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Geschäftsberichte

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Energy potential of sugarcane biomass: an application of optimal location modeling

Energiepotenzial von Zuckerrohrbiomasse: Optimale Standortmodellierung

Bagasse and trash (leaves left in the field), two sugarcane processing byproducts, are underexploited resources that can be used to provide energy. In Brazil, the development of this readily available lignocellulose biomass as feedstock for energy production would diversify the country's energy matrix and increase its energy security. This study is intended to identify and quantify the energy potential of sugarcane biomass in the forms of bagasse and trash, determine the optimal allocation of these byproducts as energy producers, and identify advantageous locations for biomass electrical generation and cellulosic ethanol production in Brazil's Centre-South.
Two scenarios were created and analyzed using a model built to evaluate the potential economic value of sugarcane bagasse and trash from the perspective of energy output. The scenarios incorporate alternative input mixes, plant locations, and time frames. Scenario 1 is designed to define the optimal allocation of bagasse and trash from the 2013/14 harvest season while Scenario 2 is designed to define the optimal allocation of this biomass from 2021 thru 2025. Using Scenario 1 parameters, cellulosic ethanol production was not advised and a negligible number of new or expanded generation facilities were recommended. Interestingly, there was found to be potential for the production of almost twice as much exportable electricity, 40,000 GWh, as was actually produced. Using Scenario 2 parameters, it was found that annual profit maximization would come from the production of approximately 9 mn m^3 of cellulosic ethanol from 68 new refinery facilities and that 36,000 GWh of exportable electricity should be generated.

Key words: bagasse, sugarcane trash, cellulosic ethanol, cogeneration, optimization

Bagasse und Zuckerrohrtrash, zwei Nebenprodukte der Zuckerrohrverarbeitung, sind unzureichend verwertete Ressourcen, die zur Energiegewinnung genutzt werden können. In Brasilien würde die Erschließung dieser leicht zugänglichen Lignocellulosebiomasse als Rohstoff für die Energiegewinnung die Energiematrix des Landes verbreitern und die Energiesicherheit erhöhen. Ziel dieser Studie war es, das Energiepotenzial von Zuckerrohrbiomasse – in Form von Bagasse und Trash – zu ermitteln, die optimale Kombination dieser Nebenprodukte als Rohstoff zur Energieerzeugung zu bestimmen und geeignete Standorte für die Gewinnung von Elektroenergie aus Biomasse und die Herstellung von Celluloseethanol in Brasiliens Zentrum/Süden zu ermitteln.
Es wurden zwei Szenarien erstellt und mit einem Modell analysiert, das zur Bewertung des potenziellen wirtschaftlichen Wertes von Bagasse und Trash hinsichtlich der Energieausbeute entwickelt wurde. Die Szenarien enthalten alternative Rohstoffmischungen, Anlagenstandorte und Zeitrahmen. Szenario 1 stellt die optimale Kombination von Bagasse und Trash in der Kampagne 2013/14 fest, Szenario 2 definiert die optimale Kombination dieser Biomasse von 2021 bis 2025. Die Auswertung des Szenarios 1 ergab, dass die Produktion von Celluloseethanol nicht zu empfehlen und die Anzahl von neuen oder erweiterbaren Energiegewinnungsanlagen vernachlässigbar ist. Interessanterweise wurde festgestellt, dass fast doppelt so viel überschüssige Elektroenergie (40 000 GWh) hätte gewonnen werden können als es tatsächlich der Fall war. Mit Szenario 2 wurde festgestellt, dass eine jährliche Gewinnmaximierung aus der Produktion von rund 9 Mio. m^3 Celluloseethanol aus 68 neuen Raffinerieanlagen resultieren könnte und 36 000 GWh exportierbare Elektroenergie erzeugt werden könnten.

Schlagwörter: Bagasse, Zuckerrohrblätter, Celluloseethanol, Kraft-Wärme-Kopplung, Optimierung

1 Introduction

Energy security is a major worldwide concern, especially given population growth with the attendant demands for food and energy. There are also new international paradigms and commitments to mitigate the environmental impacts of energy production, including constraints on greenhouse gas emissions. The drive for energy security and the commitment to environmental responsibility have added impetus to the search for alternative sources of clean, renewable energy.

Brazil's energy matrix is acutely dependent on hydroelectric power, and the need for alternative generating capacity to mitigate this dependence has become critical. The primary available substitute for hydroelectric generation is thermoelectric generation. Among the raw materials used in Brazilian thermoelectric plants, sugarcane biomass has emerged as an underutilized, economically strategic, renewable input. It is also providential that drier periods in Brazil, when hydroelectric generating capacity is at its lowest, normally occur during the height of the sugarcane harvest (April to November).

Sugarcane biomass is made up of bagasse, the residue after cane is crushed, and sugarcane trash. The trash may be left in the field after harvest or part of it could be intermixed with the cane in the harvester, shipped with the cane to the mill, and separated out there. Bagasse and sugarcane trash can be burned at the mill to provide heat energy used in the sugar and ethanol refining processes and, when converted to steam, generate electricity to power factory operations: cogeneration. Cane sugar factories incorporate a variety of cogeneration technologies that may vary significantly in efficiency and capacity; however, Brazilian cane sugar factories can still produce surplus electric energy for export to the grid.

According to the Brazilian government's Energy Research Company – EPE, the technical potential of electricity generation using biomass will be 19.5 GW in 2023 (EPE, 2015), which is equivalent to approximately 14% of the country's current electric energy production. Projections by the Brazilian Sugarcane Industry Association (UNICA, 2010), indicate that in 2021 Brazilian cane sugar factories would be able to export approximately 13 GW of electricity using only bagasse as the thermoelectric fuel.

