



Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies



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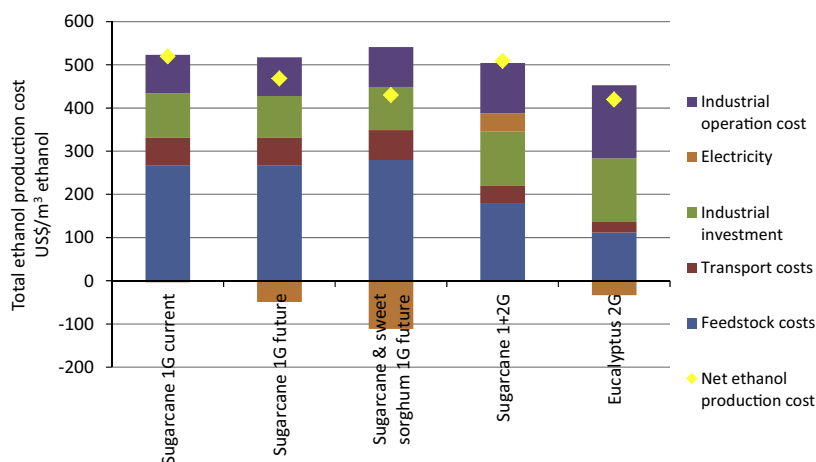
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HIGHLIGHTS

- Sugarcane 1G ethanol production costs may decrease to 432 US\$₂₀₁₀/m³ in 2030.
- 2G ethanol production utilizing eucalyptus could be reduced to 424 US\$₂₀₁₀/m³ in 2030.
- Yield, sugar content, and industrial efficiency are key drivers of cost reductions.
- Regional differences, mainly biomass yield, have a large impact on production costs.

GRAPHICAL ABSTRACT

GA.1. Breakdown of ethanol production costs of different 1st and 2nd generation ethanol production configurations in Brazil in 2010 and 2030.



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ABSTRACT

This paper presents an economic outlook of the ethanol industry in Brazil considering different biomass feedstocks and different industrial processing options. A spreadsheet model was designed to account for different feedstocks and industrial processes, and expected trends in biomass yield, sugar- and fibre content, industrial scale and efficiency. Sugarcane and energycane cultivation costs may be reduced from 35 US\$₂₀₁₀/TC in 2010 to 27 US\$₂₀₁₀/TC and 22 US\$₂₀₁₀/TC in 2030 respectively. Eucalyptus and elephant grass cultivation costs could be reduced from 32 to 23 US\$₂₀₁₀/tonne wet and 38 to 26 US\$₂₀₁₀/tonne wet for eucalyptus and elephant grass. Total ethanol production costs of first generation processing may decrease from 700 US\$₂₀₁₀/m³ in 2010, to 432 US\$₂₀₁₀/m³ in 2030. First generation ethanol production costs may decrease by reduced feedstock costs, increase in sugar content, utilization of cane trash, and use of sweet sorghum. Furthermore, the improvement in industrial efficiency of the first generation process, increasing industrial scale and change to an improved technology are other measures. For second generation technology utilizing eucalyptus, the total ethanol production costs could be strongly reduced to 424 US\$₂₀₁₀/m³ in 2030. Costs reduction measures for second generation industrial processing include reduced feedstock costs, increasing industrial efficiency and scale, and a change to more advanced

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industrial process. Overall, biomass yield, increase in sugar content of sugarcane, and improved industrial efficiency are important parameters in total ethanol production costs. Ongoing RD&D effort and commercialization of second generation industrial processing may result in the lowest ethanol production costs for second generation processing in the future.

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1. Introduction

In recent decades worldwide biofuels production and consumption expanded significantly due to supportive policies aiming to, amongst others, reduce greenhouse gas (GHG) emissions and diversifying energy sources [1,2]. It is expected that the biofuel demand will increase further in the coming years [3]. Of the total world biofuel demand, 2.9 EJ [4], around 2.0 EJ was ethanol in 2011 [5]. In the past decades, Brazil and the USA have dominated the ethanol production worldwide [6]. Up to today, Brazilian ethanol production is primarily based on the fermentation of extracted sugars from sugarcane [7], and production reached almost 0.47 EJ in 2011 [5]. The sugarcane output originates predominantly (around 90%) in the Centre-South region of Brazil [8].

Brazil has the potential to expand its ethanol production in the future [9,1,6]. Potential options include the expansion of cultivation area, improvement in agricultural or industrial yield and the introduction of new industrial processing pathways [10,9,6,11,12]. New industrial processing pathways could include improved first generation (fermentation of sugars) or second generation (conversion of lignocellulosic biomass) industrial processing. Second generation industrial processing would enable the conversion of lignocellulosic biomass feedstocks, like woody biomass, perennial grasses and agricultural or industrial by-products. The implementation of second generation technology could strongly improve the ethanol production per hectare by using these lignocellulosic by-products of sugarcane processing [13,14]. Furthermore, the use of second generation technology could enable year-round ethanol production, as the supply of lignocellulosic crops is less seasonable than sugarcane. Despite the ongoing research in 2nd generation technology, the economic performance of future technology developments remains uncertain [15]. Next to sugarcane, other biomass feedstock have been proposed for ethanol production due to their potential yield, composition or tolerance to climate and/or soil characteristics in other cultivation areas [10,16,17,18]. Especially, the development of second generation industrial processing would enable the utilization of more biomass feedstocks.

With the ongoing research and development in biomass cultivation of different ethanol feedstock and industrial processing pathways the ethanol production costs are likely to change in the future. This study focusses on the current and future ethanol production costs in Brazil, considering the utilization of different production configurations.¹ Ethanol production in Brazil is primarily based on sugarcane; no significant ethanol production is based on other feedstock [10]. Other potential ethanol production biomass feedstock include, amongst others, energycane [19,20], sweet sorghum [21,17], elephant grass (or other perennial grasses) [10,22] and eucalyptus [23,24].

Sugarcane cultivation costs have been investigated by multiple studies, amongst others [25,26,11]. Energycane is a high-yielding sugarcane variety with a potential higher total biomass yield, lower sugar content but high fibre content [20]. The main advantage of sweet sorghum as ethanol feedstock is the harvest period

is outside the harvesting season of sugarcane [10]. Cultivation costs of sweet sorghum have been investigated by Reddy et al. [17] and Koppen et al. [27]. Both eucalyptus and elephant grass have been indicated as potential (lignocellulosic) feedstock for ethanol production with second generation technology [10,23,28]. Eucalyptus is a fast growing woody biomass, cultivated in Brazil for wood and paper production [29]. Eucalyptus cultivation costs have been estimated by Florestal et al. [30], Quéno et al. [31], Gonzalez et al. [16]. Elephant grass cultivation costs are reported by Quéno et al. [31]. The above mentioned publications dealing with biomass cultivation costs indicated that biomass yield improvement and change of cultivation management practices are key issues for biomass cultivation costs reduction.

Potential ethanol production pathways can, in general, be classified into 3 main options: first generation, second generation and integrated first-and-second generation industrial processing. Numerous studies identified the current and future technical and economic performance of sugarcane first generation processing [32,33,11,12]. The conversion of lignocellulosic feedstock like eucalyptus, elephant grass and cane bagasse or trash with second generation processes have been assessed by different studies [28,34,35,23,36]. Also the utilization of sugarcane in integrated first-and-second generation industrial processes has been researched for ethanol production [35,33,37,38]. Overall these authors indicated that the industrial efficiency improvement and/or change of conversion technology or improvement of technology set-up are key factors affecting industrial processing costs.

The objective of this paper is to examine the potential development in future ethanol production costs in Brazil, up to 2030, given the technical and economic development of biomass feedstock cultivation and industrial processing of first and second generation technologies. To our knowledge no detailed and comparative supply chain analysis has been performed determining the total ethanol production costs in Brazil, taken into account different biomass feedstock and different industrial processing routes. The goal is to provide a bottom-up economic assessment of different combinations of biomass feedstock and ethanol processing routes, resulting in the total ethanol production costs of different configurations and for different settings. A uniform comparison of different potential feedstock for ethanol production could guide future research, support political debate and private investors in the Brazilian ethanol industry.

2. Industrial processing pathways for ethanol production

In general, three main ethanol conversion technologies can be distinguished: a first generation process, a second generation process and an integrated of first-and-second generation conversion processes. First generation industrial processing is the conversion of sugar- or starch-rich biomass crops to ethanol. In sugar based first generation industrial process (see Fig. 1a) sugarcane, energycane or sweet sorghum is shredded and milled to extract the sugar-rich juice. The sugar juice is treated and concentrated² by evaporation before entering the fermentation step [38]. During

¹ In this research, the term 'configuration' is used to indicate a combination of biomass feedstock (or multiple feedstocks) and industrial processing route; which could be first generation, second generation or a combination of first and second generation technologies.

² As the sucrose concentration is too low (13.7 wt.%) to reach the preferred ethanol concentration in the fermentation stage, an evaporation unit is used to increase the concentration to 19 wt.% [38].

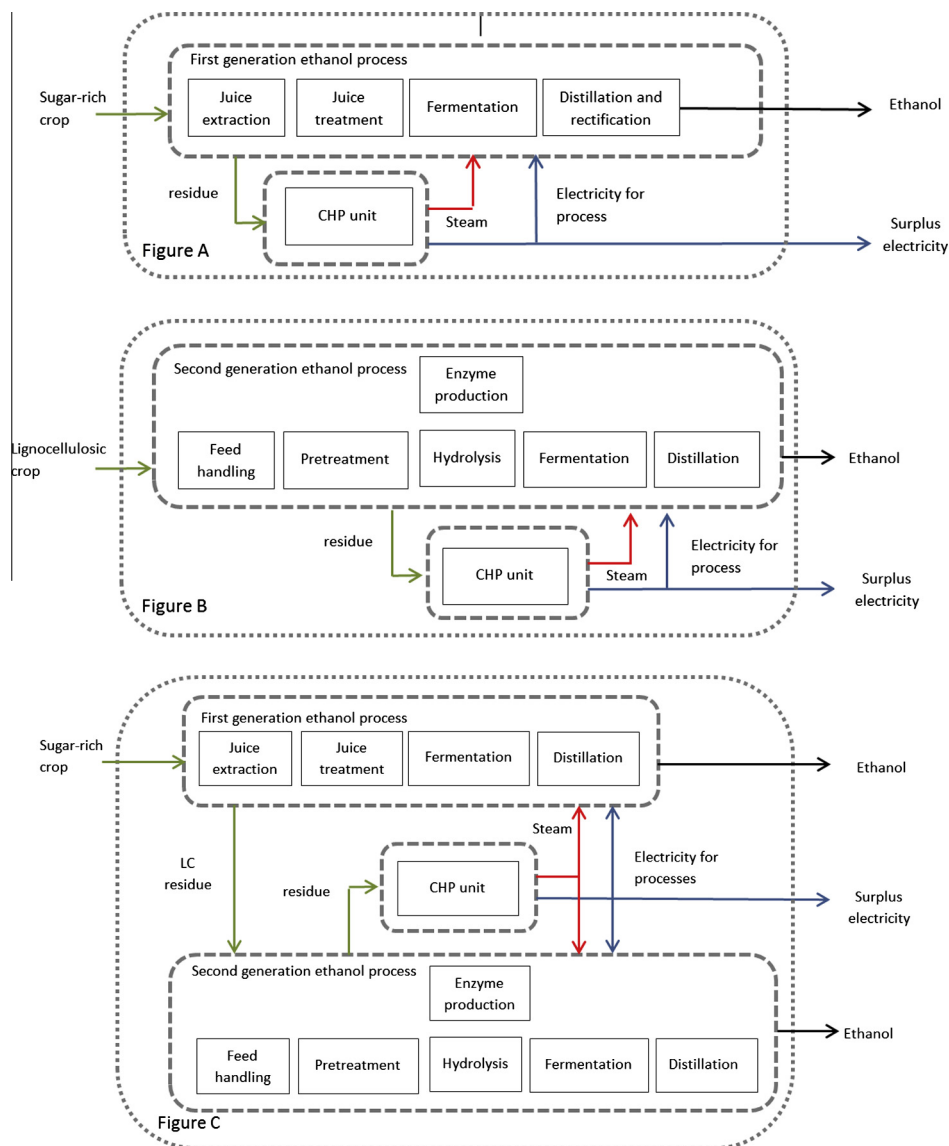


Fig. 1. Schematic overview of possible ethanol conversion concepts; (1A) First generation technology, (1B) Second generation technology, (1C) Combined first-and-second generation technology.

fermentation (an exothermic process) sucrose is converted to glucose and fructose, which are converted³ to ethanol, CO₂ and by products (alcohols, organic acids, etc.) [33]. The fermented broth is fed to a centrifuge to enable yeast separation and recovery. The fermentation gasses are fed to an absorber for ethanol recovery [39]. Both the ethanol recovered from the centrifuge and absorber are fed to a distillation column. The distillation product is fed to a rectification column which produces hydrous ethanol. After further dehydration anhydrous ethanol is formed. For first generation technologies, cane-bagasse⁴ and cane-trash⁵ are fed to a cogeneration facility to produce process steam and process/surplus electricity.

