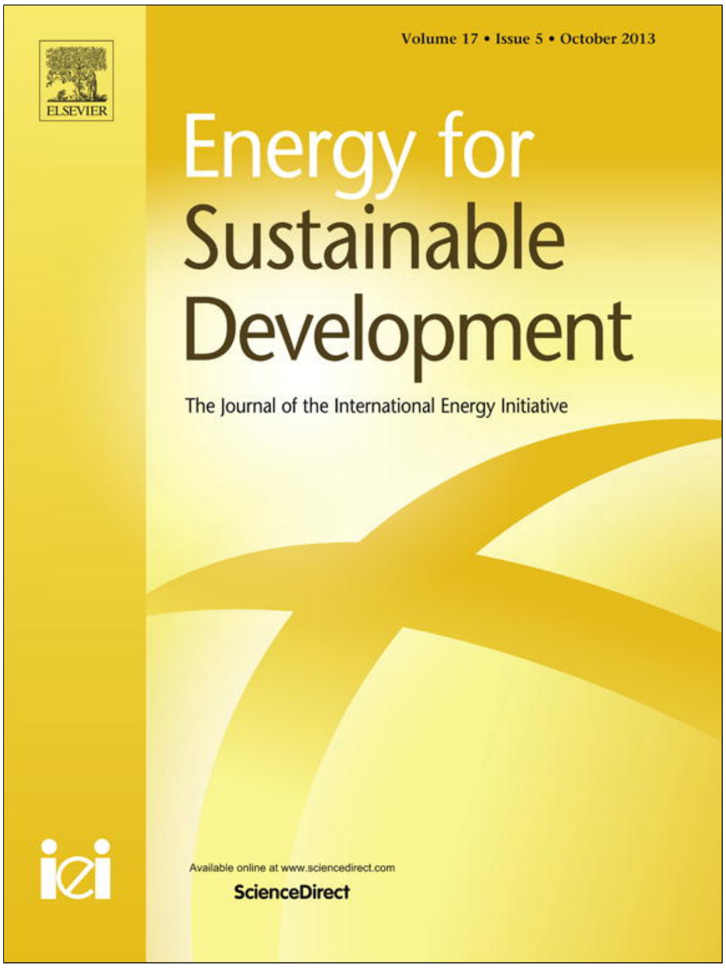
Volume 17 • Issue 5 • October 2013
ELSEVIER
Energy for Sustainable Development
The Journal of the International Energy Initiative
iei
Available online at www.sciencedirect.com
ScienceDirect

Energy for Sustainable Development 17 (2013) 531–535

Contents lists available at ScienceDirect

Energy for Sustainable Development

Reduction of water consumption in an integrated first- and second-generation ethanol plant

K.J. Mosqueira-Salazar [a], R. Palacios-Bereche [b], M. Chávez-Rodríguez [c], J. Seabra [a], S.A. Nebra [a,b,d,*]

[a] Mechanical Engineering Faculty, University of Campinas, SP, Brazil
[b] Centre of Engineering, Modelling and Social Sciences, Federal University of ABC, Santo André, SP, Brazil
[c] Energy Laboratory, Pontifical Catholic University of Peru, Lima, Peru
[d] Interdisciplinary Centre for Energy Planning, University of Campinas, Campinas, SP, Brazil

ARTICLE INFO

Article history:
Received 20 February 2013
Revised 31 July 2013
Accepted 1 August 2013
Available online 28 August 2013

Keywords:
Water
Sugarcane
Hydrolysis
Ethanol
Second generation

ABSTRACT

The aim of this study was to estimate the increase in industrial water consumption and withdrawal in a conventional sugarcane ethanol mill due to the introduction of second-generation ethanol production by a bagasse hydrolysis process, and to identify opportunities of water reuse, in order to minimize water withdrawal. Simulations in ASPEN PLUS® software were performed for mass and energy balances. Three cases were evaluated: a conventional ethanol production plant (Case I), and two second-generation plants incorporating bagasse hydrolysis differing only in their glucose concentration processes, namely by evaporation (Case II), and by membrane separation (Case III).

