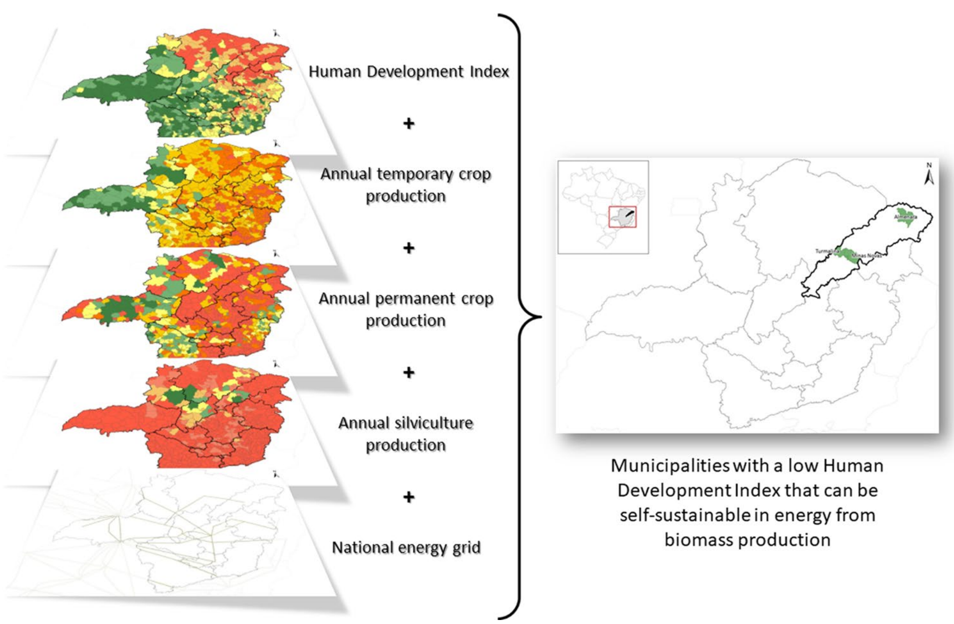
Ana Pimenta Ribeiro[1,2] · **Michael Rode**[2]

Received: 28 August 2018 / Accepted: 30 January 2019

Abstract

As a part of the United Nations new sustainable development agenda, renewable energy was one of the goals identified for the sustainable use of our planet. Previous studies on biomass energy production in Brazil have shown promising results as a renewable energy source. This paper highlights opportunities for power generation from biomass in the less developed regions of Brazil. Such opportunities create new energy generation possibilities in a country that already has an enormous rate of agricultural production, enabling access to energy and therefore increasing quality of life, optimizing available resources and decentralizing the energy system. This paper aims to evaluate the regional potential of energy generation in municipalities with a low Human Development Index. The methodological approach is divided into four steps: (1) the selection of the municipalities to be studied, (2) an assessment based on the production data from the selected municipalities, (3) the calculation of energy demand and a (4) comparison of the biomass energy potential and demand. Our results indicate that three small municipalities in the Jequitinhonha Valley (Minas Novas, Turmalina and Almenara) have the potential to be self-sustainable in energy production. In accordance with the UN recommendations, this potential should be explored more thoroughly.

Graphical abstract



Keywords Biomass energy · Sustainable development · Energy potential · Energy security

Extended author information available on the last page of the article

Published online: 06 February 2019

Introduction

In September 2015, the United Nations released a set of 17 goals as part of a new sustainable development agenda. The agenda focused on ending poverty, protecting the environment and ensuring prosperity for all by 2030. The objective was to reinforce the urgency of taking action in order to change the status quo. The topic of renewable energy is mentioned in goal 7, which aims to ensure access to affordable, reliable, sustainable and modern energy for all (United Nations 2015). Hence, the development of new technologies for energy generation is not only a topic of interest but is one of the goals for the sustainable use of our planet's resources.

Much research has been carried out in the search for cleaner and cheaper energy sources in many different countries. In order to reduce the emissions from energy generation, Panepinto et al. (2015a) explored planning possibilities for biomass energy production in Italy. They took into consideration the local demand, different types of available biomass as sources, the overall emissions and the consequent air pollution. The paper had positive results concerning the reduction in GHG emissions and the carbon footprint. Chakma et al. (2016), discussing the possibilities for bioenergy from rice residues in India, achieved favorable results in terms of energy prices and GHG emission reductions. The method provided a viable solution for the country's energy security and assisted in impact mitigation, without compromising the socioeconomic growth of the country's development. With the aim of finding ideal regions for the development of biomass energy initiatives with small impacts on the environment in Brazil, Ribeiro and Rode (2016) explored the capabilities of the country for energy production conserving and respecting the environment, as well as encouraging the creation of decentralized energy systems. Through GIS analysis, it was found that the lack of investments in technological improvements and changes in the system status quo were the determining factors for the delay in the development of the energy sector. Lillo et al. (2015) in Peru, Panepinto et al. (2015b) and Palmas et al. (2012) in Italy, Skoulou et al. (2011) in Greece, Palmas et al. (2015) in Germany, Turrado Fernández et al. (2016) in Spain, Batidzirai et al. (2016) in South Africa, Bhattacharyya (2014) in Southern Asia and Mayer et al. (2015) in Brazil are just some examples of the many researchers around the world that use different approaches and techniques to explore renewable energy opportunities.

Around 65% of Brazil's total electricity is produced by hydropower in a centralized system (EPE 2018). Even though there is a consensus in the scientific community about the damages caused to the environment and riverine communities by major hydroelectric projects (Hanna de Almeida Oliveira et al. 2016; Winemiller et al. 2016; Nobre et al. 2016; Voivodic and Nobre 2018; Castro-Diaz et al. 2018; Moran et al. 2018), it continues to be the main energy source for expansion of the country's electric system. The main geographical foci for this development are the Amazon and the Cerrado (Brazilian Savannah) (Ferreira et al. 2014), two large megadiverse biomes that suffer great pressure from agriculture, livestock farming and logging. Recent corruption scandals involving the construction of hydroelectric plants raise the question of whether the motivation for such construction is actually the generation of energy for the population or simply a way to divert public money and to attend particular financial interests (Voivodic and Nobre 2018; Moran et al. 2018).

In Brazil, discussions on renewable energy have not yet been a large focus, even though it could have a desirable positive impact on the country's GDP, employment and emissions (Lucchesi et al. 2017). Biomass used to be the primary fuel source used by human populations and still is for almost ten million people in Brazil today. Many Brazilians still rely on traditional biomass energy sources for cooking, with the majority of these people living in poor municipalities far from urban areas (Coelho et al. 2018). However, such biomass cannot be considered as a renewable source as the wood comes mainly from deforestation (Coelho et al. 2014). Additionally, hydropower energy in Brazil remains an untrustworthy source due to the risks of droughts all over the country, which is aggravated by climate change (Hunt et al. 2018; Moran et al. 2018). Natural gas thermoelectric plant is still seen as the emergential energy source in moments of water scarcity (Corrêa da Silva et al. 2016; Zurn et al. 2017). It is an element that should bring security to the country's energy supply, but instead, ends up not only leaving the system more polluted, but also leaving it more fragile as many of these thermal power plants were built in the 1960s and 1970s. With obsolete machinery, they operate at low efficiency with constant forced outages that increase energy costs (Corrêa da Silva et al. 2016). The alternative, thermoelectric energy, also intensifies inequalities within the country, as it is a more expensive type of energy and financially unattainable for the poorer population (Hunt et al. 2018).

Less developed areas are often forgotten by national politics in regard to development measures. Growth and funding continually goes to the same regions and people. In the most recent UN Human Development Report, Brazil was in the 79th position in the development ranking, out of a total of 189 countries (UNDP 2017a). However, when the index considers social inequality, Brazil is 19 positions lower. This is below the average for Latin America and the Caribbean, starkly illustrating the development issues facing Brazil. Also used to measure inequality, the Gini index does not improve the Brazilian situation. The country is ranked among the 10 worst inequality grades in the world at the 146th position, the worst performance from any Latin American country (UNDP 2017b). Inequality reduction in Brazil has stopped. The distribution of income has stagnated, poverty has returned, and the equalization of income between men and women, and blacks and whites has receded. These are undesirable setbacks for a country whose majority is made up of the poor, blacks and women (Oxfam Brasil 2018).

An extensive review of the connection between electrification and the development of rural areas by Cook (2011) reveals that this association may not always be correct. However, electrification can lead to investments in infrastructure and education, with greater chances for expansion in agricultural activities, entrepreneurism and savings. Therefore, the impact of power generation in some areas is not only related to income, but also to better education opportunities, health care and gender equality, as it is often female employment that is positively affected by access to electricity. To guarantee that such benefits are also reached with the shift to sustainable energy would mean that the country meets many of the goals of the UN sustainable development agenda.

An online search, concerning renewable energy production in Brazil, revealed new initiatives in wind energy, biogas from manure and small hydropower units. However, renewable biomass energy production is not well developed in this country (ANEEL 2008). Initiatives have been conducted almost exclusively by the private sector, by sugarcane companies aiming to reduce their electricity consumption (ANEEL 2018), by rice producers associations (Mayer et al. 2015) or by research institutes (Coelho et al. 2005; Coelho 2009). Brazil is a country that has always relied upon primary products to sustain itself. Pau-Brasil, coffee, cotton, rubber and iron are some examples of what has been produced since the arrival of the Portuguese (Furtado 1965; Rego et al. 2006). The general mind-set is that Brazil should supply primary materials for industries in developed countries, then import the more expensive end product or, alternatively, industrialize a product using imported technologies (Furtado 1974). Neither option contributes to the type of development that could bring a real improvement to the country.

The poorer regions in Brazil that rely on agriculture for a local market tend to diversify their production. The residues from agriculture are commonly left in situ to fertilize the soil or are discarded. Even though it may not be the main objective of the plantations, the residues from the cultivations could instead be used to generate energy. This would thereby bring more opportunities to the local population and not compete with food production for land. Previous studies on biomass energy production in Brazil concluded that this option appears promising. In the Brazilian Atlas of Bioenergy (Coelho et al. 2012), for example, the authors present a study that covers the entire country. They considered energy production based on residues from agriculture, silviculture activities, liquid swine sewage and solid urban waste in sanitary landfills. The results were presented on maps with potentials for the entire country and different scenarios of conversion efficiency.

In 2014, the Energy Research Company (EPE) published the Rural Residues Energetic Inventory (EPE 2014) with the main objective of assessing the energy potential of residues from agriculture, livestock and agroindustry. The report presented the specific sources in great detail, providing the production data and the potential waste production. Different conversion technologies were discussed and presented in regard to the technical potential for energy and biomethane production. They estimated a potential of 48 million toe[1] from agriculture and livestock residues.

The BREA Project (Biomass Residues as Energy Source to Improve Energy Access and Local Economic Activity in Low HDI Regions of Brazil and Colombia) was a joint effort between researchers from Brazil and Colombia, which resulted in a very comprehensive data set on energy generation from residues. The main objective of the project 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, p. 23). The methodology included conversion technologies, scenarios, policies, potentials and barriers in regard to bioenergy development for 32 municipalities in the Amazonian region.

This paper presents the opportunities for power generation in the less developed regions of Brazil. Such opportunities include access to and application of the technology, increasing people's quality of life, optimizing available resources, fostering a decentralized energy system and exploring new energy generation possibilities in a country with an enormous rate of agricultural production. The main objective of this paper is to evaluate the regional potential of energy generation in municipalities with a low Human Development Index (HDI), where it could positively impact people's life.

Materials and methods

The methodological approach is divided into different steps (Fig. 1). The first step was to select the municipalities. Then, an assessment based on the productive data from the selected municipalities was conducted, with the aim of collecting the data needed for estimating the biomass energy potential. The

[1] Tons of oil equivalent, 1 toe = 11.63 megawatt hour.

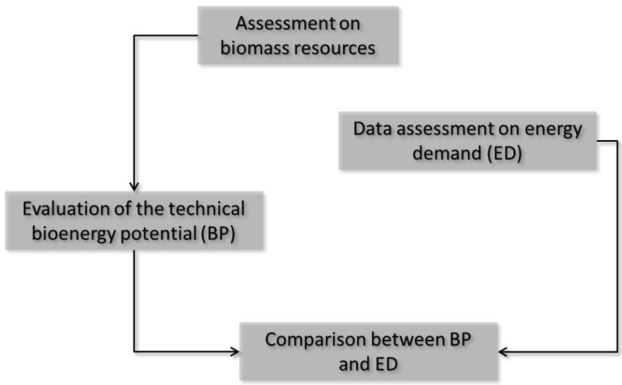


Fig. 1 Methodological approach, adapted from GNESD et al. (2015)

energy demand was calculated and, in a final step, compared to the biomass energy potential.

Selection of municipalities

We sought to identify municipalities where the energy production could help to generate social development associated with sustainability. Using the data obtained by Ribeiro and Rode (2016), information about the Human Development Index (HDI), silviculture production and temporary and permanent crops production was overlaid in a geographic information system environment. In accordance with the findings of the authors and the data availability, the Minas Gerais State was selected for the study.

The HDI (Fig. 2) was classified by ecological-economic state and zoned into five classes: very favorable, favorable, less favorable, precarious and very precarious (Oliveira et al. 2008). By employing this index, we selected municipalities from the Minas Gerais State that were classified as precarious or very precarious.

The second relevant aspect for study site selection was the crop (Figs. 3 and 4) and silviculture production rate (Fig. 5). To estimate the biomass energy production by exclusively using residues, the selected areas needed to have good residue availability in order to make the production viable. For this purpose, 2015 production data from the Brazilian Institute of Geography and Statistic (IBGE) were assessed.

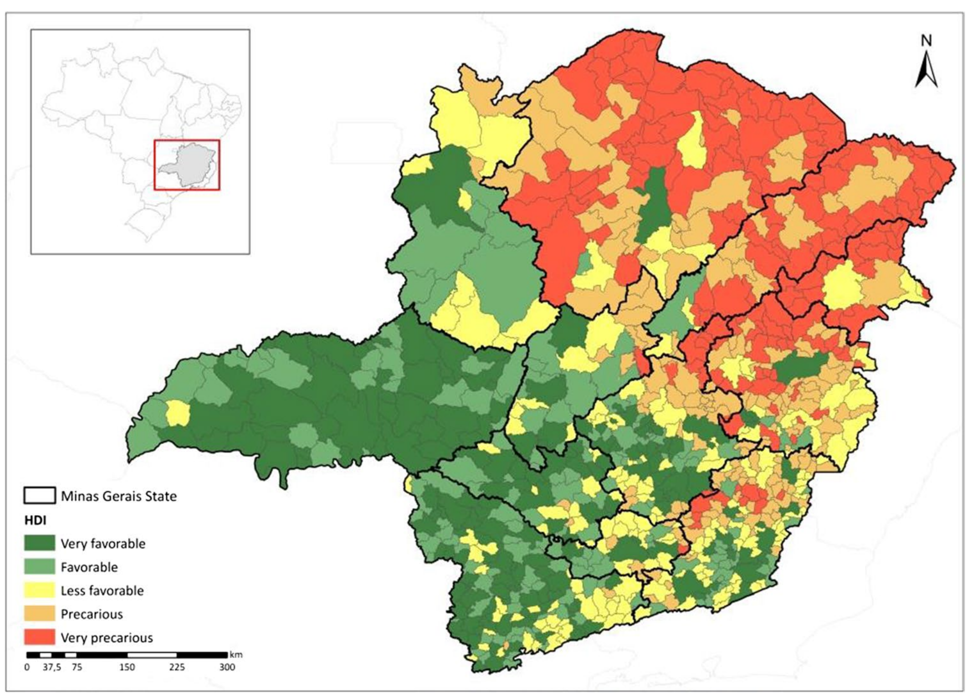
The third factor for selection of the municipalities was the distance to energy grids. Distance is an important factor as we wanted to find areas with no or poor connections to the national grid (Fig. 6), thereby promoting grid decentralization.

