

# Is bioethanol worth the energy? An energy metrics' perspective<sup>#</sup>

Steenekamp GL<sup>1</sup>, Merckel RD<sup>2\*</sup>

1 Department of Chemical Engineering, University of Pretoria, Pretoria, South Africa

2 Department of Chemical Engineering, University of Pretoria, Pretoria, South Africa (Corresponding Author)

## ABSTRACT

Typical industrial-scale sugarcane-to-bioethanol processes are evaluated using exergy and mass-based metrics. A more robust set of energy metrics, the change in energy quality and energy yield, are applied to assess the life-cycle efficiency of sugarcane upgradation. From an energy perspective, bioethanol production is not justifiable. Bioethanol achieves a poor energy recovery from sugarcane. Sugarcane to bioethanol, and subsequent electricity/power production, results in considerable energy losses even when compared to combusting the sugarcane itself. A techno-economic feasibility study would be required to justify the 3 % gain in energy yield achieved when incorporating 2G processes into existing 1G infrastructure.

**Keywords:** Bioethanol, sugarcane, energy metrics, energy quality, energy yield

## NONMENCLATURE

### Abbreviations

HHV	Higher heating value
LHV	Lower heating value

### Symbols

$\Delta_c h^\circ _{\text{HHV,p}}$	HHV of products (MJ kg <sup>-1</sup> )
$\Delta_c h^\circ _{\text{HHV,f}}$	HHV of feed (MJ kg <sup>-1</sup> )
$\Delta E_\eta$	Energy yield (%)
$\Delta E_Q$	Change in energy quality (%)
$M$	Molar mass (kg kmol <sup>-1</sup> )
$n_v$	Number of moles (kmol)
$\eta$	Mass yield (%)
1G; 2G	1 <sup>st</sup> & 2 <sup>nd</sup> generations, respectively
GHG	Greenhouse gas

## 1. INTRODUCTION

The almost 200-years long development and utilisation of fossil fuels places relatively newer biofuels at a disadvantage. The failure of biofuels to fit into the existing infrastructures and exhibit similar properties of

transportation fuels is a major criticism. Policies and subsidies have nonetheless driven the biofuel demand, especially for bioethanol, so as to decarbonise the transportation sector [1,2]. However, this is despite the utilisation of food resources for bioethanol production using first generation (1G) technologies [3]. Secondly, these 1G processes demand 40 times more freshwater resources per GJ of bioethanol produced compared to fossil petrol [4]. Thirdly, agriculture, forestry, and other land use contributed 22 % towards the total net anthropogenic greenhouse gas (GHG) emissions as of 2019 [5]. This begs the question: is the current bioethanol market artificially stimulated primarily from an economic perspective or is it in response to alleviating the water-energy-food nexus crisis? Furthermore, would the roll-out of second generation (2G) technologies, which aim to improve lignocellulosic conversion to bioethanol, make current 1G processes more sustainable?

Exergy analyses have become a popular approach, albeit difficult-to-apply practically, to quantify the sustainability of biofuels. Exergy computes the maximum useful work of a system as equilibrium is approached, relative to a reference state (e.g., ambient environmental conditions) [6–10]. Although a useful tool, exergy is very sensitive to the choice of a reference state and may be inappropriate when completing energy-based cross-field assessments of biofuel technologies. A more objective approach proposed by Merckel, Labuschagne & Heydenrych (2020) takes the form of two energy relations that assess only the specific oxidation potential of fuels, irrespective of processing and utilisation variances. The premise of these energy metrics lies in the understanding that oxygen consumption by fuels is the definitive factor that should be assessed with respect to efficiencies of upgradation and this makes cross-field universal comparisons of fuels as energy storage systems possible.

The purpose of this study is to use these energy metrics to assess the energy efficacy and overall life-

<sup>#</sup> This is a paper for the 14<sup>th</sup> International Conference on Applied Energy - ICAE2022, Aug. 8-11, 2022, Bochum, Germany.



lignin, bagasse, and/or coal depending on the process scenario. When more steam is produced by the boilers than what is required by the process, the excess steam is fed to a condensing steam turbine to generate excess electricity. The parameters defining the 1G, 2G, and cogeneration process are shown in Tables 1, 2, & 3 respectively.