³ Fermentation can be presented by the simplified chemical equations [7]: $C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6$ and $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + 23.5 \text{ kcal}$.

⁴ Cane bagasse is the by-product of sugarcane first generation process. After sugar extraction, a fibrous material remains which can be used for steam and electricity production or ethanol production.

⁵ Cane trash is a residue of sugarcane harvesting, and consists of the dry and green leaves of the sugarcane plant. During harvesting the sugar-rich cane-stalks are considered the main product, which are loaded and transported to the industrial processing plant. Cane trash is left on the field, unless it is collected, loaded and transported for use in the industrial plant.

Second generation industrial processing (see Fig. 1b) is the conversion of lignocellulose biomass to ethanol. Due to the complex structure of lignocellulose, the biomass needs to undergo treatment before embedded sugars are available for the fermentation to ethanol. In a second generation industrial process, lignocellulosic biomass feedstock is pre-treated, the hemicellulose and very little cellulose are hydrolysed, followed by fermentation and ethanol separation [15,14]. Hydrolysis combined with fermentation is more complex than fermentation of simple sugars [28]. Many different techniques to pre-treat and hydrolyse the lignocellulose biomass have been researched to improve ethanol yield and reduce ethanol production costs [38]. Currently, steam pretreatment followed by enzymatic hydrolysis is considered as one of the most viable options for lignocellulosic ethanol production [38]. The industrial processing residues of the second generation process, which mainly consist of the lignin and un-reacted cellulose from hydrolysis are fed to the cogeneration facility.

Another possibility is to integrate first-and-second generation processes: the lignocellulosic residues of the first generation process (bagasse and trash) are fed to the second generation process, see Fig. 1c. The cogeneration unit, fed with residues of the second

generation process, supplies the steam and electricity for both processes.

The selected configurations in this study include two first generation industrial processes, two second generation processes and two integrated first-and-second generation processes. For first generation processing a currently applied technology, using conventional dehydration (azeotropic distillation) with low pressure steam cycle, and an optimized technology utilizing molecular sieves and high pressure boilers are taken into account. The use of molecular sieves and high pressure boilers results in higher equipment costs, but also results in higher electricity surplus. For second generation the basic technology comprises of steam explosion (SE) pretreatment and enzymatic hydrolysis with bought enzymes for simultaneous saccharification and fermentation. The optimized second generation process comprises of liquid hot water (LHW) pretreatment, followed by enzymatic hydrolysis (with on-reactor enzyme production) and fermentation in a consolidated bioprocessing unit. In Table 1 an overview is given of the main features of the different industrial processing pathways. The integrated first-and-second generation plants combines the optimized first generation process with steam explosion pretreatment or liquid hot water pretreatment for second generation processing.

3. Methods

The production costs assessment of ethanol involves three main steps: biomass feedstock cultivation (including harvest), transport, and industrial processing to ethanol. Various parameters may affect total ethanol production costs, e.g. agricultural yield, biomass composition, industrial processing scale and industrial efficiency. For biomass cultivation, transport and industrial processing a bottom-up cost assessment is performed, making a distinction between different costs elements, e.g. capital, labour, cultivation inputs, raw materials and other expenses. A spreadsheet model is constructed to calculate the bottom-up current and future cost structure of feedstock cultivation, transport and industrial processing. The total ethanol production costs, (expressed in US\$₂₀₁₀/m³ ethanol for each configuration) is determined for the best available technology of each configuration, for each year between 2010 and 2030. A net present value (NPV) approach was used, to account for fluctuating expenses and benefits over a lifetime of a plantation or industrial plant.

3.1. Disaggregated current ethanol production costs

3.1.1. Biomass cultivation costs

Within the spreadsheet model, the cultivation costs of sugarcane, energycane, sweet sorghum, eucalyptus and elephant grass are determined. The spreadsheet model incorporates a database of all management practices or inputs used in the cultivation of all five biomass crops, based on a spreadsheet model called CanaSoft developed by the Brazilian Bioethanol Science and Technology Laboratory (CTBE) in Brazil [40] and on available literature. All management practices and cultivation inputs are calculated on a per hectare basis except for the costs of harvesting and fertilizers, which are related to the biomass yield. The total biomass cultivation costs (US\$₂₀₁₀/tonne biomass feedstock) are assessed by calculating the NPV of all costs items and the yield during the cultivation period. The biomass cultivation costs are, similar to [41] determined using Eq. (1):

$$\text{Biomass cultivation cost} = \frac{\sum_{y=1}^{Y=X} \frac{\sum_{n=1}^N (O_{ny} \times C_{ny}) + \sum_{m=1}^M (O_{my} \times C_{my} \times \text{Yield}_y)}{(1+a)^y}}{\sum_{y=1}^{Y=X} \frac{\text{Yield}_y}{(1+a)^y}} \quad (1)$$

Item	Description	Unit
Biomass cultivation costs	Discounted costs feedstock production	US\$/tonne
O_{ny}	Occurrence cost item per ha _n in year y	#
C_{ny}	Costs of cost item n in year y	US\$/ha
O_{my}	Occurrence of cost item per tonne m in year y	#
C_{my}	Costs of cost item m per tonne	US\$/tonne
Yield_y	Yield in year y	tonne/ha
a	Annuity rate	12%
y	Annuity period	years

3.1.2. Biomass transport costs

Biomass transportation costs are mainly driven by the transport distance, which is determined by industrial capacity (annual input), yield of the biomass feedstock and a factor to account for the spatial distribution of biomass cultivation fields and accessibility, similar to Leboreiro and Hilaly [42]. This factor remains constant for the different configuration and is based on the current average transport distance for industrial processing plants in Brazil, yield and capacity. As the investment costs of truck and trailer are already discounted over the lifetime of the truck and trailer, and all other are operational expenses, the elements in Eq. (2) are not discounted. The costs data for truck and trailer investment, operational expenses and other costs components is based on CTBE [40]. The amount of delivered biomass truck loads per day is determined by dividing the daily operational time of a truck by the total time needed for a return trip: sum of distance divided by average speed and loading and unloading time. Diesel consumption is determined by the transport distance and diesel consumption per km. See Eq. (2) for the transport costs calculation: more information about the individual items is given in [supportive information SI 3](#).

$$\text{Transport costs} = \frac{\frac{De}{T} + La + \left(\left(\frac{TD}{Di} \right) \times Dc \right) + Ma + Ti + Lu}{Lo} \quad (2)$$

Item	Description	Unit
Transport costs	Biomass transport costs	US\$/tonne
De	Annualised depreciation costs of capital investment of a truck + trailer	US\$/year
T	Amount of return trips a truck can make in a year	trips/year
La	Labour costs for truck operation	US\$/trip
TD	Averaged distance of return trip between biomass cultivation field and industrial processing plant	km/trip
Di	Diesel consumption	km/l
Dc	Diesel costs	US\$/l
Ma	Costs for truck and trailer maintenance	US\$/trip
Ti	Annualised costs of tires	US\$/year
Lu	Costs for lubricants	US\$/trip
Lo	Truck load capacity	tonne/truck load

3.1.3. Total ethanol industrial processing costs

The industrial processing costs consist of the capital expenses, operational costs, maintenance, labour and electricity expenses

or revenues. Investment costs of the industrial plant (including cogeneration unit) is a sum of the major equipment costs and costs for installation, building and engineering etc. Considering an increasing scale, the scale of the individual components will be scaled up with relevant scaling factors. The equipment costs, including scale factors and maximum scale can be found in Section 4. Operational expenses are all expenses to operate the industrial facility, for example chemicals used and other consumables. The operational and labour expenses of the first generation processes or second generation processes can be found in [SI.6 of the supplementary information](#). Maintenance expenses are all costs needed to maintain the plant, this includes replaced equipment and labour costs, see [supplementary information SI.6](#).

$$\text{Industrial cost} = \frac{\sum_{y=1}^{y=x} \sum (E \times I) + E_n + O_{ny} + L_{a_{ny}} + M_{a_{ny}} + A_{d_{ny}} - E_{l_{c_{ny}}}}{\sum_{y=1}^{y=x} \frac{\text{Ethanol}_y}{(1+a)^y}} \quad (3)$$

Item	Description	Unit
Industrial costs	Industrial processing costs	US\$/m ³ ethanol
<i>E</i>	Equipment costs of individual industrial component	US\$
<i>I</i>	Installation factor to account for installation and auxiliary equipment	US\$
<i>E_n</i>	Engineering costs for total installation	US\$
<i>O_{ny}</i>	Operational expenses	US\$
<i>L_{a_{ny}}</i>	Labour costs for operational staff	US\$
<i>M_{a_{ny}}</i>	Operation and maintenance costs (other than operational expenses)	US\$
<i>A_{d_{ny}}</i>	Administration expenses	US\$
<i>E_{l_{c_{ny}}}</i>	Electricity revenues	US\$
<i>a</i>	Annuity rate	12%
<i>Ethanol_y</i>	Annual ethanol yield in year <i>y</i>	m ³ ethanol
<i>y</i>	Years	year

The ethanol yield of the industrial process is based on available sugars, extraction of sugars and the conversion efficiencies to ethanol. Given Eq. (4), the ethanol yield, expressed in m³ of ethanol per tonne of wet cane or sweet sorghum from the first generation sugar-to-ethanol conversion process is formulated as follows:

$$\text{Ethanol yield 1G} = \frac{(\text{TRS} \times \eta_{\text{Ex}} \times (1 - \eta_{\text{sl}}) \times \eta_{\text{Fer}} \times \eta_{\text{Di}}) \times \text{Cmax}}{\text{Ethanol density}} \quad (4)$$

Item	Description	Unit
Ethanol yield 1G	Ethanol yield of first generation industrial processing	m ³ ethanol/tonne wet biomass
TRS	Sugar content in biomass feedstock	kg/tonne wet
<i>η_{Ex}</i>	Sugar extraction efficiency	%
<i>η_{sl}</i>	Sugar losses cane washing	%
<i>η_{Fer}</i>	Fermentation efficiency	%
<i>η_{Di}</i>	Distillation efficiency	%
<i>Cmax</i>	Stoichiometric conversion factor sugar to ethanol	0.51 kg EtOH/kg sugar
Ethanol density	Ethanol density	790 kg/m ³

