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Spatial assessment of the techno-economic potential of bioelectricity production from sugarcane straw

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ABSTRACT

The techno-economic potential of bioelectricity from sugarcane straw is highly affected by the availability and distribution of straw, the scale of the sugarcane mill and its proximity to the grid connection. All these parameters present high spatial variation. This study aims to spatially assess the techno-economic potential of bioelectricity from straw of the mills from São Paulo state (Brazil). It is assumed that all 174 mills are equipped with an adjacent power plant, and that all straw within the collection radius of the mill can potentially be used in the adjacent power plant. The straw costs are assessed making use of the spatial information on straw availability and the collection radius of the mills. The bioelectricity costs are calculated taking into account the scale efficiency, investments and operational costs, and cost of connecting to the nearest transmission infrastructure. The bioelectricity costs range between 68 and 266 US\$.MWh^{-1} across mills. The mills with high bioelectricity potential and low costs are generally large mills located in traditional sugarcane areas characterized by suitable agro-ecological conditions. Assuming a cut-off price of 80 US\$.MWh^{-1}, the techno-economic potential of bioelectricity of straw in Sao Paulo is 14.2 TWh, which equals 10% of total electricity consumption of the state.

1. Introduction

Contrasting with the expected decrease of large scale hydro-electricity production, the contributions of other renewable technologies to electricity production are expected to increase in Brazil [1]. These contributions are predominantly represented by wind, solar, small hydropower stations and biomass [1]. The latter, despite having lower expected cost reductions compared to solar and wind energy, is projected to maintain its 10% share in the renewable electricity mix up to 2025 [1]. Sugarcane residues currently contribute for more than 80% to the national bioelectricity supply [2]. In 2015, the sugarcane sector in Brazil produced approximately 20.2 TWh of bioelectricity surpluses, which represented 4.3% of the total national electricity consumption [3,4].

The advantages of producing bioelectricity from sugarcane residues are the high number of mills that cogenerates bioelectricity in the same unit along with their core products, e.g. sugar and ethanol, and their proximity to big electricity consumers in the Brazilian Center-South (e.g. state of Sao Paulo) [5,6]. Currently, the main feedstock to produce bioelectricity in Brazil is the sugarcane bagasse, which is a residue from the sugarcane stalks crushed at the mill [7]. Due to high bagasse availability at low cost, most of the mills became fully energy self-sufficient, and some of them export large surpluses to the grid [6,8]. However, the increasing competition for bagasse could harm bioelectricity supply in the long run, as the mills may draw the attention to high added-value products, such as advanced cellulosic ethanol and biomaterials [5,9]. Hence, alternative high potential residues should be assessed to cover the increasing electricity demand [10].

In the 2000's, agricultural improvements and environmental laws have led to important changes in the agricultural phase of sugarcane production [11]. Particularly, the consolidation of sugarcane mechanical harvesting instead of manual harvesting through sugarcane straw burning has stimulated the use of straw as

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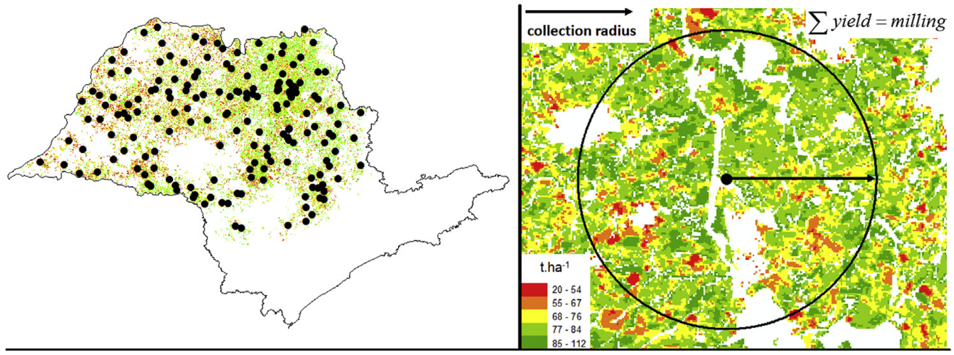

Fig. 1. Left: Sugarcane yield map and the 174 mills in operation (black dots) in the state of São Paulo in 2012 crop-year. Right: Calculation of the collection radius around the mills matching the summation of the sugarcane yield in the collection radius with milling data of the mill [25].

a source for bioelectricity. Previous studies indicated that straw have the current largest technical potential available (range of 42–105 Mt) for bioenergy in Brazil [1,12,13], which makes it the largest (and almost untapped) biomass residue source. But unlike bagasse, straw is an on-field residue that usually requires a separate costly and time consuming operation to be recovered [14].

Seabra and Macedo [15], Cardoso et al. [14] and Michelazzo [16] all show the straw recovery costs as a key parameter impacting the profitability of bioelectricity production, which is mainly explained by straw availability per hectare and transportation distance to the mill. Both parameters present high spatial heterogeneity over the sugarcane fields due to variability of agro-ecological and accessibility conditions [14,17–19]. Moreover, other techno-economic issues also affect the viability of producing exportable bioelectricity from straw [7,20–23]. Trombeta found a high regional variability in the mills' boilers and cogeneration systems, strongly related to the scale of the sugarcane mills. Additionally, Cavalcante [21] raised the importance of proximity of the mill to the electricity grid to enable low bioelectricity costs.

All the aforementioned studies highlight the effect of spatial dependent parameters at field (straw availability and transportation distances), mill and regional levels (power plant scale and availability of regional transmission infrastructure) on the bioelectricity production costs. However, there is no comprehensive assessment of how the spatial variation of each of these aspects jointly affects bioelectricity production costs. Similar studies have partially covered this knowledge gap either in a different scope [23] or in different bioenergy systems [24]. Even so, no study has reconciled spatially explicit data available at different geographical levels to provide multi-scale techno-economic information of bioelectricity production from crop field residues. Such information is crucial for investors and policy makers to comprehend and explore the techno-economic potential of bioelectricity in a given region.

The objective of our study is to spatially explicitly assess the techno-economic potential of bioelectricity production from sugarcane straw in sugarcane mills at field, mill and regional levels. We thereby also assess how the spatial variation of the key parameters affect the cost structure of bioelectricity and identify how the techno-economic potential could be improved. To provide comprehensive assessment on the techno-economic potential, we select the state of Sao Paulo in 2012 sugarcane crop-year as a case study because of the high quantity sugarcane mills (174) in this region and due to the high spatial resolution data availability for 2012 crop-year. The spatial modeling method employed in this study can be replicated in other study areas both in Brazil and other sugarcane-producing countries. The assessment is built upon the environmental potential assessment of bioelectricity from sugarcane straw of *Cervi* et al. [25].

2. Methods

The techno-economic potential of bioelectricity from sugarcane straw is assessed by carrying out a cost analysis for both the straw recovery and bioelectricity production. First, we assess the straw availability for bioelectricity production by accounting for the spatial distribution of sugarcane fields, the spatial heterogeneity of sugarcane yield and the straw removal rates. Then, we calculate the effects of the spatial distribution of sugarcane straw on the straw recovery costs, expressed in US dollars per tonne of straw (US$.t^{-1}). Thereafter, we assess the composition of the bioelectricity production costs based on the selected system configuration of a typical high-pressure power plant adjacent to the mill to produce exportable bioelectricity expressed in US dollars per megawatt-hour (US$.MWh^{-1}). By setting a bioelectricity cut-off price, we assess the techno-economic potential of bioelectricity from sugarcane straw for each of the 174 sugarcane mills as well as for the entire state of São Paulo in 2012 crop-year. All cost input data are adjusted to real values of 2015 using IGP-DI price index [26] and all the cost data available in Brazilian Reais (R$) are converted to US dollars applying exchange rate of 1 R$ = 0.4 US$ (from January of 2015).