Sugarcane trash, the majority of which is left in the field at harvest, is soon to become much more economically valuable as a Brazilian energy source. This trash has usually been burned in the field before the cane harvest; making the cost of disposal negligible; but recently passed Brazilian law 11.241 mandated the end of this practice by 2017. In some regions, this law was strengthened with the signing of an environmental protocol by local cane sugar factories, and burning has already ended. The unburned trash will have to be disposed in a manner that does not involve burning in the field, which entails costs and should stimulate the search for a profit generating use for this biomass.

In addition to its potential for electric generation, sugarcane biomass can also be used as raw material for the production of cellulosic ethanol (2Gen ethanol). Turning sugarcane biomass into cellulosic ethanol entails conversion of the cellulose and hemicellulose (composed of hexoses and pentoses) found in sugarcane bagasse and trash into simple sugar molecules, like glucoses and xyloses, that can then be turned into ethanol through fermentation. Currently, the production technology needed to economically convert this biomass to cellulosic ethanol has few examples in the commercial sector; but this should change. Technological advances spurred by increasing demand for ethanol, increasing demand for refined sugar (1st generation ethanol feedstock), the push to reduce greenhouse gas emissions, and the belief that turning waste into fuel is rational can turn the largely unwanted biomass into an economically viable, alternative liquid fuel source.

This introduction has highlighted the two main energy oriented strategic markets open to the accelerated entry of sugarcane biomass: the electricity market and the cellulosic ethanol market. The present study analyzes key variables affecting entry into either of these two markets and define the optimal location for sugarcane biomass energy production units in Centre-South[1] Brazilian mesoregions[2]. Specifically, the study proposes a mathematical model to optimize biomasses allocation, to maximize industry profits from the sale of electricity and ethanol, and to identify mesoregions with the best potential to provide sugarcane biomass and the investment capital needed to expand electricity and cellulosic ethanol production. It is hoped that this model can be applied to other similar analyses.

2 Material and methods

The study employed a mixed integer linear programming model using primary and secondary data for the sugarcane industry in Centre-South Brazilian mesoregions to identify the optimal use of sugarcane biomass to maximize profit from the production of electricity and cellulosic ethanol. The model was processed with General Algebraic Modeling System software (GAMS) version 22.5, a CPLEX 10.2.0 solver, an ESALQ-LOG server and a Windows based computer.

At the mesoregional level, the model will evaluate:

1 The potential for new cellulosic ethanol refineries or electrical generation facilities;
2 The potential for expanded cogeneration facilities or the addition of cellulosic ethanol refineries to existing mills;
3 Amounts of energy available to and from the system;
4 Optimal sugarcane biomass allocation and the mesoregional economic impacts from this allocation;
5 The potential return from new investment in cellulosic ethanol projects;
6 The optimal location for electricity and/or cellulosic ethanol production units (attached to sugarcane crushing mills or stand-alone generation units).

Figure 1 is a schematic representation of the problem to be addressed. Potential locations for the new cellulosic ethanol refineries, and single purposed electrical generation plants were restricted to areas within 200 km of a sugarcane mill to decrease transportation costs and increase economic viability. Reasonably, all cogeneration facilities would be located at mills.

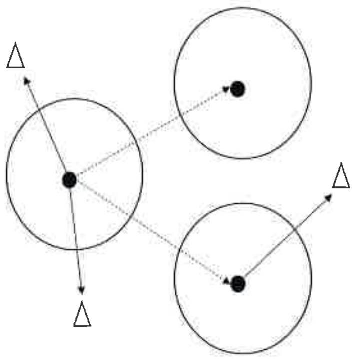

Fig. 1: Schematic representation of the location and transportation options the model considers
● Sugarcane mill; ○ Sugarcane recovering ratio by mills; △ Potential electricity plants or potential cellulosic ethanol plants locations;
---> Hypothetical biomass flows between mills; → Hypothetical biomass flows to potential electricity or cellulosic ethanol plants

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[1] Centre-South is a Brazilian region specified by sugarcane sector composed by the states of: Mato Grosso, Mato Grosso do Sul, Goiás, São Paulo, Minas Gerais, Espírito Santo, Rio de Janeiro, Paraná, Santa Catarina and Rio Grande do Sul.

[2] Mesoregion is subdivision of the Brazilian states created by the Brazilian Institute of Geography and Statistics.

The model ignores the influences of biomass specific demands, production seasonality and effects linked with economies of scale. The analyses are intended to be of aid when strategically planning long-term investment in the construction of industrial infrastructure and maximizing profit from the production of electricity and cellulosic ethanol.

2.1 Mathematical foundation

This study's model is designed to identify the proper combination of inputs and outputs to maximize sugarcane industry profits from the sale of electricity and cellulosic ethanol derived from biomass (trash and bagasse), as detailed in eqs. (1) and (2).

$$P_{max} = RE - (CG + CTB + CP_{e2g}) \tag{1}$$

P	Sugarcane industry profit in Brazilian Real (BRL);
RE	Revenue from the sale of electricity and cellulosic ethanol in BRL;
CG	Electricity generation cost in BRL;
CP_{e2g}	Cellulosic ethanol production cost in BRL;
CTB	Biomass acquisition and transport cost in BRL.