For second generation technology the ethanol yield is the sum of the ethanol yield per polysaccharides flow. Given the chemical composition of the lignocellulosic feedstock and the conversion efficiency of polysaccharides to monosaccharide's and the conversion efficiency of monosaccharide's to ethanol, see Eq. (5):

Ethanol yield 2G

$$= \frac{\sum \left(\left(\text{Sugar} \times \eta_{\text{Poly-mono}} \times \text{factor} \right) - \text{enzymes} \right) \times \eta_{\text{mono-ethanol}} \times \text{Cmax}}{\text{Ethanol density}} \quad (5)$$

Item	Description	Unit
Ethanol yield 2G	Ethanol yield of second generation industrial processing	m ³ ethanol/tonne dry biomass
sugar	Amount of C ₅ or C ₆ sugar in the respective feedstock	kg/tonne dry
<i>η_{Poly-mono}</i>	Conversion efficiency of polysaccharides to monosaccharides	%
Factor	Stoichiometric conversion factor polysaccharides to monosaccharides ^a	–
Enzymes	Sugar consumption by enzymes	kg
<i>η_{mono-ethanol}</i>	Conversion of monosaccharides to ethanol	%
<i>Cmax</i>	Stoichiometric conversion factor sugar to ethanol	0.51 kg EtOH/kg sugar
Ethanol density	Ethanol density	790 kg/m ³

^a Conversion of C₅ polysaccharides (xylan and arabinan) to monosaccharides is assumed to have a conversion factor of 1.136, while C₆ sugars chains (glucan, galactan and mannan) are converted with a ratio of 1.111 [15,43]. The conversion efficiency of polysaccharides to monosaccharides is expressed as percentage of the maximum theoretical yield; which is 1.136 and 1.111 for C₅ and C₆ sugars, given the conversion reactions given by Chovau et al. [15].

$$\text{enzymes} = \text{consumption} \times \text{ethanol yield} \quad (6)$$

Item	Description	Unit
Enzymes	Sugar consumption by enzymes	kg/tonne biomass
Consumption	Consumption of sugar by enzymes ^a	kg/m ³ ethanol
Ethanol yield	Ethanol yield (determined with formula 5, but without enzyme consumption)	m ³ ethanol/tonne biomass

^a Consumption per kg ethanol; 6.3 g sugars 9.3 g cellulose [28].

The electricity surplus is based on the steam cycle (boiler, turbine, condenser and boiler feed pump), including steam extraction point, whereas the work delivered in the turbine is the enthalpy difference in the turbine [44]. The surplus electricity is determined based on the energy embedded in the residues fed to the cogeneration unit, boiler efficiency, steam and electricity demand for the ethanol production process, see Eq. (7). The electricity surplus is based on the energy flow out of the boiler (Eq. (8)), minus the energy embedded in the steam (for process steam) and the energy leaving the turbine, after steam expansion in the turbine.

Table 1
Main differences in the different industrial processing pathways.

Main features	Basic first generation	Optimized first generation	Basic second generation	Optimized second generation
Prime feedstock	Sugarcane, energycane, sweet sorghum ^b		Lignocellulosic biomass (eucalyptus or elephant grass) or first generation residues	
Sugar extraction and mobilization	Shredder	Shredder	Steam explosion (SE) pretreatment	Liquid hot water (LHW) pretreatment
Fermentation	Fermentation reactor vessel	Fermentation reactor vessel	Simultaneous Saccharification and co-Fermentation	Consolidated bioprocessing
Ethanol dehydration	Conventional	Molecular sieves	Molecular sieves	Molecular sieves
Cogeneration unit	Lower pressure boiler	High pressure boiler	High pressure boiler	High pressure boiler
Abbreviation		Feedstock	First generation technology	Second generation technology
Basic 1G sugarcane		Sugarcane	Basic	
Basic 1G energycane		Energycane	Basic	
Optimized 1G sugarcane		Sugarcane	Optimized	
Optimized 1G sugarcane + trash		Sugarcane, cane trash	Optimized	
Optimized 1G sugarcane + trash + sweet sorghum		Sugarcane, cane trash, sweet sorghum	Optimized	
Optimized 1G energycane + trash + sweet sorghum		Energycane cane trash, sweet sorghum	Optimized	
Basic 2G eucalyptus		Eucalyptus		Basic
Basic 2G elephant grass		Elephant grass		Basic
Optimized 2G eucalyptus		Eucalyptus		Optimized
Optimized 2G elephant grass		Elephant grass		Optimized
Sugarcane 12G basic		Sugarcane	Optimized	Basic
Sugarcane 12G optimized		Sugarcane	Optimized	Optimized
Sugarcane 12G optimized + trash		Sugarcane, cane trash	Optimized	Optimized
Sugarcane + sweet sorghum 12G optimized + trash		Sugarcane, cane trash, sweet sorghum	Optimized	Optimized
Sugarcane + sweet sorghum 12G optimized + trash 300 days ^a		Sugarcane, cane trash, sweet sorghum	Optimized	Optimized

^a This configuration incorporates the storage of bagasse. Available cane trash is used during harvest season of sugarcane, outside the harvest season the available bagasse is utilized. The scale of the second generation process is scaled on the highest scale needed to process the trash during sugarcane harvest season, or available bagasse outside the harvesting season. The total operational time of the plant is maximal 300 days.

^b Sweet sorghum is only used as complementary feedstock, meaning sweet sorghum is only cultivated on fallow cane-land, between two cane cycles (between the last ratoon and replanting).

$$\text{Electricity surplus} = \frac{E_{ab} - E_{sc} - E_{at}}{3.6} - \text{own elec use} \quad (7)$$

Item	Description	Unit
Electricity surplus	Electricity surplus for grid supply	kW h
E_{ab}	Energy embedded in steam (high pressure, high temperature)	MJ
E_{sc}	Energy embedded in steam for own use	MJ
E_{at}	Energy flow embedded in steam after turbine (low pressure, low temperature)/	MJ
Own elec use	Own electricity use	kW h
3.6	Conversion MJ/kW h	MJ/kW h

$$E_{afterboiler} = \frac{\text{Boiler feed} \times \text{HHV} \times \eta_{\text{boiler}}}{\Delta H \text{ Boiler}} \times \Delta H \text{ steam} \quad (8)$$

Item	Description	Unit
Boiler feed	Flow of available residues (boiler feed)	kg
HHV	Higher heating value residues	MJ/kg
η_{boiler}	Efficiency boiler	%
$\Delta H \text{ boiler}$	Heat content change in boiler (difference feed water and steam Leaving boiler)	MJ
$\Delta H \text{ steam}$	Heat content steam after boiler	MJ

3.2. Future outlook for total ethanol production costs

As the biomass yield, composition of the biomass feedstock, conversion efficiencies and scale of the industrial plant are expected to change over time, the total ethanol production costs change as well. A future outlook of the total ethanol production costs should incorporate the potential trend of the most important variables. The variables considered in this study are the biomass agricultural yield, sugar- and fibre content of sugarcane, energycane and sweet sorghum, ethanol production efficiency of the first and second generation processes and the scale of the industrial plant. For each year between 2010 and 2030 the input parameters are determined and applied in the above mentioned Eqs. (1)–(8). For the input parameters the current value and the potential trend in the future is based on literature and expert opinion. This gives insights in the potential future ethanol production costs of the best available technologies for the different configurations up to 2030. Section 4 provides an overview of the data input required and the trend for the different variables.

3.3. Sensitivity analysis

A sensitivity analysis is performed on the different ethanol production configurations in 2030. The potential effect of biomass yield, ethanol industrial yield, capital investment, fertilizer prices and electricity revenues on ethanol production costs is considered. Historically, yield has been the main driver for the observed trend in cultivation costs of sugarcane [11] and eucalyptus [45]. Similar to agricultural yield, the industrial yield (ethanol yield) is an important driver for total ethanol production costs, due to its crucial role in Eq. (3). Next to feedstock costs, the capital expenses are indicated as another major cost component in total ethanol production costs [46,11], especially for second generation technology [15,46]. Electricity revenues also play an important role in total ethanol production costs as electricity surplus can be as high as

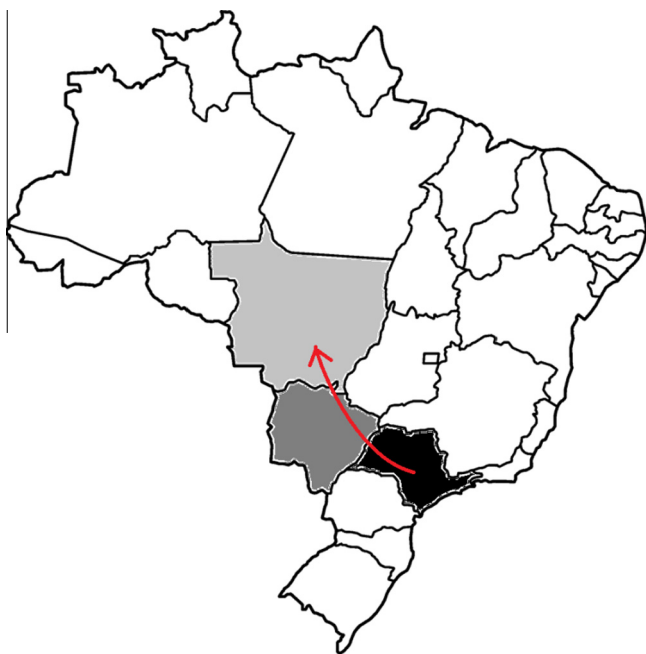


Fig. 2. Current dominant sugarcane cultivation area (São Paulo) and potential expansion areas for biomass cultivation in Brazil.

2 kW h_e/L ethanol for first generation technology or 0.85 kW h_e/L ethanol for integrated first-and-second generation technology [32]. For the economically most interesting options for first-, second and first-and-second generation technology a sensitivity analysis is performed and presented in a spider diagram by varying the selected parameters.

With the potential expansion of cultivation area in Brazil, biomass feedstock cultivation may expand to regions more or potentially less suitable for certain biomass crops, compared to São Paulo state. Yield may be affected by agro-ecological suitability and therefore, total ethanol production costs may vary between regions. As land costs in São Paulo are much higher compared to other regions [47], the expansion of cultivation area may lead to lower cultivation costs as land costs are reduced. In Fig. 2, the potential expansion areas of Mato Grosso do Sul (dark grey) and Mato Grosso (light grey) are presented, next to São Paulo state (black). This potential expansion is derived from Cerqueira Leite et al. [9]. To provide more insight in the potential of different configurations in regions outside of São Paulo state a regional analysis is performed. Such regional analysis includes the potential yield ranges of biomass feedstocks and potential land prices of the respective regions.