2.1. Straw availability

The data on the spatial distribution of sugarcane straw availability is based on the assessment of the environmental potential of bioelectricity from sugarcane straw for each sugarcane mill in São Paulo for the 2012 crop-year developed in *Cervi* et al. [25]. The study combined the spatial distribution of sugarcane and its yield levels in São Paulo at 250 m "pixel" resolution with the location of the 174 operating mills in 2012 crop-year (Fig. 1 - left). Each mill was fed by its respective milling (crushed) data in 2012 crop-year. Based on that, the collection radius was defined by the circular area of which the cumulative sum of the sugarcane yield matches the amount of sugarcane crushed in 2012 crop-year (Fig. 1 - right).

In the study of *Cervi* et al. [25], different scenarios of straw recovery were assessed based on the amount of straw that is assumed to be left on the field for agronomic and environmental purposes. In the scenarios, fixed rates of straw mulching of 3.2 t ha^{-1}, 5.4 t ha^{-1} and 7.5 t ha^{-1} on dry basis were assumed based on literature [11,27,28]. In this study, we use the moderate scenario of 5.4 t ha^{-1} of straw mulching on dry basis, which on average represents approximately 50% of the total straw available on the field. In total, this scenario account for an environmental potential of 28.3 Mt of sugarcane straw for bioelectricity production comprising all the

Fig. 2. The sugar cane straw baling system, including straw operations (in green) and transportation (in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

sugarcane mills in São Paulo.

2.1.1. Straw recovery costs

Sugarcane straw can be collected by many recovery routes [29], which should be selected based on the trade-off between the quality required by the end-product and the recovery costs [16]. For our analysis, we select the baling system, which is currently one of the most common straw recovery routes used in Brazil for bioelectricity and cellulosic ethanol production (Raízen/Shell mill, *pers. comm.* [30]). In the conventional mechanized harvesting of sugarcane, the harvester releases the straw back to the field. The straw remains on the field for approximately 15 days for natural drying. Then, with the appropriate machinery, the straw is windrowed, baled, loaded into the truck (representing the on-farm straw operation costs) and transported to the mill (representing the transportation costs) (Fig. 2). For further details of these operations, see see the studies of Cardoso et al. [14,17,28].

To calculate the total straw recovery costs, we consider both the farm-gate and transportation costs. See equation (1):

$$C_s = C_f + C_t \times d \quad (1)$$

Item	Description	Unit
C_s	Total straw recovery cost	$US\$.t^{-1}$
C_f	Straw farm-gate cost	$US\$.t^{-1}$
C_t	Straw transportation costs	$US\$.t^{-1}\ Km^{-1}$
d	Transportation distance	Km

In this study, the farm-gate cost of straw (C_f) is composed by the cost of agricultural input required for the following crop-year to compensate the nutrient losses related to the straw removal from the field, plus the straw operational costs (e.g. machinery costs, depreciation, diesel and labor for windrowing and baling) [14]. The farm-gate costs of sugarcane straw decrease with increasing yield levels [31], in a nonlinear way due to economies of scale. We based our calculation of the farm-gate cost of sugarcane straw on the study of Cardoso et al. [17]. Using their data, we fitted a power trend line to estimate the relation between straw availability and the farm-gate cost. We only include the fields with more than 1 t ha^{-1} of sugarcane straw available to ignore negligible amounts of straw recovery and avoid outlier straw recovery costs. See equation (2) and the supp. material (Appendix 1):

$$C_f = 65.35 \times Y^{-0.631} \quad (2)$$

Item	Description	Unit
C_f	Straw farm-gate cost	$US\$.t^{-1}$
Y	Straw availability	$t.ha^{-1}$

Michelazzo [16] has assessed the transportation cost of the baling system of sugarcane straw, and showed the relation between distance and cost. Accordingly, we estimate the average transportation cost of sugarcane straw (C_t) at 0.19 $US\$.t^{-1}\ Km^{-1}$. In our study, the distance (d) from straw field to the mill is calculated spatial explicitly using a Geographic Information System (GIS). Due to the lack of data on non-paved roads at which the sugarcane is mainly transported, we assume a tortuosity factor of 1.4, as suggested by Monforti et al. [32].

2.2. Bioelectricity production costs

Currently, most of the mills only use sugarcane bagasse as feedstock for bioelectricity production and have low efficient cogeneration systems to fulfill their own energy demand [20]. To scale-up the bioelectricity production using all recovered sugarcane straw, a retrofit to large boilers would be needed. As no information on the current status of the boilers in sugarcane mills is available, our selected system comprises a new power plant adjacent to the main sugarcane mill, which is fully dedicated to generate bioelectricity to be exported to the grid (Fig. 3). To standardize the assessment, the adjacent power plant comprises a Condensing Extraction Steam Turbines (CEST) system with medium/high pressure and temperature [15,33], which is implemented in all 174 mills assessed in São Paulo. According to Dantas et al. [7], this technology will remain a competitive bioelectricity production option in the medium to long term.

To calculate the bioelectricity production costs, we assume that all adjacent power plants operate with full scale, i.e. all the sugarcane straw available within the collection radius of the mill is used for bioelectricity production. With the scale determined by the amount of straw available, we adapt a realistic range of electrical conversion efficiency in sugarcane mills [22,34] that varies from 20% to 35% as function of the electricity generating capacity of the adjacent power plants (see supp. material - Appendix 3).

As highlighted by Leal et al. [35] and Menandro et al. [36], there are technical limitations (e.g. size of particles, chemical compounds) in operating a power plant exclusively fed by sugarcane straw. Therefore, we assume that part of the bagasse that are not

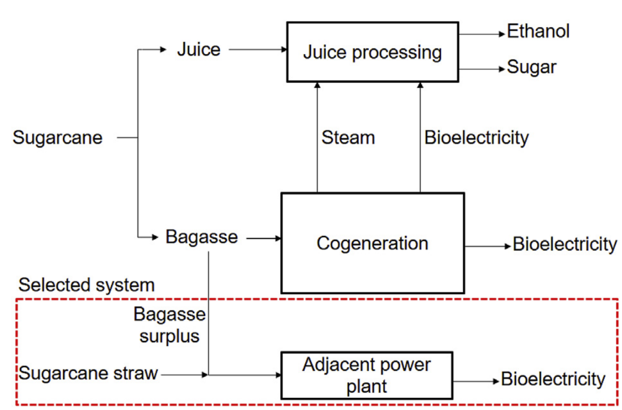

Fig. 3. System configuration of sugarcane mill with an adjacent plant to produce exportable bioelectricity (red dashed outline). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Sugarcane bagasse and sugarcane straw used in the mill and in the adjacent power plant.