Revenues *RE* from the sale of electricity and cellulosic ethanol are expressed by eq. (2).

$$RE = \left(\begin{array}{l} \sum^{i}\sum^{j}\sum^{k} B_{ijk} \cdot f_{jk} \cdot Pe_j + \sum^{i}\sum^{l}\sum^{k} B_{ilk} \cdot f_{lk} \cdot Pe_l \\ + \sum^{i}\sum^{m}\sum^{k} B_{imk} \cdot f_{mk} \cdot Pe_m + \sum^{i}\sum^{m}\sum^{k} BE_{imk} \cdot f_{e2gk} \cdot Pe \\ + \sum^{i}\sum^{l}\sum^{k} BE_{ilk} \cdot f_{e2gk} \cdot Pe \end{array} \right) \tag{2}$$

The cost of electricity generation, cellulosic ethanol production and biomass acquisition and transportation is calculated using eqs. (3), (4) and (5).

$$CG = \left(\begin{array}{l} \sum^{i}\sum^{j} B_{ij} \cdot f_j \cdot C_{cogen} + \sum^{i}\sum^{j}\sum^{k} B_{ijk} \cdot f_{jk} \cdot C_{cogen} \\ + \sum^{i}\sum^{l}\sum^{k} B_{ilk} \cdot f_{lk} \cdot \left(C_{cogen} + C_{icoger} + C_{redel}\right) \\ + \sum^{i}\sum^{m}\sum^{k} B_{imk} \cdot f_{mk} \cdot \left(C_{cogen} + C_{icoger} + C_{redem}\right) \end{array} \right) \tag{3}$$

$$CP_{e2g} = \left(\begin{array}{l} \sum^{i}\sum^{l}\sum^{k} BE_{ilk} \cdot f_{e2gk} \cdot \left(C_{pe2gl} + C_{ie2gl}\right) \\ + \sum^{i}\sum^{m}\sum^{k} BE_{imk} \cdot f_{e2gk} \cdot \left(C_{pe2gm} + C_{ie2gm}\right) \end{array} \right) \tag{4}$$

$$CTB = \left(\begin{array}{l} \sum^{i}\sum^{j} B_{ij} \cdot C_{ij} + \sum^{i}\sum^{j}\sum^{k} B_{ijk} \cdot C_{ijk} \\ + \sum^{i}\sum^{l}\sum^{k} B_{ilk} \cdot C_{ilk} + \sum^{i}\sum^{m}\sum^{k} B_{imk} \cdot C_{imk} \\ + \sum^{i}\sum^{m}\sum^{k} BE_{imk} \cdot C_{imk} + \sum^{i}\sum^{l}\sum^{k} BE_{ilk} \cdot C_{ilk} \end{array} \right) \tag{5}$$

i	Sugarcane mills able to supply biomass;
j	Sugarcane mills with biomass demand;
l	Potential locations for electric generation, and cellulosic ethanol refineries;
m	Mills that would benefit from expanded cogeneration facilities and/or the addition of cellulosic ethanol refineries;
k	Types of sugarcane biomass available to the system.
B_{ij}	Flow (in t) of sugarcane bagasse between origin *i* and destination *j*;
B_{ijk}	Flow (in t) of sugarcane biomass *k* between origin *i* and destination *j*;
B_{ilk}	Flow (in t) of sugarcane biomass *k* between the origin *i* and destination *l*, to identify the potential of new stand-alone units;
B_{imk}	Flow (in t) of sugarcane biomass *k* between origin *i* and destination *m*, to identify existing processing plants with an economic incentive to expand cogeneration;
BE_{ilk}	Flow (in t) of sugarcane biomass *k* between origin *i* and destination *l*, to identify potential stand-alone cellulosic ethanol production units;
BE_{imk}	Flow (in t) of sugarcane biomass *k* between origin *i* and destination *m*, identifying units that would benefit from the addition of a cellulosic ethanol refinery.
P_{ej}	Price of electricity at destination *j* (in BRL/MWh);
P_{el}	Price of electricity at destination *l* (in BRL/MWh);
P_{em}	Price of electricity at destination *m* (in BRL/MWh);
P_e	Price of ethanol (in BRL/L);
f_j	Energy conversion factor (in MWh/t) of bagasse *k* at destination *j*;
f_{jk}	Energy conversion factor (in MWh/t) of biomass *k* at destination *j*;
f_{lk}	Energy conversion factor (in MWh/t) of biomass *k* at destination *l*;
f_{mk}	Energy conversion factor (in MWh/t) of biomass *k* at destination *m*;
f_{e2gk}	Conversion factor (in L/t) of biomass *k* into second generation ethanol;
C_{ijk}	Transport cost (in BRL/t) of biomass *k* between origin i and destination *j*;
C_{ilk}	Transport cost (in BRL/t) of biomass *k* between origin *i* and destination *l*;
C_{imk}	Transport cost (in BRL/t) of biomass *k* between origin *i* and destination *m*;
C_{cogen}	Cost of cogeneration (in BRL/MWh) at the sugarcane mill;

C_{icoger}	Investment costs for energy generation and cogeneration facilities (in BRL/MWh);
C_{redel}	Electricity transmission cost from destination l to the National Interconnected System – SIN (in BRL/MWh);
C_{redem}	Electricity transmission cost from destination m to SIN (in BRL/MWh).
C_{pe2gl}	Second-generation ethanol production cost at biomass destination l (in BRL/L);
C_{pe2gm}	Second-generation ethanol production cost at biomass destination m (in BRL/L);
C_{ie2gl}	Investment cost for a second-generation ethanol plant at destination l (in BRL/L);
C_{ie2gm}	Investment cost for a second-generation ethanol plant at destination m (in BRL/L).

2.2 Constraints

The model is subject to constraints on the biomass supply and demand and the capacity to utilize biomass for electricity generation and cellulosic ethanol production.
Biomass supply restrictions are represented by eqs. (6) and (7).

$$\sum^{j} B_{ij} = OFERTABC_{j} \tag{6}$$

$$\sum^{j} B_{ijk} + \sum^{l} B_{ilk} + \sum^{m} B_{imk} + \sum^{l} BE_{ilk} + \sum^{m} BE_{imk} \le OFERTA_{ik} \tag{7}$$

$OFERTABC_{i}$	Amount of bagasse consumed by the process at origin i;
$OFERTA_{ik}$	Biomass k available at origin i.