*Tab. 1 Parameters for 1G production*

Parameters	Value
Plant capacity [14,16,19,20]	500 ton <sub>bm</sub> h <sup>-1</sup> *
Trash produced (dry basis) [23,24]	140 kg ton <sub>bm</sub> <sup>-1</sup>
Trash moisture [15,23]	15 %
<b>Cleaning</b>	
Sugar recovery [19]	98.5 %
Dirt removed [14]	90 %
<b>Milling</b>	
Sugar recovery [16,18]	96 %
Water for imbibition [16]	0.28 ton ton <sub>bm</sub> <sup>-1</sup>
Electrical consumption [19]	16 kWh ton <sub>bm</sub> <sup>-1</sup>
<b>Pre-treatment</b>	
Preheating steam consumption (2.5 bar) [12]	35124 kg
CaO concentration [19]	10 % (kg kg <sup>-1</sup> )
CaO flowrate [19]	2 kg ton <sub>bm</sub> <sup>-1</sup>
Steam consumption for preheating after CaO addition (2.5 bar) [12]	34244 kg h <sup>-1</sup>
Sugar recovery after juice treatment [14]	99.5 %
Clarified juice sugar concentration [18]	15 %
<b>Evaporation &amp; sterilisation</b>	
Steam consumption for evaporation (2.5 bar) [12]	57069 kg h <sup>-1</sup>
Sugar concentration after evaporation	26 %
Water loss after evaporation	49 %
Steam consumption for sterilization (6 bar) [12]	16068 kg h <sup>-1</sup>
<b>Fermentation</b>	
Sucrose to glucose mass yield **	100 %
Glucose to ethanol mass yield [16]	90 %
<b>Distillation &amp; dehydration</b>	
Hydrous ethanol concentration [16]	93 wt. %
Steam consumption for distillation (2.5 bar) [32]	1.5 kg L <sub>EtOH</sub> <sup>-1</sup>
Anhydrous ethanol concentration [16]	99.6 %
Molecular sieves steam consumption (6 bar) [15,16]	0.6 kg L <sub>EtOH</sub>
Ethanol recovery for distillation & dehydration [14]	99.7 %
Electrical consumption for auxiliary operations [14]	14 kWh ton <sub>bm</sub>

\* ton<sub>bm</sub>: Tonne of sugarcane processed (wet basis)

\*\* Assumption

*Tab. 2 Parameters for 2G production*

Parameters	Value
Bagasse produced (dry basis) [31]	0.12 ton ton <sub>bm</sub> <sup>-1</sup>
Bagasse moisture content (wt. %) [14,20,24].	50 %
Electrical consumption [31]	24 kWh ton <sub>bagasse</sub> <sup>-1</sup> *
<b>Pre-treatment</b>	
Steam consumption [8]	0.55 kg ton <sub>bagasse</sub> <sup>-1</sup> *
Steam pressure [8]	12.5 bar
Temperature [8]	190 °C
SO <sub>2</sub> consumption [8]	2 % (kg kg <sup>-1</sup> )
Hemicellulose solubilisation [27]	82.7 %
Hemicellulose hydrolysis [31]	70 %
Lignin solubilisation [27]	7.9 %
Cellulose solubilisation [27]	11.5 %
Water content in liquid fraction **	56 %
<b>Fermentation</b>	
Xylose fermentation yield [31]	80 %
<b>Alkaline delignification</b>	
NaOH consumption [27]	1 % (kg m <sup>-3</sup> )
Temperature [31]	100 °C
Lignin solubilisation [27]	92.7 %
<b>Precipitation</b>	
Lignin recovery **	95 %
Water content in recovered lignin **	34 %
<b>Enzymatic hydrolysis</b>	
Cellulose hydrolysis [31]	70 %
Hemicellulose hydrolysis [31]	70 %
Water content of glucose rich stream **	40 %

\* ton<sub>bagasse</sub>: Tonne of bagasse processed (wet basis)

\*\* Assumption

*Tab. 3 Parameters for cogeneration*

Parameters	Value
Boiler steam pressure [23]	90 bar
Boiler steam temperature [23]	520 °C
Boiler efficiency [31]	87 %
Bagasse LHV *	-7.33 MJ kg <sup>-1</sup>
Trash LHV *	-14.93 MJ kg <sup>-1</sup>
Lignin LHV *	-15.03 MJ kg <sup>-1</sup>
Back pressure steam turbines efficiency	78 %
Condensing steam turbine efficiency	78 %
Condensing steam turbine outlet pressure	8 kPa

\* Wet LHV considers energy consumed to vapourise both the moisture in the lignocellulosic material as well as the water produced during combustion.