Results show that external withdrawals of 738 L/t of cane for Case I, 955 L/t of cane for Case II and 853 L/t of cane for Case III are required to cover the water deficit of the plant. These values are lower than the mandated limit of 1000 L/t of cane for the sugar cane industry in the State of São Paulo. Moreover, for Cases II and III, which need large additional amounts of water for the hydrolysis stage, water usages of 10.77 and 9.38 L of water per litre of ethanol produced were achieved, approaching the figure of 9.34 L water per litre of ethanol produced by the conventional plants (Case I). This highlights the high potential for reduction practices based on the concept of energy and water integration.

Introduction

Production and consumption of biofuels grew rapidly in recent years. However, this has raised questions regarding their sustainable production throughout the supply chain. Among them, water use may become as important as the indirect land-use change issue or the food-versus-fuel battle (Dale, 2011; Zuurbier and van de Vooren, 2008).

Water is necessary in two steps during biofuel production: in crop production, and in the industrial stage. Since sugarcane in São Paulo State is mainly a rain-fed crop, the industrial stage of ethanol production accounts for most of the blue water consumption (Chavez-Rodriguez and Nebra, 2010). Previous studies have been done for water consumption minimization in the production of first-generation ethanol from sugarcane (Chavez-Rodriguez, 2010; Chávez-Rodríguez et al., 2011; Elia Neto, 2009; Jannuzzi et al., 2012).

Sugarcane bagasse, as well as other lignocellulosic materials, can also be used for ethanol production. However, from the perspective of energy and water use, the introduction of bagasse hydrolysis in the current ethanol production system is a real challenge, because bagasse, used as fuel in the current process, would become the feedstock in the new one (Palacios-Bereche, 2011; Palacios-Bereche et al., 2011, 2012a, 2012b). Thus, the aims of this study are to estimate the increase in industrial water consumption and withdrawal in ethanol production by the bagasse hydrolysis process, and to identify opportunities of reuse with the purpose of water withdrawal minimization.

Materials and methods

Ethanol production process simulation

In order to estimate the water demand and assess the reuse potential in an autonomous distillery (first-generation ethanol), as well as in an integrated plant for second-generation ethanol production, we used the simulation described in (Palacios-Bereche, 2011; Palacios-Bereche et al., 2011). The simulations were modelled in Aspen Plus®, based on data collected from the literature, as well as actual data for the case of the conventional process, and experimental data for the case of second-generation process. The basic characteristics of the modelled plant are: mill capacity, 2,000,000 t cane/year; crushing rate, 500 t cane/h; season operations hours, 4000 h/year; bagasse production, 277 kg/t cane; steam consumption, 500.9 kg/t cane; anhydrous ethanol production, 79 L/t cane.

* Corresponding author at: Centre of Engineering, Modelling and Social Sciences, Federal University of ABC, Santo André, SP, Brazil. Tel.: +55 11 49968215.
E-mail address: silvia.nebra@pq.cnpq.br (S.A. Nebra).

0973-0826/$ – see front matter © 2013 International Energy Initiative. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.esd.2013.08.001

The plant simulated for Case I represents the typical operating parameters and process configuration of the current Brazilian industry, and comprises the following operations: cleaning, preparation and extraction, cogeneration, juice treatment, juice concentration, must preparation, fermentation, distillation, and dehydration for anhydrous ethanol production. For Cases II and III, part of the sugarcane bagasse is used as feedstock for second-generation ethanol production by means of an enzymatic hydrolysis process with a steam explosion pretreatment. A block flow diagram of the integrated first- and second-generation ethanol production from sugarcane is shown in Fig. 1.

In the integrated process, the glucose liquor needs to be previously concentrated to meet the conditions suitable for fermentation. Two systems were examined for liquor concentration: multiple effect evaporation (Case II), and membrane separation (Case III). Six assessment scenarios were generated by combining each of the two concentration systems with three levels of solids load for enzymatic hydrolysis. The scenarios were named EV5, EV8 and EV10 for Case II, and ME5, ME8 and ME10 for Case III. The main operational characteristics for Cases II and III are shown in Table 1.

Table 1
Operational parameters for the integrated first- and second-generation ethanol production plant.