The biomass demand constraint is represented by eq. (8).

$$\sum^{i} B_{ij} \cdot f_{v} \ge ENERGIAC_{j} \tag{8}$$

f_{v}	Bagasse to steam conversion factor (in t steam/t bagasse) at destination j;
$ENERGIAC_{j}$	Amount of steam consumed (steam tons) by unit j processes.

Generation capacity restrictions, electricity exports and cellulosic ethanol production are set forth in eqs. (9) to (17).

$$\sum^{i}\sum^{k} B_{ilk} \cdot f_{lk} \ge BIN_{l} \cdot GERAMIN \tag{9}$$

BIN_{l}	Binary decision variable to construct a stand-alone electrical generation unit at locality l;
$GERAMIN$	Minimum electricity production in MWh/season.

$$\sum^{i}\sum^{k} B_{imk} \cdot f_{mk} \ge BINA_{m} \cdot GERAMIN \tag{10}$$

$BINA_{m}$	Binary decision variable to add generation capacity at sugarcane mill m;

$$\sum^{i}\sum^{k} B_{ijk} \cdot f_{jk} \le CNOMINALE_{j} \tag{11}$$

$CNOMINALE_{j}$	Nominal electricity production capacity in MWh/season at unit j;

$$\sum^{l}\sum^{k} B_{ilk} \cdot f_{lk} \le BIN_{l} \cdot REDE \tag{12}$$

$$\sum^{m}\sum^{k} B_{imk} \cdot f_{mk} \le BINA_{m} \cdot REDE \tag{13}$$

$REDE$	Limit of electricity exportation (in MWh/season) to the distribution system to obtain the 50% transmission and distribution tariff discount[3].

$$\sum^{i}\sum^{k} BE_{ilk} \cdot f_{e2gk} \ge BINE2G_{l} \cdot CAPMINE2GL \tag{14}$$

$$\sum^{i}\sum^{k} BE_{imk} \cdot f_{e2gk} \ge BINAE2G_{m} \cdot CAPMINE2GM \tag{15}$$

$$\sum^{i}\sum^{k} BE_{ilk} \cdot f_{e2gk} \ge BINE2G_{l} \cdot CAPMAXE2GL \tag{16}$$

$$\sum^{i}\sum^{k} BE_{imk} \cdot f_{e2gk} \ge BINAE2G_{m} \cdot CAPMAXE2GM \tag{17}$$

$BINE2G_{l}$	Binary decision variable to build a stand-alone cellulosic ethanol facility in locality l;
$BINAE2G_{m}$	Binary decision variable to attach a cellulosic ethanol facility to sugarcane mill m;
$CAPMINE2GL$	Minimum cellulosic ethanol production capacity (in L) at l;
$CAPMINE2GM$	Minimum cellulosic ethanol production capacity (in L) at m;
$CAPMAXE2GL$	Maximum cellulosic ethanol production capacity (in L) at l;
$CAPMAXE2GM$	Maximum cellulosic ethanol production capacity (in L) at m.

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[3] Brazilian law n° 9.427 of 1996 established that thermoelectric facilites that use biomass as a raw material could receive a 50% discount on TUSD (distribuition tariff) and TUST (transmission tariff) when the intalled capacity would be less than 30 MW.

Table 1: Brazilian mesoregions and states addressed in the study (*Trombeta*, 2015)

Brazilian mesoregions and states		
Araçatuba (SP)	Norte de Minas (MG)	Norte Mato Grosso (MT)
Araraquara (SP)	Oeste de Minas (MG)	Sudeste Mato Grosso (MT)
Assis (SP)	Sul/Sudoeste de Minas (MG)	Sudoeste Mato Grosso (MT)
Bauru (SP)	Vale do Mucuri (MG)	Litoral Norte ES (ES)
Campinas (SP)	Triângulo Mineiro (MG)	Sul Espírito-Santense (ES)
Itapetininga (SP)	Zona da Mata (MG)	Baixadas (RJ)
Marília (SP)	Centro Norte MS (MS)	Norte Fluminense (RJ)
Piracicaba (SP)	Leste MS (MS)	Centro Ocidental Paranaense (PR)
Presidente Prudente (SP)	Sudoeste MS (MS)	Noroeste Paranaense (PR)
Ribeirão Preto (SP)	Centro Goiano (GO)	Norte Central Paranaense (PR)
São José do Rio Preto (SP)	Leste Goiano (GO)	Norte Pioneiro Paranaense (PR)
Central Mineira (MG)	Norte Goiano (GO)	Noroeste Rio Grande do Sul (RS)
Noroeste de Minas (MG)	Sul Goiano (GO)	

Table 2: Sugarcane biomass conversion rate (*Trombeta*, 2015)

Biomass	Availability
Bagasse[1] in kg/t cane	250
Trash[2] in kg/t cane	140
Load trash (6% IV[3]) in % total	25
Load trash (8% IV) in % total	33
Baled trash[4] in % total	37.5

[1] Bagasse on wet base (50% water content); [2] Trash on wet base (15% water content); [3] Vegetal imputrity; [4] Assumption that 50% of trash that stays on field after sugarcane harvest could be baled and recovered.

2.3 Data

The majority of the sugarcane industry data for the 2013/14 season used in this study were obtained from *Trombeta* (2015). These data address 37 mesoregions in Centre-South Brazilian states (Table 1). Secondary industry data were obtained from the Brazilian Sugarcane Industry Association (UNICA, 2010), the Brazilian Energy Regulatory Agency (ANEEL, 2014), and the Sugarcane Technology Center (CTC, 2014). The model considers two categories of bagasse and two categories of trash:

1 Bagasse consumed to meet the mill's thermal and electric demands (self use);

2 Surplus bagasse and of trash:
   - I Baled trash;
   - II Load trash[4].

Biomass transportation cost data were obtained from CTC (2014), which provided estimates for the cost to transport baled and loose trash. The sugarcane transportation (after harvester) cost figures could be used as proxies for the cost to transport biomass derived from the mill's crushing process: bagasse and load trash. Through the use of linear regression, these data generate average cost curves for the acquisition and processing of sugarcane biomass, which include agricultural, industrial, and transportation costs. Figure 2 shows the cost curves for each case.