## 2.2 Energy metrics approach to data analysis

### 2.2.1 Higher and lower heating values

The mass and energy balances are calculated on a dry and ash free basis. Only the energy carrying components of the material streams contribute to the change in energy quality and utilisation of an operation. By convention, the lower heating value (LHV) is calculated from the measured higher heating value (HHV) on the dry basis and considers only the hydrogen present in the fuel that is converted to water during combustion. The foundations of the paper lie in the strong correlation between HHV,  $\Delta_c h_{\text{HHV}}^\circ$ , and the mass of oxygen combusted per mass of the fuel,  $m_{\text{O}_2}$ , described by

$$\Delta_c h_{\text{HHV}}^\circ = \gamma m_{\text{O}_2} \quad (\text{Eq. 1})$$

where  $\gamma = -13.87 \text{ MJ kg}_{\text{O}_2}^{-1}$ , and  $\Delta_c h_{\text{HHV}}^\circ$  may also be approximated as [11]

$$\Delta_c h_{\text{HHV}}^\circ = -13.87 \left( n_{\text{vC}} + \frac{1}{4} n_{\text{vH}} - \frac{1}{2} n_{\text{vO}} \right) \frac{M_{\text{O}_2}}{M_{\text{fuel}}} \quad (\text{Eq. 2})$$

where  $n_{\text{vC}}$ ,  $n_{\text{vH}}$  and  $n_{\text{vO}}$  are the moles of carbon, hydrogen, and oxygen present in the fuel, and  $M_{\text{O}_2}$  and  $M_{\text{fuel}}$  are the molar masses of the oxygen and fuel consumed during combustion, respectively.

Both the HHV and LHV may be reported on a wet basis, which accounts for any moisture present in the fuel prior to combustion, or on a dry basis. Therefore, water content of process streams is considered only for the purpose of determining the wet LVH of a material stream wherever appropriate (*e.g.*, for the determination of the quantity of energy evolved during combustion with respect to a boiler).

### 2.2.2 Change in energy qualities

The energy quality,  $\Delta E_Q$ , is defined as the difference in HHV's of the product,  $\Delta_c h_{\text{HHV,p}}^\circ$ , and feed,  $\Delta_c h_{\text{HHV,f}}^\circ$ , divided by  $\Delta_c h_{\text{HHV,f}}^\circ$ :

$$\Delta E_Q = \frac{\Delta_c h_{\text{HHV,p}}^\circ - \Delta_c h_{\text{HHV,f}}^\circ}{\Delta_c h_{\text{HHV,f}}^\circ} \quad (\text{Eq. 3})$$

and may be reported as a fraction or percentage. Thus, if  $\Delta E_Q$  increases, the resulting product has a higher calorific value per mass than that of the feed and is therefore a denser energy-carrier [11]. Based on Equation 1, Equation 3 may be rewritten in terms of the mass of oxygen consumed by a fuel:

$$\Delta E_Q = \frac{m_{\text{O}_2}|_p}{m_{\text{O}_2}|_f} - 1 \quad (\text{Eq. 4})$$

Subsequently, it can be seen that it is the increase of combustible oxygen of a fuel that gives rise to the improvement of energy quality.

### 2.2.3 Energy yields

While Equation 3 describes the upgradation or degradation of energy density for an energy product, it does not account for the quantity of energy transferred from feedstock to product [11]. The energy yield,  $\Delta E_\eta$ , accounts for this accordingly and is defined as

$$\Delta E_\eta = \eta \frac{\Delta_c h_{\text{HHV,p}}^\circ}{\Delta_c h_{\text{HHV,f}}^\circ} \quad (\text{Eq. 5})$$

As with Equation 3,  $\Delta E_\eta$  is a function of  $m_{\text{O}_2}$ :

$$\Delta E_\eta = \eta \frac{m_{\text{O}_2}|_p}{m_{\text{O}_2}|_f} \quad (\text{Eq. 6})$$

This Equation implies that  $\Delta E_\eta$  is a function of both the mass yield and the change in energy quality and these two parameters may be used collectively to assess the efficiency of upgradation processes.