Parameter	Value					
	EV5	EV8	EV10	ME5	ME8	ME10
Steam consumption (kg/t of cane)	793.2	754.7	742.3	689.8	690	690.2
Bagasse for enzymatic hydrolysis (kg/t of cane)	110.3	149.5	172.7	195.9	206.2	212.4
Trash processed (kg/t of cane)	78	78	78	78	78	78
Anhydrous ethanol production (L/t of cane)	86.7	88.1	88.7	92.6	91.5	90.9

Water consumption in the simulated plant

The water consumption estimate in the industrial process took into account all water demands. To represent them, the plant was simulated without any closed circuit for reuse, and adopting average water consumption rates found in the literature, and in actual mills. Table A1 of the Appendix A shows the water streams and their parameters for all three cases. A value of 13.68 m3/t of cane crushed was reached for Case I — less than the 15 m3/t of cane for the same purpose reported by Elia Neto (2009) and Hugot (1986). The difference is due to the adoption of a dry cleaning system, which consumes less water than the conventional water washing system, and barometric condensers instead of multi-jet condensers. Water requirements in the distillation and dehydration systems correspond to 31% of the total water used in the plant.

In second-generation ethanol production, new processes, such as pre-treated biomass washing (xylose washing), and enzymatic hydrolysis, significantly increase water consumption. The large volume of must resulting from the fermentation step increases water requirements for cooling must and vats; this represents on average 40% of the total consumption. Liquor concentration by evaporation in Case II significantly increases water consumption for the barometric condenser, leading to a higher total demand than in Case III (concentration by membrane).

Water savings by closing circuits

The large amounts of water spent in the production of first-generation ethanol have led Brazilian mills to adopt the practice of closing circuits, whether by treating effluents (regeneration), or by reusing them directly. Typical choices for closing circuits are: cooling tower water, spray pond cooling water, scrubber water from boiler, and boiler blowdown. In the present study, some losses were assumed in each of them (Elia Neto, 2009; Ensinas and Ensinas, 2008; Hugot, 1986; Pizaia et al., 1999). In Appendix A, two tables were included; the first one shows the water consumption for each process without any kind of reuse, the second one shows the water consumption considering that all the circuits before mentioned were closed.

With this practice, the effective water demand for Case I has dropped to 1070 L/t cane for the process as a whole. This is a reduction of about 80–90%, demonstrating the massive impact of closing circuits. Nevertheless, an integrated production of first- and second-generation ethanol would shoot up demand to 3000 or 4000 L/t cane — substantially higher than the base case.

Water streams for reuse in the simulated plant

The next step was the identification and quantification of candidate reuse water streams to supply the needs of the plant. For the

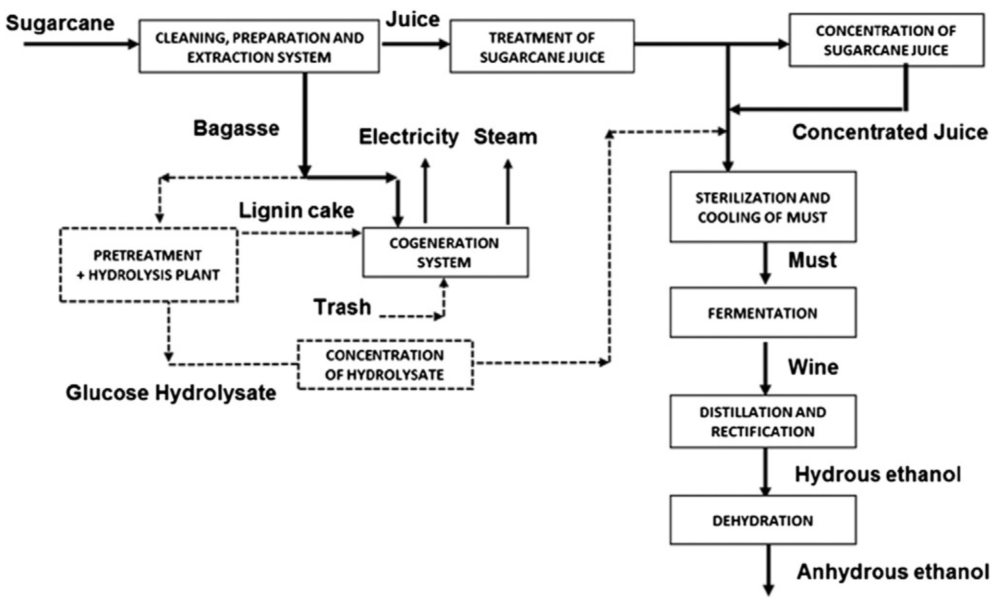

Fig. 1. Simplified block flow diagram of the integrated production of first- and second-generation ethanol from sugarcane.