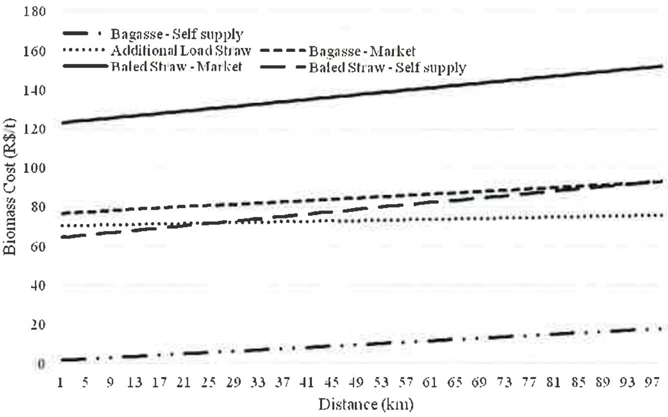

Fig. 2: Sugarcane biomass logistics and processing cost

Information regarding the amount of trash and bagasse available was estimated using specific conversion rates (Table 2).

In the case of bagasse and baled trash, the cost to transfer this biomass between units or localities will be added to the opportunity cost of each raw material, which for this study was BRL75.00/t and BRL90.00/t, respectively. Load trash has traditionally been used to supply the mill with operational inputs (self-supply) through cogeneration, and when estimating transportation costs, it is considered part of the bagasse.

The possible locations for stand-alone installation of electrical generation or cellulosic ethanol facilities in the area under study were selected from among the cities found in the Brazilian Institute of Geography and Statistics database (IBGE, 2014). One notable location constraint was to limit the selection of sites to within 200 km of one or more existing sugarcane mills. Distances were calculated using geo-referenced information from IBGE (2014), data from the National Department of Infrastructure and Transport (DNIT, 2015) and TransCAD software version 4.5. The data base included information from 295 sugarcane mills and 1778 cities.

Estimates of the investment cost for the expansion of electricity generation facilities or the construction of stand-alone electrical generating units were based on data provided by CTC (2014) and the Continuing Education Program in Company Economics and Management (PECEGE, 2014), respectively. In order to convert the investment amounts to annual present values, it was assumed that this capital investment will be depreciated over 25 years with a residual value of 20% and an opportunity cost of 11%. It was determined that the typical expansion of generation facilities that include the installation of high pressure boilers and turbine generators with a capacity of 50 MW would cost approximately BRL70.00/MWh per year. Using CTC (2014) data, the average cost to construct electric transmission lines between exporting plants and the SIN grid was determined to average BRL600,000/km. This cost will be considered at the present value of equivalent parameters (project duration, residual value and interest rate). Distances between plants and candidate cities were calculated using Transcad 4.5 software with data provided by UNICA (2010) and ANEEL (2014). Estimates relating to electricity genera-

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[4] Load trash: During the harvest, trash enters the harvester with cane and can be separated out in the field using the harvester's extractor fans. This extraction process is not 100% efficient. Some trash always arrives with the cane at the mill and is then separated out. In the study, this trash is referred to as "load trash."

Table 3: Cellulosic ethanol: short and medium term parameters (*Milanez*, 2015)

Parameters	Short term		Medium term	
	4^1	7^1	$5B^1$	$8B^1$
Production cost in BRL/L	1.52	1.47	0.74	0.68
Investment cost in BRL/L^2	0.57	0.39	0.21	0.18
Ethanol production capacity in mn L	94	92	260	218
Biomass supply change^3 in %	–	–	15	
Bagasse ethanol conversion in L/t	150			
Trash ethanol conversion in L/t	250			
Ethanol price in BRL/L	1.34			

[1] *Milanez* scenarios names: Scenarios 4 and 5B consider the investment for an integrated ethanol plant (1st and 2nd generation) and scenario 5B is based on a longer crushing season (330 days). Scenarios 7 and 8B consider the investment for an independent cellulosic ethanol industrial plant. The letter "B" means a cellulosic ethanol process with C5 (five carbon sugar, e.g. xylose), and C6 (six carbon sugar, e.g. glucose) co-fermentation. [2] Investment at present value for cellulosic generation implementation. [3] Growth in production from the 2013/14 sugarcane harvest.

tion, electricity prices at the rated capacity, biomass conversion factors, energy consumption (thermal and electrical), and steam process consumption came from *Trombeta* (2015).

Finally, production costs and investments needed to implement and maintain cellulosic ethanol refineries are the short and medium term parameters called for in columns 4, 7, 5B and 8B from *Milanez* (2015), as shown in Table 3.

2.4 Scenarios

Two scenarios were created for this study. Scenario 1 is structured so as to indicate the most profitable allocation of sugarcane biomass from the 2013/14 harvest in Centre-South Brazilian mesoregions to electrical generation and cellulosic ethanol production. Scenario 2 is designed to indicate the most profitable allocation of sugarcane biomass to produce electric energy and cellulosic ethanol over the medium term, 2021 thru 2025. Evaluation of results from the model's application to conditions envisioned in each scenario will also identify the most favorable locations for new or expanded generation or cellulosic ethanol refining capacity in each studied mesoregion. Information provided from these scenarios can aid in the rational allocation of private investment funds and future public policy in regards to Brazil's sugarcane sector and increase Brazil's competitive position in the international sugar and ethanol markets.