For  $\Delta E_Q$ , the recoverable components only include product streams that contribute to the generation of bioethanol whereas  $\Delta E_\eta$  considers energy products associated with bioethanol (including electricity output) in relation to the biomass-associated energy inputs. The additional utilities requirements (*i.e.*, non-biomass-derived energy that is consumed,  $\Delta E_{\text{cons.}}$ ) per unit of biomass-derived energy valorised,  $\Delta E_f$ , by the same process may be included in the description of energy yield:

$$\begin{aligned} \Delta E_\eta &= \frac{\Delta E_p}{\Delta E_f} - \frac{\Delta E_{\text{cons.}}}{\Delta E_f} \\ \Delta E_\eta &= \frac{m_p \Delta_c h_{\text{HHV,p}}^\circ}{m_f \Delta_c h_{\text{HHV,f}}^\circ} - \frac{\Delta E_{\text{cons.}}}{m_f \Delta_c h_{\text{HHV,f}}^\circ} \\ \Delta E_\eta &= \eta \left( \frac{\Delta_c h_{\text{HHV,p}}^\circ - \Delta E_{\text{cons.}}/m_p}{\Delta_c h_{\text{HHV,f}}^\circ} \right) \quad (\text{Eq. 7}) \end{aligned}$$

where  $\Delta E_{\text{cons.}}/m_p$  describes the energy consumed per quantity of biofuel produced. It is important to note that the energy yield is normalized to the energy of the biomass into the process.

## 2.3 Scenario definition

Four groups of scenarios are modelled (Fig. 2): scenario 1 represents the ideal bioethanol production limit from sugarcane. Scenario 2.1 represents 1G bioethanol production where all of the bagasse is directed to cogeneration (*i.e.*, energy recovery via combustion of trash and bagasse). Scenario 2.2 considers a 1G and 2G-integrated plant that utilises bagasse in the production of bioethanol, and the remaining bagasse, lignin by-product, and trash are sent to boilers to meet the steam demand of the process. Scenario 2.3 is similar to scenario 2.2, but where all bagasse is utilised for bioethanol production and coal supplements utility requirements of the process. Scenarios 3.1 & 3.2 are similar to scenario group 2 except that scenarios 3.1 & 3.2 consider the energy acquired through the end use of

bioethanol. Scenario 3.1 evaluates the use of bioethanol in an internal combustion engine to emulate the end life-cycle of the fuel in a vehicle. Scenario 3.2 considers bioethanol combustion for electricity production. Scenario 4 considers combustion of the sugarcane and

50 % for electricity production only without any upgradation to bioethanol. The bioethanol plant was modelled using Microsoft Excel (365) and Python programming language (Python Software Foundation, <https://www.python.org/>).