Parameters	Biomass	
	Bagasse[c]	Straw
Residue to sugarcane ratio ($kg.t^{-1}$)[a]	260	140
Use in the main mill power plant (%)	65	0
Use in the adjacent power plant (%)	35	100[d]
Moisture content (%)[b]	50	15

[a] Bagasse: available at the mill [37]. Straw: available at the field [11].
[b] Lower Heating Value (LHV): 13.3 MJ kg^{-1} for straw (at 15% moisture content) and 7.2 MJ kg^{-1} for bagasse (at 50% moisture content) [37]. The potential reduction in moisture content of the bagasse stored for off-season is not considered.
[c] Bagasse storage costs are neglected in the cost analysis as it represents less than 5% of the straw recovery costs [38].
[d] Total amount of straw recovered from the field (i.e. the environmental potential).

used in the cogeneration system in the main mill (i.e. 35% of bagasse surplus for external use, based on [15,37]) is used to feed the adjacent power plant jointly with the sugarcane straw (i.e. mixed composition) (Fig. 3). The bagasse normally has moisture content of 50% [11] and it is available at no additional cost [15]. Moreover, the bagasse is mostly used in the adjacent power plant during the off-season (i.e. December to March) to avoid technical risks of storing sugarcane straw (e.g. accidental fire). The assumptions on the biomass availability are described in Table 1:

The bioelectricity production costs are calculated using the Levelized Cost of Energy – LCOE, which comprises all the costs throughout the supply chain of bioelectricity production from sugarcane straw. The discounted feedstock (straw recovery) costs and capital and operational expenditures (CAPEX and OPEX) over the lifetime of the plant are divided by the total discounted bioelectricity production output. The LCOE is commonly employed in economic assessments of renewable electricity systems [39], and it allows for the comparison of the costs structures of bioelectricity production of different sugarcane mills. The LCOE is calculated at field (pixel) level, taking into account the field specific straw recovery costs and the mill specific CAPEX and OPEX, as shown in equation (3):

$$LCOE^{pm} = \frac{\sum_{t=1}^{n}\left(I_t^m + M_t^m + \left(Cs \times LHV \times \frac{eff}{3.6}\right)_t^{pm}\right) \times (1+r)^{-t}}{\sum_{t=1}^{n} E_t^m \times (1+r)^{-t}} \quad (3)$$

Item	Description	Unit
$LCOE^{pm}$	Bioelectricity production costs at field p of mill m	$US\$.MWh^{-1}$
I_t^m	CAPEX in year t at mill m	$US\$.MW^{-1}$
M_t^m	OPEX in year t at mill m	$US\$.MW^{-1}$
Cs_t^{pm}	Straw recovery costs in year t at field p of mill m	$US\$.t^{-1}$
LHV	Lower Heating Value	$MJ.kg^{-1}$
eff	Conversion efficiency	%
3.6	Conversion MJ to KWh	MJ/KWh
E_t^m	Electricity generated in year t at mill m	MWh
n	annuity period	years
r	discount rate	%

The CAPEX and OPEX vary across the mills by virtue of their plant scale and the grid connection distance from the mill to the nearest distributor substation. To standardize the assessment, we

Table 2
Techno-economic parameters of the adjacent power plant.

Parameter	Units	Value
Reference scale[a]	MW	50
Operating time[b]	hours	8406
Scale factor[c]	–	0.7
Electrical conversion efficiency[d]	%	20–35
CAPEX[e,f]	$MUS\$_{2015}$	77.4
Transmission line[g]	$MUS\$_{2015}.Km^{-1}$	0.33
OPEX[h]	$MUS\$.MW.y^{-1}{}_{2015}$	0.21
Discount rate[i]	%	12
Project lifetime[j]	years	25

[a] As simulated by Seabra et al. [37].
[b] In this configuration, the adjacent power plant operates during both harvest season and off-season for approximately 11 months in total. In the power plant of the main mill (cogeneration), the bioelectricity is exclusively produced from bagasse, only operating during the season (6 months). Based on Seabra and Macedo [15].
[c] Typical scale factor used in techno-economic assessments of sugarcane biorefineries [23,26].
[d] The variation of efficiency in the adjacent plant is available in Cervi et al. [25].
[e] The majority of CAPEX is composed of the FCI for a 50 MW reference power plant estimated at 77.4 $MUS\$_{2015}$, including working capital (4 $MUS\$_{2015}$) [15].The project finance was assumed as 100% Equity.
[f] The additional part of CAPEX stems from the fixed transmission investments of 9.3 $MUS\$_{2015}$ for grid connection (e.g. substation, converters), which is not scale dependent [21].
[g] Variable investment in grid connection per kilometer of transmission line [21].
[h] Operational costs: include consumables, labor, overhead, maintenance and insurance [15].
[i] Commonly applied for private investments in bioelectricity projects in Brazil. Adapted from Dantas et al. [7].
[j] Plus 3 more years to build the power plant before the first year of production, which refers to the years −2, −1 and 0.

assume that all the mills still have to connect to the grid, while in reality some of the mills are already (partly) connected to the grid. To calculate the Fixed Capital Investment (FCI) of each mill, we assume a reference capacity of 50 MW [15] and typical scale factor for power plants of 0.7 [26] (Table 2).

Embedded in the CAPEX, the grid connection investments are not considered scale dependent, which means that the all mills need to invest equally in a substation facility and general connection equipment in order to export the bioelectricity from sugarcane straw (i.e. the fixed investments). In addition, there are also the variable connection investments related to the length (distance) of the transmission lines (Table 2), which are calculated spatially explicitly from the mill point to nearest distributor substation. A tortuosity factor of 1.2 was applied to the Euclidian Distance to account for geographical constraints, such as terrain slope, conservation and built-up areas [40]. Table 2 summarizes the techno-economic parameters of the adjacent power plant.

2.3. Techno-economic potential of bioelectricity

The techno-economic potential is assessed by assuming a bioelectricity cut-off price of 80 $US\$.MWh^{-1}$, which represents a typical value in the regular Brazilian bioelectricity market and is also used as reference in some studies [38,41]. The techno-economic potential is estimated at mill level and field level. In the first, all sugarcane straw fields available within the collection radius of each mill is used in the adjacent plant, accounting for the average straw recovery costs and the bioelectricity conversion costs given the related scale of the adjacent plant result in the average bioelectricity costs at mill level. The mills with an average bioelectricity production costs below 80 $US\$.MWh^{-1}$ are considered to be part of the techno-economic potential.