Productivity Data Analysis

Data on crop and silviculture production in Brazil are available from the SIDRA platform. For temporary and permanent crops, data for the chosen municipalities were collected on crops that had a production level of higher than 1000 ton/year in 2015. As they were present across the entire state, the three crops chosen were coffee, manioc and sugarcane.

For the silviculture data, we selected data pertaining to the production of eucalyptus charcoal, firewood and wood

Fig. 2 Human Development Index in Minas Gerais State (Oliveira et al. 2008)



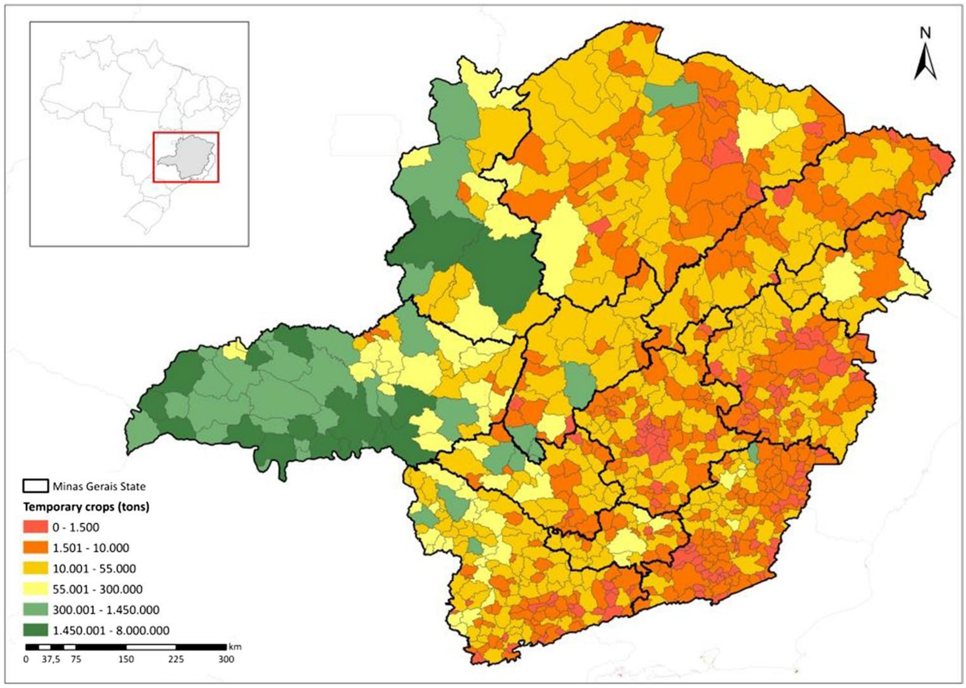


Fig. 3 Annual temporary crop production in Minas Gerais State (SIDRA-IBGE 2015)

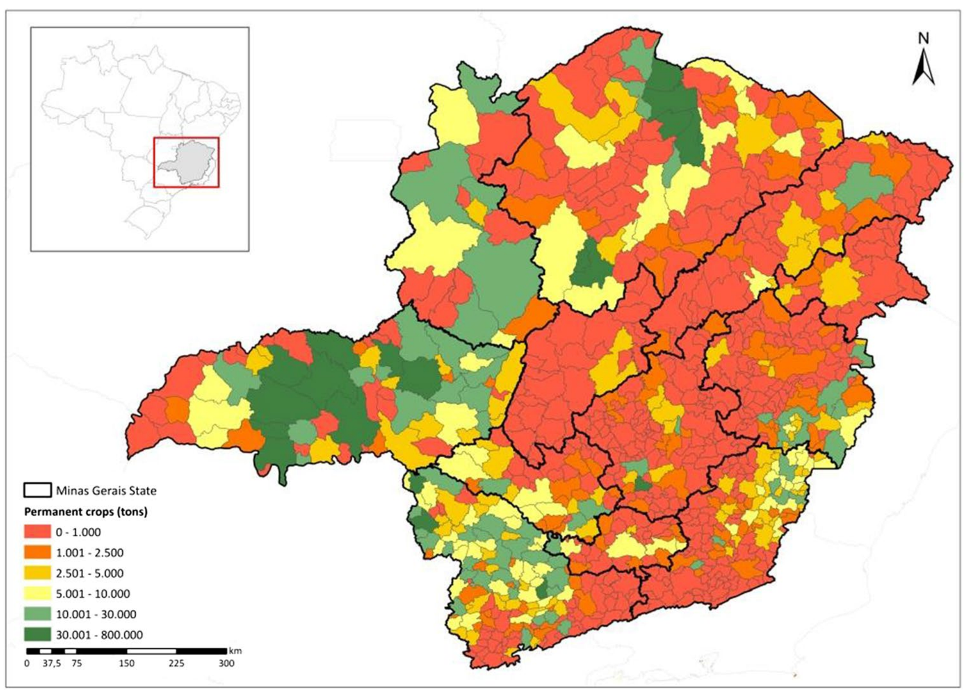


Fig. 4 Annual permanent crop production in Minas Gerais State (SIDRA-IBGE 2015)

in 2014. To ensure the sustainability of the process, data regarding wood products from native vegetation were not considered in this study.

The theoretical potential, or the maximum energy that could be produced with 100% efficiency, was calculated by multiplying the annual production of residues by the lower heating value (LHV) of each crop. The theoretical potential indicates the amount of energy that could be produced with improvement through conversion technologies.

The production data per municipality were organized, and for each product, we calculated the proportion of residues within the production total, or the technical coefficient. We also used the LHV for each crop, making it possible to calculate the potential energy production.

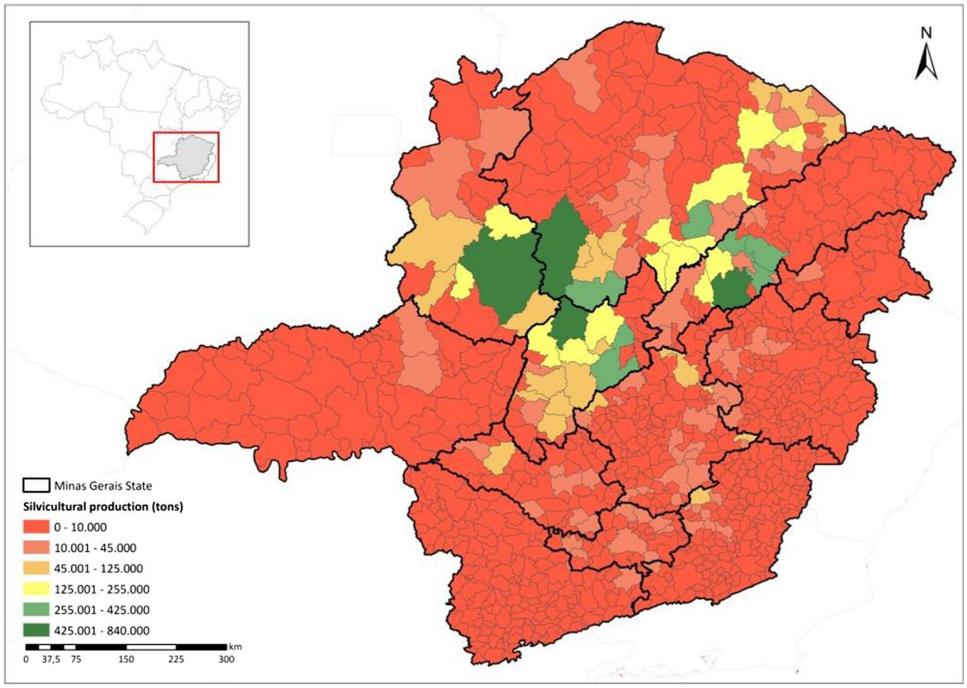


Fig. 5 Annual silviculture production in Minas Gerais State (SIDRA-IBGE 2015)

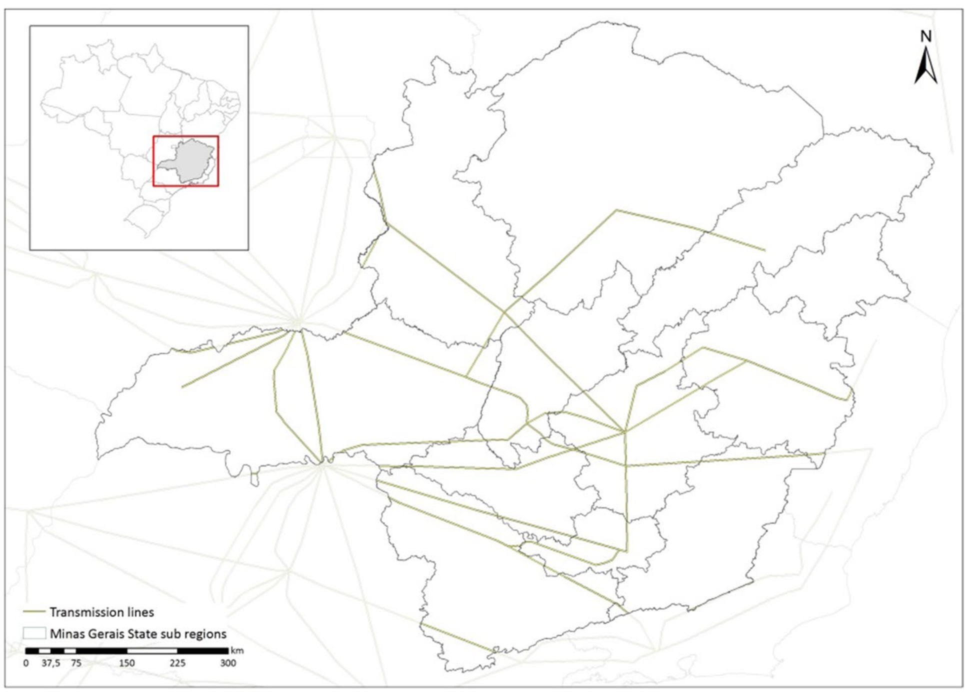


Fig. 6 National energy grid (IBGE; ANEEL 2016)

Application of formulas

To calculate the technical potential or the amount of energy that could be produced, including consideration of any losses during the process, we applied different formulas to different sources. All the formulas were used by GBIO et al. (2015) for the BREA Project.

- **Crops**: The conversion efficiency adopted for the residues was 15%, with low thermodynamic yield—20 bar boiler compound systems, atmospheric condenser turbine (GBIO et al. 2015).

$$\text{Potential (MW/year)} = \frac{\left[\left(\text{Crops}_{\text{tons}} \times \text{TC}\right) \times \text{LHV}_{\text{kcal/kg}} \times 0.15\right]}{\left(860 \times 8322_{\text{hours}}\right)}$$

where:

- $Crops_{tons}$: 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
- 8322: working hours per year (considering that the energy would be produced in 95% of the year's hours. This factor converts the results from megawatt hour to megawatts per year).

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

$$\text{Potential (MW/year)} = \frac{\left(\text{Sugarcane}_{\text{tons}} \times 30_{\text{kWh/ton}}\right)}{\left(1000 \times 5563_{\text{hours}}\right)}$$

where:

- $Sugarcane_{tons}$: total of harvested sugarcane in a year
- $30_{kWh/ton}$: energetic yield of sugarcane in cogeneration systems
- 1000: conversion from kW to MW
- 5563: 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.

$$\text{Potential (MW/year)} = \frac{\left[\left(\text{Wood}_{\text{tons}} \times \text{TC}\right) \times \text{LHV}_{\text{kcal/kg}} \times 0.15\right]}{\left(860 \times 8322_{\text{hours}}\right)}$$

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
- 8322: working hours per year (considering that the energy would be produced in 95% of the year's hours. This factor converts the results from megawatt hour to megawatts per year)

Demand Calculation

We adopted the energy ladder from Coelho and Goldemberg (2013) 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 500–1000 kWh per person per year.

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

- First phase (basic human needs)

$$\text{Electricity demand}_{\text{(low)}} = \text{number of inhabitants} \times \text{access rate}_{(\%)} \times 50\ \text{kWh},$$

$$\text{Electricity demand}_{\text{(high)}} = \text{number of inhabitants} \times \text{access rate}_{(\%)} \times 100\ \text{kWh}.$$

- Second phase (productive uses)

$$\text{Electricity demand}_{\text{(low)}} = \text{number of inhabitants} \times 500\ \text{kWh},$$

$$\text{Electricity demand}_{\text{(high)}} = \text{number of inhabitants} \times 1000\ \text{kWh}.$$

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:

$$\text{Electricity demand}_{\text{(average)}} = \frac{\left(\text{Electricity demand}_{\text{(low)}} + \text{Electricity demand}_{\text{(high)}}\right)}{2}.$$

Results

Selection of the study areas

By combining the HDI, the crop or silviculture production rate and the distance to energy grids, it was possible to select three municipalities: Turmalina, Minas Novas and Almenara (Fig. 7). The first two municipalities were selected due to their high production in temporary (Fig. 3) and permanent crops (Fig. 4), as well as their large amount of silviculture activity (Fig. 5). The region is a supplier of eucalyptus charcoal for the iron industries in western Minas Gerais. Almenara was selected so that the methodology could be tested in a municipality with a larger population and for comparison to the other two study areas.

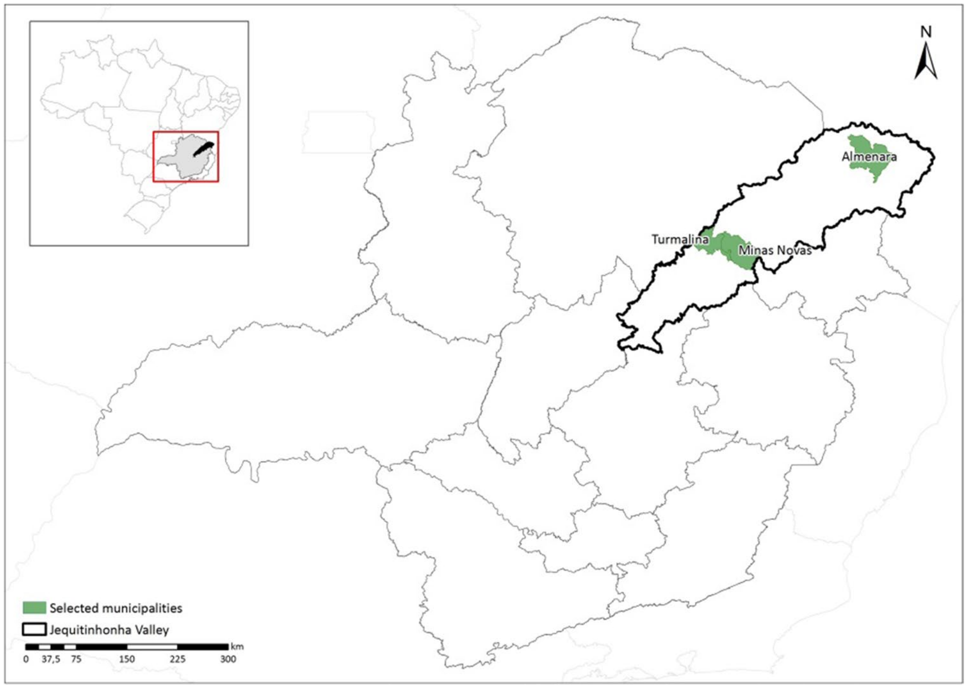


Fig. 7 Selected municipalities (IBGE)

The three municipalities are part of the Jequitinhonha River Valley, an area known historically for its poverty, but which is nevertheless abundant in cultural and natural richness. Eucalyptus plantations were established in the region as part of a strategy by the military government to develop the area through investments, jobs and use of the traditional common collective areas (Ribeiro et al. 2007).

