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Is bioethanol worth the energy? An energy metrics' perspective

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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 technoeconomic 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	
$\Delta_{\mathrm{c}} h^{\circ}\big\|_{\mathrm{HHV,p}}$	HHV of products $(\mathrm{MJ\ kg^{-1}})$
$\Delta_{\mathrm{c}} h^{\circ}\big\|_{\mathrm{HHV,f}}$	HHV of feed $(\mathrm{MJ\ kg^{-1}})$
ΔE_{η}	Energy yield $(\%)$
ΔE_{Q}	Change in energy quality $(\%)$
M	Molar mass $(\mathrm{kg\ kmol^{-1}})$
n_{ν}	Number of moles (kmol)
η	Mass yield $(\%)$
1G; 2G	1st & 2nd 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-cycle efficiency of 1G and 2G bioethanol production pathways. The change in energy quality, ΔE_{Q}, and energy yield, ΔE_{η}, are used on a unit-specific and overall production basis, and to compare these scenarios against the ideal route of upgradation. The primary biomass under consideration is sugarcane with a reliance on literature data for typical bioethanol refineries.

2. MATERIALS AND METHODS

2.1 Process description

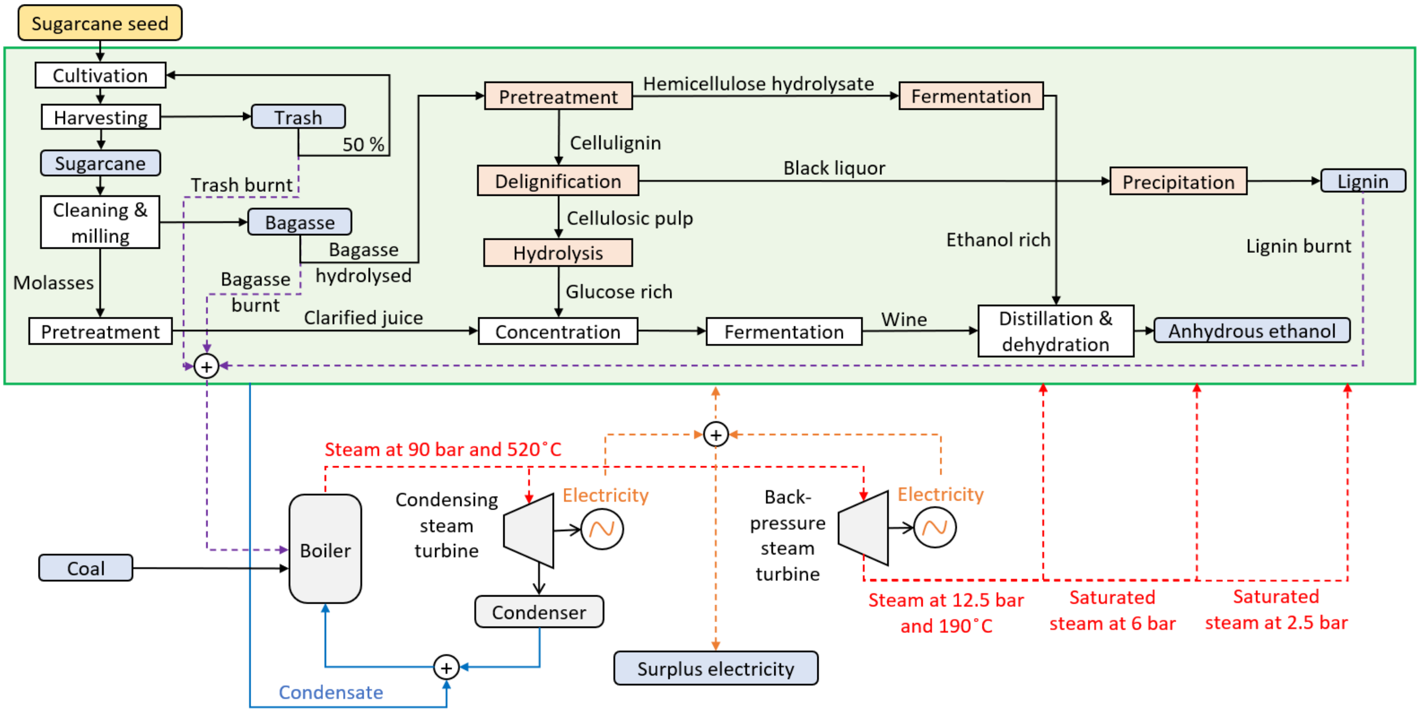

Fig. 1 Process diagram of the 1G & 2G bioethanol production process with cogeneration. The orange block is the sugarcane seed at the inception of the life-cycle. Blue blocks indicate intermediate and final products/feeds. The white, orange, and grey blocks are the 1G, 2G, and cogeneration infrastructure respectively. Purple lines indicate the material from the process that is burnt. Red and orange lines are the steam and electrical fluxes respectively.