The drawback of mill level assessment is that all the fields in the

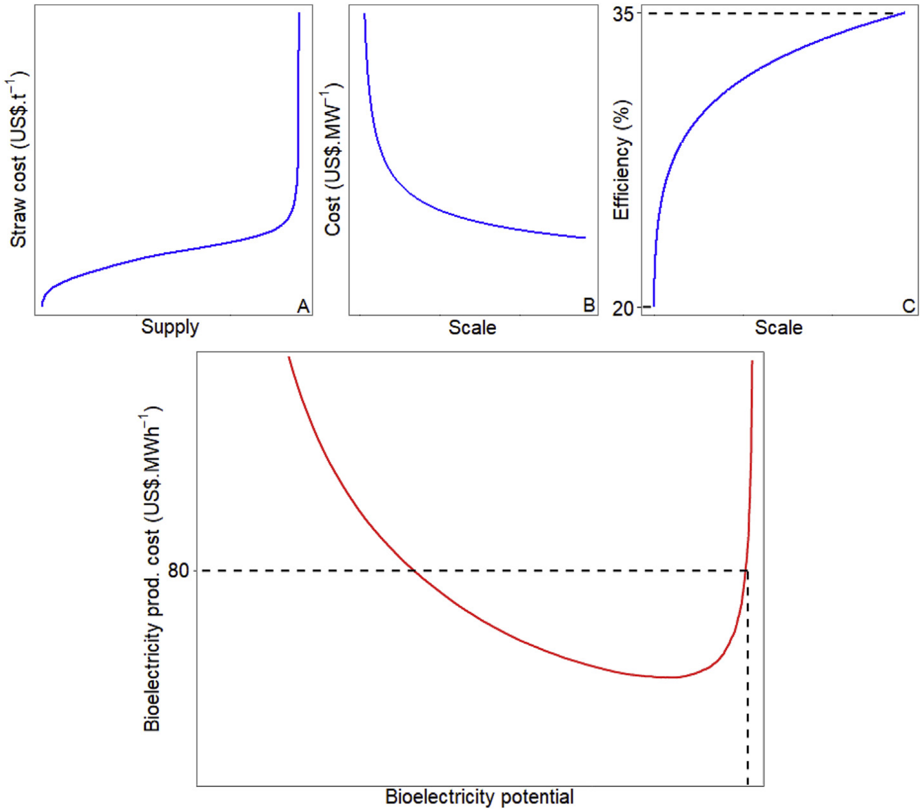

Fig. 4. Schematic representation on how the techno-economic potential is estimated at field level through the optimization of the adjacent power plant scale. Blue curves: graphical representation of cumulative straw cost-supply (A) cost-scale (B) efficiency-scale (C) of bioelectricity production from sugarcane straw. Red curve: optimal bioelectricity potential. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

collection radius of the mill are included in calculating the average straw recovery costs, including the ones with very high straw recovery costs. This could result in excluding some mills from the techno-economic potential because of a few costly outliers' straw fields. If it is assumed that only the fields with low straw recovery costs are included, the average straw recovery costs at the mill level go down. However, when only part of the straw available in the collection area of the mill is used in the adjacent power plant, the scale and the conversion efficiency need to be adjusted to match the lower straw supply, which results in higher bioelectricity conversion costs. Therefore, we determine the techno-economic potential at field level by making use of the cumulative straw cost-supply curve (A - Fig. 4), the cost-scale (B - Fig. 4) and the efficiency-scale curve (C - Fig. 4) of each mill. The optimal scale and related efficiency is assessed for which the techno-economic potential is maximized for each mill. This optimization calculates the maximum amount of bioelectricity that could be produced with costs <80 US$.MWh^{-1} (red curve - Fig. 4).

To assess the sensitivity in the techno-economic potential of bioelectricity from sugarcane straw, we consider the uncertainty of the following parameters: straw mulching levels, bioelectricity cut-off price; discount rate; straw moisture content; conversion efficiency; bagasse availability and cost; FCI and OPEX. The high volatility of bioelectricity prices in Brazil is a key concern regarding the economic viability of power plants in sugarcane mills [6]. In addition, fluctuations in the FCI, OPEX and discount rate due to influencing economic factors (e.g. exchange ratio of imported equipment, annual inflation, political issues, financing options) could have strong effect on the bioelectricity costs [7,15,37,42]. In regards of straw, the mulching level is dependent on agronomic features [17], which results in high uncertainty of the amount of straw that can be recovered and therefore, in the cost-supply of straw and the techno-economic potential of bioelectricity [14]. Similarly, the moisture content of sugarcane straw has a great variability over the fields, because of agronomic and operational reasons that highly affects the electricity generating capacity and efficiency [15]. There is a high variation in the reported conversion efficiency of bioelectricity from straw, which is only partly explained by the variation in scale. The conversion efficiency strongly affects the amount and the cost of bioelectricity produced [43]. At last, we consider variation in the assumption of 35% bagasse surplus supplied to the adjacent plant at no additional cost, influencing the feedstock costs and the adjacent plant capacity. The variation rate for each parameter is based on similar ranges found in literature, see Table 3.

3. Results

The results are based on the individual techno-economic assessment of all 174 operating mills in São Paulo in 2012 crop-year. In section 3.1, we firstly present the spatial variation of straw recovery costs at mill level. In section 3.2, we show the variation in bioelectricity production costs and the different cost structures across the mills. Based on the bioelectricity production costs and the selected cut-off price, the techno-economic potential of bioelectricity from sugarcane straw is presented in section 3.3. The sensitivity of the bioelectricity potential for variations in key parameters is presented in section 3.4.

3.1. Straw recovery costs

Fig. 5 (left) shows the spatial distribution of the 174 mills

Table 3
Considered variations in the key techno-economic parameters in the sensitivity analysis.

Parameter	Unit	Original values	Variation	Variation rate (% of original value)
Straw mulching levels[a]	$t.ha^{-1}$	5.4	3.2–7.5	59–138
Bioelectricity cutoff price[b]	$US\$.MWh^{-1}$	80	56–104	70–130
Discount rate[c]	%	12	8.4–15.6	70–130
Straw moisture content[d]	%	15	0–40	70–115
Conversion efficiency[e]	%	20–35	15–30; 25–40	82–117
Bagasse availability rate[f]	%	35	20–50	57–143
Bagasse cost[g]	$US\$.t^{-1}$	0	0–6	–
FCI[h]	M.US$	77.4	61.9–92.8	80–120
OPEX[i]	$M.US\$.MW.y^{-1}$	0.21	0.17–0.25	80–120

[a] Straw mulching levels: Amounts of sugarcane straw that should be left on the field to comply with environmental and agronomic requirements of sugarcane fields. Based on Cervi et al. [25].
[b] Bioelectricity cut-off price: bioelectricity selling prices threshold between 2008 and 2009 in the regular market reported by Grisi et al. [8]. Prices in the spot market are not accounted due to high variation in short periods.
[c] Discount rate: ±30% variation agree with debt financing options of bioelectricity projects in Brazil and with the Brazilian macro-economic conjunctures [7]. Differently from high value-added bioproducts, bioelectricity from sugarcane residues does not have the innovative appeal leading to extremely low discount rates [44].
[d] Straw moisture content: although it is unrealistic to supply sugarcane straw on a dry basis due to variability of environmental conditions on the field, many studies have been used dry basis as reference [5,9]. Therefore, we vary the straw moisture content from 40% (9.3 $MJ.kg_{straw}$) to dry basis (15.6 $MJ.kg_{straw}$).
[e] As the variation of 20–35% represents the reality of power plants in Brazilian sugarcane mills, we applied a small variation of ±5% based on reported values from literature [34].
[f] The bagasse availability rate is related to the thermal energy required by the mill to produce sugar and ethanol. We vary ±15% around the assumed fixed rate of 35% to address annual variation in sugarcane supply. A scenario with no bagasse available is possible, but not assessed due to technical constraints of operating boilers using only straw as fuel [36].
[g] The opportunity cost of sugarcane bagasse could increase according to the demand of competitive uses (e.g. animal feed, 2G ethanol). According to Carpio and Souza [6], current bagasse opportunity cost can be set at 6 $US\$.t^{-1}$.
[h] A similar variation rate of ±20% for both FCI and OPEX are applied in the sensitivity analysis carried out by Seabra et al. [15].