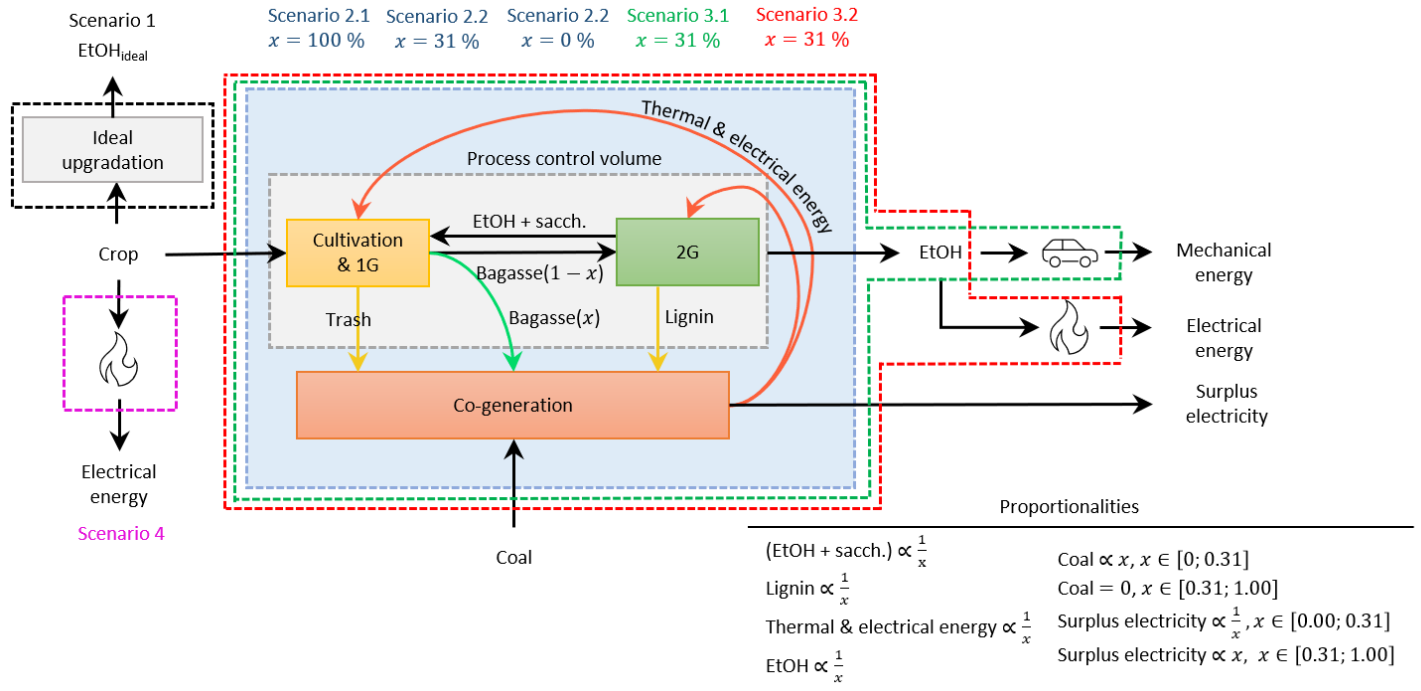


Fig. 2 Summary of the proportionalities between the mass & energy fluxes and the amount of bagasse burnt ( $x$ ).

### 3. RESULTS AND DISCUSSION

#### 3.1 Simulation results

Tab. 4 Summary of the energy metrics for the 4 sets of scenarios

Scenario	Bagasse combusted (%)	Ethanol produced ( $\text{L ton}_{\text{bm}}^{-1}$ )	Electricity surplus ( $\text{kWh ton}_{\text{bm}}^{-1}$ )	Steam utility ( $\text{kg ton}_{\text{bm}}^{-1}$ )	Mass yield (%)	Overall $\Delta E_Q$ (%)	Overall $\Delta E_\eta$ (%)	Total energy produced ( $\text{MJ ton}_{\text{bm}}^{-1}$ )
1	—	187	—	—	49	63	80	6210
2.1	100	80	167	454	17	63	33	3258
2.2	31	105	68	601	22	63	36	3731
2.3	0	116	76	854	24	63	31	3503*
3.1	31	—	234**	601	0	-100	10	842
3.2	31	—	249	1229	0	-100	11	896
4	—	—	311	1676	0	-100	16	1120

\* Coal-derived energy is subtracted from the total energy produced – only biomass-derived energy is relevant for the energy metrics assessment.

\*\* Mechanical and electrical energy equivalent.

The change in energy quality for converting biomass to bioethanol is  $\Delta E_Q = 63\%$  and confirms bioethanol as a more energy-dense fuel. Even so, the ideal conversion of sugarcane to bioethanol (as demonstrated with scenario 1, Table 4) is not an energy efficient conversion of biomass, with an energy yield of 80% ( $187 \text{ L}_{\text{EtOH}} \text{ ton}_{\text{bm}}^{-1}$ ). Regardless of the real-life scenarios

(2.1–2.3), the highest practical energy yield (1G: 33%; 1G + 2G: 36%) is less than half of the ideal case. Even with an attempt to maximise bagasse upgradation to bioethanol via coal supplementation to meet utility requirements, the energy yield suffers (scenario 2.3: 31%). When comparing the 1G and 2G unit operations (Fig. 1), it is obvious that the 2G process (not yet technologically mature at the industrial scale)

represents a considerable portion of the process. The 2G process is only able to increase the energy yield by a mere 3 % by conservative estimates. The 2G process not utilising coal is also only able to increase the mass yield of bioethanol from 17 % (35 % of the ideal mass yield) for the 1G process to 22 % (45 % of the ideal case). Although scenario 2.3, which uses coal to meet utility requirements for the process, achieves a slightly higher mass yield of 24 % (49 % of the ideal case), this scenario is not sustainable. The total energy produced for scenarios 2 – 4 is always lower than for the ideal scenario of  $6210 \text{ MJ ton}_{\text{bm}}^{-1}$ .