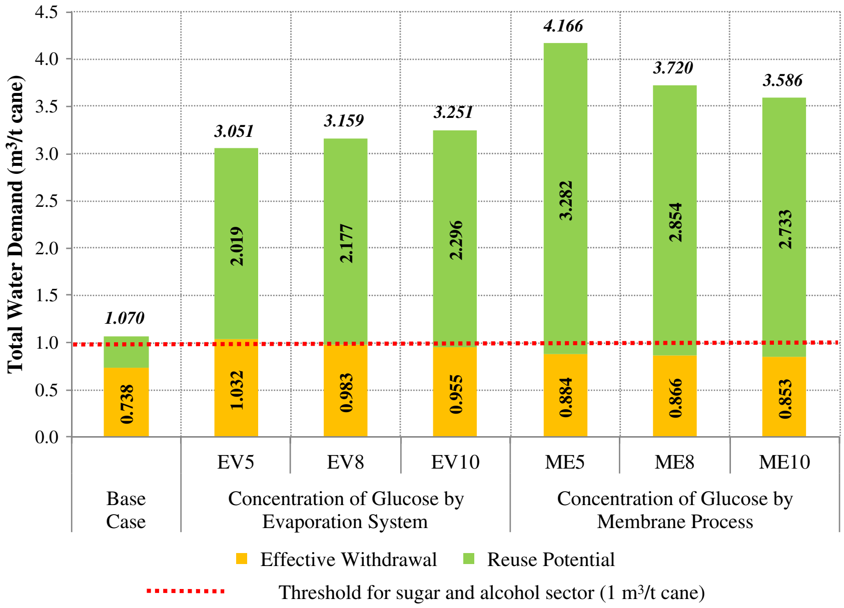

Fig. 2. Total water demand and effective withdrawal in integrated first- and second-generation ethanol plant from sugarcane (m^3/t cane).

conventional mill, a volume of 332 L/t cane was achieved, with condensates as the main reuse currents. Similar to Case I, condensates from evaporation systems correspond to a large fraction of the total reuse water potential. Besides, water for hydrolysis and for xylose washing could be recovered at the glucose concentration system and from the pentose liquor, respectively, with appropriate effluent treatment techniques.

Results and discussion

Volumes of potential water reuse were subtracted from the water demands for all processes of first- and second-generation ethanol production, resulting in the effective withdrawal needed to meet the deficit of the plant.

As shown in Fig. 2, the base case meets the environmental threshold of 1 m3/t cane mandated by the State of São Paulo (Companhia Ambiental do Estado de São Paulo, 2008). Estimates of current water withdrawal in the production of first-generation corn ethanol typically range from 3 to 4 L of water per litre of ethanol produced (Aden, 2007). In the present study, a range of about 9 to 12 L of water per litre of

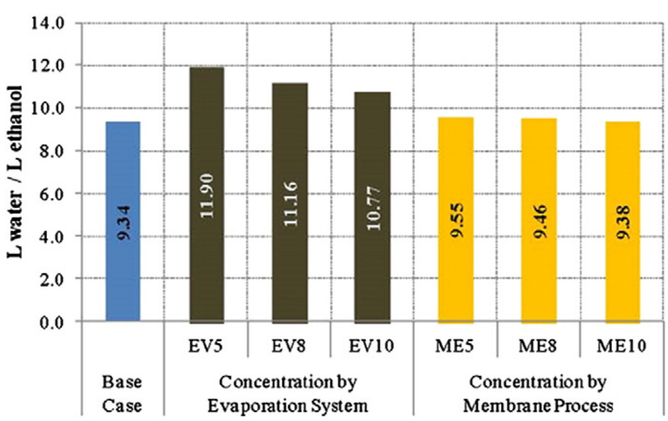

Fig. 3. Fresh water consumed in the conversion processes.

ethanol produced was found, depending on the scenario (Fig. 3); these ratios do not take into account water consumption by evapotranspiration during sugarcane production (crop production stage). Freshwater consumption for Cases II and III are close to that of conventional production (Case I) in spite of the large additional amounts of water required for the hydrolysis stage, showing the high potential for reduction practices using the concept of energy and water integration.