3 Theory

Tolentino et al. (2007) proposed a mathematical model to optimize the use of sugarcane biomass at a sugarcane mill in the Botucatu region of São Paulo. Their results showed that the model was applicable to the analysis. In similar work, *Sartori* and *Florentino* (2002) evaluated five sugarcane varieties from the perspective of residual biomass minimization and profit maximization from the sale of biomass generated electricity. Their proposed model's goal was to find the variety that minimized residual biomass, maintained the cultivated area, efficiently produced sugar, and maximized profitable system power production from the available amount of residual biomass.

A study developed by *Illukpitiya* et al. (2013) analyzed different raw materials to optimize profit from the production of sugar, ethanol and electricity on the island of Maui, Hawaii. They proposed a linear programming model processed by Lindo 12 software to evaluate ethanol production targets for the year 2020. The study considered four types of biomass (energy cane, sugarcane, elephant grass and sorghum); the conversion rates per ton of biomass to sugar, ethanol, electricity and fiber, the biomass acquisition cost, the unit costs to produce each of the four different products from each type of biomass, and the price paid for each product. The sugarcane crop was selected because of lower production costs for a more profitable product (sugar) but it became clear that to achieve the desired levels of sugar and ethanol production, electricity production would be impaired (*Illukpitiya* et al., 2013).

Lin et al. (2014) proposed a mixed integer linear programming model that made use of a CPLEX solver and GAMS software to minimize ethanol production costs with biomass as the feedstock. They applied their model to three scenarios that considered the costs of biomass acquisition, transportation, biomass pretreatment, storage, biorefinery and ethanol distribution.

Other studies have addressed the biomass supply chain using mixed integer linear programming models. *Dyken* et al. (2010) created a mixed integer linear programming model that was applied to an entire chain of biomass supply, from origination through to final use. Their "eTransport" model was divided into two modules, an operating module and an investment module, both fed by economic and environmental variables. The model considered input flows, feasibility, and the relationship between energy production and biomass water content. The authors noted that biomass water content has a significant impact in the selection of conversion processes.

Xavier (2008) proposed a mixed integer linear programming model to indicate the best areas for increased investment in facilities for biofuel ethanol storage and distribution from the transportation cost perspective. Candidate locations were determined through a market analysis of sugarcane producing regions. The main results were that ethanol storage and distribution facilities should be located in conjunction with sugarcane processing plants, with the only candidate for a new stand-alone facility being located in Brazil's Centre-South.

Yue et al. (2013) applied optimization techniques to the biofuels supply chain, focusing on optimizing biomass transportation logistics and processing facility locations to maximize electricity, biofuel, and food production. The authors proposed a multi-scale optimization model designed from a holistic perspective. It was intended to provide information regarding the entire system; from unit operation, process design, supply chain management, sustainability to molecular engineering.

Galvão Jr. (2004) used a mathematical and heuristic strategy to determine if the amount of reasonably available woody biomass to supply the thermoelectric electricity needs of a sugarcane mill, the minimum size of the truck fleet to transport that biomass, and the proper biomass delivery schedule. The author identified a network of 62 biomass suppliers and 177 appropriate vehicles. Genetic algorithms were found to be of significant assistance.

Meyer et al. (2014) classified a series of 71 studies related to the biomass supply chain using the following criteria: mathematical optimization methodology used; decision variables adopted, and the model's purpose. It became clear that the high cost of supply is the main barrier to the increased use of biomass in current energy systems. It was also found that mixed integer linear programming was the most often used technique for analysis. The most often addressed decision variables were processing facility location, optimal biomass allocation, choice of subcontractors, and the technology to be adopted. The objective functions were concerned with economic issues, such as cost of transport, investment, risk, NPV (net present value), cost of environmental constraints, available energy supply and demand, and the social costs and benefits.

4 Results and discussion

Results obtained from Scenario 1 showed that the system's usable biomass flows justified the expansion of only one mill's cogeneration capabilities and the construction of no new stand-alone generating facilities. It was found that almost twice the amount or electricity could have been produced from the 2013/14 harvest's available sugarcane biomass than was actually generated. Results also showed that the production of cellulosic ethanol was of no economic benefit.

The optimal allocation of available biomass for electricity generation was estimated to be approximately 135 mn t of bagasse, 20.5 mn t of load trash and 5.5 mn t of baled trash, which represents the use of about 91%, 98% and 17% of the area's supply from the 2013/14 harvest (Fig. 3).

It was found that total system profit maximization from the 2013/14 sugarcane harvest seasons' bagasse and trash came from the generation of approximately 40,000 GWh of electricity for export to the Brazilian National Interconnected System (SIN), enough for approximately 17 mn homes. This level of generation is almost twice as high as was actually generated over the period and was arrived at through optimized biomass allocation and the use of current generation technology.

Only one mill was identified in Scenario 1 as economically benefiting from the expansion of its generation facilities. The mill was located in the middle of the Araraquara mesoregion, in the center of the Brazilian state of São Paulo. The mesoregion contains 8 sugarcane mills and shows a lower level of biomass utilization, especially bagasse (the cheaper biomass), than the other analyzed mesoregions. Investment in new, stand-alone generation facilities was considered uneconomical; especially in this mesoregion as the average distance from existing mills to electric transmission lines is only 8.3 km, one third the Brazilian average.

Results from modeling the scenario indicated that no biomass should be allocated to cellulosic ethanol production. This result was expected. The model was designed with profit maximization as the goal, and cellulosic ethanol projects proved unattractive from the profit perspective with production and investment costs higher than sales revenue at the average price received for ethanol during the period.

Scenario 1 results are consistent with the actual allocation and use of biomass in the mesoregions during the period, but as was noted earlier, the potential for electricity generation indicated by present model is about twice the level that was actually achieved. It was found that the bagasse derived from the mix of sugarcane and residual trash delivered to the mills is used almost entirely in cogeneration facilities to operate their core businesses: the production of sugar and first generation ethanol. The majority of the trash was left in the field; less than 20% of that trash was baled and used. The unused trash represents a large supply of potential energy.