If it is now considered that bioethanol is first produced from a combined 1G & 2G process (scenario 2.2), and then utilised in an internal combustion engine (scenario 3.1) and in a power generation plant (scenario 3.2), the total energy produced at the end of this energy lifecycle is  $842 \text{ MJ ton}_{\text{bm}}^{-1}$  and  $896 \text{ MJ ton}_{\text{bm}}^{-1}$ , respectively. If instead the neat biomass was converted to electricity directly, the total energy produced would be much higher, at  $1120 \text{ MJ ton}_{\text{bm}}^{-1}$ .

These criticisms stem from the strong relation between the HHV and the masses of oxygen and fuel collectively combusted. The efficient conversion of biomass to bioethanol is based on two principles, namely (i) the increase in the oxidation potential of the fuel relative to its parent feedstock (*i.e.*, increase in  $m_{\text{O}_2}$ ) and (ii) maximising mass yield (*i.e.*,  $\eta = m_{\text{EtOH}} m_{\text{bm}}^{-1}$ ). The first principle may be achieved via three primary routes: decarboxylation, dehydration, and/or decarbonylation, while achieving the second principle is intuitive. In all scenarios assessed, the energy quality of product remains the same ( $m_{\text{O}_2}|_{\text{p}} m_{\text{O}_2}|_{\text{f}}^{-1} = 1.63$ ) and is the entity that qualifies the first principle. As  $\Delta E_{\eta}$  is a function of  $\Delta E_{\text{Q}}$ , the only other parameter that may be employed in increasing conversion efficiency is mass yield. Therefore, while the 2G process attempts to bring about considerable enhancements to the 1G process, it falls short due to the small increase in mass yield achieved: a pursuit of marginal returns. The same logic applies for scenarios 3.1, 3.2, and 4: the considerable loss in energy with respect to combustion (24.8 % loss compared to the direct biomass-to-electricity scheme) or electricity generation (20.0 % loss) cannot be justifiable considering the large disadvantage of mass yield with regards to the upgradation process.

#### 4. CONCLUSIONS & RECOMMENDATIONS

The energy efficiency of typical industrial-scale sugarcane-to-bioethanol processes that utilise 1G and 2G technologies were assessed using recently-developed

energy metrics, namely the change in energy quality and the energy yield, which are defined on an oxygen-consumed basis. The ideal route of conversion for sugarcane-to-bioethanol as well as the direct biomass-to-electricity route were used for comparisons with various scenarios based on 1G and 2G processes. The ideal conversion of sugarcane-to-bioethanol is associated with a change in energy quality of 63 % and an energy yield of 49 %, with a maximum total energy output of  $6210 \text{ MJ ton}_{\text{bm}}^{-1}$  achievable. The energy losses when associated with the conversion of biomass-to-bioethanol and subsequent combustion of bioethanol to electricity and/or power are substantial when compared to the direct biomass-to-electricity route: losses of between 24.8 % and 20.0 % in energy was observed. Most of these losses occur during the biomass-to-bioethanol conversion, where only 33 % (1G) and 36 % (combined 1G & 2G) of biomass-derived energy reports to the bioethanol. Despite the good intentions of increasing sugarcane conversion to bioethanol using the 2G process, this process is only able to increase this energy yield by 3 %. The question remains: is manufacturing bioethanol worth the energy?

#### ACKNOWLEDGEMENT

The authors acknowledge Professor Sebastian Schwede at Mälardalen University for his meaningful contributions.

#### REFERENCE

- [1] Fulton LM, Körner A, Agency IE. The need for biofuels as part of a low carbon energy future 2015:476–83. <https://doi.org/10.1002/bbb>.
- [2] Holmatov B, Schyns JF, Krol MS, Gerbens-Leenes PW, Hoekstra AY. Can crop residues provide fuel for future transport? Limited global residue bioethanol potentials and large associated land, water and carbon footprints. *Renewable and Sustainable Energy Reviews* 2021;149:111417. <https://doi.org/10.1016/j.rser.2021.111417>.
- [3] Duque A, Álvarez C, Doménech P, Manzanares P, Moreno AD. Advanced bioethanol production: From novel raw materials to integrated biorefineries. *Processes* 2021;9:1–30. <https://doi.org/10.3390/pr9020206>.
- [4] Berger M, Pfister S, Bach V, Finkbeiner M. Saving the planet's climate or water resources? The trade-off between carbon and water footprints of European biofuels. *Sustainability (Switzerland)* 2015;7:6665–83. <https://doi.org/10.3390/su7066665>.
- [5] Intergovernmental Panel on Climate Change. Mitigation of Climate Change Summary for