4. Data input

4.1. Biomass cultivation

Sugarcane is cultivated in a cycle⁶ of 6 years, with 5 harvestings, starting 12–18 months after planting [49], each harvest yield is reduced compared to previous one⁷. Around 8.6 Mha of sugarcane was harvested in 2009 [50]. In the supportive information an overview of management practices and cultivation inputs are given for

sugarcane and energycane. Energycane is a high yielding (high fibrous) group of sugarcane varieties, it is therefore assumed to follow a similar cultivation management cycle and cultivation techniques. In this outlook we consider the use of the ETC harvesting machine, next to conventional harvesting machine and manual harvesting system (the latter being currently replaced by mechanical harvesting⁸). The ETC machine is currently under development at the Brazilian Bioethanol Science and Technology Laboratory (CTBE), capable of performing harvesting and planting operations [52,53,54]. Sweet sorghum can be cultivated in various regions due to its adaptability, rapid growth, sugar accumulation, drought tolerance, tolerance to water logging and tolerance to acidity toxicity [21,49]. The cultivation period of sweet sorghum is around 120–130 days, with one final harvest [21,27]. No information was found on the cultivation area of sweet sorghum in Brazil. In this study we assume the use of harvesting machines for sweet sorghum similar to sugarcane. Eucalyptus is cultivated in ratoon cycles of 7 years, with a plantation renewal after the third harvest (21 years). Yield levels are described as averaged annual yields, commonly expressed in cubic metre per hectare. In 2009, eucalyptus occupied 4.5 Mha of land in Brazil [55]. Selected harvesting equipment is typical for harvesting of woody biomass; harvesting costs are expressed per m³ of harvested eucalyptus. Elephant grass can be harvested twice a year, apart from first year after plantation establishment, with the time before renewing the site up to 20 years [56]. In Table 2 an overview is given of current yield of all biomass feedstock and the sugar- and fibre content of sugarcane, energycane and sweet sorghum in the state of São Paulo. The chemical composition of eucalyptus and elephant grass, shown in the supplementary information SI.1, is assumed to remain constant over time.

4.2. Technical data industrial processing

4.2.1. First generation technology

For first generation technology the sugar extraction efficiency and extraction losses are considered, together with the fermentation and distillation efficiency, leading to the industrial ethanol yield. For those parameters the 2010 value is considered based on literature, and for the future outlook updated with the expected annual change, until it reaches the maximum or minimum value, see Table 3. No difference in ethanol production efficiency is considered between the basic and optimized first generation set-up, as the dominant element do not differ. The scale of first generation industrial processing in 2010 is assumed to be 500 TC/hour, a relatively large scale autonomous distillery [32]. The electricity consumption for the basic and optimized process are 28 kW h/TC input and 46 kW h/TC input [32,54]. The steam demand is set to 500 kg steam/TC for the basic configuration, based on the values found in Ensinas et al. [63], Pellegrini and de Oliveira Junior [66]. For the optimized configuration a steam reduction of 75 kg steam/TC, compared to the basic configuration, is considered due to the use of molecular sieves [32].

4.2.2. Second generation technology

For the ethanol production from lignocellulosic biomass feedstock the conversion efficiency from polysaccharides to monosaccharides and the conversion to ethanol is applied for the basic and optimized set-up. Based on available literature, a 2010 value, annual change and a maximum value for conversion efficiency is assumed for both types (basic and optimized). In Table 4 an overview of the data used for the production of second generation ethanol is given. The scale of a second generation technology is based

⁶ Sugarcane is cultivated in a cultivation period of 6 years. As yield decrease over time (roughly 20%) compared to the previous harvest [48], the plantation is renewed after 6 years.

⁷ Macedo et al. [48] found that an average yield of 68.7 TC/ha year corresponds to 106, 90, 78, 71 and 67 TC/ha for the five consecutive harvests in a ratoon.

⁸ The state of São Paulo has approved a law in 2002 to gradual eliminate pre-harvest burning of sugarcane field by 2021 in mechanized areas and by 2031 by non-mechanized areas [51].

Table 2

Technical parameters for biomass cultivation; yield and annual yield increase, and sugar- and fibre content of first generation biomass feedstock.

Item	2010 value (common range)	Unit ^k	Annual change ^l (%)	2030 value (based on 2010 value and annual change)
Yield SC ^a	85 (80–92)	TC/ha	0.9	100
Yield EC ^b	85 (80–92)	TC/ha	2.0	126
Yield SS ^c	50 (49–63)	TC/ha	2.0	65
Yield EU ^d	47 (27–53)	m ³ /ha year	3.0	70
Yield EG ^e	30 (29–36)	dry tonne/ha year	1.6	45
Sucrose content sugarcane ^f	14.5 (14.0–15.0)	%	0.5	16.6
Sucrose content energycane ^g	14.5 (14.0–15.0)	%	–1.0	12.0
Sucrose content sweet sorghum ^h	12.0 (10.9–15.5)	%	1.0	12.6
Fibre content SC ⁱ	14.0 (11.0–16.0)	%	–1.0	12.4
Fibre content EC ^g	14.0 (11.0–16.0)	%	2.0	17.0
Fibre content SS ^j	14.0 (13.9–14.5)	%	0	14.0

^a Current achieved yield in São Paulo state is around 80–85 tonne cane/ha year [57], historically, the yield trend has been fairly linear [58], extrapolating this trend, this would lead to a yield of 102 TC/ha year in 2030, in line with future yield expectations of Leal et al. [20]. The yield range (between brackets) is the averaged yield found in the traditional sugarcane cultivation regions (Centre-South region of Brazil), as reported by XAVIER et al. [25].

^b Energycane is seen as high yielding fibrous sugarcane, therefore current yield is assumed to be similar to sugarcane, while the annual increase is higher reaching 126 TC/ha year, similar to the energycane yield expectations of Leal et al. [20].

^c Current yield are around 50–60 tonne wet sweet sorghum/rotation period (100–120 days), an yield increase of 2% would support the yield expectations of Agroenergia [59]. Yield ranges found are between 54 and 69 short ton [21].

^d Eucalyptus yields of 47 m³/ha year can be attained in São Paulo state, which would represent 23.5 dry tonne/ha year. Yields of 70 m³/ha year are foreseen to be achievable [29]. In 2009 the yield range in Brazil was between 27 and 53 m³/ha year, for the regions Pará and Paraná respectively [60], similar to Bacha [61].

^e Current elephant grass yields are around 30 dry tonne/ha year [62]; the yield range for research plot is between 24.5 and 34.4 dry tonne/ha year, the yield trend is assumed to be similar to sugarcane; due to the lack of data.

^f Common values found in literature indicate a current sugar content between 14% [63] and 15.3% [35]. Next to yield also the sucrose content of sugarcane is expected to increase in the future [20], an annual increase of 0.5% is assumed, in line with the expected sucrose content of sugarcane of 16.5% in 2030 by Leal et al. [20] and in line with the historically observed trend between 1980 and 2004 [11].

^g The start point for energycane is similar to sugarcane, but the annual change is selected as such that future values are in line with the future expected sugar- and fibre content as presented by Leal et al. [20].

^h The current sugar content of sweet sorghum varieties designed for ethanol production are between 10.9% and 15.5% [64,65] potential increase in sugar content is assumed to be similar to sugarcane.

ⁱ On average the fibre content of sugarcane is around 140 kg dry/TC, or 14% [32], common range is 11–16% [52].

^j Fibre content of sweet sorghum is around 13.9–14.5% [52], a value of 14% is selected in line with sugarcane.

^k The yield of the different biomass types does not compare easily due to differences in moisture content. We provided the data in most commonly used units, despite that easy comparison is difficult.

^l The annual change is specified as the annual increase or decrease of the parameter at hand. For example sugarcane yield would increase to 102 TC/ha/year.

Table 3

technical parameters first generation ethanol production technology.

Item	2010 value (%)	Annual change ^f (%)	Maximum/minimal value (%)
Extraction efficiency ^a	96	1	100 ^g
Extraction losses ^b	0.5	0	0.2
Fermentation efficiency ^c	90	1	94.5 ^d
Distillation efficiency ^e	99	0.1	100 ^g

^a Historically the extraction yield improved from 92% to 97.5% for the best available technology, common average extraction efficiency 96% [12].

^b Extraction losses were reduced from 2% to 0.2% for the best available technology [12]. For extraction losses.

^c Fermentation efficiency improved from 83% to 91.2% nowadays by better yeast selection, microbiological and process control. Also the production time decreased, ethanol percentage in broth increased and large-scale continuous fermenters were developed. Best available technology fermentation steps reach efficiencies of 93% [12].

^d Given the chemical equations, the stoichiometric conversion of 1 kg sugars is 0.511 kg ethanol and 0.489 kg CO₂ [7]. Given the coproduction of glycerol, organic acids and yeast the maximal potential yield is 0.483 kg ethanol per kg of sugars (this represents 94.5% of the theoretical value) [7].

^e Due to improvements in process control and higher ethanol percentage ethanol distillation improved from 96% in the 1990s to 99.5% currently achieved [12].

^f The annual change is specified as the increase or decrease of the parameter as hand, for example the fermentation efficiency could increase to almost 100% with this annual increase in 10 years, if there would be no maximum scale specified.

^g For extraction efficiency and distillation efficiency no maximum value was found, therefore the maximum value is set to 100%, although debatable, no information was found on the practical limit of these efficiencies.

first-and-second generation plant. To enable fair comparison the scale of a second generation plant with an integrated first-and-second generation process, the dry tonne input (e.g. cane bagasse or eucalyptus wood) for the second generation process is similar. The electricity consumption for the basic and optimized second generation process are 218 and 190 kW h/tonne dry input respectively [28]. Steam consumption, mainly caused by the pretreatment section, is set to 1400 and 2300 kg steam/tonne dry input for the basic and optimized configuration [28].

4.3. Economic data for industrial processing

4.3.1. First generation technology

To assess the total equipment costs of a first generation industrial processing plant, the installation is broken down into 6 elements, see Table 5. The total installation costs of a basic first generation facility, capable of processing 2 million tonne cane would be around 172 MUS\$. This is in line with the investment range of 57–86 US\$ per tonne cane input [69], but higher compared to the 117 MUS\$ for a 2 million tonne cane processing plant as described by Macrelli et al. [38].

4.3.2. Second generation technology

A second generation facility is broken down into 8 main elements; feed handling, pretreatment, hydrolysis and fermentation, distillation, solid separation, waste water treatment, cogeneration and others, as shown in Table 6. The equipment costs of the different elements in second generation processing are predominantly based on the equipment costs as specified by Hamelinck et al. [28], Humbird et al. [46]. According to a review performed

on the size of the second generation process of an integrated first-and-second generation process. This scale is based on the processing of all available bagasse by-products of a sugarcane based

Table 4
Technical parameters second generation ethanol production technology.

Item	Basic set-up			Optimized set-up		
	Value (%)	Annual change (%)	Maximum value (%)	Value (%)	Annual increase (%)	Maximum value (%)
Glucan–glucose conversion ^{a,c}	75	1	80	91	1	95
Xylan–xylose conversion ^b	60	1	80	80	1	90
Arabinan–arabinose conversion ^b	60	1	80	80	1	90
Galactan–galactose conversion ^b	60	1	80	80	1	90
Mannan–mannose conversion ^b	60	1	80	80	1	90
Glucose–ethanol conversion ^d	80	1	95	90	1	95
Xylose–ethanol conversion ^e	75	1	90	75	1	90
Arabinose–ethanol conversion ^f	0	–	–	75	1	90
Galactose–ethanol conversion ^f	0	–	–	0	–	–
Mannose–ethanol conversion ^f	0	–	–	0	–	–

^a The conversion of glucan to glucose is set to 75% for the basic set-up in 2010, similar to the low end provided by Hamelinck et al. [28], given the trend between current and 2015 hydrolysis efficiency, as provided by Dias et al. [35], a maximum of 80% is assumed, well below the estimation of 91% of Humbird et al. [46].

^b Conversion of xylan, galactan and mannan sugars to xylose, galactose and mannose efficiency is set to 60%, similar to Dias et al. [35] and Humbird et al. [46], maximum value assumed are 80, in line with maximum values of basic set-ups of Humbird et al. [46]. For more advanced set-ups the conversion efficiencies are similar to xylan conversion [15].