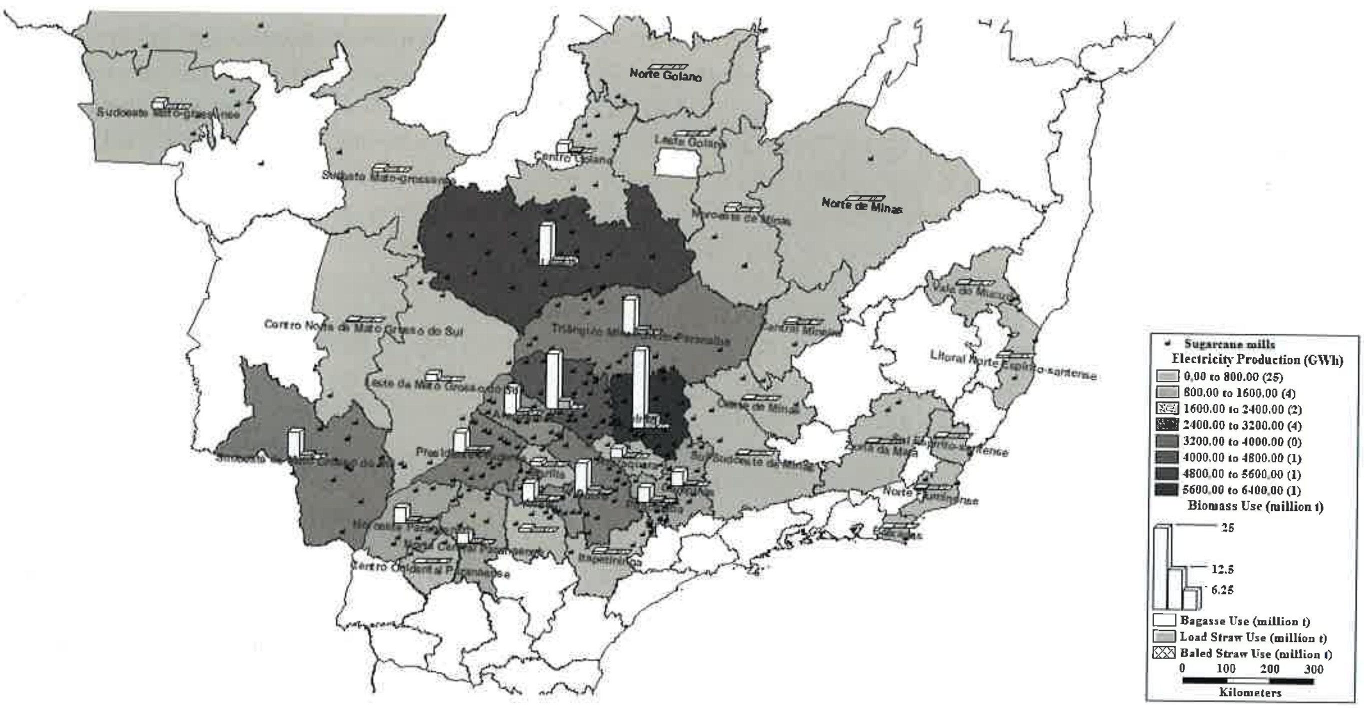

Fig. 3: Scenario 1: Biomass use in mn t and electricity production in GWh in each mesoregion

Results from modeling Scenario 2 show that expansion or construction of electrical generation facilities during the period would not be justified. The allocation of available biomass for this purpose should be limited to the supply of existing cogeneration facilities. In addition to providing heat and electricity for mill operations, these facilities could generate approximately 36,000 GWh of exportable electricity per crop year.

It was found that over the medium term represented in Scenario 2, 68 cellulosic ethanol refineries producing approximately 9 mn m^3 of cellulosic ethanol could be profitably added to existing sugarcane mills. The additional facilities would consume about 25 mn t of bagasse and 22 mn t of baled trash, representing 15% and 61% of total available supply, respectively. This production would be equivalent to about 20% of the ethanol demand projected by Brazil's "Plano de Expansão de Energia 2022."

Among the more important results from modeling Scenario 2 was that the construction of stand-alone cellulosic ethanol refineries or stand-alone electrical generation units was discounted in favor of the physical and technological expansion of existing mills, finding that this would be more cost effective and competitively advantageous. The areas for expansion were concentrated in the main sugarcane producing regions where industrial plants are generally larger, better suited for expansion, and often part of an industrial park effectively linked with outside markets. Sites for 38 potential cellulosic projects were identified in just three of the studied mesoregions: Ribeirão Preto, São José do Rio Preto and Bauru.

Biomass consumption in Scenario 2 was about 86% of the bagasse, 96% of the load trash and 75% of the baled trash, showing that biomass availability should not be a hindrance to the implementation of the suggested projects (Fig. 4).

The model was not designed to individually address regional fuel markets and mill specific characteristics, such as the technology employed. Information in this regard might better explain the results and indicate economically justifiable mill modifications and/or marketing strategies. Despite these limitations, the results can serve to guide investments in the sector, biomass allocation priorities, and the direction of public policies that facilitate a technological upgrade of cogeneration and cellulosic ethanol processes.

5 Conclusion

Results from the scenario that simulated the 2013/14 sugarcane harvest, Scenario 1, indicated that the most profitable use of bagasse and trash from that harvest would have been to generate 40,000 GWh of exportable electricity. This is double the actual exportable electricity generated with sugarcane biomass over the period but using the same amount of available biomass. The significant disparity between actual electricity generation and potential electricity generation speaks to variation among the mills' cogeneration equipment and biomass use. The cogeneration facilities of studied mills had an average conversion factor below that assumed in this scenario yet attainable using the latest generation of available equipment.