- Polymakers (SPM). Cambridge University Press 2014:1–30.
- [6] Dewulf J, van Langenhove H, van de Velde B. Exergy-based efficiency and renewability assessment of biofuel production. *Environmental Science and Technology* 2005;39:3878–82. <https://doi.org/10.1021/es048721b>.
- [7] Shahbeig H, Shafizadeh A, Rosen MA, Sels BF. Exergy sustainability analysis of biomass gasification: a critical review. *Biofuel Research Journal* 2022;9:1592–607. <https://doi.org/10.18331/brj2022.9.1.5>.
- [8] Silva Ortiz P, de Oliveira S. Exergy analysis of pretreatment processes of bioethanol production based on sugarcane bagasse. *Energy* 2014;76:130–8. <https://doi.org/10.1016/j.energy.2014.04.090>.
- [9] Velásquez-Arredondo HI, de Oliveira Junior S, Benjumea P. Exergy efficiency analysis of chemical and biochemical stages involved in liquid biofuels production processes. *Energy* 2012;41:138–45. <https://doi.org/10.1016/j.energy.2011.06.025>.
- [10] Romero JC, Linares P. Exergy as a global energy sustainability indicator. A review of the state of the art. *Renewable and Sustainable Energy Reviews* 2014;33:427–42. <https://doi.org/10.1016/j.rser.2014.02.012>.
- [11] Merckel RD, Labuschagne FJWJ, Heydenrych MD. Energy metrics of fuel juxtaposed with mass yield metrics. *Renewable Energy* 2020;159:371–9. <https://doi.org/10.1016/j.renene.2020.05.013>.
- [12] Dias MOS, Modesto M, Ensinas A v., Nebra SA, Filho RM, Rossell CEV. Improving bioethanol production from sugarcane: Evaluation of distillation, thermal integration and cogeneration systems. *Energy* 2011;36:3691–703. <https://doi.org/10.1016/j.energy.2010.09.024>.
- [13] Dias MOS, Junqueira TL, Rossell CE v., Maciel Filho R, Bonomi A. Evaluation of process configurations for second generation integrated with first generation bioethanol production from sugarcane. *Fuel Processing Technology* 2013;109:84–9. <https://doi.org/10.1016/j.fuproc.2012.09.041>.
- [14] Dias MOS, Cunha MP, Jesus CDF, Scandiffio MIG, Rossell CEV, Filho RM, et al. Simulation of ethanol production from sugarcane in Brazil: Economic study of an autonomous distillery. *Computer Aided Chemical Engineering* 2010;28:733–8. [https://doi.org/10.1016/S1570-7946\(10\)28123-3](https://doi.org/10.1016/S1570-7946(10)28123-3).
- [15] Dias MOS, Junqueira TL, Cavalett O, Cunha MP, Jesus CDF, Rossell CEV, et al. Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. *Bioresource Technology* 2012;103:152–61. <https://doi.org/10.1016/j.biortech.2011.09.120>.
- [16] Dias MOS, Junqueira TL, Cavalett O, Pavanello LG, Cunha MP, Jesus CDF, et al. Biorefineries for the production of first and second generation ethanol and electricity from sugarcane. *Applied Energy* 2013;109:72–8. <https://doi.org/10.1016/j.apenergy.2013.03.081>.
- [17] Cavalett O, Junqueira TL, Dias MOS, Jesus CDF, Mantelatto PE, Cunha MP, et al. Environmental and economic assessment of sugarcane first generation biorefineries in Brazil. *Clean Technologies and Environmental Policy* 2012;14:399–410. <https://doi.org/10.1007/s10098-011-0424-7>.
- [18] Dias MOS, Ensinas A v., Nebra SA, Maciel Filho R, Rossell CEV, Maciel MRW. Production of bioethanol and other bio-based materials from sugarcane bagasse: Integration to conventional bioethanol production process. *Chemical Engineering Research and Design* 2009;87:1206–16. <https://doi.org/10.1016/j.cherd.2009.06.020>.
- [19] Furlan FF, Filho RT, Pinto FH, Costa CB, Cruz AJ, Giordano RL, et al. Bioelectricity versus bioethanol from sugarcane bagasse: Is it worth being flexible? *Biotechnology for Biofuels* 2013;6:1–12. <https://doi.org/10.1186/1754-6834-6-142>.
- [20] Furlan FF, Costa CBB, Fonseca G de C, Soares R de P, Secchi AR, Cruz AJG da, et al. Assessing the production of first and second generation bioethanol from sugarcane through the integration of global optimization and process detailed modeling. *Computers and Chemical Engineering* 2012;43:1–9. <https://doi.org/10.1016/j.compchemeng.2012.04.002>.
- [21] Canettieri EV, da Silva VP, Neto TGS, Hernández-Pérez AF, da Silva DDV, Dussán KJ, et al. Physicochemical and thermal characteristics of sugarcane straw and its cellulignin. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 2018;40:1–13. <https://doi.org/10.1007/s40430-018-1331-1>.
- [22] Macedo IDC, Leal MRLV, Silva JEAR da. Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil 2004:37.