While not attracting as much attention as the Amazon, the Jequitinhonha Valley has nevertheless a great natural and cultural richness. The region has specific and unique vegetation due to the transition of Savanna, Atlantic Forest and Dry Forest (Gontijo 2001). This natural wealth, however, is not associated with the material wealth of the local human population. The Jequitinhonha Valley has a social structure marked by relationships based on clientelism. It is also a place where effective local development measures, which usually do not consider regional potentials in their diverse forms, are not commonly perceived or prioritized by the national or state government. The potentials of these areas to produce biomass energy have never been explored.

Evaluation of the technical bioenergy potential

The *theoretical potential* indicates the maximum of energy that could be produced, not considering efficiency and conversion losses. For now, there is no technology available that could achieve these values. The relevance of the calculation is to show the full potential of the residues from the area and to evaluate which would be the best conversion technology to be applied.

The two municipalities with wood production had significantly higher theoretical values for energy production (Table 1). In Almenara, the municipality with the lowest result, the potentiality is stronger with sugarcane and manioc residues. If production with these residues were feasible, the combined energy alone would produce almost three times more energy than Brazil's biggest hydroelectric power station, Itaipu. Itaipu is the second largest hydroelectric dam in the world and generated 103.1 million MWh in 2016 (Itaipu Binacional 2017).

The *technical potential* gives a more accurate estimation of energy potential. A low conversion efficiency was adopted, particularly as this is a cheaper technology that could be applied to the study areas. In Table 2, it is possible to see the capacities of the silviculture residues in the final energy potentials. In both Turmalina and Minas Novas,

Table 1 Total theoretical potential of renewable energy from biomass on the investigated municipalities

	Turmalina kWh/year	Minas Novas kWh/year	Almenara kWh/year
Coffee	79,770,170	2,485,913	2,386,476
Sugarcane	6,636,078	16,590,195	17,696,208
Manioc	1,156,301	4,827,557	23,241,653
Wood	474,644,211	410,009,835	0
TOTAL	562,206,760	433,913,500	43,324,337

Table 2 Total technical biomass energy potential for the selected municipalities

	Turmalina		Minas Novas		Almenara	
	MW/year	kWh/year	MW/year	kWh/year	MW/year	kWh/year
Coffee	1.44	11,963,372	0.04	372,820	0.04	357,907
Sugarcane	0.03	180,000	0.08	450,000	0.09	480,000
Manioc	0.02	173,414	0.09	724,003	0.42	3,485,620
Wood	8.55	71,183,819	7.39	61,490,407	0.00	0
Total	10.04	83,500,605	7.60	63,037,230	0.55	4,323,527

Table 3 Energy demand according to the energy ladder in the selected municipalities

	Inhabitants	% Energy access (2010)	Basic needs kWh/year (average)	Productive uses kWh/year (average)	Power demand (kW)		
					8 h/day	12 h/day	24 h/day
Turmalina	18,055	99	1,340,584	13,541,250	1237	1855	24,733
Minas Novas	30,794	97	2,240,264	23,095,500	2109	3164	42,184
Almenara	38,775	96	2,791,800	29,081,250	2656	3984	53,116

silviculture is responsible for more than 85% of the total bioenergy potential.

Data assessment on energy demand

As shown in Table 3, in the three municipalities, most of the population has access to energy. It was postulated that with a higher rate of energy access, the development of a new sector in the region could increase the income of the population (by reducing the energy prices) and also help to develop a market for the sustainable use of resources, generating new jobs. This would also help guarantee a continued supply of energy. Almenara, the most populated municipality, showed the lowest rate of energy access and the highest demand.

Comparison between the bioenergy potential and the local demand

A comparison of *energy potential* and *energy demand* indicates the following scenarios: For Turmalina and Minas Novas, the crop and the silviculture potentials would be more than enough to supply their energy requirements. For Almenara, a municipality without silviculture industries, the energy potential from crop residues could meet the demands of the population's basic need. However, a gap of more than 24 million kilowatt-hours for a productive scenario would be left.

Discussion

The methodology, applied previously to municipalities in the Amazon (Coelho et al. 2015), presents a feasible approach for the estimation of biomass potential, considering losses involved in the process. Calculations regarding the collection logistics, transport of materials, purchase, installation and operation of a power generating unit and training were not addressed in this paper.

The municipality Turmalina showed the best results. With a strong and diverse range of agriculture production, the municipality also has a large eucalyptus plantation area. Calixto et al. (2009) present a historic review of how the eucalyptus plantations were established in the Jequitinhonha Valley. In the seventies, the military dictatorship government (1964–1985) wanted to stimulate the iron and steel industry, but the lack of coal was an obstacle. To solve this issue, an incentive program was created giving a 50% tax reduction to companies and private entrepreneurs that wanted to invest in the wood plantations. In the Jequitinhonha Valley, those initiatives helped to bring development and national integration. The high plateau areas were chosen for the eucalyptus plantations due to their lack of agricultural capacity and, in most of the cases, their lack of legalized ownership. Those areas were traditionally used as a common exploration area by farmers in the region, mostly smallholdings managed by families (Galizoni 2000). This explains the large amount of eucalyptus in Minas Novas. The municipality's potential corresponds to the establishment of a small hydroelectric dam (ANEEL 2018), with the silviculture residues responsible for the larger potential of energy production.

In Almenara, the picture is different: The agricultural production provides the entire energy potential of the municipality. Due to a smaller silviculture production, it was the only municipality without an adequate potential to meet the productive demand. However, the number of inhabitants in Almenara is tenfold higher and is therefore also a factor when compared to Turmalina and Minas Novas (Table 4). However, as an area with a consolidated cattle activity (Ruas 1998), a study that considers the production

Table 4 Comparison of the technical bioenergy production potential versus energy demand for the investigated municipalities

	Crop residues (kWh)	Silviculture residues (kWh)	Total (kWh)	Production–demand (basic needs) kWh/year	Production–demand (productive uses) kWh/year
Turmalina	12,316,786	71,183,819	83,500,605	82,160,021	69,959,355
Minas Novas	1,546,823	61,490,407	63,937,230	61,696,967	40,841,730
Almenara	4,323,527	0	4,323,527	1,531,727	24,757,723

of energy through manure biogas (as shown in Salomon and Lora 2005, 2009; GBIO et al. 2015) should lead to better results for Almenara.

Almenara is also comprised of a large amount of degraded pastures (SIDRA-IBGE 2015). Other possibilities for energy production could be the recovery of such areas by using native crops and trees with the potential for energy production in an agroforestry system. Previous studies in the same river basin have produced good results for soil and vegetation recovery of degraded areas on small farms (Pereira et al. 2007).

The results also show that silviculture industry is strong in the region. In Turmalina and Minas Novas, these residues alone could fulfill the highest energy demand. In the region, three companies are responsible for 95% of the eucalyptus plantations (Calixto et al. 2009). The same authors point out that one of the main objectives of reforestation (job creation) has not been satisfactorily fulfilled. Dominating 38% of the agricultural land, eucalyptus cultivation occupies around 4% of the workforce. The development of a biomass energy sector in the region may not only lead to improvements in the energy system, but also create local jobs in different sectors of the productive chain (ANEEL 2008). Such effects are shown by Dinkelman (2010) in cases of areas without previous electrification, and by Moreno & López (2008) who analyzed different types of renewable energy jobs in Spain.

It should be noted that all calculations were made taking into account a viable technology for the local area: a cheap technology with low conversion efficiency. Considering that investment into sustainable energy to improve people's lives is not necessarily a lucrative business, together with the current economic downturn in Brazil, environment issues are not priority. The 2018s elections raised international concern for how the new government will conduct its environmental agenda (Tollefson 2018). Without mentioning this subject during the polls, the elected president threatened to leave the Paris Agreement (Escobar 2018), expand the exploitation of the Amazon region and reduce the protected areas. Brazil has already rescinded as host of COP25 in 2019 (Chiaretti 2018; Pontes and Resende 2018). Within this context, a modern and expensive technology with a high conversion coefficient is unrealistic. Importantly, the results for the *theoretical potential* represent the maximum amount of energy that could be generated, for production attainable with the technological development. One of the conclusions of the BREA report (GBIO et al. 2015) is that Brazil needs the know-how to develop the biomass energy sector, if economically viable. Obtaining a result that indicates that municipalities can sustain themselves through the generation of energy from agricultural residues, using cheap technology, indicates that there is space for even more improvement.

As highlighted by Lillo et al. (2015), the chance of success, for individual or micro-grid projects in communities, is directly related to the communities' demand for those projects. Even though the municipalities studied here do not actively have this demand, they are examples of areas where the power production could improve income and life quality. Following the recommendation of Panepinto et al. (2015b), the acceptance of the communities involved emerges as a necessary next step for the implementation of projects for bioenergy generation.

Conclusions

Brazil presents itself as a country with an energy matrix centered on hydroenergy. Having faced cyclical periods of drought, the alternative for times of lack of water is the natural gas-fired thermoelectric plants. This goes against the current reduction in GHG emission recommendation, adherence to which is essential for the planet to achieve emission reduction targets. There is an urgent need for investigation of new possibilities for electric energy generation that promotes environmental sustainability, a situation aggravated by the current context of climate change.

Conducting an investigation on the potential for energy production in Brazilian low HDI regions indicated that three small municipalities can be self-sustainable in energy from biomass production. Even when applying low conversion efficiency on waste, it is possible to produce enough energy to meet the demand of small townships by using silviculture and agricultural residues. As the focus of the study was regions with low human development indices, this study presents a possibility for clean development and new sources of income generation for regions that should be targeted by local development policies.

The success of biomass energy production from agriculture residue enterprises depends on more than just energy efficiency. It also depends on, for example, logistics, team training, operational costs and equipment acquisition. In accordance with UN recommendations, this potential should be explored more thoroughly. Considering that the dominant discourse for increasing the energy capacity in Brazil is based on hydroelectric potential, the findings of this paper indicate that there are indeed other possible ways for such increases, bringing to light a possible new energy path.

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2.4 Paper #3: Bringing to light a new energy path: the case of Minas Gerais State, Brazil

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Paper purpose

After analyzing the energy potential on the local level, the scale of the study was expanded in the third step, where the potential of biomass energy production in one entire state was assessed, investigating if it is possible to sustainably attend the demand in a larger scale. Continuing to use the findings of the first step, the chosen state was the one better ranked on the results of first paper.

A conservative index that considerers the portion of residues that could be used maintaining the soil health was developed, as a way to guarantee that the sustainability on the long term would be committed.

The paper shows its relevance presenting as an outcome that 78% of the municipalities in a state with the tradition of agriculture could have their basic energy needs met by residues of crops and silviculture production, bringing light to a relevant possibility of change on the energy matrix.

Figure 6: Graphical abstract of the third step.

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

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Abstract

Background: In Brazil, more than 60% 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. Characterized by its multiple opportunities of sources and conversion technologies for energy, biomass has a high potential to become responsible for a relevant share on 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 the energy productivity, a Sustainable Technical Coefficient was adopted: a conservative index that considerers the portion of residues that could be used maintaining the integrity of the soil.

Results: This index was applied, together with the data on the silviculture and selected crops yield. 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 residues of crops and silviculture production.

Conclusion: For the state Minas Gerais, with its tradition of agriculture, the biomass residual energy is viable and should be considered by policymakers.

Keywords: Biomass energy; sustainable development; renewable energy; energy potential.

1. Background

Brazil presents a unique model for the structural development of an energy sector: having made advances in technology for hydropower since the 19th century, which have dominated the country's energy matrix since the 1970s. During this period, several supply crises were faced. The most severe occurred in 2001, where general blackouts began to take place. 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 (Vedovato et al. 2016; de Oliveira et al. 2017), contain about 70% of the potentials 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 (Fearnside 2009; Fearnside and Pueyo 2012; Abramovay 2014; Fuchs 2016; Winemiller et al. 2016). Moran et al. (2018) point that without considering the real social, environmental and cultural costs involved in the water dams construction, it cannot be considered a sustainable source of energy.

In the context of global climate change, Brazil has experienced precipitation and temperature shifts 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 60% of the energy for the whole country comes from hydroelectricity, obtained from a mix of energy sources that makes the system highly vulnerable (chart 1) (EPE 2018). Without investment in the sector, the necessary amount of water, and without alternative sources of clean energy, the country is dependent more 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).

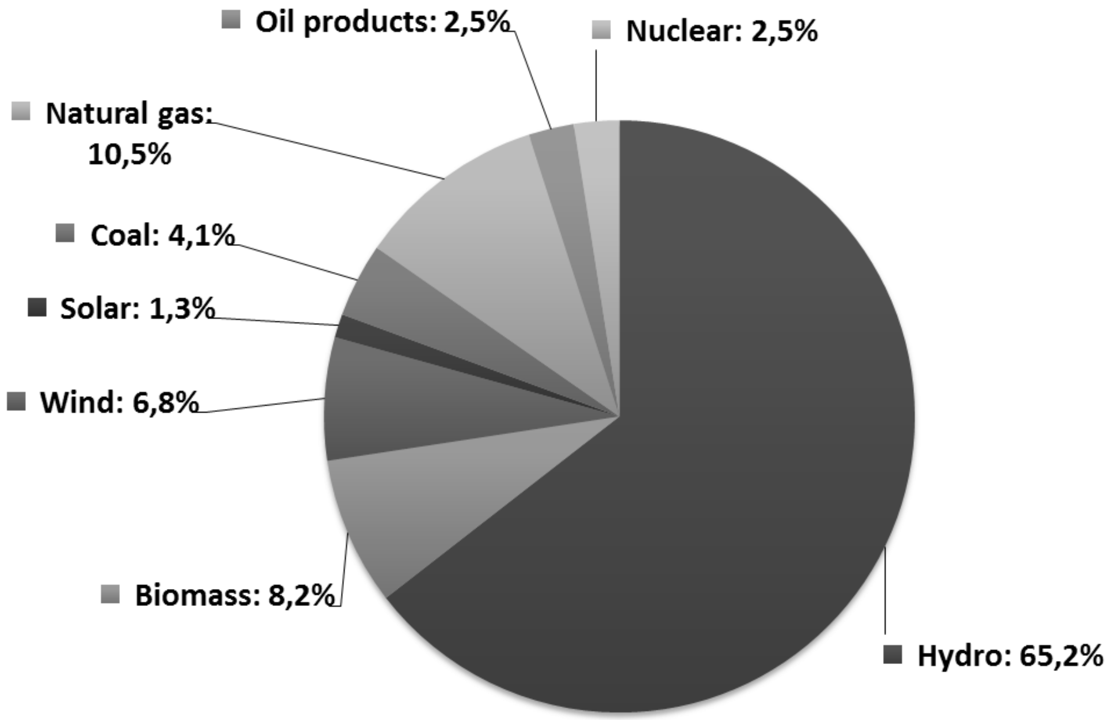

Chart 1: Domestic electric supply by source: EPE (2018).