coupling their average straw recovery costs and straw environmental potential of the 2012 crop-year in São Paulo. Based on that, a sugarcane straw cost-supply curve ranging from 21 to 35 $US\$.t^{-1}$ is drawn by combining the 174 operating mills of the state of São Paulo (Fig. 5 - right). The size of the circles in Fig. 5 represents the sugarcane straw available at each mill, ranging from 5.7 to 632.4 kt of straw. In general, mills with a significant straw supply (i.e. > 200 kt) present average straw recovery costs between 26 and 30 $US\$.t^{-1}$. Although these mills profit from economies of scale due to a large straw supply, they also face higher transportation costs due to longer a collection radius. Differently, most of the mills with a low sugarcane straw supply (i.e. < 100 kt) are either concentrated in the higher (>30 $US\$.t^{-1}$) or lower (<26 $US\$.t^{-1}$) range of average straw recovery cost. Therefore, the straw cost supply curve hints no apparent relationship between the amount of sugarcane straw supply in each sugarcane mill and their respective average straw recovery costs. On the other hand, the map of Fig. 5 shows a geographic pattern due to high presence of mills with high straw recovery costs in the west of São Paulo and the occurrence of mills with low straw supply costs in the east of São Paulo.

To highlight the difference among the regions in the state of São Paulo, we divide the mills into four classes based on the straw recovery costs and potential of sugarcane straw per mill. Using the threshold of average costs at 27.1 $US\$.t^{-1}$ and the average straw supply at 163.1 kt, we establish the following classes: HCHS – high costs and high supply; HCLS - high costs and low supply; LCHS – low costs and high supply; LCLS – low costs and low supply. Fig. 6 presents the geographical distribution of the four classes of mills and their respective cost-supply curves.

LCHS mills (i.e. 23 mills labeled with blue circles and the blue line in Fig. 6), typically represent the traditional big mills established in the beginning of sugarcane ethanol program in Brazil in the 1970's, and are mostly clustered in the northeast of São Paulo. This region is characterized by optimal agronomic conditions for sugarcane cultivation, in contrast to other regions of the state [45]. LCHS mills have the highest average straw availability

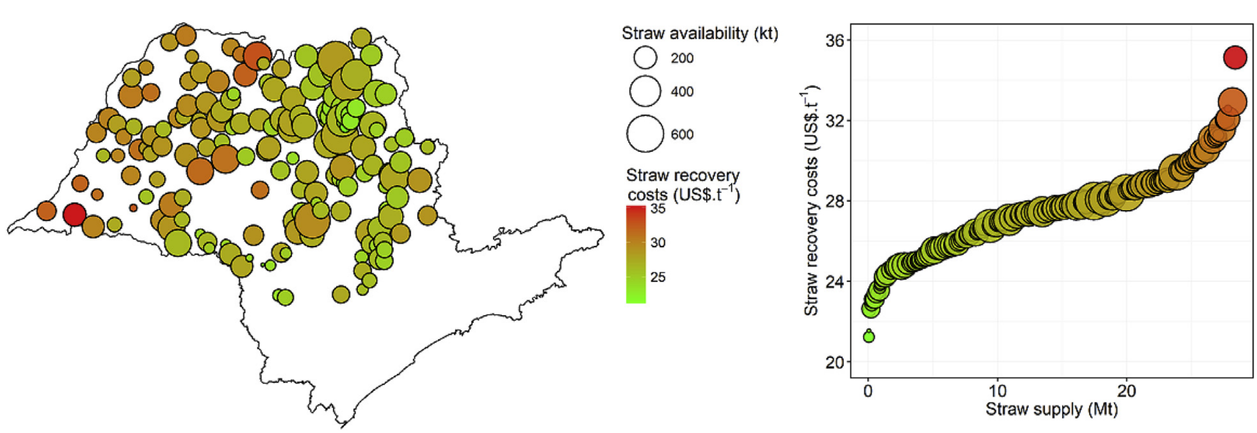

Fig. 5. Left: Spatial distribution of the sugarcane mills with their respective technical potential of sugarcane straw (size of the circles) and average straw recovery costs (color of the circles). Sharing the same legend, in the right, the regional cost-supply curve of sugarcane straw given the average straw recovery costs per mill in 2012 crop-year in São Paulo. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

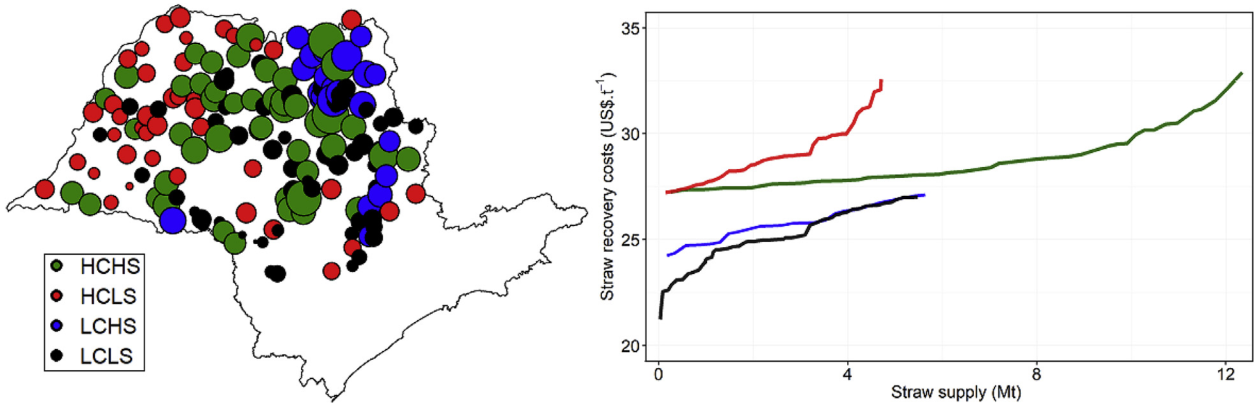

Fig. 6. Spatial distribution of the mills according to their cost-supply classification (left) and their respective supply curves (right): HCHS – High Costs and High Supply; HCLS - High Costs and Low Supply; LCHS – Low Costs and High Supply; LCLS – Low Costs and Low Supply.

($\bar{x}$ = 6.4 t ha^{-1}) and reasonable mobilization distances (one-way: $\bar{x}$ = 14.1 km), which assure low recovery costs. Contrasting, HCLS mills (43 mills identified with the red circles), represent a group of small and old distilleries generally located in the western part of the state. HCLS mills are characterized by a considerable mobilization distance (one-way: $\bar{x}$ = 20.5 km) due to the low average straw availability ($\bar{x}$ = 5.3 t ha^{-1}) in the direct surroundings of the mills.