- [23] Walter A, Ensinas A v. Combined production of second-generation biofuels and electricity from sugarcane residues. *Energy* 2010;35:874–9. <https://doi.org/10.1016/j.energy.2009.07.032>.
- [24] de Almeida MA, Colombo R. Production Chain of First-Generation Sugarcane Bioethanol: Characterization and Value-Added Application of Wastes. *Bioenergy Research* 2021. <https://doi.org/10.1007/s12155-021-10301-4>.
- [25] Carpio LGT, Simone de Souza F. Optimal allocation of sugarcane bagasse for producing bioelectricity and second generation ethanol in Brazil: Scenarios of cost reductions. *Renewable Energy* 2017;111:771–80. <https://doi.org/10.1016/j.renene.2017.05.015>.
- [26] Rocha GJM, Gonçalves AR, Nakanishi SC, Nascimento VM, Silva VFN. Pilot scale steam explosion and diluted sulfuric acid pretreatments: Comparative study aiming the sugarcane bagasse saccharification. *Industrial Crops and Products* 2015;74:810–6. <https://doi.org/10.1016/j.indcrop.2015.05.074>.
- [27] Rocha GJM, Gonçalves AR, Oliveira BR, Olivares EG, Rossell CEV. Steam explosion pretreatment reproduction and alkaline delignification reactions performed on a pilot scale with sugarcane bagasse for bioethanol production. *Industrial Crops and Products* 2012;35:274–9. <https://doi.org/10.1016/j.indcrop.2011.07.010>.
- [28] Rocha GJM, Martín C, da Silva VFN, Gómez EO, Gonçalves AR. Mass balance of pilot-scale pretreatment of sugarcane bagasse by steam explosion followed by alkaline delignification. *Bioresource Technology* 2012;111:447–52. <https://doi.org/10.1016/j.biortech.2012.02.005>.
- [29] Oliveira FMV, Pinheiro IO, Souto-Maior AM, Martín C, Gonçalves AR, Rocha GJM. Industrial-scale steam explosion pretreatment of sugarcane straw for enzymatic hydrolysis of cellulose for production of second generation ethanol and value-added products. *Bioresource Technology* 2013;130:168–73. <https://doi.org/10.1016/j.biortech.2012.12.030>.
- [30] Oliveira CM, Cruz AJG, Costa CBB. Improving second generation bioethanol production in sugarcane biorefineries through energy integration. *Applied Thermal Engineering* 2016;109:819–27. <https://doi.org/10.1016/j.applthermaleng.2014.11.016>.
- [31] Dias MOS, Junqueira TL, Cavalett O, Cunha MP, Jesus CDF, Rossell CEV, et al. Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. *Bioresource Technology* 2012;103:152–61. <https://doi.org/10.1016/j.biortech.2011.09.120>.
- [32] Dias MOS, Cunha MP, Jesus CDF, Rocha GJM, Pradella JGC, Rossell CEV, et al. Second generation ethanol in Brazil: Can it compete with electricity production? *Bioresource Technology* 2011;102:8964–71. <https://doi.org/10.1016/j.biortech.2011.06.098>.