A relevant change in the energy sector requires investment, legislative and organizational 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 to exponentially lower 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 characterized by its diverse sorts of sources and conversion technologies for energy, presenting a relevant potential for supply through renewable energy. The term biomass includes plant material produced through photosynthesis and all its by-products, as cultivated crops, forest-wood, animal manures and organic matter (Vidal and da 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 et al. 2019), Italy (Palmas et al. 2012), Greece (Skoulou et al. 2011), Germany (Palmas et al. 2015), 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 2018), previous studies on biomass energy production conclude that it is an option that should be considered on the development of the country's energy sector. In the Brazilian Atlas of Bioenergy (Coelho et al. 2012), a national-wide methodology was presented. 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.

The Rural Residues Energetic Inventory (EPE 2014) was produced by the Brazilian Energy Research Company in order to explore the potential as 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. A potential of 48 million toe[1] for the agriculture and livestock waste was estimated, considering different conversion technologies, presented 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). In a cooperative effort between Brazilian and Colombian scientists, a complete data set on energy generation from residues was presented. 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, p. 23). 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. 2013a), and it could be related to a potential conflict with other land uses (Söderberg and Eckerberg 2013). Without considering careful planning, the competition between biomass energy, conservation, agriculture, and forestry is inevitable (Blaschke et al. 2013b). Concerning sustainability, any enterprise that seeks biomass as a source of power must guarantee the soil health, the biodiversity and water cycle, lowering the negative impacts in the long term.

One alternative for minimizing 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. The crop residue retention is, in fact, one of the three pillars of Conservation Agriculture (Hobbs et al. 2008; Sommer et al. 2018). This measure can avoid the necessity of the input of fertilizers and protect against soil degradation, as well as increase the carbon sequestration in the soil. However, some studies point out that 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).

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 minimize environmental impacts, promote the sustainable development of the population, and guarantee

[1] Tonnes of oil equivalent, 1 toe = 11.63 megawatt-hour

the energy security should be seriously considered. In this paper, an estimation of the regional potential of energy production from biomass residues is assessed; recommendations from literature for how much residue could be removed without damaging the soil is also considered. This potential energy production is compared to the local energy demand. We aimed to answer the following questions:

- How much energy from residues can be produced sustainably without compromising the soil?
- Can sustainable potential meet the local demand for energy?

According to Ribeiro and Rode (2016), the state of Minas Gerais in Brazil presents favorable characteristics for the development of biomass energy initiatives. The authors conducted an analysis with the objective of finding 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 the higher potential for proving the sources to the development of a biomass energy initiative, respecting the environment fragilities and its regulations.

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.

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 the production of 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 main agricultural goods produced are coffee, sugar, milk, various types of meats, soy, corn, and beans. In 2008, the exportation from the agribusiness reached US$ 5.9 billion, corresponding to 8.2% of Brazilian agribusiness exports that year (Bastos and Gomes 2011). The rural universe dominates the cultural identity of the population that, despite being known as *miners* (mineiros), has a historical and affective cultural relationship with the countryside culture (Souza 2013).

The Brazilian electrical distribution sector is mainly divided by state. Until the early 1990s, most of the states governments were the owners of the companies that provide the local operations on the energy distribution system (Tovar et al. 2010). This condition changed with the privatizations 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 on the 1980s (Fagundes de Almeida and Queiroz Pinto Junior 2000; Lorenzo 2002; Tovar et al. 2010). The privatization 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 commercialization 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, a factor that facilitates the creation and application of policies. The state of Minas Gerais has positive environmental and economic characteristics for the development of this study. Therefore, has been elected as the focus area of this paper

To analyze the self-sufficiency in sustainable bioenergy of a federative unit with the fourth largest territorial area, the second largest number of inhabitants and the largest number of municipalities in the country (IBGE 2017a) aims to bring light to the possible new paths that can guide the decision making on the direction of sustainable energy diversification in Brazilian energy matrix.

2. Material and methods

2.1. 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 that are produced in the entire state area, some predominantly in a large-scale agricultural model (corn, sugarcane, and coffee), and another more commonly in a family production model (manioc). Municipalities that had a production rate of higher than 1,000 tonnes per year in the last agriculture census were selected to be analyzed. The intention of this was to calculate the potential for municipalities where the yield would make the installation of an energy production unit worthwhile. The chosen crops were coffee, corn, beans, manioc, and sugarcane. The assessment of production data is important for the estimation of the amount of residues generated during the production process. For all the crops, the literature indicates a percentage of rests remaining from harvesting or primary processing.

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. From the total of 853 municipalities in the state of Minas Gerais, 804 met the conditions and were analyzed.

For all the energy sources the maintenance of current land use was presupposed. 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 not only productivity but also sustainability (Ribeiro and 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 was followed. To estimate the energy productivity, a Sustainable Technical Coefficient (TC_S) was adopted (see table 1). The Traditional Technical Coefficient (TC_T) represents the proportion of residues within the total yield (Coelho et al. 2015). For each of the crops and for 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, adequate for the tropical conditions, was adopted. Only for the case of coffee, as no specific literature was present, the general recommendation of leaving 70% in the soil was assumed. Even though it may be considered a conservative value, the decision of removing a minor amount of residues aims to avoid solving one problem by creating another (soil degradation). The practice of conservation tillage has already 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 1 represents the values of TC_S used in the calculation.

Table 1: 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**

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 correspond to the litter, which represents an important share on the nutrient cycling process. Foelkel (2016) recommends that the litter, leaves and small branches are indispensable for the maintenance of 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 2.

Table 2: 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
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

2.2. Application of formulas

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, we applied different formulas to different sources. All the formulas were used by Coelho et al. (2012) (Coelho et al. 2012) for the Brazilian Bioenergy Atlas. These calculations provide an overview of how biomass energy is distributed in the state per source and are detailed presented in Ribeiro and Rode (2019).

All the calculations were made taking into consideration 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 a context of economic crisis. Modern and expensive technology with a higher conversion coefficient would be unlikely to be financed.

2.3. 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) and applied by Ribeiro and Rode (2019), low and high electricity requirements were calculated.

3. Results

From a total of 853 municipalities in the Minas Gerais state, only 49 didn’t 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.

3.1. 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 1) had the highest results from all the sources, reaching values up to 60 MW with the yearly harvesting per municipality. The west sub-region, known as *Triângulo Mineiro*, had the best result, due to the dominance of modern large scale agribusiness in. This sub-region is the main producer of sugarcane and corn in the state (Bastos and Gomes 2011).

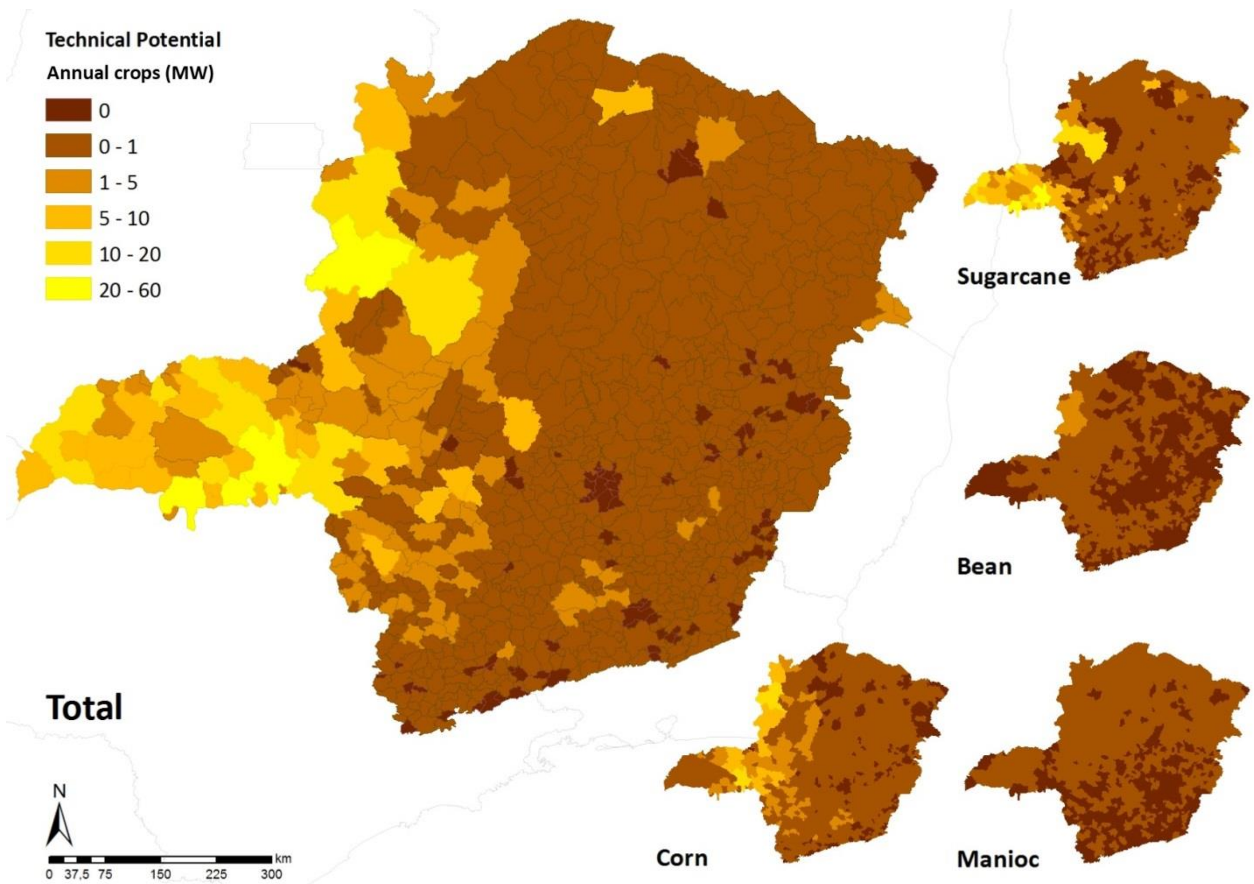

Figure 1: Sustainable technical potential of energy production from annual crop residues with the yearly harvest per municipality

Standing out as the largest producer and exporter of coffee in Brazil, 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 2), the results are considerably lower than those of energy production from annual crop residues.

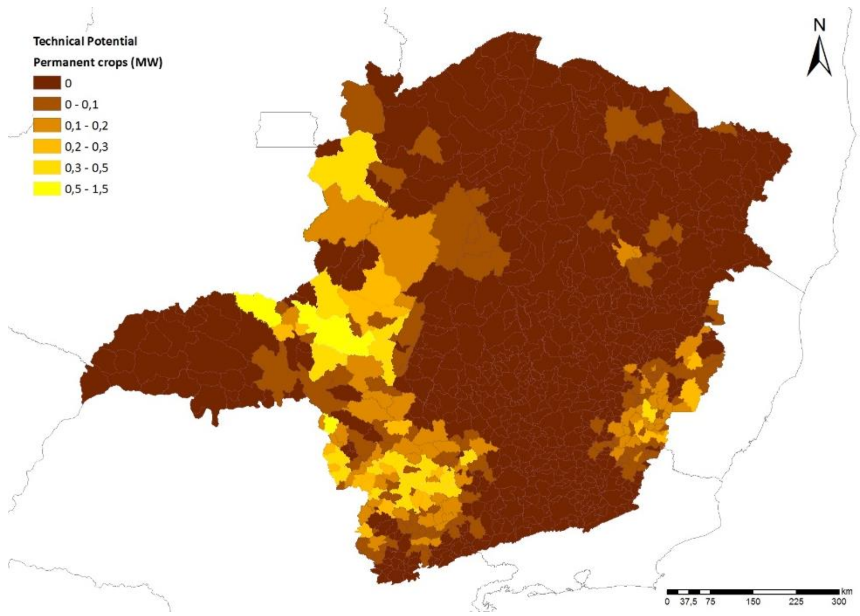

Figure 2: Sustainable technical potential of energy production from coffee residues with the yearly harvest per municipality.

The state of Minas Gerais also has a strong silviculture sector. Having its origins with the stimulation of the steel and iron industries on 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 then created, where a 50% reduction on the taxes was given to private owners and companies that were 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 was produced per year in Minas Gerais (SIDRA - IBGE 2015b). In the more productive areas, the estimation of the potential energy production from silviculture residues (figure 3) could reach values of up to 8 MW with the annual yearly harvest per municipality.

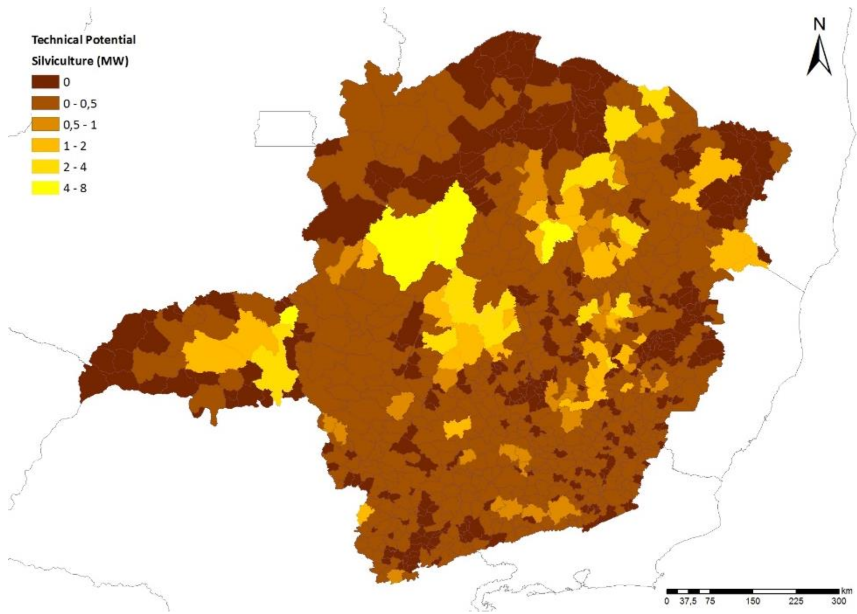

Figure 3: Sustainable technical potential of energy production from silviculture residues with the yearly harvesting per municipality.

The combination of the values presented in the above generated scenario, 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 4).