The other two classes, HCHS and LCLS mills, are scattered across the state and more heterogeneous. In general, HCHS mills are located in the West and Central-West of the state refer, and to new brownfield mills that have been leading the sugarcane expansion in the state. These mills present a very high variation in straw recovery costs (see Fig. 7) because some areas present unsuitable agronomic and operational conditions for straw recovery, which increase the straw recovery costs. Distinctively, great part of the LCLS mills are identified as smaller branches of association of mills, located in regions with affordable straw recovery costs (i.e. the majority of the fields are composed by straw recovery costs lower than 27 US$.$t^{-1}$ - Fig. 7) that are used to supply the main mill of the association, which can be either HCLS or LCHS.

3.2. Bioelectricity production costs

The average bioelectricity production costs at mill level range from 68 to 266 US$.$MWh^{-1}$ (Fig. 8), which represents an average cost at state level of 93 US$.$MWh^{-1}$ in the 2012 crop-year. The total bioelectricity production costs consist of four major cost components: feedstock costs (i.e. straw recovery costs), operational costs, and FCI and transmission costs. The mills with relatively low average bioelectricity costs (shades of blue in Fig. 8), all have a relatively low contribution of transmission costs. High average bioelectricity costs of mills (e.g. > 130 US$.$MWh^{-1}$) are predominantly caused by high FCI and transmission costs (shades of yellow and red in Fig. 8). This occurs in less than 5% of the mills and are all located in the South-West of São Paulo. The FCI and transmission costs (i.e. jointly representing the CAPEX costs) show a strong correlation between each other (R^2 0.87) (supp. material - Appendix 3), because the mills with high FCI costs are often located in regions with sparser grid distribution infrastructure. Across all mills, the FCI costs vary between 20 and 95 US$.$MWh^{-1}$ (Fig. 9), which represents a share of 28%–45% of the total bioelectricity production cost. When the share of FCI costs increases beyond 35%, the average bioelectricity production costs increase sharply. These mills are normally characterized by electricity generating capacity lower than 25 MW and high specific investments ranging from 2 to 5 MUS$.$MW^{-1}$.

The feedstock costs contribution ranges from 21 to 40 US$.$MWh^{-1}$, representing a relative contribution of 10%–34% to the total bioelectricity production costs (Fig. 9). The cost breakdown indicates that just 3 mills present feedstock costs as the main the cost component. These mills also present high electricity generating capacity that assures low FCI costs, which results in average bioelectricity production costs between 78 and 90 US$.$MWh^{-1}$. Differently, the operational costs have an absolute contribution fixed at 27 US$.$MWh^{-1}$ as the operational costs is function of the electricity generating capacity of the adjacent plant of each mill. However, the relative contribution of operational costs has the highest variation across the mills (10%–39%). Consequently, mills with a high electricity generating capacity have generally relatively low bioelectricity production costs with a relatively high contribution of operational cost.

3.3. Techno-economic potential of bioelectricity from sugarcane straw

The results of the techno-economic potential assessment at mill level show that 31 mills present average bioelectricity production costs below 80 US$.$MWh^{-1}$. The techno-economic potential varies from 273 GWh to 817 GWh per mill, in a total techno-economic potential of 12.5 TWh of bioelectricity from sugarcane straw. These mills are predominantly located in traditional areas of sugarcane production in the Northeast and Center-East of São Paulo (e.g. Ribeirão Preto and Piracicaba region).

When the power plants are optimized based on field level information on the straw cost-supply, scale-efficiency and the scale-cost curves, 37 mills (including those 31 mills before the optimization) present bioelectricity costs lower than 80 US$.$MWh^{-1}$, resulting in a maximized techno-economic potential of 14.2 TWh (cost-supply curve in Fig. 10). The map in Fig. 10 indicates the mills that contribute to the techno-economic potential of bioelectricity from sugarcane straw. The economically viable mills have a large range of straw availability (206–632 kt per mill) and are characterized by straw recovery costs below 34 US$.$t^{-1}$. These mills present an optimal electricity generating capacity between 41 MW and 154 MW for an overall electrical conversion efficiency ranging from 27% to 35%. This high variability shows that not only the large mills with high input capacity contribute to the techno-economic bioelectricity potential. Mills with medium capacity but located in regions with good agronomic conditions and high infrastructure availability (e.g. hubs of electricity distribution) are likely to be economically viable.

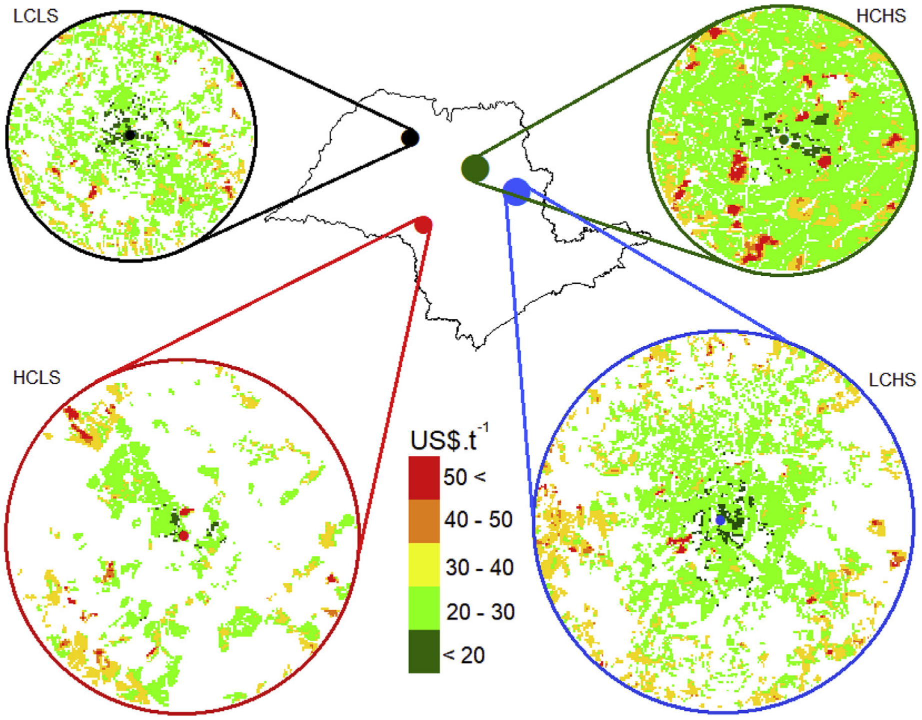

Fig. 7. Spatial distribution of the straw recovery costs of typical sugarcane mills of the four groups according to the cost-supply classification: HCHS – High Costs and High Supply; HCLS - High Costs and Low Supply; LCHS – Low Costs and High Supply; LCLS – Low Costs and Low Supply.

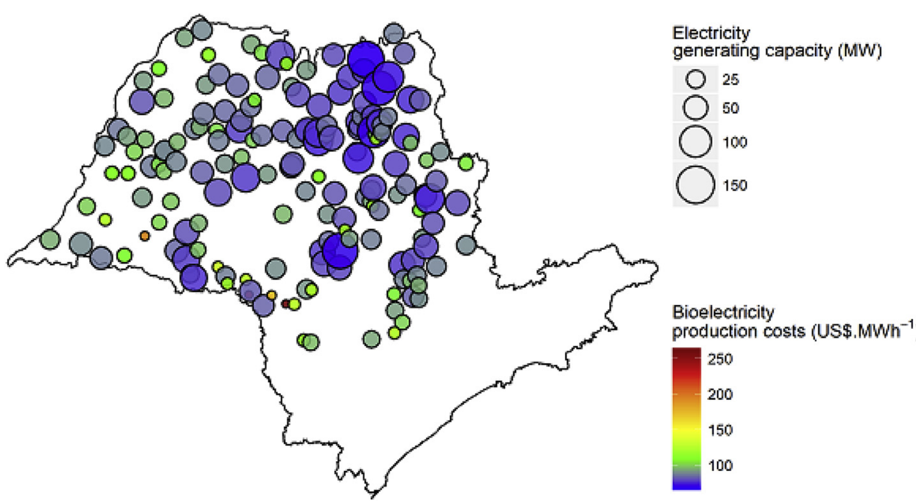

Fig. 8. Average bioelectricity production costs of the sugarcane mills in São Paulo and their respective electricity generating capacity.