The industrial bioethanol process under investigation was developed using several literature sources [12–24]. The process considers the total input of field-acquired sugarcane at $582\ \mathrm{ton\ h^{-1}}$ with a moisture content of $64\ \%$, which includes all biomass grown excluding roots. Pre-fermentation processing includes cleaning, milling, and pre-treatments, with a saccharide recovery of $94\ \%$. After evaporation and sterilisation, a saccharide mass fraction of $0.27\ \mathrm{kg\ kg^{-1}}$ is achieved. Fermentation produces $0.61\ \mathrm{L_{EtOH}\ kg_{sacch.}^{-1}}$. After distillation and dehydration, $99.7\ \%$ of anhydrous bioethanol is recovered at a purity of $99.6\ \%$. The utilities include mechanical energy, electrical energy, and process steam.

The 2G process considers bioethanol production from C_5 and C_6 saccharides where some of the infrastructure with the 1G process is shared. The 2G process is modelled using various literature sources [8,20,23,25–31]. The pre-treatment method selected is sulphur dioxide-catalysed steam explosion, which produces about $25\ \%$ (d.b.) of xylose from bagasse. The cellulignin produced undergoes alkaline delignification, and the cellulose rich pulp is hydrolysed via enzymatic hydrolysis. After alkaline delignification and precipitation using H_2SO_4, a total lignin recovery of $81\ \%$ $(176\ \mathrm{kg_{lignin}\ ton_{bagasse}^{-1}})$ is achieved. The total bioethanol yield from the 2G process is $151\ \mathrm{L\ ton_{bagasse}^{-1}}$.

Cogeneration is used to produce high pressure steam ($90\ \mathrm{bar}$ at $520\ ^{\circ}\mathrm{C}$) to fulfil the utility requirements of the process. The steam is sent to a back-pressure steam turbine to supply process electricity and process steam at $2.5\ \mathrm{bar}$ (saturated), $6.0\ \mathrm{bar}$ (saturated), and $12.5\ \mathrm{bar}$ $(190\ ^{\circ}\mathrm{C})$. The material burnt includes trash[1],

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[1] Trash includes the dry leaves, green leaves, and tops of the sugarcane.

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

* $\mathrm{ton_{bm}}$: Tonne of sugarcane processed (wet basis)

** Assumption

Tab. 2 Parameters for 2G production

Parameters	Value
Bagasse produced (dry basis) [31]	$0.12\ \mathrm{ton\ ton_{bm}^{-1}}$
Bagasse moisture content (wt. %) [14,20,24].	$50\ \%$
Electrical consumption [31]	$24\ \mathrm{kWh\ ton_{bagasse}^{-1}}$*
Pre-treatment	
Steam consumption [8]	$0.55\ \mathrm{kg\ ton_{bagasse}^{-1}}$*
Steam pressure [8]	$12.5\ \mathrm{bar}$
Temperature [8]	$190\ ^{\circ}\mathrm{C}$
SO_2 consumption [8]	$2\ \%\ (\mathrm{kg\ kg^{-1}})$
Hemicellulose solubilisation [27]	$82.7\ \%$
Hemicellulose hydrolysis [31]	$70\ \%$
Lignin solubilisation [27]	$7.9\ \%$
Cellulose solubilisation [27]	$11.5\ \%$
Water content in liquid fraction **	$56\ \%$
Fermentation	
Xylose fermentation yield [31]	$80\ \%$
Alkaline delignification	
NaOH consumption [27]	$1\ \%\ (\mathrm{kg\ m^{-3}})$
Temperature [31]	$100\ ^{\circ}\mathrm{C}$
Lignin solubilisation [27]	$92.7\ \%$
Precipitation	
Lignin recovery **	$95\ \%$
Water content in recovered lignin **	$34\ \%$
Enzymatic hydrolysis	
Cellulose hydrolysis [31]	$70\ \%$
Hemicellulose hydrolysis [31]	$70\ \%$
Water content of glucose rich stream **	40%

* $\mathrm{ton}_{bagasse}$: Tonne of bagasse processed (wet basis)