^c Glucan to glucose conversion can be rather efficient, values found are in the range 90–98% [15], a current value of 91% is assumed, in line with [46] slowly increasing to 97% for future technologies [46].

^d The conversion of glucose to ethanol is in the range of 80–95% [35,46], therefore a current value of 80% and 90% are chosen for the basic and optimized set-up, with a maximum of 95% [46].

^e The range of efficiency for xylose to ethanol found is between 76% and 80–90% [28,46], both high-end values. A value of 75% is chosen as start point, with an increase to 90%.

^f For arabinose, galactose and mannose to ethanol conversion is neglected by Humbird et al. [46]; efficiencies have been set to 0% for the basic technology set-up. For the optimized set-up, conversion efficiency for arabinose to ethanol is assumed similar to xylan-ethanol based on Chovau et al. [15].

Table 5
Technical parameters second generation ethanol production technology.

Component first generation	Base scale	Investment base costs (MUS\$)	Scale factor	Maximum scale	Installation factor
Cane reception and juice extraction ^a	500 tonne cane/h	13.18	0.6	500	1.38
Juice treatment ^b	75 t ATR/h	5.264	0.71	–	1.84
Fermentation ^c	75 t ATR/h	14.14	–	75	1.88
Distillation and dehydration ^d	44 m ³ EtOH/hour	10.69	0.68	25	1.51
CHP ^e	362 MW _{HHV}	33.00	0.75	–	1.4
Other ^f	–	1.83	–	–	–

^a The investment costs of cane reception and juice extraction is based on the investment costs of Dias et al. [32] and the contribution of cane reception to total equipment costs, as specified by Júnior et al. [54] and Macedo et al. [48] provided information on the mills tandem sizing needed to provide 120,000 L ethanol/day, corresponding to 250,000 tonne wet sugarcane/year. The installed mill tandem size is 30" × 54" for sugarcane crushing. Given the mill tandem sizing estimating, as shown by Sugartech [67], the mill capacity of a 54" in. (roll diameter is assumed to be half of the roll length, roll speed 4 rpm and 14% fibre) diameter mill is about 94 TC/hour. A 102" in. roll diameter crusher, maximum size in the Sugartech equipment sizing calculator, would under the same parameter capable to process 542 TC/hour. Given an overcapacity of 25% this would be in the same range as the 500 TC/hour of Dias et al. [32]. Therefore, the base scale and maximum scale is set to 500 TC/hour.

^b The juice treatment section cover about 9% of the total equipment costs of a first generation industrial processing plant [54]. Given a total equipment costs of 150 MUS\$, for a 2 MTC/year processing plant [32], the juice treatment section would be around 5.26 MUS\$. Given that the main elements in the juice treatment section are tanks and settler, no maximum scale is assumed, with a scale factor of 0.71, based on the scale factor of a overliming tank as specified in Humbird et al. [46]. Given a sugar content of 14%, this means the juice treatment section specified by Dias et al. [32] is capable of processing 75 tonne TRS/hour. Although this unit is unconventional it does enable to scale the equipment for cane with a variety of sugar content; like the difference between sugarcane and energycane, given all other parameters remain constant.

^c The fermentation section in total covers 25% of the total equipment costs of a first generation industrial processing plant [54], which would represent 14.14 MUS\$₂₀₁₀/2 M tonne installation [46]. Most of the scale factors have been found in Humbird et al. [46]; this sources does not specify a scale component for fermenters. As the maximum scale is similar to the scale of the costs source, we consider no scale effect: a 2 million tonne sugarcane per year processing plant corresponds to a flow of 75 tonne TRS/hour. Given a continuous fermentation process, with a production time of 8.5 h [12], and the scale of fermentation tanks between 300 and 3000 m³ [68], the max processing capacity is 75 tonne TRS/hour, based on a specific density of slurry of 1 kg/L and a sugar content of 22.5 wt% [32].

^d A distillation section does represents 15% of the equipment costs of a 2 million (500 TC/hour) first generation plant, resulting in 10.69 MUS\$/plant [54,32]. The maximum scale for distillation is assumed to be 25 m³ ethanol/hour as specified for distillation of ethanol for second generation [46]. A scale factor of 0.68 is applied [46]. With an ethanol yield of 88 L ethanol/TC and a sugarcane processing capacity of 500 TC/hour would yield 44 m³/hour [32]. For the optimized technology an increase of 10% is assumed for the use of molecular sieves [32].

^e The largest share of equipment costs are spend on the cogeneration unit to convert residues (cane bagasse, cane trash or lignin-rich residues) into steam and electricity for the process and surplus electricity. Dias et al. [32] provided an investment costs of 33 MUS\$₂₀₀₉ for a 375 MW (Dias et al. [33] provided the LHV of bagasse as 7.565 MJ/kg (50% moisture); which corresponds to a HHV of 18 MJ/kg given a hydrogen fraction of 0.062, evaporation heat of water of 2.26 MJ/kg, and a water mass of 8.9 (kg/kg) [76].) CHP unit [32]. No maximum size for a combined heat and power unit was found, therefore, no maximum scale is assumed. A scale factor of 0.75, similar to the scale factor of a combustion reactor [46]. The scale of the CHP unit is designed on the HHV of the residue input (18 MJ/kg for bagasse). For the use of high pressure boilers a 40% increase in equipment costs is assumed, similar to Dias et al. [32].

^f Given the percentages of the total capital investment costs of a first generation plant, as provided by Júnior et al. [54], an additional 6%, or 1.83 MR\$ is added as additional costs.

by Chovau et al. [15], the total equipment costs of these publications are on the high end of the spectrum, but result in low ethanol production costs due to the high industrial conversion efficiencies.

4.4. Sensitivity analysis

The different variables used in the sensitivity analysis are depicted in Table 6.

Parameter	Value of standard sensitivity analysis (%)	Value of regional sensitivity analysis
Land costs	– ^a	456/190/216 US\$/ha ^b
Sugarcane yield	50–120 ^c	60–115%/40–85%/ 60–120% ^d
Eucalyptus yield	50–120 ^c	65–135%/60–110%/ 60–120% ^e
Fertilizer prices	70–130 ^f	
Capital investment	70–130 ^g	
Ethanol yield	70–105 ^h	
Electricity revenues	70–160 ⁱ	

^a Land costs are not varied for the general sensitivity analysis.

^b Land costs for Sao Paulo, Mato Grosso and Mato Grosse do Sul respectively, based on the variation in land costs for agricultural land historically, based on Gasques et al. [47].

^c The yield variation found in sugarcane cultivation in the conventional sugarcane cultivation area and the expansion regions is between 55 and 105 TC/ha year, therefore a yield variation of 50–120% is chosen [25]. A similar yield variation is selected for eucalyptus.

^d For sugarcane yield a variation of 60–115% is considered for Sao Paulo. For Mato Grosso (40–85%) and Mato Grosso do Sul (60–120%) similar ranges are considered; the ranges relate to the base value of Sao Paulo [70].

^e For eucalyptus a yield variation compared to the base value of Sao Paulo of 65–135% (Sao Paulo), 60–110% (Mato Grosso) and 60–120% (Mato Grosso do Sul) based on the current average yield [60], and the variation in yield found in field plot [29].

^f Due to the variation in fertilizer prices found, the fertilizer prices for all types of fertilizers range between 70% and 130%.

^g For capital costs the range is set to 70–130%, similar to Chovau et al. [15].

^h The ethanol yield for first generation is reaching practical limits and is highly robust, for second generation processing however, the ethanol yield is less certain. Given the variation in ethanol yield found by Chovau et al. [15] for second generation processing 290–385 L ethanol/dry tonne input, a range of 70–105% is considered, as the ethanol yield considered in this analysis are at the high end of the spectrum and reaching theoretical limits.

ⁱ Electricity revenues may vary greatly; Dias et al. [35] valued electricity revenues up to 0.091 US\$/kW h, while Chovau et al. [15] ranged between 0.058 and 0.078 US\$/kW h. A range of 70–160% is considered, compared to our base value, to determine the impact of fluctuating electricity revenues.

5. Results

5.1. Current and future biomass cultivation costs

In Fig. 3, the breakdowns of biomass cultivation costs for sugarcane, energycane, sweet sorghum, eucalyptus and elephant grass are shown, expressed in US\$/tonne wet biomass and in US\$/G_{JHHV} (see Appendix SI.1 for heating values of the different biomass feedstock). The total cultivation costs are broken down into several components, e.g.: costs of land, machines, fertilizers, agrochemicals, seed/seedlings and other costs. The graph shows the bottom-up cultivation costs for São Paulo state. Due to the yield increase and the utilization of mechanized and ETC cane harvesting, the total cultivation costs decrease and the cost breakdown changes towards 2030. The costs of land, labour, and agrochemicals, (expressed in costs per hectare) are directly affected by yield. While costs related to the use of machinery (machine investment, operational labour, diesel, amount of seedlings used, machine maintenance and lubricants) are reduced due to the utilization of machinery. The fertilizer requirements are assumed to be directly linked to yield. Therefore, the fertilizer costs per tonne of cane remains constant over time. For energycane a similar trend is observed for the different costs elements. However, due to a stronger yield increase, the total cultivation costs are lower for energycane compared to sugarcane in 2030. As the ‘other’ costs are determined as fixed percentage of all other elements, the ‘other’ costs for energycane are lower as well.

For sweet sorghum, land costs are included in Fig. 3, even though sweet sorghum is used as complementary crop with cane which would exclude land costs as sweet sorghum is cultivation in between sugarcane rotations. The machinery costs are mainly determined by harvesting equipment. The costs of fertilizers (labelled as N-fertilizer costs), is the main cost component of sweet sorghum cultivation, caused by the high fertilizer input requirements.

For eucalyptus cultivation costs, the land and machinery costs are the most prominent factors of the total cultivation costs, while fertilizer costs only add a minor share. The total land costs are 14.0 US\$/₂₀₁₀/tonne wet eucalyptus in 2010, and total machine and machinery operation costs add up to 8.9 US\$/₂₀₁₀/tonne wet eucalyptus in 2010. The total machinery operation costs (operational labour, diesel, machinery, and machinery maintenance) consists predominantly of the harvesting costs of eucalyptus.

Elephant grass has a similar costs structure as eucalyptus, but next to land costs and harvesting costs (machinery, diesel, machinery maintenance) also fertilizer costs are important elements of the total cultivation costs. Total elephant grass plantation establishment costs (not shown) are relatively high, but are spread over the total biomass production of the total lifetime of the plantation (20 years).

5.2. Total ethanol production costs based on first generation technology

In first generation ethanol production, sugarcane, energycane and sweet sorghum are processed to ethanol and bagasse and cane-trash are converted to electricity. The annual amount of sweet sorghum used in the industrial processing facility is corrected for the potentially available production of sweet sorghum on cane-land between two consecutive cultivation cycles of sugar- or energycane. Figs. 4 and 5 show the improvement potential of changing from a basic to an optimized 1st generation technology, using energycane instead of sugarcane, complementing cane with sweet sorghum, and collecting and using cane-trash for (more) surplus electricity. Several (theoretical) combinations of biomass feedstock and industrial processing technologies are possible, only configurations which show the impact the utilized feedstock or choice of technology are shown. In short, the configurations shown in Figs. 4 and 5 are:

- Basic first generation technology using sugarcane (Basic 1G SC).
- Optimized first generation technology using sugarcane (Optimized 1G SC).
- Optimized first generation technology using sugarcane and sugarcane-trash (for a larger surplus of electricity) (Optimized 1G SCT).
- Optimized first generation technology using sugarcane, sweet sorghum and sugarcane trash (Optimized 1G SC + SST).
- Basic first generation technology using energycane (Basic 1G EC).
- Optimized first generation technology using energycane, sweet sorghum and energycane trash (Optimized 1G EC + SST)

Compared to 2010, all configuration show a decrease in total ethanol production costs towards 2030. This trend in the costs of ethanol production pathways is mainly determined by the reduced feedstock costs (as shown in Fig. 3), the higher ethanol yield (a combination of increased sugar content and improved industrial efficiency), and the lower specific investment costs due to the economy of scale (mainly in the cogeneration section). The most important improvement option is to increase the sugar content of sugarcane; this leads to higher ethanol yield per tonne of feedstock; but also to lower investment costs as the crusher is scaled

Table 6

Technical parameters second generation ethanol production technology.