3.4. Sensitivity analysis

The variation in the techno-economic parameters of bioelectricity production from sugarcane straw results in a wide range of uncertainty in the optimized techno-economic potential (Fig. 11). The sensitivity analysis shows that the bioelectricity potential is most sensitive for variations in the bioelectricity price. For prices below 56 US$.MWh^{-1}, there is no techno-economic potential of bioelectricity, whereas prices higher than 104 US$.MWh^{-1} result in a potential of more than 30 TWh. Another crucial economic parameter is the discount rate: if the discount rate is reduced to 8.4%, the techno-economic potential of bioelectricity increases to 26 TWh. Conversely, the techno-economic potential declines smoothly, being less sensitive for discount rates over 12%. Variations in the FCI and OPEX affect the techno-economic potential of bioelectricity in a similar way.

The variability of straw mulching levels results in a large variation in the techno-economic potential as it affects both the availability of straw as well as key techno-economic variables (e.g. straw farm-gate costs, electricity generating capacity). Variations in the conversion efficiency highly affects the bioelectricity production: a 5% increase in the electrical efficiency of the adjacent plants almost double the bioelectricity potential.

In case of straw being available on a dry basis (i.e. no moisture content), the techno-economic potential is estimated at 20 TWh. For straw with moisture content of 40%, the bioelectricity potential

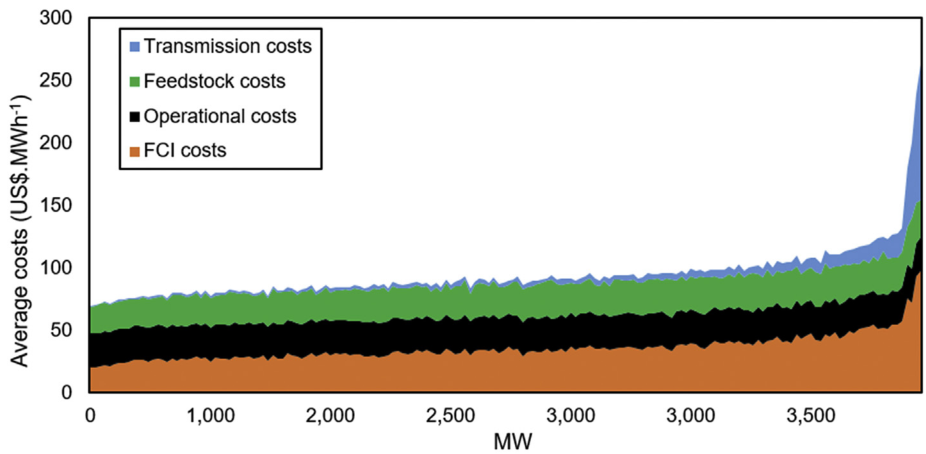

Fig. 9. Breakdown of the average the cost supply of bioelectricity from sugarcane straw of the 174 sugarcane mills in São Paulo.

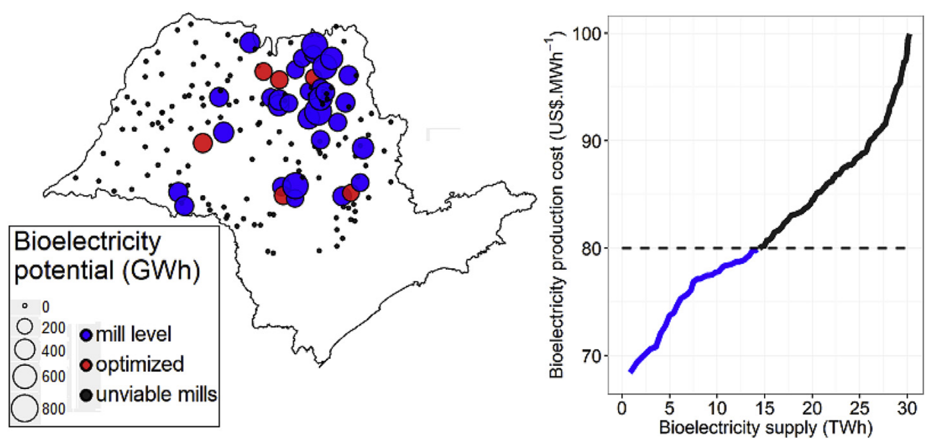

Fig. 10. Left: the circles in the map indicates the size and the location sugarcane mills contributing to the techno-economic potential of bioelectricity from sugarcane straw. Blue and red circles refer to the techno-economic potential at mill level and optimized at mill level, respectively. The small black circles are the remaining sugarcane mills with no techno-economic potential (i.e. bioelectricity production costs >80 US$.MWh^{-1}). Right: cost-supply curve of bioelectricity form sugar cane straw in São Paulo for the 2012 crop year. The blue part of the graph indicates the techno-economic potential when the scale of the adjacent plants is optimized, i.e. the amount of bioelectricity that can be produced below the cut off prince of 80 US$.MWh^{-1}. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

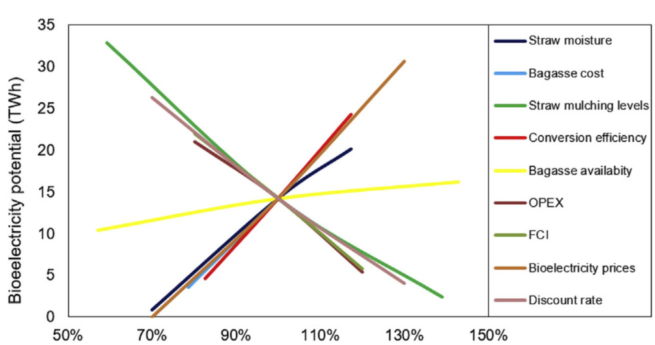

Fig. 11. Sensitivity analysis of the optimized techno-economic potential of bioelectricity from sugarcane straw in Sao Paulo for the crop year 2012.

reduces to less than 1 TWh. Differently, the techno-economic potential of bioelectricity is much less sensitive for bagasse availability, presenting the narrowest variation of 10–16 TWh (Fig. 11). Moreover, if the bagasse available present an opportunity cost of 6 US$.t^{-1}, the bioelectricity potential decreases to 3 TWh.