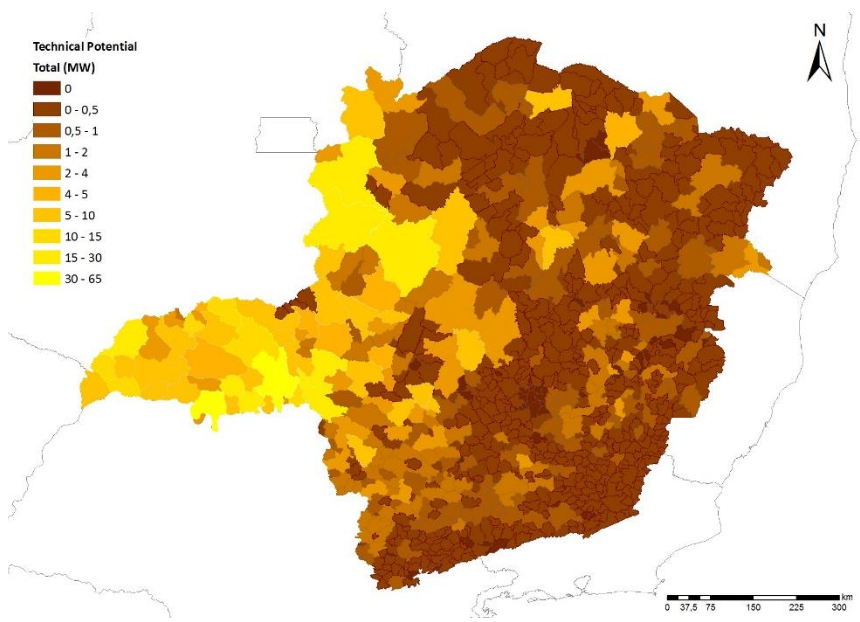

Figure 4: Sustainable technical potential of energy production from all agriculture residues with the yearly harvest per municipality.

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

3.2. 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 5 and 6).

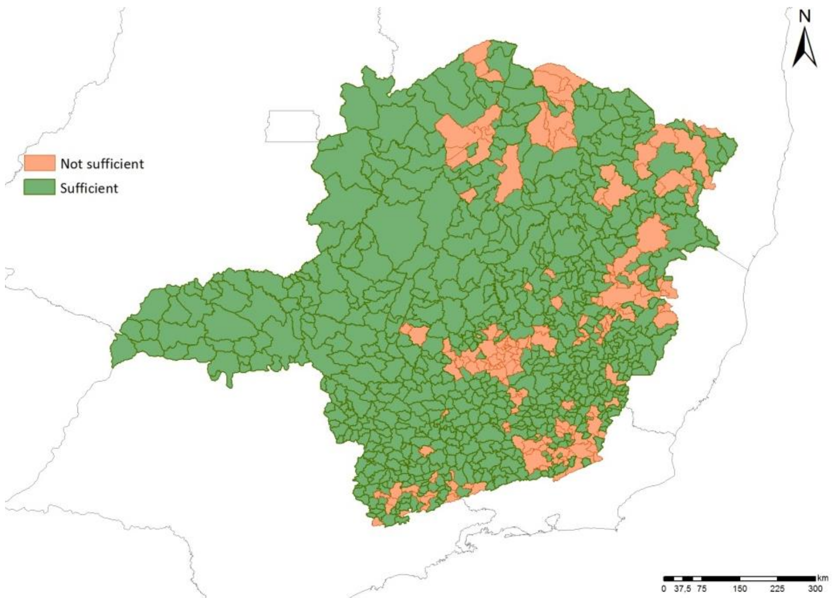

Figure 5: Demand vs. production in a scenario of basic needs.

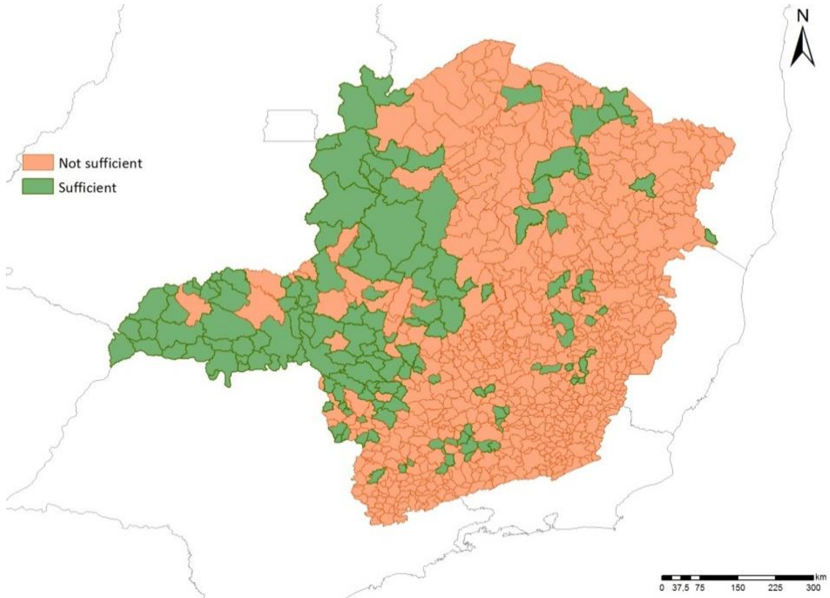

Figure 6: Demand vs. production in a scenario of productive uses.

The municipalities where the demand was met in the basic needs scenario, reach 79% of the total municipalities (table 3) and 83% of the analyzed municipalities. Most of the places where the results were not sufficient represent large metropoles, with no space for agriculture and high demand for energy. 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 at the west sub-region, where the agribusiness is concentrated and the highest GDP on the state is located.

Table 3: 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 analyzed	49	6%	49	6%

4. Discussion

For the scenario of basic needs for the whole state, a surplus of 6,704 GWh/year was estimated. One possibility for optimization 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 of areas with lower residues and generate income for the places with additional residues. A Brazilian law resolution from 2015 (ANEEL 687/15) began to facilitate the process of decentralized energy production, regulating the distribution of micro and mini energy generation. Therefore, creating an ideal context for the development of small energy generation units.

According to the Brazilian Institute of Geography and Statistics (IBGE), Minas Gerais is the fourth biggest state in the country and the second largest in terms of the inhabitant numbers, with an estimated population of 20,869,101 inhabitants in 2016 (IBGE 2017a). From 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, while also having less area to produce agriculture and residues. These municipalities are responsible for 12% of the energy potential and, as it is 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 kind of research has not been carried yet in Brazil and could figure as the next step on way of creation a sustainable energy system for Minas Gerais. As assed on this paper, biomass could figure as a supplier of 78% from the basic needs demand and 18% of the energy in a scenario of productive uses (table 3). 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 that comes from residues could be directed to the low-income population, focusing on the rural area where it is produced and on improving locally produced goods, as well as raise its attractiveness for new local business (Venghaus and 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 the increment of income. It could also have a significant role in the improvement of education and health possibilities, as well as gender equality, considering that the improvement of electricity access usually has a larger effect on female employment (Cook 2011). Considering the environmental and social risks involved with new hydropower projects (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.

Among the production means existing in the state, family farming is the main responsible for the food supply for the state population. Characterized by small properties, managed essentially by the family, it presents a larger amount of properties (79% of the farms on the state (IBGE 2017b)), with greater work and income generation per cultivated area (Abramovay 1997). Those small farmers are commonly organized in cooperatives production systems and associations, in order to increase the competitiveness of their product and their market insertion (Costa et al. 2015). Being a model that is already applied by those farmers for other purposes, the organization in cooperatives of biomass energy production from their crop residues could optimize the logistics for collection and processing of this residue, as well as the distribution of the energy generated.

One concept that could be applied for the development of 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 type of social problem that meets the necessities of simplicity, low cost, easy applicability, replicability and proven social impact. The creation of a model for energy production, that works for lower income communities and that is simple to replicate with minor adaptations could improve the local and regional development without generating impacts on the environment and improve the local economy.

5. 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 that was pointed out by previous researches as promising for this type of assessment. A Sustainable Technical Coefficient was developed, taking into consideration that part of the residues would be let on the soil with the objective of maintaining the nutrient cycling and soil health, ensuring the 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 for being 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 Minas Gerais, with its tradition of agriculture, 78% of the municipalities could have their basic energy needs met by residues of crops and silviculture production. When more elaborated uses are considered, there is a drop where 18% of the municipalities would be able to be self-sufficient in energy supply. Even with a significant reduction on the percentage, this would relieve pressures placed on the construction of new hydroelectric plants, which have substantial negative impacts on the environment and in the way of life of the communities on 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 elected government in 2018. The results obtained here can be used to empower the local population or stakeholders, as a base to seek for renewable energy projects, creating the ground for changes in the country’s energy system.

It should be noted that calculations regarding collection logistics, transport of materials, purchase, installation, and operation of a power generating unit and training, were not addressed in this paper and should be taken in consideration in future studies.

6. Declarations

- Ethics approval and consent to participate: Not applicable.
- Consent for publication: Not applicable.
- Availability of data and material: The datasets analyzed during the current study are available in the SIDRA (Brazilian Institute of Statistic and Geography Automatic Recovery System) repository, at https://sidra.ibge.gov.br. The datasets generated during the current study are available from the author on reasonable request.
- Competing interests: Not applicable.
- Funding: This research is fully financed by the Brazilian research incentive program Science Without Borders, from the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES Foundation, Proc. n BEX 12957/13-5) and a doctorate research project from the Institute of Environmental Planning (Institut für Umweltplanung – IUP), the Leibniz Universität Hannover.
- Authors' contributions: Not applicable.
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2.5 Paper #4: Biomass energy as a possibility for innovative agriculture initiatives

Ribeiro, Ana Pimenta; Dalmolin, Silvio. Submitted to the Journal *Energy, Ecology and Environment*: May 2020.

Authors' contributions: conceptualization, APR; methodology, APR; analysis on bioenergy potential, APR; analysis on costs and power plants unities allocation, SD; writing, review and editing, APR.

Paper purpose

On this final step, the municipality level was once again investigated, considering this time cost and social acceptance for biomass enterprises.

The study area was located in the state of Minas Gerais. The region was affected by a human-environmental catastrophe, and its population started to pursue innovative initiatives for agriculture. Following the community's intention of increasing the cultivation of certain crops, the possibility of using the agricultural residues for electricity production was assessed in this paper, also investigating the implementation costs and trying to evaluate the acceptance by the population.

The calculation of the costs was made considering the market prices in Brazil. This fact brings a full context to the research, adding the economic and operational aspects to the analysis.

The evaluation of the population acceptance could not be presented in the text.

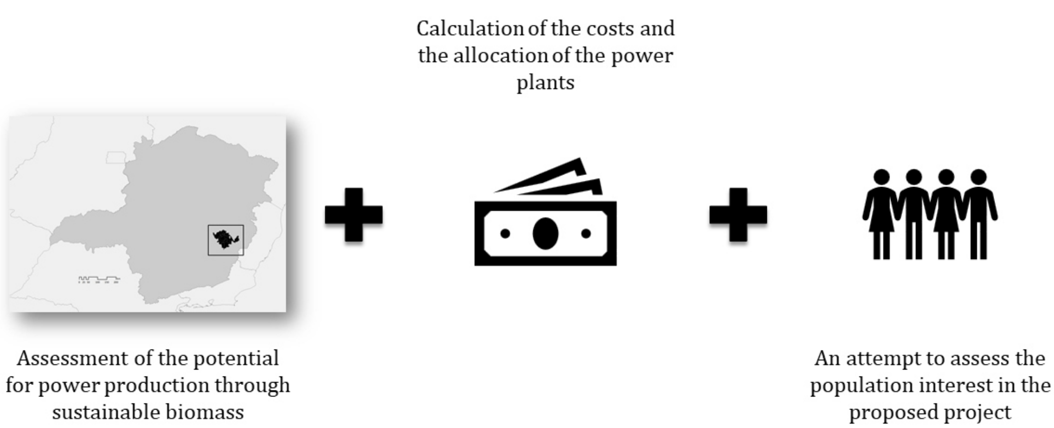

Figure 7: Graphical abstract of the fourth step

Biomass energy as a possibility for innovative agriculture initiatives

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Abstract: In searching for sustainable solutions for humans' necessities, clean and safe energy possibilities have been pursued. The objective of this research is to develop a procedure that improves the integration of renewable technologies into local planning processes. The methodology should be suitable for different contexts. The objective of this paper is to evaluate the potential of energy production through agricultural waste, ensuring the sustainability and development of clean technologies, the ideal allocation of the energy production unit and the costs involved in the enterprise. The research hypothesis is that the potential for sustainable use of biomass can be identified and evaluated, thus showing the way for an improved energy plan for Brazil. The study area is within the Doce River Basin in Brazil. The results show that with proper investment, the energy generation through biomass residues could be viable. The methods developed in the study could be relevant for municipalities to record their potentials for energy production and pursue investments and local arrangements, promoting sustainable biomass energy generation.

Keywords: Renewable energy, Biomass potential, Doce River Basin, Spatial planning

Declarations

• Funding: This research is fully financed by the Brazilian research incentive program Science Without Borders, from the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES Foundation, Proc. n BEX 12957/13-5) and a doctorate research project from the Institute of Environmental Planning (Institut für Umweltplanung – IUP), the Leibniz Universität Hannover.

• Competing interests: not applicable.

• Availability of data and material: The datasets analyzed during the current study are available in the SIDRA (Brazilian Institute of Statistic and Geography Automatic Recovery System) repository, at https://sidra.ibge.gov.br. The datasets generated during the current study are available from the author on reasonable request.

• Authors' contributions: Conceptualization, APR; methodology, APR; analysis on bioenergy potential, APR; analysis on costs and power plants unities allocation, SD; writing, review and editing, APR.

Acknowledgments

We want to thank Sónia M. Carvalho Ribeiro for the information given on the local population; Michael Rode and Sylvia Herrmann for the valuable comments.

1. Introduction

1.1 Background

As part of the United Nations sustainable development agenda, renewable energy is one of the goals for the sustainable use of our planet (United Nations 2015). As an example of a centralized source of power generation, the Brazilian case has hydropower as the energy source of almost 65% on the total energy supply and with an extremely centralized distribution system (EPE 2018). When there are risks of droughts, intensified by the climate change context (Hunt. et al. 2018; Moran et al. 2018), natural gas thermoelectric energy still is seen as the alternative energy source (Corrêa da Silva et al. 2016; Zurn et al. 2017). Around 70% of the country's hydropower potential is located in the Amazon and Cerrado (Ferreira et al. 2014), the two biggest Brazilian biomes, both with a high level of endangerment. Negative impacts of these projects both on nature and on the way of life of the communities around the rivers are impossible to be avoided (Moran et al. 2018).

One way to reduce such negative effects is to use other renewable energies. Mainly considered by its diversity of possibilities in terms of origin and conversion technologies for energy products (McKendry 2002b, a), biomass energy presents itself as a relevant player with potential for supplying renewable energy. The term biomass encompasses plant material produced through photosynthesis and all its by-products (Vidal and da Hora 2011). A substantial volume of research has already been developed on the topic in a diverse sort of regions such as Peru (Lillo et al. 2015), Spain (Díaz-Cuevas et al. 2019), Italy (Palmas et al. 2012), Greece (Skoulou et al. 2011), Germany (Palmas et al. 2015), South Africa (Batidzirai et al. 2016) and Southern Asia (Bhattacharyya 2014). Responsible for 8% of the energy supply in Brazil (EPE 2018), previous studies on biomass energy production conclude that it should be considered on the advance of the country's energy sector. A national-wide methodology was presented in the Brazilian Atlas of Bioenergy (Coelho et al. 2012). There, it was considered residual energy production from agriculture and silviculture activities, liquid swine sewage, and solid urban waste in sanitary landfills.