** Assumption

Tab. 3 Parameters for cogeneration

Parameters	Value
Boiler steam pressure [23]	$90\ \mathrm{bar}$
Boiler steam temperature [23]	$520\ ^{\circ}\mathrm{C}$
Boiler efficiency [31]	$87\ \%$
Bagasse LHV *	$-7.33\ \mathrm{MJ\ kg^{-1}}$
Trash LHV *	$-14.93\ \mathrm{MJ\ kg^{-1}}$
Lignin LHV *	$-15.03\ \mathrm{MJ\ kg^{-1}}$
Back pressure steam turbines efficiency	$78\ \%$
Condensing steam turbine efficiency	$78\ \%$
Condensing steam turbine outlet pressure	$8\ \mathrm{kPa}$

* 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, $\Delta_{\mathrm{c}} h^{\circ}_{\mathrm{HHV}}$, and the mass of oxygen combusted per mass of the fuel, m_{O_2}, described by

$$\Delta_{\mathrm{c}} h^{\circ}_{\mathrm{HHV}} = \gamma\, m_{O_2} \qquad \text{(Eq. 1)}$$

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

$$\Delta_{\mathrm{c}} h^{\circ}_{\mathrm{HHV}} = -13.87\left(n_{\nu_{\mathrm{C}}} + \frac{1}{4} n_{\nu_{\mathrm{H}}} - \frac{1}{2} n_{\nu_{\mathrm{O}}}\right)\frac{M_{\mathrm{O}_2}}{M_{\mathrm{fuel}}} \qquad \text{(Eq. 2)}$$

where $n_{\nu_{\mathrm{C}}}$, $n_{\nu_{\mathrm{H}}}$ and $n_{\nu_{\mathrm{O}}}$ are the moles of carbon, hydrogen, and oxygen present in the fuel, and M_{O_2} and M_{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, ΔE_{Q}, is defined as the difference in HHV's of the product, $\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,p}}$, and feed, $\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,f}}$, divided by $\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,f}}$:

$$\Delta E_{\mathrm{Q}} = \frac{\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,p}} - \Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,f}}}{\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,f}}} \qquad \text{(Eq. 3)}$$

and may be reported as a fraction or percentage. Thus, if ΔE_{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:

$$\Delta E_{\mathrm{Q}} = \frac{\mathrm{m}_{\mathrm{O}_2}\big|_{\mathrm{p}}}{\mathrm{m}_{\mathrm{O}_2}\big|_{\mathrm{f}}} - 1 \qquad \text{(Eq. 4)}$$

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, ΔE_{η}, accounts for this accordingly and is defined as

$$\Delta E_{\eta} = \eta\, \frac{\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,p}}}{\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,f}}} \qquad \text{(Eq. 5)}$$

As with Equation 3, ΔE_{η} is a function of m_{O_2}:

$$\Delta E_{\eta} = \eta\, \frac{\mathrm{m}_{\mathrm{O}_2}\big|_{\mathrm{p}}}{\mathrm{m}_{\mathrm{O}_2}\big|_{\mathrm{f}}} \qquad \text{(Eq. 6)}$$

This Equation implies that ΔE_{η} 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 ΔE_{Q}, the recoverable components only include product streams that contribute to the generation of bioethanol whereas ΔE_{η} 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, $\Delta E_{\mathrm{cons.}}$) per unit of biomass-derived energy valorised, ΔE_{f}, by the same process may be included in the description of energy yield:

$$\Delta E_{\eta} = \frac{\Delta E_{\mathrm{p}}}{\Delta E_{\mathrm{f}}} - \frac{\Delta E_{\mathrm{cons.}}}{\Delta E_{\mathrm{f}}}$$

$$\Delta E_{\eta} = \frac{\mathrm{m}_{\mathrm{p}} \Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,p}}}{\mathrm{m}_{\mathrm{f}} \Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,f}}} - \frac{\Delta E_{\mathrm{cons.}}}{\mathrm{m}_{\mathrm{f}} \Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,f}}}$$

$$\Delta E_{\eta} = \eta\left(\frac{\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,p}} - \Delta E_{\mathrm{cons.}}/\mathrm{m}_{\mathrm{p}}}{\Delta_{\mathrm{c}} h^{\circ}\big|_{\mathrm{HHV,f}}}\right) \qquad \text{(Eq. 7)}$$

where $\Delta E_{\mathrm{cons.}}/\mathrm{m}_{\mathrm{p}}$ 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/).