4. Discussion

4.1. Straw recovery costs

The average straw recovery costs at mill level found in this study range from 21 to 35 US$.t^{-1}. This is in line with the range of 22–36 US$.t^{-1} found by Cardoso et al. [17] and with the average of 30 US$.t^{-1} observed in practice (Raízen/Shell mill, *pers. comm.* [30]). The mills with high straw supply and low costs are located in the traditional sugarcane areas characterized by suitable agro-ecological conditions. The mills with relatively high straw costs are located in the western part of the state with a lower density of sugarcane fields and/or lower agro-ecological suitability for sugarcane cultivation. These geographical constraints result in long transportation distances, increasing straw transportation costs. Despite that, the straw transportation costs usually have a lower contribution to the total recovery costs in baling systems because of the costly on-farm operations.

The straw recovery costs are highly impacted in areas with low straw availability. To reduce the straw recovery costs in those areas, the deployment of an integral harvest system instead of baling system can be more economically viable. The integral harvest system could be more appropriate for areas with low availability, as the straw is transported together with the harvested sugarcane [14]. Therefore, differentiate the straw recovery route according to straw availability of a given field could potentially improve the techno-economic feasibility of bioelectricity from sugarcane straw [28]. Moreover, we assume that each mill recovers all straw available within the collection radius of the mill and produces bioelectricity at the location of the mill. Instead, analysis at sub-regional level is required to assess potential interactions among mills in order optimize the use of straw and minimize its recovery costs.

4.2. Bioelectricity production costs

The average bioelectricity production costs vary from 68 to 266 US$.MWh^{-1} across the mills. However, for more than 95% of the mills, the average bioelectricity production costs range from 68 to 130 US$.MWh^{-1}. These average bioelectricity costs agree with the majority of bioelectricity prices found in the literature and regular bioelectricity auctions [3,8]. For the mills with relatively low bioelectricity costs (i.e. > 100 US$.MWh^{-1}), the feedstock, operational and FCI have about equal contributions to the total costs and very low transmission costs. These mills have generally a high electricity generating capacity, are located in the regions with high agro-ecological suitability for sugarcane cultivation, and with high availability of transmission infrastructure. On the other hand, very high bioelectricity costs are mainly the result of a low electricity generating capacity and high transmission costs associated with long distances to the distributor substations. As long connection distances highly affects the total bioelectricity costs, this has to be taken into account in the allocation planning of future power plants at the mills [20]. In parallel, investments from the energy distributors and dealers in grid infrastructure (e.g. new substations and transmission lines) are required to improve the economic feasibility of bioelectricity projects in sugarcane mills [21].

The mills with a very low electricity generating capacity are largely concentrated in the South-West and West of São Paulo. As no decrease in the FCI is expected for the adjacent power plant system in the coming years [7], the FCI costs reduction must rely on economies of scale, increasing the electricity generating capacity by using more bagasse or gathering alternative biomass sources, such as forestry residues. The latter has yet been used as supplementary source for bioelectricity production in small sugarcane mills [46]. Therefore, the integration with other biomass chains (e.g. pulp and paper industry) close to the mills can be a strategy to improve the techno-economic potential of bioelectricity at regional level [47].

The bagasse surplus sourced from the cogeneration system in the main mill is assumed to supply the adjacent power plant to accomplish a process design consistent with the current technical stage of power plants in the sugarcane mills. Currently, it is strongly recommended to mix straw with bagasse in order to reduce the boiler corrosion due to presence of mineral impurities in the straw [48]. In the future, the adoption of biomass gasification systems may allow the use of higher rates of sugarcane straw. The bioelectricity production costs are linked with the design of the adjacent power plants (based on Seabra et al. [37]), which uses all the straw available in the mill's surroundings. Alternatively, other scenarios of straw power plant (e.g. stand-alone plants) can be spatially explicit modeled to assess whether the techno-economic potential can be improved.

4.3. Techno-economic potential of bioelectricity from sugarcane straw

The optimized techno-economic potential of bioelectricity from sugarcane straw is estimated at 14.2 TWh produced from more than 11 Mt of straw, which represents around 10% of the electricity consumption of the São Paulo in 2012 [49]. In 2012, approximately half of bioelectricity (7.2 TWh) was produced by the whole sugarcane industry in the same crop-year in the state of São Paulo [50]. The 37 mills that contribute to the techno-economic potential could supply more than the total amount of bioelectricity surplus in Brazil in 2012 (12.2 TWh) [51]. Compared to the environmental potential of bioelectricity from sugarcane straw in Cervi et al. [25], the techno-economic constraints reduce the bioelectricity potential by 55% in the 2012 crop-year in São Paulo. The techno-economic potential relies on the scale of the adjacent power plants modeled, which are based on the straw available given the milling capacity of the mill. However, in reality, the scale of sugarcane power plant is not fully dependent on the actual sugarcane milling capacity. This also varies according to the energy policy adopted by the company (mill), the importance of bioelectricity business in the mills' overall revenues and other local contextual factors.

The sensitivity analysis addresses the variations in many (local contextual) techno-economic parameters on the bioelectricity potential. Of the technical aspects, the variation in straw moisture content shows the largest effect on the bioelectricity potential. Hence, more than investing in a very efficient system to operate with straw, mills have to foremost assure the low moisture content of the straw recovered [36]. The bioelectricity potential is also highly sensitive for changes in the discount rate and in the bioelectricity cut-off prices. We have now assumed a variation of 30% in the bioelectricity prices. However, variations could even be much higher as part of the bioelectricity surplus is currently sold in the demand-driven free market at much higher prices [52]. If even higher bioelectricity prices are assumed, the techno-economic potential of bioelectricity from sugarcane straw is much higher.

To enable the realization of the techno-economic potential, the bioelectricity from sugarcane straw should be better exploited in periods of high demand (between April and October) when the hydropower supply is usually lower [53]. However, in practice, the mills with high potential of bioelectricity from sugarcane straw (e.g. large scale traditional mills) are still progressing towards high efficient boilers [34]. Additionally, the bioelectricity market in Brazil still requires regulatory strategies to strength the economic competitiveness [6,21]. As a positive side, straw can be stored and bioelectricity can be produced on demand, which is the main advantage compared to other renewable sources in Brazil, such as wind and solar. Moreover, electricity market projection indicates the increase of distributed generation close to the large demand centers in order to reduce large investments in long transmission systems [54]. This could be beneficial to the sugarcane industry given the location of the sugarcane mills in Brazil. Therefore, comprehending the spatial distribution of the techno-economic potential of bioelectricity from sugarcane straw could contribute in addressing the appropriate energy planning for the sugarcane mills based on their regional characteristics.

5. Conclusion

This is the first study that combines spatial datasets at different geographical scales to assess the potential and the production costs of bioelectricity from sugarcane straw. We assess the techno-economic potential of 174 operating sugarcane mills in the state of São Paulo (Brazil) for 2012 crop-year. In total, 37 mills are able to produce bioelectricity with production costs below 80 US$.MWh^{-1}. This corresponds to a techno-economic potential of 14.2 TWh (which is almost twice as high as the bioelectricity production in 2012 in the entire state of Sao Paulo). These economically viable mills have a large electricity generating capacity and are mostly located in the Northeast of São Paulo, which is characterized by suitable agro-ecological conditions, and high density of electricity distribution network. The results could support stakeholders in local decisions at farm and mill level, and policy making at state level. It is recommended that further dedicated studies focused on local resource assessment explore the spatial variability in straw mulching levels and optimal recovery routes, and also investigate the technical specifications of the cogeneration systems in the sugarcane mills.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2019.11.151.

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