Aiming to explore the potential as an energy source from agriculture, agroindustry, and livestock residues, the Rural Residues Energetic Inventory (EPE 2014) was produced by the EPE (Brazilian Energy Research Company). Different sources were presented, detailing the agriculture production and the estimation of its residues. A potential of 48 million toe[1] for agriculture and livestock waste was estimated, considering different conversion technologies.

Another example of Brazilian biomass energy potential assessment is the BREA Project (GBIO et al. 2015). A complete data set on energy generation from residues was presented, with the

[1] Tonnes of oil equivalent, 1 toe = 11.63 megawatt-hour

objective of developing "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, p. 23). The methodology included an exploration of different technologies for conversion, potentials, policies, scenarios, and barriers to the development of bioenergy in the Brazilian Amazonian region.

Regarding other renewable energy sources, biomass could be related to a potential conflict with other land uses (Söderberg and Eckerberg 2013), and it requires the major area per produced energy unit (Blaschke et al. 2013a). Without taking into account careful planning, the competition between biomass energy, conservation, agriculture, and forestry is predictable (Blaschke et al. 2013b). Concerning sustainability, any enterprise that seeks biomass as a source of power must guarantee the soil health, the biodiversity, and the water cycle.

One possibility for minimizing adverse environmental impacts of biomass use is to produce energy from residues. Several agricultural systems base their natural cycle on nutrient cycling, where part or particular residue of the main crop is left on the soil, to protect it physically from rain, sun, and wind and to nurture soil biota (Hobbs et al. 2008; Sommer et al. 2018). This operation can avoid the need for adding fertilizers, protecting the soil against degradation and increasing the carbon sequestration. Some researches indicate that there is no need to place all the available 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).

Against this background, the use of residual biomass can contribute to energy system transformation in Brazil (Ribeiro and Rode 2016) and at the same time reduce the negative effects resulting from the policy focus on the use of water for electricity generation in Brazil (EPE 2017). To drive this process forward, a spatial approach is needed to improve the integration of renewable technologies into regional and local processes by combining renewable energy potentials with environmental protection issues. Therefore, the objective of this paper is to evaluate the potential of energy production through agricultural waste, ensuring the sustainability and development of clean technologies, the ideal allocation of the energy production unit and the costs involved in the enterprise.

1.2 Study area

Based on previous studies (Ribeiro and Rode 2016, 2019), the Brazilian area chosen to be the focus of the analysis should be within the state of Minas Gerais. A study area was selected encompassing 16 municipalities in the Doce River Basin (figure 1), Brazil. At the end of 2015, a human-environmental catastrophe occurred with the rupture of a mining tailings dam, spilling

62 million cubic meters of tailings along the river, damaging over 680 km, until they reached the ocean (Borges 2018).

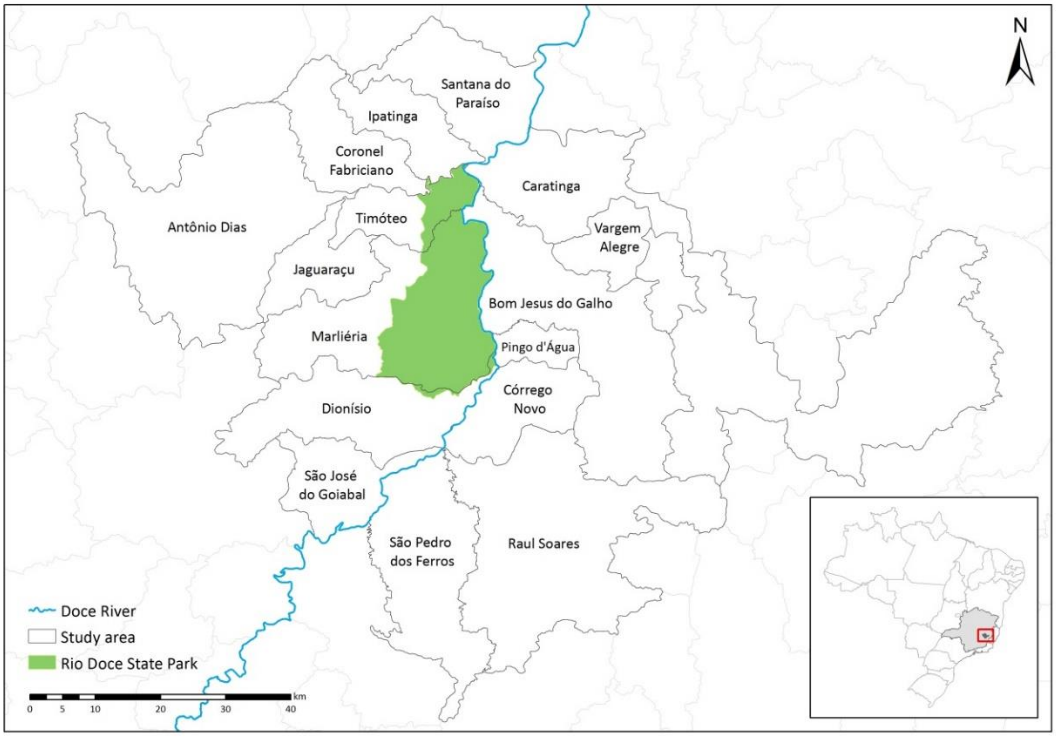

Figure 1: Municipalities included in the analysis. Source IBGE (2015).

The impact has altered thousands of lives profoundly, disturbing the economy of the affected cities in the states of Minas Gerais and Espírito Santo. The number of affected people is challenging to reach, but the estimation is that the population living at the Doce River Basin was around 3.2 million inhabitants. Nineteen people have died, and it is estimated that up to 500,000 people have been affected (Wallauer, 2018), including communities of fishermen, indigenous and farmers, who rely on that water to live.

Many initiatives have been carried out in order to create new opportunities for people affected by the dam rupture in different parts of the basin. On this context, it was pursued innovative initiatives for agriculture in the municipalities surrounding the Doce River State Park. One possibility proposed to the communities was to increase the plantation area, using the agricultural waste for electricity production.

The objective of this paper is to evaluate the potential of energy production through agricultural waste, ensuring the sustainability and development of clean technologies, the ideal allocation of the energy production unit and the costs involved in the enterprise.

2. Material and methods

2.1 Productivity Data Analysis

For the investigations two scenarios were evaluated: one considering the production data from 2017 and the other with an increase of production on the crops indicated by the population, reaching the maximum limit of the project viability.

Data were collected from the governmental statistics (SIDRA - IBGE 2015) considering the crops of interest for the local population, in order to assess the distribution of biomass residues. In previous workshops conducted by UFMG researchers, the population was consulted about which crops they would like to expand the cultivation area. The chosen crops were corn, beans, manioc, and sugarcane. The assessment of production data is vital for the estimation of the amount of residues generated during the production process. For all the crops, the literature indicates a percentage of rests remaining from harvesting or primary processing.

Considering soil health as the central necessity for the continuation of production activities for crops, the recommendations in the literature regarding the percentage of the residues that should be left in the field for soil recovery was followed. This factor was selected as an indicator for a good ecological status. A Sustainable Technical Coefficient (TC_S) was adopted to estimate the energy productivity (see table 1). The Traditional Technical Coefficient (TC_T) represents the proportion of residues within the total yield (Coelho et al. 2015). For each of the crops, literature was found indicating how much could be used to maintain the soil health. For all the sources, a percentage indicated by studies in Brazil, adequate for the tropical conditions, was adopted. In this paper, it was considered that the guarantee of supply for bioenergy production depends directly on soil productivity. A more conservative coefficient was adopted in order to guarantee sustainability due to conserving the soil humus content. Table 1 represents the values of TC_S used in the calculation.

Table 1: Traditional Technical Coefficient and Sustainable Technical Coefficient

Source	Type of residue	Traditional Technical Coefficient	Percentage left on the soil	Sustainable Technical Coefficient
Sugarcane	Straw	0.20	50%	**0.1**
Beans	Husk	1.16	60%	**0.45**
Manioc	Aerial	0.65	60%	**0.25**
Corn	Stover	1.68	60%	**0.65**

The TC_T and TC_S for beans, manioc and corn were found on EPE (2014). For sugarcane, the coefficient adopted were from Dias et al. (2012).

2.2 Application of formulas

To calculate the amount of energy that could be produced, considering the losses in the process, we applied different formulas to different sources. All the formulas were used by Coelho et al. (2012) and Ribeiro and Rode (2019). The calculation results inform how biomass energy is distributed in the region.

- **Crops**: the conversion efficiency adopted for the residues was 15%, of the low thermodynamic yield - 20 bar boiler compound systems, atmospheric condenser turbine (GBIO et al. 2015).

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

Where:

- $Crops_{tons}$: 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's hours. This factor converts the results from Megawatt hour to Megawatts per year).

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

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

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, the 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's hours. This factor converts the results from Megawatt hour to Megawatts per year)

The entire calculation was made, taking into consideration a viable technology: a standard technology with low conversion efficiency (15%). Considering that investing in sustainable energy to improve people's lives is not necessarily an attractive business, as well as the economic downturn that Brazil is facing, environmental issues are not a priority (Escobar 2018). Modern and expensive technology with a higher conversion coefficient would be too far from reality.

2.3 Demand estimation

The demand for the municipalities was considered as the monthly average consumption per residence on the state (Reis and Reis 2017), assessed by the local energy company, CEMIG. The value applied for the study area is 150 kWh/month per capita.

2.4 Implementation costs

The current market prices from October 2018 were applied for the calculation, carried out by Solidda Energia (Solidda Energia 2019), a company that operates in the area of thermoelectric power generation with biomass in the country. As the methodology for those calculations is property from a private company, it was not possible to describe the exact formulas and procedures. The results of the economic assessment represent the market values applied nowadays in Brazil. The calculations of the costs involve collection logistics, transport of materials, purchase, installation, and operation of a power generating unit and team training.

3. Results

Being large and somewhat industrialized cities, three out of the 16 evaluated municipalities were not analyzed due to its irrelevant agricultural production (figure 2).

Together, the 13 analyzed municipalities presented a production capable of meeting about 20% of local demand (table 2). The values had an extensive range of variability, with an emphasis on São Pedro dos Ferros, a place where agricultural waste is enough to meet 329% of the intern energy demand.

3.1 Implementation costs

The analysis of the implementation costs took into consideration the most efficient arrangement for residues transportation logistics and resulted in a setting where it would be built two power plants, on the municipalities of São Pedro dos Ferros and Marliéria (table 3). As shown in figure 2, the study area was divided into municipalities that would supply residues to the Marliéria Power Plant (MP) and São Pedro dos Ferros Power Plant (SPFP).

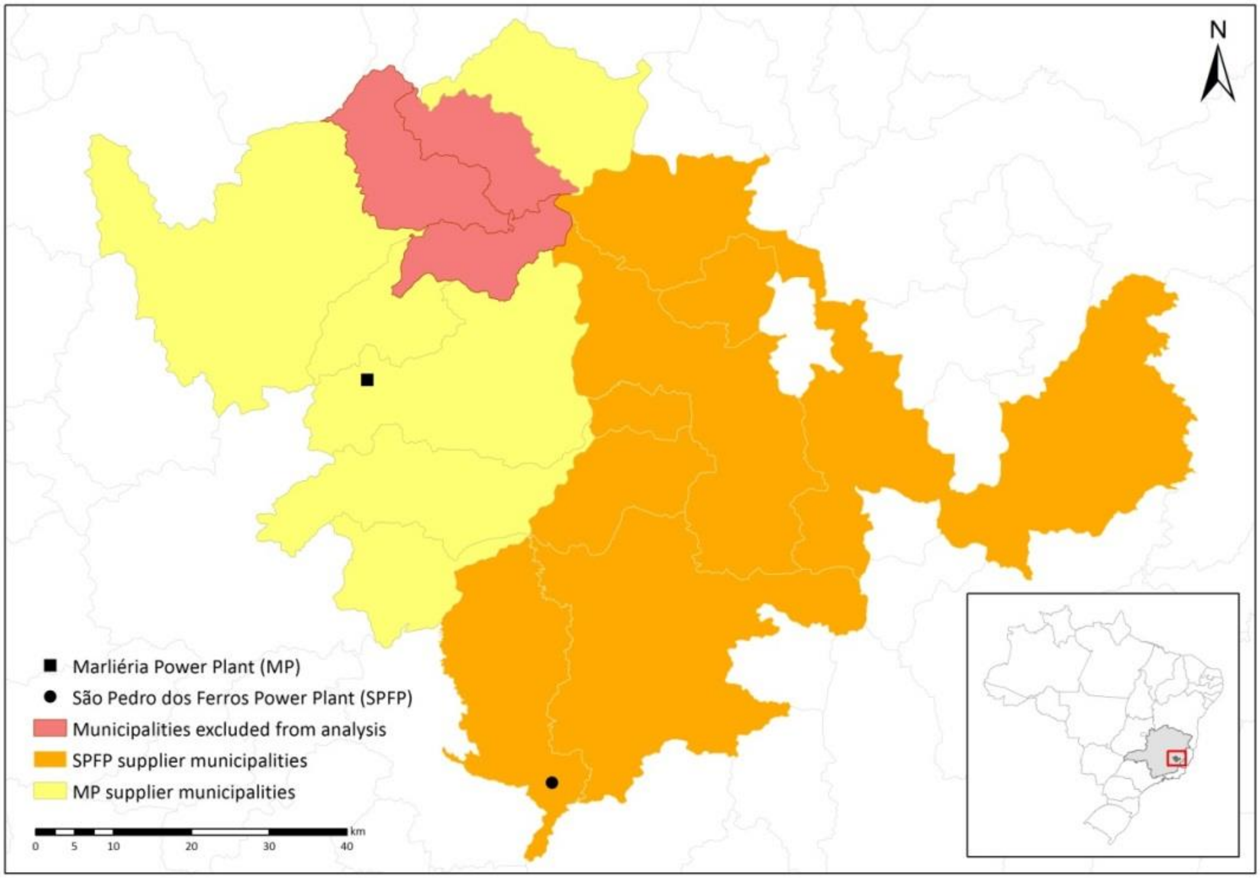

Figure 2: Results from the viability analysis and power plants location: Marliéria Power Plant (MP) and São Pedro dos Ferros Power Plant (SPFP). Source: IBGE 2015.

It was considered an operation as an energy cooperative, distributing energy through the Resolution of the Distributed Generation 482/687 - RDG (Brasil and ANEEL 2012). The farmers themselves could consume the energy produced with the waste. In this case, the average price of 78 US$/MWh was applied, which would be the purchase price of the energy if the consumers would buy directly from the energy company, CEMIG. Considering selling on the market, the price would be from 40 to 50 US$/MWh.