Conclusions

A conventional ethanol production (Case I) and an integrated production of first- and second-generation ethanol (Cases II and III) from sugarcane were modelled in order to quantify water use and identify reuse possibilities in the conversion stage. The main results show that water demands, estimated at 13,680 L/t of cane for Case I, and about 20,000 L/t of cane for Cases II and III, can be dramatically reduced – by as much as 90% – when water circuits are closed. Furthermore, reuse of water effluents such as condensates allows external withdrawals required to cover the plant water deficit to be reduced to 738 L/t of cane for Case I, 955 L/t of cane for Case II and 853 L/t of cane for Case III. All these values are below the limit of 1000 L/t of cane established for the sugarcane industry in the State of São Paulo. In terms of freshwater consumption per litre of ethanol, Case III achieves approximately the same ratio of Case I, with a value of 9.38 L of water/L of ethanol.

Acknowledgments

The authors wish to thank CNPq (National Council for Scientific and Technological Development) for the master and researcher fellowships (135595/2008-8, 556212/2010-0 and 304820/2009-1) and the Research Project Grant (Process 470481/2012-9), FAPESP (Foundation for Research Support of the State of São Paulo) for the Post PhD fellowship (Process 2011/05718-1) and the Research Project Grant (Process 2011/51902-9) and FINEP (Research and Project Financing) for the financial support (FINEP-FUNCAMP Contract No. 01/06/004700).

Appendix A

Table A1
Water consumption in the stand alone and integrated production of first- and second-generation ethanol from sugarcane *without reuse*.

Water consumption (L/t cane)	Base	EV5	EV8	EV10	ME5	ME8	ME10
Imbibition	300	300	300	300	300	300	300
Bearings cooling	50	50	50	50	50	50	50
Lube oil cooling	400	400	400	400	400	400	400
Preparation of lime mixture	8	8	8	8	8	8	8
Filters' barometric condensers	214	214	214	214	214	214	214
Filter cake washing	30	30	30	30	30	30	30
Polymer preparation for settling	15	15	15	15	15	15	15
Evaporation barometric condenser of juice	619	641	649	654	619	619	619
Cooling of must for fermentation	3741	4186	4283	4321	4544	4502	4468
Cooling of fermentation vats	2000	4733	4748	4755	4791	4783	4778
Dilution of yeast broth	141	158	161	163	171	170	168
Carbon dioxide scrubber for fermentation	27	29	30	30	31	31	31
Condenser of distillation column	2606	2927	2994	3020	3187	3150	3123
Condenser of rectification column	815	868	875	878	900	888	884
Condenser of extractive column	667	732	744	749	781	773	768
Condenser of recuperation Column	108	119	121	121	127	125	124
Solvent cooling	65	71	71	71	73	71	73
Anhydrous ethanol cooling	91	100	101	102	106	105	105
Turbo generators cooling	200	200	200	200	200	200	200
Washing scrubber (boiler)	1002	1588	1511	1487	1379	1380	1380
Boiler feed water	501	794	756	743	690	690	690
Hydrolysis process	–	742	575	499	1317	793	614
Evaporation barometric condenser of glucose	–	4405	3240	2695	–	–	–
Xylose washing	–	889	1204	1391	1578	1661	1711
General cleaning	50	50	50	50	50	50	50
Drinkable uses	30	30	30	30	30	30	30
Total	13,680	24,277	23,359	22,976	21,592	21,038	20,832

Table A2
Water consumption in the stand alone and integrated production of first- and second-generation ethanol from sugarcane *with water circuits closed*.

Water consumption (L/t cane)	Base	EV5	EV8	EV10	ME5	ME8	ME10
Imbibition	300	300	300	300	300	300	300
Bearings cooling[a]	1	1	1	1	1	1	1
Lube oil cooling[a]	12	12	12	12	12	12	12
Preparation of lime mixture	8	8	8	8	8	8	8
Filters' barometric condensers[a]	9	9	9	9	9	9	9
Filter cake washing	30	30	30	30	30	30	30
Polymer preparation for settling	15	15	15	15	15	15	15
Evaporation barometric condenser of juice[a]	25	26	26	26	25	25	25
Cooling of must for fermentation[a]	112	126	128	130	136	135	134
Cooling of fermentation vats[a]	60	142	142	143	144	143	143
Dilution of yeast broth	141	158	161	163	171	170	168
Carbon dioxide scrubber for fermentation	27	29	30	30	31	31	31
Condenser of distillation column[a]	104	117	120	121	127	126	125
Condenser of rectification column[a]	33	35	35	35	36	36	35
Condenser of extractive column[a]	27	29	30	30	31	31	31
Condenser of recuperation column[a]	4	5	5	5	5	5	5
Solvent cooling[a]	3	3	3	3	3	3	3
Anhydrous ethanol cooling[a]	4	4	4	4	4	4	4
Turbo generators cooling[a]	6	6	6	6	6	6	6
Washing scrubber (boiler)[a]	50	79	76	74	69	69	69
Boiler feed water[a]	20	32	30	30	28	28	28
Hydrolysis process	–	742	575	499	1317	793	614
Evaporation barometric condenser of glucose liquor	–	176	130	108	–	–	–
Pre-treated bagasse washing	–	889	1204	1391	1578	1661	1711
General cleaning	50	50	50	50	50	50	50
Potable water uses	30	30	30	30	30	30	30
Total	1070	3051	3159	3251	4166	3720	3586