Results from the scenario that simulated the 2021 thru 2025 period, Scenario 2, showed that the most profitable allocation of available sugarcane biomass came from the annual production of 9 mn m^3 of cellulosic ethanol and the generation of 36,000 GWh of exportable electricity, demonstrating that both uses of biomass can coexist. The increase in cellulosic ethanol production from Scenario 1, in which no production of cellulosic ethanol was recommended, was the result of the addition of 68 cellulosic ethanol refineries to existing mill facilities and an enormous increase in the use of surplus sugarcane trash. As was the case with electricity generation, this dramatic increase is contingent on the efficient allocation of available biomass and technological progress, in this case, in the refining of cellulosic ethanol.

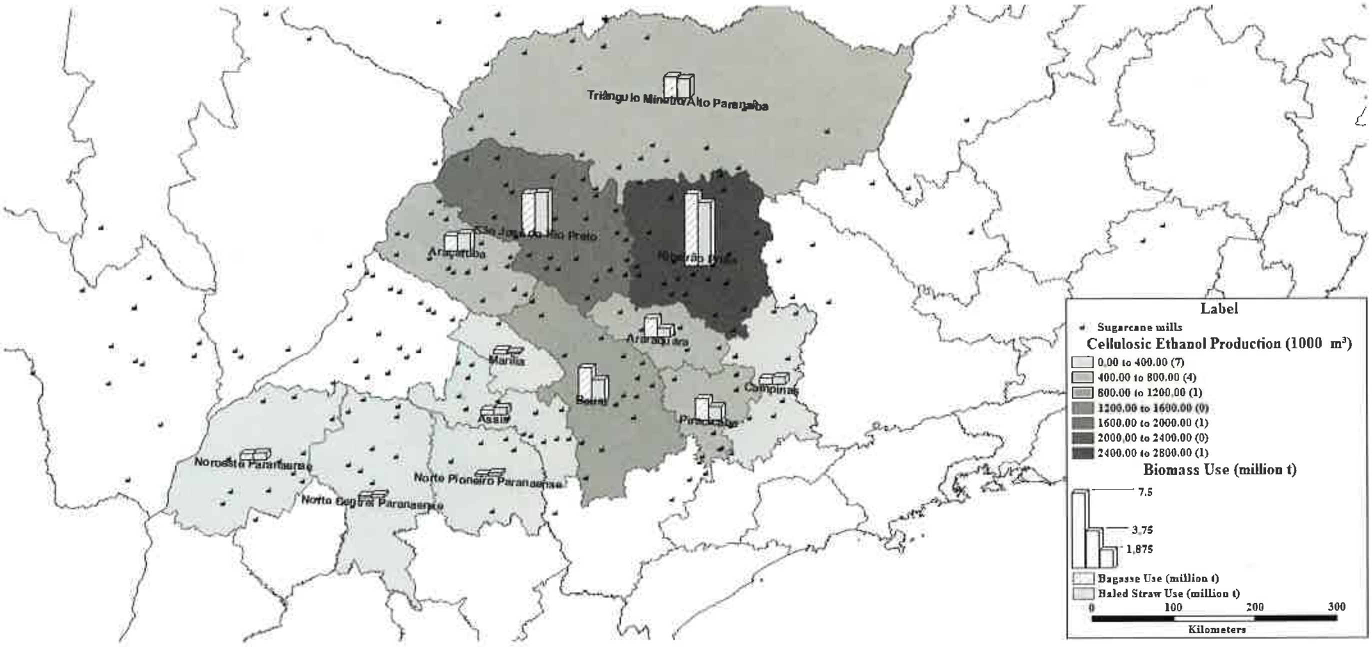

Fig. 4: Scenario 2: Biomass use in mn t and cellulosic ethanol production in 1000 m^3 in each mesoregion

In both scenarios it was found that the construction of stand-alone facilities to either generate power or produce cellulosic ethanol was a much less viable alternative to the expansion and upgrade of existing mill facilities. A majority of this investment should occur in the country's main sugarcane producing regions to take advantage of a more developed logistical network, superior mill infrastructure and biomass availability. Sites for 38 of the 68 potential cellulosic projects identified in Scenario 2 were located in just three of the studied mesoregions: Ribeirao Preto, São José do Rio Preto and Bauru.

The study's results in regard to potential cellulosic ethanol production and electrical generation are contingent on an assumption that over the medium and long terms the production of these energy sources using sugarcane biomass will become commercially and technologically viable, especially in regards to biofuel. Currently, the conversion of biomass to cellulosic ethanol is not economically justifiable; and the risks involved in developing technology to make this production profitable are daunting for the independent Brazilian entrepreneur. The potential for greater electrical output is less problematic, but requires investment in a risky, opaque economic environment.

Industry and government could mitigate economic risk by organizing, conducting and overseeing more open, publicized biomass energy auctions to provide clarity in the formation and calculation of energy prices. Government support would also be an effective risk minimization alternative, especially for crucial private industries in need of an expensive technological upgrade. This support could come from public policies and incentives focused on the production of cellulosic ethanol and can take many forms:

1. Guaranteeing domestic demand for cellulosic ethanol by requiring its use in the government's mandated ethanol-gasoline mix;
2. Quantifying, pricing, and promoting the positive externalities gained from the use of ethanol;
3. Offering financial incentives to reduce the so called "Brazil cost;"
4. Continuing and expanding funding of technologically directed initiatives, such as the government's Plan to Support Innovation in the Sugarcane and Sucrochemical Sectors (PAISS) and the Inova Energy program.[5]

A concerted and coordinated effort by both industry and government is needed to bring about the modernization of Brazil's sugarcane industries. Only the efficient planning of biomass utilization, a technological upgrade of existing facilities and support for research into the conversion of biomass to cellulosic ethanol will permit the profitable and socially responsible use of the sector's abundant biomass resources.

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[5] Inova Energy program – a government supported program that finances studies and innovative projects in the energy sector.