Table 2: Energy potential of agricultural waste Vs. average annual energy consumption

Municipality	Energy potential (MW/year)	Energy potential (kW.h/year)	Average annual energy consumption (kW.h/year)	Potential-average consumption (kW.h/year)	Percentage of the total demand
Antônio Dias	0.02	177,085.47	5,173,200	-4,996,115	3%
Bom Jesus do Galho	0.16	1,294,496.51	8,674,200	-7,379,307	15%
Caratinga	0.39	3,255,043.60	47,986,200	-44,729,126	7%
Córrego Novo	0.05	377,773.26	1,794,600	-1,416,330	21%
Dionísio	0.06	464,133.14	4,766,400	-4,301,502	10%
Jaguaraçu	0.02	130,037.79	1,598,400	-1,468,074	8%
Marlieria	0.09	759,236.34	2,239,200	-1,477,973	34%
Pingo d'Agua	0.03	269,968.60	2,341,800	-2,071,044	12%
Raul Soares	0.20	1,635,343.60	13,887,000	-12,246,292	12%
Santana do Paraiso	0.04	297,671.51	14,203,800	-13,905,153	2%
São Jose do Goiabal	0.17	1,430,795.93	3,115,800	-1,679,430	46%
São Pedro dos Ferros	1.80	15,016,480.47	4,566,600	10,512,865	329%
Vargem Alegre	0.02	207,265.12	3,668,400	-3,460,155	6%
Σ	3.04	25,315,331	114,015,600	-88,617,636	22%

Even presenting significant potential for biomass energy production, the municipality of Caratinga figures as a supplier municipality, and cannot be considered as a potential host of a power plant. As the calculations of power plants locations were developed considering the best spatial arrangement for the entire area, the costs of the collection logistics and material transportation were favorable for the installation on the municipality of Marliéria.

Table 3: Costs involved in the implementation of two power plants covering 20% of the region's energy demand

Power Plant	Capacity (MW)	Investment (US$)	Deadline for implementation (years)	Net income from energy sales (US$/year)	Investment return (years)
São Pedro dos Ferros	2.90	4,240,000	1.50	1,241,500	3.42
Marliéria	0.43	1,060,000	1.00	72,800	14.56

3.2 Future Scenarios

Three scenarios of an increase in local production were assembled: meeting 50%, 70% and 100% of local demand for electricity (table 4). For the increase in production, only the crops of interest for expansion by the local population were considered.

Table 4: Production increment scenarios directed to attend local energy demands

Beans				Manioc				Corn					
Average yield (ton/ha)	50%	70%	100%	Average yield (ton/ha)	50%	70%	100%	Average yield (ton/ha)	50%	70%	100%	Σ Scenarios 100%	
0.72	30,718	43,006	61,437	12.68	5,394	7,552	10,789	3.03	38,722	54,211	77,445	149,670	Total hectares
	17,077	29,365	47,796		2,999	5,157	8,393		21,527	37,016	60,249	116,438	Increased hectares

To attend 100% of the demand, it would be necessary two power plants with a 7 MW capacity. Above 5 MW (gross power) it is not possible for the enterprise to meet the requirements of the RDG, and only the sale in the free market is possible. The 7 MW power plant, for example, would have an average monthly financial loss of 9,000 US$. Thus, the best option is to disregard economically unviable units, whose power is higher than 5 MW.

The calculation of the costs took into consideration the scenario covering 70% of the local demand and the maximum viable production of 5 MW (table 5).

Table 5: Costs involved in the implementation of two power plants covering 70% of the region's energy demand

Power Plant	Capacity (MW)	Investment (US$)	Deadline for implementation (years)	Net income from energy sales (US$/year)	Investment return (years)
São Pedro dos Ferros	5.00	6,625,000	1.50	2,039,000	3.25
Marliéria	5.00	6,625,000	1.50	2,120,600	3.12

4. Discussion

The methodology, used previously in Amazonian municipalities (Coelho et al. 2015), present a feasible approach for the estimation of biomass potential, considering the losses involved in the process. This methodology was also applied by Ribeiro and Rode (2019) in a different region of the state of Minas Gerais. As a result, they found out that the energy potential from residual biomass could be enough to attend the local demand there. Those cases, among others, show a potential that should be explored more thoroughly, creating opportunities for diversification on the energy matrix and therefore a safer energy system in Brazil. The current agricultural production would cover around 20% of the local energy demand.

A closer assessment in the municipalities, analyzing the local demand, more accurate data on the local yield could bring a complete set of information to build the analysis. Also, in the next step, the quality of the local production and the possibilities of storage should be assessed. Even though this result already points to an interesting outcome, where the diversification of the energy matrix can move towards a sustainable path.

São Pedro dos Ferros stands out for its high productivity, to the point of enabling the installation of a power plant in its area. The primary source of waste of the municipality is sugarcane, which even without the increase of its production in future scenarios remains the largest producer of energy in the region. Been the cheapest and most common source of biomass energy in the country (Leal et al. 2013; Corrêa da Silva et al. 2016), sugarcane plays an essential role in this scenario.

The time for the investment return drops significantly on the 70% scenario, foremost on the Marliéria power plant. As power generation capacity increases, the costs involved in implementing the power plant pays faster the investment. The increase in agricultural crop areas needs to be limited to local environmental constraints. Considering that it is a region around a protected area, a spatial planning study for allocation of these new agricultural areas should be developed and presented to the communities in an action plan.

In October 2018, a workshop to present a comprehensive study on possible technological innovations to be applied in the region was held with the population and decision-makers of the studied municipalities. The results of this study were presented there, but it did not figure as a choice of the locals for their future development. A more in-depth work should be conducted with the local population of the region, focusing specifically on the theme of biomass energy and its possibilities. It may provide thrilling inputs for the continuation of this research.

5. Conclusions

This paper explores opportunities for energy generation through biomass residues and the costs involved in the initiative. The study area is a region affected by a human-environmental catastrophe, which led its communities to explore the possibilities for innovative agriculture initiatives.

The results show that, even though a significant investment is required, the energy generation through biomass residues could be viable and pay itself in a short amount of time. This statement is even more applicable in a scenario where the agricultural area is increased, growing the power generation capacity of a biomass power plant.

The methods developed in the study presented here could be relevant for municipalities to record their potentials for energy production from residual biomass and seek for investments and local arrangements, depending on their potentials and affinities, in order to promote biomass energy generation. Working together, the municipalities can generate energy and create better power availability, jobs, income and more opportunities for energy decentralization. It could be used by public or private initiative, as a basis for projects aimed at sustainable energy development. Further studies should elaborate spatial limitations for the agricultural expansion and modeling scenarios where environmental constraints are respected. The input of the population on the matter is also fundamental for the continuity of such a biomass energy project.

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3. Results

3.1 Overall achievements

This study has been structured taking into consideration how bioenergy initiatives could bring benefits to society, mainly in strata where a development boost could carry significant improvements. In order to achieve this goal, an overview of the potential of sustainable bioenergy production throughout the national territory was accessed, which was followed by an evaluation of the potential in peripheral areas. Another scale of research was carried out, evaluating the availability of residues for energy generation, considering this time, the integrity of the soil.

3.2 Synthesis of results

Q1. How are the potential areas for sustainable biomass energy production spatially distributed in Brazil in relation to power demands?

In the first step, four factors were identified as relevant for the analysis: energy demand, exiting transmission lines, exiting power plants, land use and environmental preservation (paper 1, chapter 2.1). Maps with those factors were organized by different weights, where the lowest values correspond to the areas with the best potential for sustainable biomass energy production.

The demand factor was highly concentrated in the Southeast region, an area with 42% of the country's population (IBGE 2014). The transmission lines and power plant maps presented a common pattern of spatial concentration, together configuring the supply element of the analysis. Data over the land use and the priority conservations areas was considered, aiming to avoid the inclusion of areas with native vegetation or endangered areas.

The resultant combined map showed that the Southeast, Midwest, and Southern regions had the greatest number of areas with potential for energy production. Only two states, when combined, held about 52% of the best areas for energy production, which corresponds to circa 20.000.000 hectares.

Q2. Is there potential to develop the biomass energy sector to meet the demand of peripheral areas?

Three municipalities were chosen for the study (paper 2, chapter 2.3) on the second step: Almenara, Minas Novas and Turmalina. All of them are part of the Jequitinhonha River Valley, on the Northeast of the state of Minas Gerais, an area marked by a history of material poverty but with abundant cultural and natural resources. The region has specific and unique vegetation due to the combination of Savanna, Atlantic Forest and Dry Forest (Gontijo 2001). The potentials for the areas to produce biomass has never been explored.

Considering the theoretical potential for residual biomass energy production (maximum of energy that could be produced, not considering efficiency and conversion losses), two municipalities with wood production (Minas Novas and Turmalina) had significantly higher theoretical values. The technical potential, an approach with a more accurate estimation of energy potential, highlighted the contribution of wood residues to the final score, even when considering low conversion efficiency. The demand calculation resulted in an average use of energy by the municipality populations under different scenarios: basic need and productive use scenarios.

A comparison of energy potential and energy demand indicated the following scenarios: For Turmalina and Minas Novas, the crop and the silviculture potentials would be enough to supply their energy requirements in both scenarios. For Almenara, a municipality without silviculture activity, the energy potential from crop residues could meet the demands of the population’s basic need. However, a gap of more than 24 million kilowatt-hours for a productive scenario would be left.

Q3. How much energy from residues can be produced sustainably without compromising the soil?

The sum of the values presented in the scenario that was generated on the third step (paper 3, chapter 2.4), indicated that 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.

In total, from all the assessed sources, the annual crops show the highest residual biomass potential for the state of Minas Gerais, reaching a total of 6,495 GWh/year. This reflects the consolidated agriculture industry present in the state, mainly in the west. The permanent crops have the smallest value: 259 GWh/year. Considering that the only permanent crop type assessed was coffee. The silviculture potential shows a more distributed result, with no concentration in one specific region of the state, reaching a total of 1,409 GWh/year.

Q4. Can the sustainable potential meet the energy demand of an entire state?

On the third step, the municipalities where the demand was met in the basic needs scenario (paper 3, chapter 2.4), amounted to 79% of the total municipalities and 83% of the analyzed municipalities. Most of the locations where the results were not sufficient to meet energy needs were large metropolis, which have no space for agriculture and a high demand for energy. 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 west sub-region, where agribusiness is concentrated and the highest GDP in the state is located.

Q5. What is the potential of energy production from agricultural waste, the ideal allocation of the energy production unit and the costs involved in the enterprise?

The 13 analyzed municipalities on the fourth step (paper 4, chapter 2.5) had residue productions capable of meeting about 20% of their local energy demand. There was a large range of residue variability between the municipalities, most predominantly São Pedro dos Ferros's agricultural waste is enough to meet 329% of the local demand for energy.

The analysis determined that the most efficient arrangement would be to build two power plants: one in São Pedro dos Ferros and the other in Marliéria. The investment needed for this scenario would be approximately 4.240.000 US$ for the São Pedro dos Ferros power plant, with a capacity of 2,90 MW. The investment would pay for itself after 3,42 years. For the Marliéria power plant, the investment needed would be approximately 1.060.000 US$ and have a capacity of 0,43 MW. Return from the investment would come after 14,56 years.

To meet 100% of demand, it would be necessary to have two power plants with a 7 MW capacity. Above 5 MW (gross power) it is not possible for the enterprise to meet the requirements of the Resolution of the Distributed Generation 482/687 - RDG (Brasil and ANEEL 2012), and only sale in the free market would be possible. Thus, the best option is to disregard economically unviable units, whose power is greater than 5 MW. Calculation of the costs took into consideration the scenario covering 70% of the local demand and the maximum viable production of 5 MW. The investment into this scenario would be about 6.625.000 US$ for both power plants, with a capacity of 5 MW. The investment would pay for itself after 3,25 years for the São Pedro dos Ferros power plant and for the Marliéria power plant after 3,12 years. The variability on the investment return is due to the different distances for the transportation of residues, and a consequent difference in the final costs.

4. Discussion

Exploring the possibilities of generating clean and decentralized energy in Brazil, the most common is solar energy used for residential supply (Borges Neto et al. 2010; Hollanda et al. 2015; FGV Energia 2016). The idea of small generations to supply communities is still commonly found with the use of fossil fuels in isolated communities, mainly in the northern region of the country (Coelho and Goldemberg 2013). There are hardly any studies on the use of biomass residues as a contribution to a decentralized, sustainable and socially acceptable power supply in Brazil. This work is the first of its kind and is a very important step in this direction.

A similar discussion can be found in Nobre et al. (2019). Both studies seek to exploit abundant resources locally and use them for renewable energy generation, benefiting mainly the local population. The authors go in another direction, calculating the possible income that producers could earn by directly selling the energy generated by solar panels to the grid. Such an activity would require a change in Brazilian legislation, not yet put on the agenda. Another aspect that calls attention is the intention to use degraded areas for the installation of solar panels. Both studies focus on the premise of not promoting change in land use.

While endeavoring to answer the first research question, investigating how the potential areas for sustainable biomass energy production are distributed in Brazil, similar studies were assessed (Okello et al. 2013; Jenjariyakosoln et al. 2014). These studies reinforced that there is a potential for biomass energy that remains unexplored around the world. It is clear that what is impeding the development of the sector is mainly the policies and not an issue of technology or supply: the lack of investments in technological improvements and changes in the system *status quo* result in an immobile system, which does not move forward to become cleaner, safer and less dependent on climatic factors or pollutant technologies. Instead of creating a new pathway towards renewable energy, Brazil continues to prefer natural gas thermoelectric plants in moments of water shortage (Abramovay 2014; Corrêa da Silva et al. 2016; Zurn et al. 2017). For developing countries, the adoption of cleaner technologies at an early stage has the potential to save a lot of effort, money, and natural resources.

Brazil's Northern region showed the largest lack of energy access. The Brazilian government has been investing in multiplying the population's access to energy since 2003, through the large scale program *Luz para Todos* (Light for all). Even with these advances, most of the new connections were based on a grid extension approach (Gómez and Silveira 2012), which still excludes around 200 thousand households.

Isolated communities in the Amazon forest are impossible to connect to the grid, relying on off grid solutions based on diesel generator technology. The region has a potential for energy production based on the residues of local agricultural production activities (Fuso Nerini et al. 2014), creating a favorable scenario for decentralized renewable energy production. The benefits of rural electrification (Ley et al. 2006) range from the creation of health centers, improved access to medication and related services, productive application and change in the way of life of communities (Foster et al. 2006; Corsair and Ley 2008), enabling the opening of new businesses and improvement of their community life.

The Southeast region is responsible for 53,2% of the total Brazilian GDP (IBGE 2017b), a consequence of the large amount of industry, commerce, the main proportion of the country's population and energy connections. The region had the three states with the best scores - Minas Gerais, Espírito Santo, and São Paulo. Despite its good performance, the Southeast region has a long history of environmental pressure on native vegetation, mainly in the Atlantic Forest biome. Recent data indicates that the vegetation currently covers only 12,4% of its original area (Fundação SOS Mata Atlântica et al. 2018). A mix of renewable energy sources that harness local potentials could ease the pressure on water resources and ensure a cleaner, safer system for the population.