[a] Water reposition in closed circuits.

References

Aden A. Water usage for current and future ethanol production. Southwest Hydrol 2007;6:22–3.

Chávez-Rodríguez M. Water use in the production of ethanol from sugarcane. Master thesis: University of Campinas, Campinas, SP, Brazil; 2010 [In Portuguese].

Chávez-Rodríguez MF, Nebra SA. Assessing GHG emissions, ecological footprint, and water linkage for different fuels. Environ Sci Technol 2010;44:9252–7.

Chávez-Rodríguez MF, Mosqueira-Salazar KJ, Ensinas AV, Nebra SA. Water reuse and recycling in a sugar–ethanol plant according the stream qualities. 6th Dubrovnik Conference on Sustainable Development of Energy Water and Environment Systems, September 25–29, Dubrovnik, Croatia; 2011.

Companhia Ambiental do Estado de São Paulo (Environmental Company of State of São Paulo). SMA resolution 88/2008; 2008.

Dale BE. Biofuels and water — another opportunity to 'do biofuels right'. Biofuels Bioprod Bioref 2011;5:347–9.

Elia Neto A. Use and reuse of water in the sugarcane industry. Workshop on The Impact of new technologies on the sustainability of the sugarcane/bioethanol production cycle. Campinas, São Paulo, Brazil: Brazilian Bioethanol Science and Technology Laboratory – CTBE; 2009 [In Portuguese].

Ensinas AV. Thermal integration and thermoeconomic optimization applied to the industrial process of sugar and ethanol production from sugarcane. Doctoral thesis. Campinas, São Paulo, Brazil: Mech. Eng. School, University of Campinas; 2008 [In Portuguese].

Hugot E. Handbook of sugar cane engineering. Amsterdam: Elsevier Science; 1986.

Jannuzzi GM, Gomes RDM, Chávez-Rodríguez MF, Mosqueira-Salazar KJ, Nebra SA, 2012. Water usage in bioethanol production in the State of São Paulo; Cap. 4, pp. 71–87, in Sustainability of sugar cane bioenergy; Poppe, Marcelo Khaled e Cortez, Luis Augusto Barbosa (Editors); Edit. CGEE.

Palacios-Bereche R. Modelling and energetic integration of the ethanol production from sugarcane biomass. Doctoral Thesis. Mech. Eng: School, University of Campinas, Campins, São Paulo, Brazil; 2011 [in Portuguese].

Palacios-Bereche R, Ensinas AV, Nebra SA. Energy consumption in ethanol production by enzymatic hydrolysis — the integration with the conventional process using pinch analysis. Chem Eng Trans 2011;24:1189–94.

Palacios-Bereche R, Ensinas A, Modesto M, Nebra SA. Ethanol production by enzymatic hydrolysis from sugarcane biomass — the integration with the conventional process in proceedings of ECOS 2012. 25th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems, June 26–29, Perugia, Italy; 2012a. p. 189-1–189-14.

Palacios-Bereche R, Modesto M, Ensinas A, Nebra SA. Comparison study: ethanol production increase through the introduction of bagasse enzymatic hydrolysis & surplus electricity increase, in ethanol distilleries. 14th Brazilian congress of thermal sciences and engineering, November 18–22, Rio de Janeiro, RJ, Brazil; 2012b.

Pizaia WN, Oliveira T, Tostes D. Alternatives for reduction of consume of water in the process. Piracicaba, Brazil: Copersucar; 1999 [In Portuguese].

Zuurbier P, van de Vooren J. Sugarcane ethanol — contributions to climate change mitigation and the environment. The Netherlands: Wageningen Academic Publishers; 2008.