Component second generation	Base scale	Investment base costs (MUS\$)	Scale factor	Maximum scale	Installation factor
Feed handling ^a	110 dry tonne/hour	6.50	0.6	110 dry tonne/hour	1.81
Steam explosion ^b	83 tonne dry biomass input/hour	1.70	0.78	83	2.36
LHW ^c	83 tonne dry biomass input/hour	3.06	0.78	83	2.36
On-site enzyme production ^d	50 kg cellulase/hour	2.62	0.8	50	2.03
SSCF reactor ^e	1.04 tonne EtOH/hour	0.80	0.8	–	1.89
CBP reactor ^e	1.04 tonne EtOH/hour	0.80	0.8	–	1.89
Distillation ^f	44 m ³ EtOH/hour	35.69	0.68	25	1.51
Solids separation ^g	10.1 tonne dry solids/hour	1.30	0.65	10.1	2.2
Water treatment, including digestion ^h	400 tonne waste water/hour	1.83	0.51	–	1.04
CHP ⁱ	362 MW	46.00	0.75	–	1.4
Other utilities ⁱ		6.00	1	–	–

^a Total equipment costs of the feed handling is 11.68 MUS\$₂₀₁₀, for an installation capable of handling 110 tonne dry/hour [46]. As the main component, the shredder, reached already its maximum scale at this capacity, a maximum scale of 110 tonne dry/hour is assumed, with a scale factor of 0.6 [46]. Overall for this section an installation factor of 1.81 is assumed [46]. For first-and-second generation installation this section is eliminated, as the sugar-crop is already shredded in the first generation process.

^b Steam explosion is currently being considered as a viable option for pretreatment. For steam explosion total equipment costs, including ion exchange and overliming, would result in an equipment costs of 5.4 MUS\$ (capacity 83 tonne/hour) [28].

^c A LHW reactor would cost around 3.06 MUS\$₂₀₁₀ for a 83 tonne dry biomass input/hour reactor. For both steam explosion and LHW a scale factor of 0.78 and an installation factor of 2.36 is assumed [28].

^d For the optimized technology (LHW pretreatment and on-site enzyme production) an enzyme unit is incorporated. A cellulase production unit capable of producing 50 kg cellulase/hour would cost 2.62 MUS\$, a scale factor of 0.8, installation factor of 2.03 [28].

^e Two main types are distinguished in this research; a SSCF reactor and a CBP reactor, but the equipment costs are similar for both, similar to Hamelinck et al. [28]. For both reactors the equipment costs are set to 0.80 MUS\$₂₀₁₀, to produce 1.04 tonne ethanol/hour, a scale factor of 0.8 and an installation factor of 1.89 [28].

^f Similar to the first generation ethanol dehydration, see Table 5.

^g The scale of the solids separation unit is based on the available residues; all residues not being converted to ethanol or CO₂. The equipment costs of 1.30 MUS\$ for an unit capable of processing 10.1 dry tonne/hour [28].

^h The digester is scaled based on the amount of waste water from the process, in line with [28] this is set to 9.4 tonne waste water per tonne ethanol produced [28]. Equipment costs are based on Hamelinck et al. [28].

ⁱ Similar to the cogeneration unit in first generation process, see Table 4.

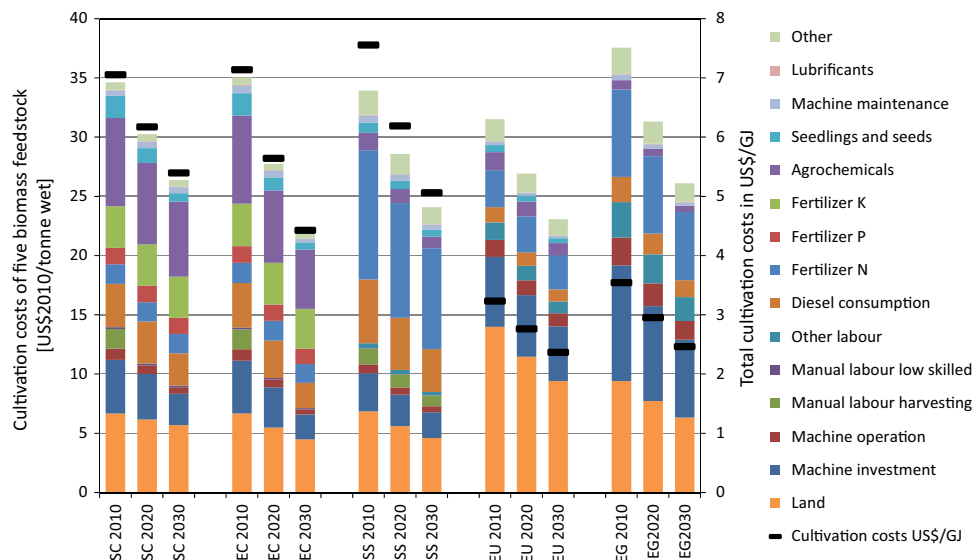


Fig. 3. Projected biomass cultivation costs of sugarcane (SC), energycane (EC), sweet sorghum (SS), eucalyptus (EU) and elephant grass (EG) in São Paulo state, in 2010, 2020 and 2030.

to the feedstock flow. For configurations utilizing sugarcane, the basic technology set-up is the most expensive configuration. An option to reduce the costs is to change from the basic to the optimized configuration, as the increased electricity revenues reduce overall ethanol production costs. By utilizing trash, the surplus electricity reduces the total ethanol production costs, despite the higher investment costs (of the cogeneration unit) and the costs related to the collection and transport of trash. The use of sweet sorghum leads to a minor reduction in the ethanol production costs, as the capital investment is spread over a larger ethanol output, but feedstock costs (sweet sorghum also has a lower sugar content) are higher.

For energycane, the lower sugar content leads to a reduced ethanol yield causing only a small reduction in total ethanol production costs for basic first generation technology; despite the lower biomass feedstock costs, increased industrial processing scale, and improved industrial efficiency. Over time the ethanol production costs even increase, as the benefits of low feedstock costs and increased efficiency are counteracted by the lower sugar content. The use of sweet sorghum with energycane and cane-trash with optimized first generation technology reduces the costs compared to the basic first generation technology with energycane.

The transportation costs of biomass, from field to industrial plant have a small share in total ethanol production costs. The

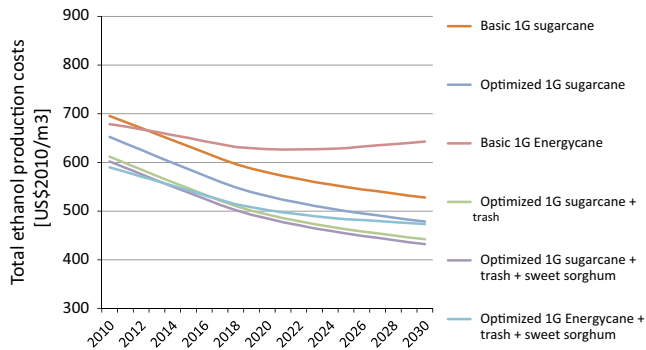


Fig. 4. Ethanol production costs of the different first generation configurations between 2010 and 2030; using combinations of sugarcane, energycane and sweet sorghum.

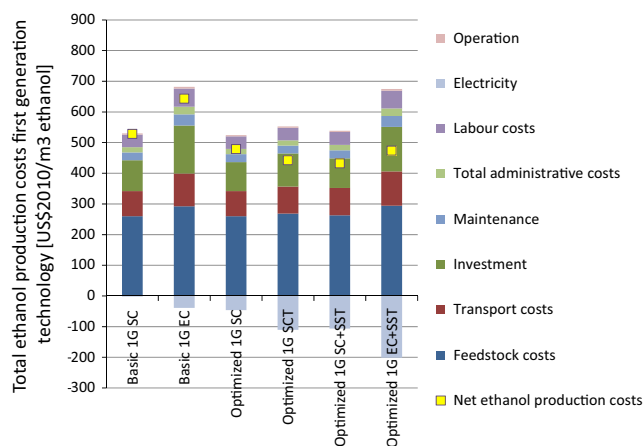


Fig. 5. Ethanol production costs breakdown of the different first generation technologies in 2030, using combinations of sugarcane, energycane and sweet sorghum.

costs of transportation are dominated by the capital costs of the truck and trailer and the diesel expenses.

5.3. Total ethanol production costs based on second generation technology

The use of second generation technology enables ethanol production of lignocellulosic biomass like eucalyptus and elephant grass, but also sugarcane bagasse and trash. Fig. 6 gives an overview of the trend in total ethanol production costs of second and integrated first-and-second generation processes. For second generation processing a basic and an optimized technology processing eucalyptus and elephant grass are considered. In Fig. 7, the cost breakdowns of selected second generation and integrated first-and-second generation processes are shown.

In short, the selected configurations in Figs. 6 and 7 are:

- Basic second generation technology using eucalyptus (Basic 2G EU).
- Basic second generation technology using elephant grass (Basic 2G EG).
- Optimized second generation technology using eucalyptus (Optimized 2G EU).
- Optimized second generation technology using elephant grass (Optimized 2G EG).
- Optimized 1G and basic 2G technology using sugarcane (Basic 1 + 2G SC).

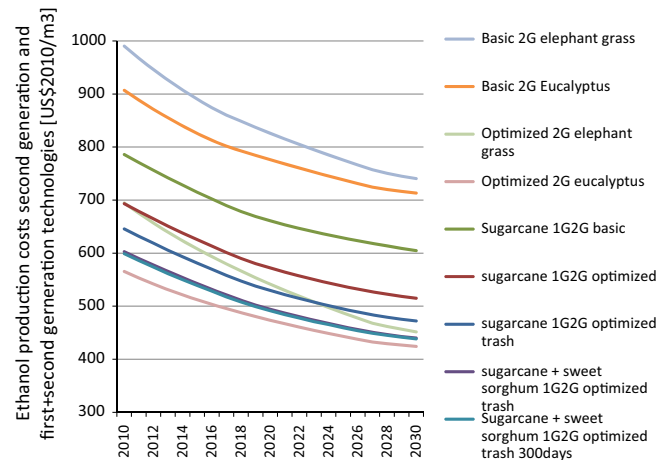


Fig. 6. Ethanol production costs of the different second and integrated first-and-second generation configurations between 2010 and 2030; using eucalyptus, elephant grass or combinations of sugarcane, energycane and sweet sorghum.

- Optimized 1G and optimized 2G technology using sugarcane, utilizing bagasse during sugarcane harvest season (Optimized 1 + 2G SC).
- Optimized 1G and optimized 2G technology using sugarcane, utilizing bagasse and cane trash during sugarcane harvest season (Optimized 1 + 2G SCTr).
- Optimized 1G and optimized 2G technology using sugarcane and sweet sorghum, utilizing bagasse and cane trash during sugarcane harvest season (Optimized 1 + 2G SC + SSTr).
- Optimized 1G and optimized 2G technology using sugarcane and sweet sorghum, utilizing cane trash during harvest season, utilizing bagasse outside sugarcane harvest season (Optimized 1 + 2G SC + SSTr 300 days).