A new model of energy transmission can also contribute to the modernization of the electrical system. Brazil has a distribution system where production is centralized (large hydroelectric plants), but consumption is distributed throughout the country (Nobre et al. 2019). According to Armstrong et al. (2016), the future of the energy networks relies on a distributed, multi-source and multidirectional system, not based on large connections. Biomass energy has the potential to meet such conditions, making it a promising future clean source of energy.

The state of Minas Gerais, which had the best score, is where the first hydropower plant was located in the country. Even though it is a state with a high level of biodiversity, mostly caused by the different biomes found in its area (Klink and Machado 2005) – Savanna, Atlantic forest and Dry forest – the areas historic land use of agriculture and mining has removed large portions of the native vegetation. The state has the third highest GDP in the country, mainly due to the mining industry and activities related to it (FJP 2012). The development of a robust and sustainable system of renewable energy would lower the pressure and dependency on the hydropower system, allowing the region to develop socially and economically in an environmentally friendly way.

In order to explore the potential of the state of Minas Gerais, three peripheral municipalities within it (Almenara, Minas Novas and Turmalina) were chosen to have their potential for residual biomass energy assessed. The methodology, applied previously to municipalities in the Amazon (Coelho et al. 2015), presents a calculation that considers the possible losses occurring in the process of energy generation. The municipalities contain areas which performed best in the previous phase of the research and thus, were chosen for an evaluation on a different scale.

The two municipalities with the best results had not only a strong agriculture sector, but also a consolidated silviculture sector. Turmalina, the municipality with the highest potential, had a productivity that, if converted to electricity, would correspond to the establishment of a small hydroelectric dam (ANEEL 2018). The silviculture residues would be responsible for the largest potential of energy production. For Minas Novas, the silviculture residues alone could fulfill the highest energy demand, showing how strong the silviculture industry is in the region. Considering the low level of employment offered by this sector, the biomass energy sector could create local jobs in different sectors of the production chain (ANEEL 2008). Such effects are shown by Dinkelman (2010) in cases of areas without previous electrification, and by Moreno & López (2008) who analyzed different types of renewable energy jobs in Spain.

The technology chosen for the calculations have a low efficiency in energy conversion. Being a cheaper option, easily found in the national market, it was selected for being the most viable. Since 2015, Brazil has faced an economic downturn that tends to decrease the attractiveness of 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 elected government in 2018 (Tollefson 2018). Without mentioning this subject during the 2018 polls, the elected president threatened to leave the Paris Agreement (Escobar 2018), expand the exploitation of the Amazon region and reduce the protected areas. Brazil has already rescinded as host of COP25 in 2019 (Chiaretti 2018; Pontes and Resende 2018). Importantly, the results of the *theoretical potential* represent the maximum amount of energy that could be generated, for production with the technological development. Obtaining a result that indicates that municipalities can be self-sustaining from the generation of energy from agricultural waste, indicates that there is potential for further improvement.

With further analysis of the results obtained in the first part of this research (chapter 2.1), the potential for the whole state of Minas Gerais was explored and compared with local demand. A similar methodology was applied, but here, the possibilities for soil conservation were considered. For the scenario of basic needs, a surplus of 6,704 GWh/year was estimated. One possibility for optimization is the trade of residues between regions with energy surplus to places where the agricultural and silviculture residues cannot meet 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. Palletization of agricultural and agro-industrial residues involves the compaction of these residues in order to produce a dry and more dense product, with higher energy content than the original residues (Junginger et al. 2001; McKendry 2002; Dias et al. 2012). This alternative could provide a solution to meet the demand of areas with lower residues and also generate income for the places that have additional residues. A Brazilian law resolution from 2015 (ANEEL 687/15) began facilitating the process of decentralized energy production, regulating the distribution of micro and mini energy generation. This creates an ideal context for the development of small energy generation units, which could be fueled with residues from different parts of the state.

Minas Gerais is the fourth biggest state in the country and the second largest in terms of population numbers, with an estimated number of 20,869,101 inhabitants in 2016 (IBGE 2017a). From the total of 853 municipalities, 32 have large cities (more than 100 thousand inhabitants) and hold 45% of the state's population. The intensely populated municipalities have a greater capacity for increasing the energy demand, while also having less area to produce crops, wood and its residues. These municipalities are responsible for 12% of the energy potential and, as it is calculated based on the population, 45% of the energy demand. This unbalanced relation means that 11 of those 32 municipalities meet the demand in a basic needs scenario and only one in a productive uses scenario. Studies on possibilities of ideal sustainable energy mixes, such as Palmas et al. (2015), could be carried out in Brazil in order to explore alternative possibilities for meeting local energy demands and creation of a sustainable energy system for Minas Gerais. This study showed that biomass could figure as an energy supplier for 78% of the basic needs demand and 18% of energy in a scenario of productive uses. 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.

Access to electricity can lead to investments in infrastructure and education, with greater chances for expansion in agricultural activities, entrepreneurism and savings. Therefore, the impact of power generation in some areas is not only related to income, but also to better education opportunities, health care and gender equality, as it is often female employment that is positively affected (Cook 2011). Considering the environmental and social risks involved in new hydropower projects (Ferreira et al. 2014b), the development of technologies and programs, that support the propagation of the biomass residues use for energy production, can play an important role in future sustainable and social development in Brazil. Discussed by Nobre et al. (2019), positive results in renewable energy potentials may suggest changes in public policies at different levels, involving the private sector, non-governmental organizations, and small producers, increasing the chances of achieving a positive impact on the economy, environment, and education. The development of public policies that take into account local potential can more effectively promote regional economic development and social inclusion. Lillo et al. (2015) and Panepinto et al. (2015) also highlight the necessity of involvement of the affected communities in the process of decision making on biomass energy projects. There is a potential for improvement on local quality of life, but local acceptance is a necessary step in the process of implementation.

The state of Minas Gerais is mainly characterized by small properties (79% of the farms on the state (IBGE 2017c)), managed essentially by families who have been responsible for the food supply of the state population. With greater income generation per cultivated area (Abramovay 1997), these small farms are commonly organized into cooperative production systems and associations, aiming at increasing the competitiveness of their product and their market insertion (Costa et al. 2015). Being a model that is already applied by these farmers, the organization of their crop residues into biomass energy production cooperatives could optimize residue collection logistics and processing, as well as the distribution of the energy generated, following a model already tested in other parts of the world (Hanley et al. 2001; Stokes 2013). Together with the cooperatives model, the development of a Social Technology for energy production through biomass residues could guarantee the replicability and establishment of a new model for energy production. One that works for lower income communities and that is simple to replicate with minor adaptations, leading to improvement of local and regional development, boosting the local economy without generating impacts on the environment.

In order to evaluate the possibilities for energy generation, including the costs of the venture, a new region in the state of Minas Gerais was chosen for assessment. The watershed of the chosen area was directly affected by an environmental disaster in 2015, when 62 million cubic meters of mine tailings spilled into a river, damaging over 680 km (Borges 2018). A search for innovative solutions for the regions affected agriculture, motivated researchers from regional projects to join forces and propose a biomass power unit as a way to optimize local resources and generate new opportunities for the population (Velázquez et al. 2010).

The municipality of São Pedro dos Ferros stands out because of its high productivity. The main source of waste in the municipality is sugarcane which, even without an increase in production in future scenarios, remains the largest producer of energy in the region. Being the cheapest and most common source of biomass energy in the country (Leal et al. 2013; Corrêa da Silva et al. 2016), sugarcane plays an important role in this scenario.

Two scenarios were drawn: one representing the current production and a second considering an increase in agricultural production that would be enough to meet 70% of the local demand. The time needed for an investment return drops significantly in the 70% scenario, foremost for the Marliéria power plant. As power generation capacity increases, the cost involved in implementing the power plant pays back the investment faster. Any increase of agricultural crop areas needs to be limited by local environmental constraints. Considering that it is a region near to a protected area, a spatial planning study for allocation of these new agricultural areas should be developed and presented to the communities in an action plan.

The calculations of the economic viability of the enterprise were made considering a reduction in energy costs equivalent to the amount of energy produced and supplied to the central distribution network. As discussed by Nobre et al. (2019), this compensation model is more advantageous for large consumers of energy, still having much room for improvement concerning small consumers. Even so, the results of the above-mentioned study indicate that the productive use of energy generated on the property would bring significant annual savings to rural producers.

5. Conclusions and outlook

5.1 Relevance of the results for a sustainable and socially acceptable energy supply in Brazil

One aspect, essential for the implementation of residual biomass initiatives, was acceptance from the communities involved in bioenergy projects. This step proved to be a significant impediment to the development of the sector.

The results obtained in chapter 2.5 were presented in a Workshop to the communities where future multifunctional landscape scenarios would be set up. The items related to bioenergy were unanimously refuted by all present. Exploring the reasoning behind this, it was found that the community directly associated the term 'bioenergy' with 'biofuel'. In 2017, a company wanted to implement a castor bean (*Ricinus communis* L.) seed oil biofuel power plant. Farmers were encouraged to grow the seedlings and, at the time of harvest, it was found that the quality of the oil was not good enough for the fuel production. The farmers could not sell their production, losing their initial investment and the whole area dedicated to planting.

Not only does this highlight the inefficiency of top-down actions, these results show that the general population has little access to possibilities regarding alternative energy sources. Initiatives that seek to develop this sector within the country should also focus on initiatives that inform and teach about the possibilities of bioenergy and its potential in the country's energy mix. The predominance of hydroelectricity and the widespread belief that it is a completely clean and endless source of energy, not only slows down the development of new technologies but also dominates popular knowledge on the subject.

Keeping in mind that the main objective of this project was to investigate the role that biomass can play in the Brazilian electricity mix, the potential in different contexts was investigated, as well as possible implementation arrangements and costs involved. The effectiveness of these initiatives and how they impact people's life still relies on the engagement and acceptability of rural producers, which could not be ascertained in the development of this research and figure as future developments of the research presented here.

A deeper evaluation, not only in rural communities but also in the general population, on people's knowledge of bioenergy unveil interesting insights into the development of public policies aimed at achieving different energy sources in Brazil. More specifically, in the study area evaluated in chapter 2.5, work with the communities that is directed towards awareness of electric energy from agricultural waste should be conducted. It should assess whether, even after education on the topic, this new source of energy could be accepted in the future by the local population. Human and institutional actors are the key to the success of any renewable energy project since the motivation of human actors in the implementation of projects is a determining factor for its success (Ley and Corsair 2008).

As discussed in the previous chapters, Brazil has a strong dependence on hydropower, mainly through large-scale projects. In the absence of a renewable source as a backup in situations of water scarcity, thermoelectricity from natural gas fulfills this role.

Abramovay (2014) raises the question of a limit on carbon emissions that cannot be reached without endangering humanity. The *unburnable carbon* corresponds to the share of fossil fuel reserves that, if burned, would result in global temperature increases above the target of 2°C by the end of the century. According to the author, large corporations that exploit fossil fuels rely on a reserve that can only become wealthy if it destroys the climate system, thus justifying investment that would not be profitable in the medium term. The author describes how new renewable sources of energy have an immense market growth potential and would greatly reduce the final price of the product, while also generating energy.

The results of this study sought to comprehend different scales, where the bioenergy approach could be assessed and where parts of its technical viability could be evaluated. The utility of the results lies in the fact that even when adopting less efficient technologies, the availability of residues for energy generation was sufficient enough to be relevant to the local energy mix.

In the context of political uncertainties and dubious environmental policies, where climate change has already been dubbed a conspiracy (Abessa et al. 2019), a survey of potentialities or a methodology to do so are relevant to the development of newer technologies. The possibility to replicate and apply them in different scales/situations can implicate those studies with the aim of implementing bioenergy initiatives to be developed with greater speed and efficiency. The results presented here can be used as a basis for further studies, both in deepening the knowledge in the regions investigated here (i.e. evaluation of productivity *in situ* studies and information about bioenergy for the local population) and as a foundation for additional research in other areas. Observing the local production characteristics, it is possible to replicate the study in different regions.

The relevance of scientific research has been jeopardized in the last few years, all over the world, through a massive influx of fake news and anti-science trends (Pettorelli et al. 2019). Even though this has generated a disconnection between science and politics, and some governments do not take action to mitigate climate change, initiatives that unite civil society, academia and NGOs must be conducted in pursuit of a greater good. Following the current trends of global warming, the poorest strata of society will be the first to suffer its negative effects: droughts, diseases, lack of potable water, and food (Wallauer et al. 2018). In a large and disparate country such as Brazil, with a population of 54.8 million people (26.5% of the population) living below the poverty line (IBGE 2018), such efforts are even more urgent.

5.2 Main conclusion

The dominance of hydroelectricity as a source of energy in Brazil acts as an inhibiting factor for the emergence of new technologies. Even existing potential, viable technology, the pressures to maintain `business as usual´ put the energy system in a stationary state. Finding and applying alternatives for energy sources that are sustainable, would guarantee a safe energy system for Brazil in the coming years.

By bringing together the results of the entire study, it is possible to conclude that the areas indicated as ideal in Paper #1 (chapter 2.1), are proven to have a high potential for biomass production. The marginal areas are also a relevant. Following the study of Longato et al. (2018), a quantification of marginal areas, unused and contaminated areas for cultivation of biomass plants should also be used as a possible alternative that aims to save native vegetation and not threaten the country's food security.

Results presented in Papers #2 and #3 (chapters 2.3 and 2.4) point to new promising directions, not only for environmental problems but also for some of the social issues that have occurred in the country for centuries. When three small municipalities can be self-sustainable in energy from biomass production, even when applying low conversion efficiency on waste, this illustrates that it is possible to produce enough energy to meet the demand of small townships by using silviculture and agricultural residues. This study presents a possibility for clean development and new sources of income generation for regions that should be targeted by local development policies.

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 historical and economically relevance of the state. A highly populated state can fulfill part of its energy demand with a resource that is available, without the necessity of land use change or competition with other markets that are established. This is an important finding concerning the energy matrix change. It means that, if it works there, it could also 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, not only for the state of Minas Gerais, but also for 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 material, adding value to the final product.

An aspect that arose in the last part of the research (Paper #4) were the costs involved in such an enterprise. It was shown that, even though a significant investment is required, the enterprise could be viable and pay for itself after a short amount of time. This statement is even more applicable in a scenario where the agricultural area is increased, increasing the power generation capacity of the power plant. Assessments on potential investors or programs that could facilitate its implementation could figure as a follow up measure.

Further studies should explore the spatial limitations of agricultural expansion; possibly modeling scenarios where the environmental constraints are respected. The input of population is also fundamental for the continuity of the project.

It is relevant for municipalities knowing their potentials and seeking investments. This method could lead to local arrangements, depending on their potentials and affinities, in order to promote biomass energy, and also as a tool to organize the information on possibilities of generation of energy by public or private initiative, as a basis for projects aimed at sustainable energy development. The methods can be a foundation for planning of energy generation from biomass, reducing the dependence of hydro energy in the country, promoting the decentralization of energy generation, and creating better conditions of social and economic development.

The potential for biomass energy production exists and could play an essential role in the energy transition. This potential can be explored respecting the environmental limitations and prioritizing populations in need of development initiatives, but the involvement of the population in the initiatives is an essential step towards their effectiveness.

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I hereby assure you that I have written this dissertation independently and that I have not used any other sources and aids than those indicated. The work has not yet been submitted as a dissertation or as an examination paper.

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