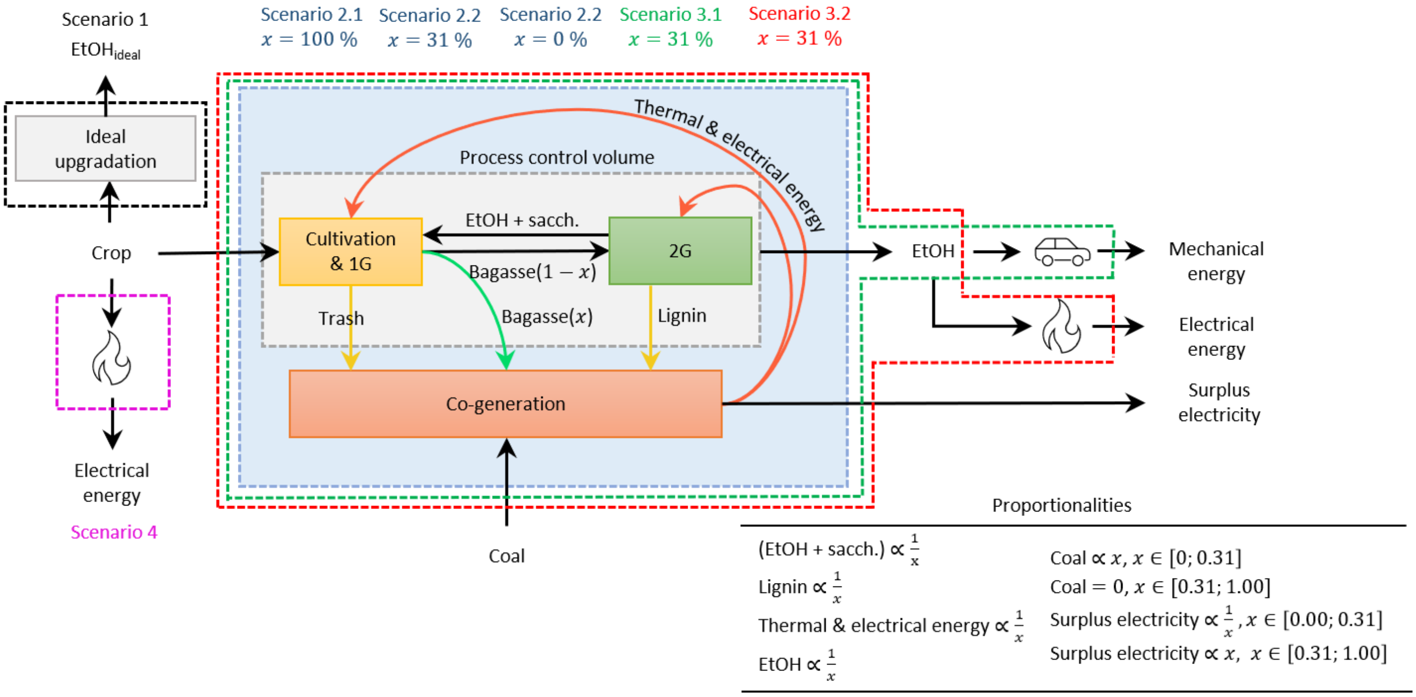

Fig. 2 Summary of the proportionalities between the mass & energy fluxes and the amount of bagasse burnt (x).

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 (L ton$_{bm}^{-1}$)	Electricity surplus (kWh ton$_{bm}^{-1}$)	Steam utility (kg ton$_{bm}^{-1}$)	Mass yield (%)	Overall ΔE_Q (%)	Overall ΔE_η (%)	Total energy produced (MJ ton$_{bm}^{-1}$)
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 % ($187\ L_{EtOH}\ ton_{bm}^{-1}$). 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 $6210\ \mathrm{MJ\ ton_{bm}^{-1}}$.

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 $842\ \mathrm{MJ\ ton_{bm}^{-1}}$ and $896\ \mathrm{MJ\ ton_{bm}^{-1}}$, respectively. If instead the neat biomass was converted to electricity directly, the total energy produced would be much higher, at $1120\ \mathrm{MJ\ ton_{bm}^{-1}}$.

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 $\mathrm{m_{O_2}}$) and (ii) maximising mass yield (*i.e.*, $\eta = \mathrm{m_{EtOH}\ m_{bm}^{-1}}$). 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 ($\mathrm{m_{O_2}}\big|_{\mathrm{p}}\mathrm{m_{O_2}^{-1}}\big|_{\mathrm{f}} = 1.63$) and is the entity that qualifies the first principle. As $\Delta\mathrm{E}_{\eta}$ is a function of $\Delta\mathrm{E_Q}$, 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 $6210\ \mathrm{MJ\ ton_{bm}^{-1}}$ 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?

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