The reduction in total ethanol production costs of the different configurations are caused by the increased efficiency for industrial processing (both first generation and second generation), increased scale and reduced feedstock costs over time. For the optimized second generation technology utilizing eucalyptus, the reduced feedstock costs and improved industrial efficiency are the dominant factors. The economy of scale plays a minor role. Given the increase in industrial efficiency and the decrease in feedstock costs, second generation technologies have a stronger reduction in total ethanol production costs, compared to first or first-and-second generation technology.

The industrial processing costs of the basic and optimized second generation process follow a similar trend as first generation processing. The main difference between the basic and optimized second generation technology is the on-site enzyme production, which excludes the costs for cellulose for the optimized configuration. Investment costs remain the dominant factor in the total ethanol production costs of second generation industrial processing. Prominent elements in the total investment costs are the equipment costs of the cogeneration unit (38% of total equipment costs), the pretreatment (17%), and the distillation and solid separation sections (combined 18%). When commercially available the optimized second generation industrial processing is preferred over the basic second generation process, as conversion efficiencies of the optimized process are higher. Furthermore, the operational costs are reduced (no cellulose costs); the little additional investment is easily compensated by the reduced operational costs and higher ethanol output.

The integrated first-and-second generation processes use sugarcane as feedstock for ethanol production. The overall ethanol yield

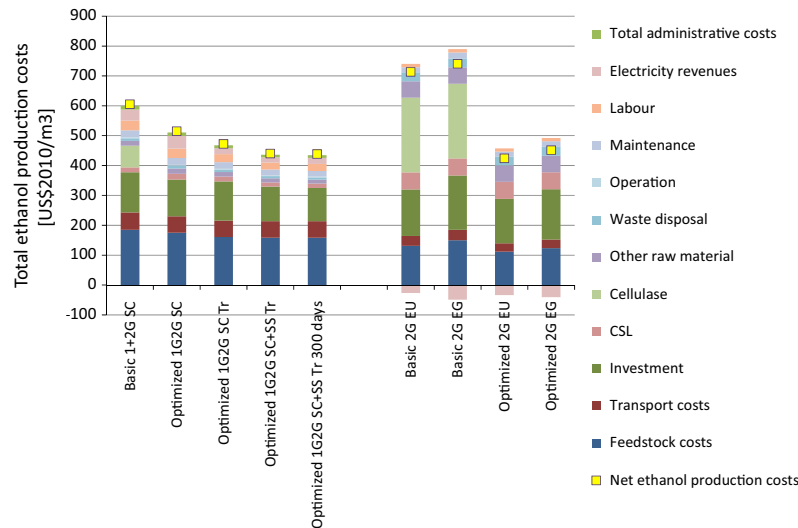


Fig. 7. Ethanol production cost breakdowns of the different second and integrated first-and-second generation technologies in 2030, using eucalyptus, elephant grass or combinations of sugarcane, energycane and sweet sorghum.

is mainly determined by the first generation part of the installation, and the total ethanol yield of sugarcane is superior to energycane. Therefore, the overall ethanol production costs of sugarcane are more favourable compared to energycane cellulase from an economic point of view. The ethanol yield of the first generation process mainly increases due to the sugar content of sugarcane, while in energycane the fibre content increases at the expense of the sugar content. Interesting is that the optimized second generation technology using eucalyptus follows a similar trend as the best performing integrated first-and-second generation processes, despite the difference in feedstock, conversion efficiencies, and capital investment costs.

5.4. Sensitivity analysis total ethanol production

5.4.1. Sensitivity analysis individual parameters

In Fig. 8a–c, the sensitivity of the total ethanol production costs of the best performing first, second and first-and-second generation industrial processing configurations is shown. The total ethanol production costs are determined for first generation optimized process fed with sugarcane, cane trash and sweet sorghum, optimized second generation processing using eucalyptus and the use of sugarcane in optimized first-and-second generation process. For biomass yield, capital expenses, ethanol yield, electricity revenues and fertilizer prices a variation is chosen given their

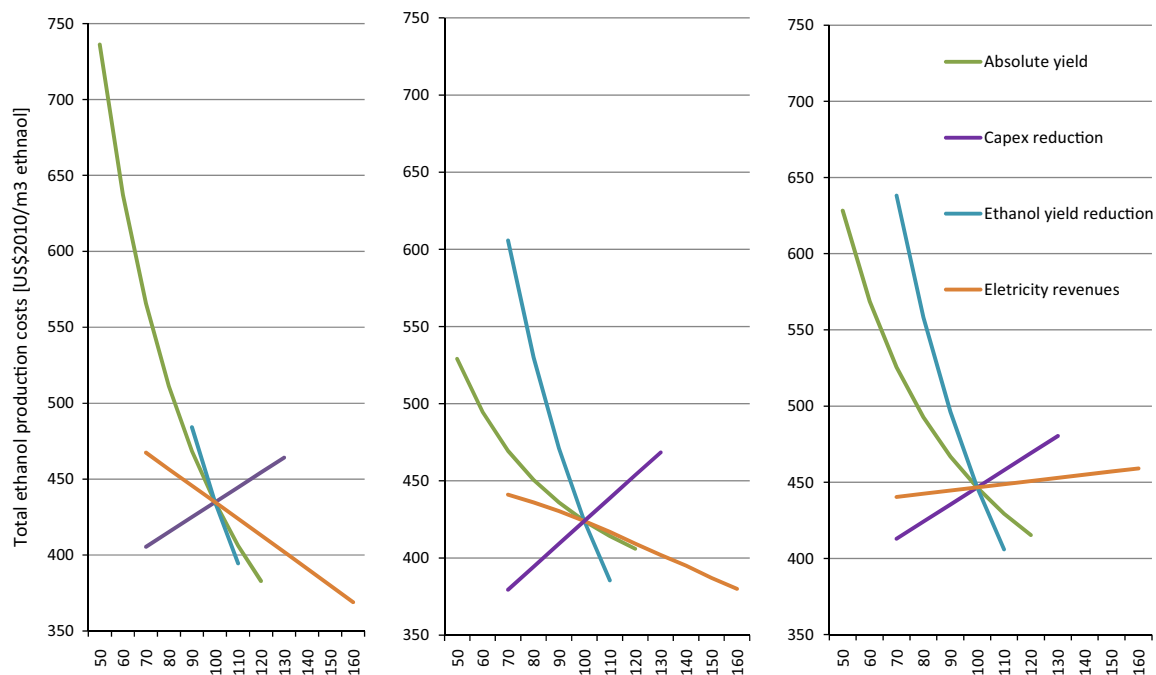


Fig. 8. Left: Sensitivity analysis of ethanol production costs of first generation optimized technology with sugarcane, sweet sorghum and cane-trash. Centre: Sensitivity analysis of optimized second generation technology with eucalyptus. Right: Sensitivity analysis of optimized first-and-second generation technology with sugarcane, sweet sorghum and cane trash. On the x-axis the percentage change of the base figure.

potential ranges, see methodology section. For the selected configurations the total ethanol production costs are most sensitive to biomass yield and ethanol yield on biomass. As seen in Fig. 5, biomass feedstock costs are an important element in first generation processing, therefore, first generation ethanol production costs are most sensitive to yield variation. The yield variation impact especially biomass cultivation costs, but also transport costs, as transport distances increases with decreasing yield. For second generation technology a change in ethanol yield has a high impact on total ethanol production costs. A change in ethanol yield does impact most costs components (apart from the operational expenses linked to ethanol yield), including biomass feedstock costs, transport costs and capital expenses. As depicted in Fig. 7, the total ethanol production costs of the optimized configurations are dominated by capital expenses, which could affect ethanol production costs, as seen in Fig. 8b. The integrated first-and-second

generation configuration is most sensitive to ethanol yield, biomass yield and capital expenses.

5.4.2. Region selection for ethanol production

Taking into account the importance of yield in overall ethanol production costs as presented in Fig. 8, and the importance of land costs in cultivation costs (see Fig. 3), a regional sensitivity analysis is performed. For São Paulo, Mato Grosso and Mato Grosso do Sul the combined effect of regional differences in yield and land costs on the total ethanol production costs are shown in Fig. 9. Fig. 9 provides insight in the ranking of the different configurations given the potential yield ranges in the three selected regions. As land costs are fixed per region, the ethanol production costs, as function of yield variation, follow a similar trend per configuration. At similar yield levels the region Mato Grosso would result in the lowest ethanol production costs per technology due to the low land costs. Second generation eucalyptus ethanol production is the most attractive option and is only little affected by yield reduction. Therefore, first generation sugarcane ethanol production is only attractive at higher yield. In Fig. 10, the yield ranges of the different technologies in the different regions are shown. For first generation processing the yield variation and the impact of yield on total ethanol production costs are much larger compared to second generation processing of eucalyptus.

6. Discussion and conclusion

6.1. Biomass cultivation costs

The main goal of this study was to determine detailed production cost structures of different ethanol production configurations in the state of São Paulo and potential expansion areas in Brazil. The development in total ethanol production costs were determined for first and second generation processing pathways between 2010 and 2030. The considered biomass feedstocks are sugarcane, energycane, sweet sorghum, eucalyptus, and elephant grass. As there is limited data available on the cultivation of energycane in Brazil, we have considered similar cultivation practices and inputs for energycane as for sugarcane. As no detailed data was found on the cultivation costs structures of eucalyptus and elephant grass in Brazil, the aggregated costs of mechanized plantation management practices of eucalyptus and elephant grass have been divided over the different elements (machine investment, operation labour, diesel, machine maintenance) with fixed factors based on sugarcane cultivation. This does not change the total cultivation cost, however, the disaggregation of total mechanized plantation management for eucalyptus and elephant grass plantations may be different.

Different elements in the cultivation costs structure are affected by biomass yield; overall, yield improvement is a prominent driver for cost reduction next to utilization of new machinery. For all five biomass crops, significant cost reductions can be achieved in the future. Yield increase is the main driver for all crops, whereas for sugarcane and energycane the utilization of novel harvest machinery may also reduce costs. The yield development is determined per biomass crop, using available literature regarding the yield outlook of these crops. Dominant elements in biomass cultivation costs are land and machinery costs (including machine investment, machine operational labour and diesel expenses). Machinery costs are mainly related to harvesting operations, especially for eucalyptus and elephant grass.

The main uncertainties of the biomass cultivation costs are the limited available data sources for a detailed cost breakdown of cultivation costs. The total cultivation costs are in line with other sources providing sugarcane cultivation costs [71,25] and sweet

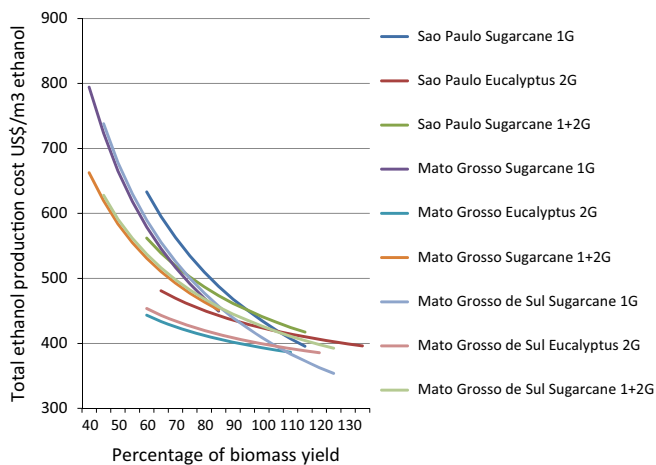


Fig. 9. Total ethanol production costs in US\$₂₀₁₀/m³ ethanol in 2030 for the three most promising configurations for the states of São Paulo, Mato Grosso and Mato Grosso do Sul given the variations in yield (as a percentage of the average yield level in São Paulo).

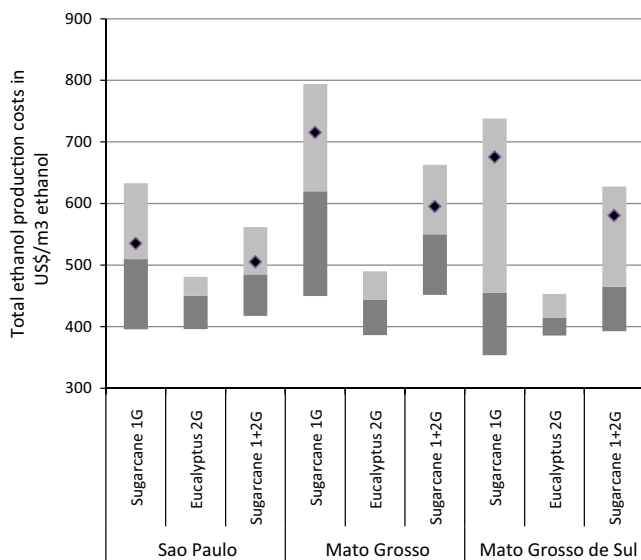


Fig. 10. Total ethanol production costs in US\$₂₀₁₀/m³ in 2030 for the different regions, given the regional variations in yield ranges and land costs. The grey boxes show the yield range of the 30% most suitable land. The range is extended to the 80% best performing suitability classes to give a larger range. The point indicates the yield levels of the largest land class in the respective regions.

sorghum cultivation costs [72]. No information was found on the cultivation costs of energycane in Brazil, so unfortunately our results cannot be compared to other studies. Minor information was found on the costs of cultivation practices and cultivation inputs of eucalyptus and elephant grass, but overall cultivation costs are in line with De Wit et al. [45] and Queno et al. [56]. The study of Crago et al. [73] compared Brazilian sugarcane ethanol production with USA ethanol production using corn. Despite the use of different categories for the detailed cost breakdown, Crago et al. [73] showed the importance of total machine cost, fertilizers and chemicals in total Brazilian sugarcane cultivation, while land cost play a relatively small role, compared to our results. In the publication of Crago et al. [73] land costs are based on the leasing cost, related to the yield and potential price of total recoverable sugars in sugarcane for 2007. Corn cultivation cost in the USA are more dependent on land costs, while also fertilizers and machinery play a reasonable share [73].

6.2. Transportation costs

The costs of biomass transportation play a minor role in total ethanol production costs. This is in line with sugarcane transportation costs as provided by XAVIER et al. [25]. Local conditions regarding road network, land availability, distribution of land, biomass yield and scale of the industrial plant affect transportation costs of individual industrial plants. The assumed increase in capacity of the ethanol plant would require longer transportation distances. However, this is counteracted by the assumed increasing biomass yield over time. Transport distances are the main determining factor of transportation costs, which may vary per location due to the local conditions. Between the different biomass feedstock only minor differences in transport costs have been observed. Although eucalyptus has a lower moisture content compared to sugarcane, resulting in lower transport costs per dry tonne, the ethanol yield per tonne eucalyptus is lower, which would increase transportation costs if expressed per m^3 of ethanol. Overall, feedstock transportation costs per m^3 of ethanol are similar.

6.3. Industrial processing

The industrial processing costs, excluding feedstock and transport costs, are dominated by the capital investment costs of the industrial plant. Especially for second generation capital costs are an important share in industrial processing costs, but also in the total ethanol production costs. A higher ethanol yield would reduce depreciation of capital investment, expressed in US\$ per cubic metre of ethanol. The ethanol yield of first generation processing is in line with other studies [12,25,32]. As the ethanol yields reach their maximum operational efficiency, a further increase in ethanol yield (without an increase in sugar content) seems hardly possible. For several first generation ethanol production pathways, a considerable cost reduction can be achieved in the future. This is due to reduced feedstock costs: a combination of increases in yield and sugar content, utilization of cane-trash and sweet sorghum, increase in industrial efficiency, the use of more efficient cogeneration, and economies of scale. The dominant drivers of cost reductions are the increase in sugar content and the use of cane-trash, the latter one resulting in higher electricity revenues. As the ethanol yield of energycane is lower compared to sugarcane, energycane has higher ethanol production costs, even with lower biomass cultivation costs. In general, the most economically attractive option involving first generation technology is the use of sugarcane, sweet sorghum and cane trash in an optimized first generation industrial facility. Energycane is not an attractive option for first generation processing. Total first generation ethanol production costs are in line with other studies (e.g.

[73,25], but substantial lower compared to Tao and Aden [74]. The lower costs found by Tao and Aden are most likely a result of their more optimistic assumptions regarding feedstock costs (26 US\$₂₀₀₅/tonne sugarcane), scaling factors (overall 0.6), and plant operation time (350 days/year). The Brazilian ethanol production costs in 2010 found in this study are in the lower range of the production costs of corn based ethanol in the USA, which are approximately between 460 and 860 US\$₂₀₁₀/m³ ethanol [1]. For second generation industrial processing, large cost reductions can be achieved. The ethanol output of second generation processes are less certain as those processes are still in the research and development stage. The efficiencies for second generation processing assumed in this study, reaching 90% of its theoretical maximum in 2030, are relatively uncertain, especially for the optimized technology. If the efficiencies for second generation industrial processing do not reach the level anticipated in this research, the total ethanol production costs are heavily affected, making second generation ethanol economically less attractive. A shift from the basic process to the optimized process is potentially a major step in reducing ethanol production costs. Further reduction in ethanol production costs can be obtained by increasing the conversion efficiency and reducing biomass cultivation costs. Due to a more favourable biomass composition, eucalyptus is a preferred feedstock over elephant grass, as the ethanol yield is higher. Capital expenses remain the largest costs factor of second generation industrial processing. As industrial efficiencies have not been proven yet at large scale, ethanol production costs of second generation industrial processing are less robust compared to first generation configurations. Studies showing the ethanol production costs of second generation feedstock in Brazil were not found. An economic assessment of ligno-cellulosic feedstock in the USA showed ethanol production costs in line with the optimized configuration. Gonzalez et al. [75] showed the ethanol production cost of eucalyptus (590 US\$/m³ ethanol) and switchgrass (660 US\$/m³), the later one having a higher cultivation costs and less favourable composition compared to eucalyptus in the USA. The ethanol production cost of Gonzalez et al. [75] are lower compared to the basic second generation processing options, however, for the optimized configuration the ethanol production cost are similar for 2010. Interestingly, Gonzalez et al. [75] showed similar cost breakdowns of second generation ethanol production compared to this analysis, namely 35% for biomass feedstock and 31% for capital depreciation.

The potential cost reduction of integrated first-and-second generation processes are based on the reduction of biomass feedstock costs, increased sugar content, increased industrial efficiency (both for the first and second generation processes) and utilization of sweet sorghum and cane trash.

The electricity revenues as specified in this study are important for first generation industrial processing configurations [39], and to a lesser extent for second generation industrial processing. The future prices for biomass-derived electricity are highly uncertain. The electricity surplus for first generation processing is based on the utilization of efficient boilers and consumption of trash. It is uncertain whether a 50% trash recovery is feasible and sustainable, or if an even higher recovery rate is possible. If cane trash cannot be recovered, and the electricity revenues decrease, the total ethanol production costs will increase, especially for first generation processing. The methodology to estimate the electricity surplus is a simplified approach compared to e.g. Hamelinck et al. [28]. A detailed technical modelling approach could improve the robustness of the results on the electricity surplus.

6.4. Overall ethanol production costs

The total ethanol production costs are expressed as potential costs of the best available technology in the year under research

(between 2010 and 2030). With the increase of industrial scale, biomass yield, and industrial efficiency, the ethanol production costs decrease over time. To attain this at commercial scale, especially for second generation technologies, significant investments and research and development are necessary for the corresponding ethanol production pathways.

As the total ethanol production costs are determined by many parameters, the sensitivity analysis showed the impact of the most important parameters. The general sensitivity analysis shows the impact of biomass yield, ethanol yield, capital investment and electricity revenues. Biomass yield, especially for first generation processing, and ethanol yield, especially for second generation processing, are the most important parameters in total ethanol production costs. Potentially attainable ethanol output in the future is uncertain, especially for second generation processing, as those industrial efficiencies or sugar content have not been realized at commercial scale. The biomass yield may vary according to local conditions like soil, weather and cultivation management style. Combining the potential biomass yield and variation in land costs in Sao Paulo, Mato Grosso, and Mato Grosso do Sul provides insights in the most promising configurations in these regions until 2030. Land costs have a considerable share in biomass cultivation costs, especially for eucalyptus and elephant grass, therefore, second generation ethanol production is economically most attractive in regions with low land costs. Land costs and biomass yield may vary considerably within the regions and from region to region. Furthermore, a potential link between biomass yield and potential land costs and link between land costs and large-scale biomass cultivation are not included.

Overall, significant reductions can be achieved in ethanol production costs in Brazil. Important drivers are biomass yield, sugar content and industrial processing efficiencies; the economies of scale play a minor role. Biomass yield increase seems an evident option to reduce costs, but yield increase in terms of dry matter should not be at the expense of favourable characteristics, such as the sugar content of sugarcane, or the glucan content of lignocellulosic feedstock. Furthermore, also transportation costs can be reduced when biomass yield is increased, but this only has a marginal impact on total production costs. The anticipated increase in conversion efficiency of biomass to ethanol holds great potential for cost reduction, especially for second generation processing. First generation industrial processing is already used at commercial scale and its efficiencies are already high.

Ultimately, especially in the current Brazilian context, the pathways involving sugarcane and (optimized) first generation technology are considered likely scenarios, as the transition to optimized configurations can be done in incremental steps (both for cultivation and conversion). While a radical shift to eucalyptus and second generation on the short term seems less likely in the Brazilian context, this study shows that optimized second generation ethanol production using eucalyptus may ultimately result in competitive overall production costs. Introduction of these pathways will also depend on the success of ongoing Brazilian and worldwide RD&D efforts to further develop and commercialize second generation technologies.

The detailed ethanol production cost breakdown provides insight in the important cost elements and the potential for improvement. This can be used for biofuel support policies, research and development strategies and strategic decisions of the ethanol industry. The results indicate that in the future second generation industrial processing might have the lowest production costs. An important prerequisite is the development of commercial scale, highly efficient second generation processes. All configurations can benefit from crop improvement to improve yields while holding, or even improving sugar content. Future research should focus on crop improvement, research and utilization of

improved industrial processing pathways, and detailed supply chain analysis. Furthermore, the adjoining regions of Sao Paulo state have the potential to become economically attractive ethanol production regions. The utilization of these regions would require suitable biomass varieties, and proper road infrastructure for biomass supply to the plant and the distribution of ethanol to users. Although, the total costs are important for the economic viability of ethanol production, the selection of biomass feedstocks and conversion technologies should also be based on the potential environmental and socio-economic impacts, including the impacts of land use change. Therefore, future research should focus on an integrated impact assessment of bioethanol supply chains to enable a sustainable expansion of the bioethanol sector in Brazil.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apenergy.2015.01.090>.

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