

Integrated anaerobic digestion and gasification processes for upgrade of ethanol biorefinery residues

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Abstract

The upgrading of the biorefineries residues is a possible way to increase the overall process efficiency while attaining economical revenues from wastes that otherwise would be discarded. In this sense, anaerobic digestion and gasification represent interesting alternatives to convert organic residues into biofuels, electricity or other bioproducts. However, few studies have explored energy integration possibilities between those options or evaluated various final product pathways. Thus, in this work, various scenarios aimed at capitalizing the main residues of the sugarcane ethanol industry (vinasse and bagasse) are investigated. Two process layouts combining anaerobic digestion and gasification are proposed for each desired product (methane, hydrogen or power). The highest exergy efficiency (48%) was obtained for the configuration focused on methane production and using a combined cycle, since it requires fewer resources and separation steps to convert feedstock into exportable products. On the other hand, exergy was primarily destroyed in vinasse disposal, since a significant fraction of its organic wastes are inert to anaerobic digestion, followed by the bagasse gasifier and utility systems, due to the irreversible reactions occurring in these processes. In short, this study points to some improvement opportunities and reinforces the advantages of the waste capitalization concept.

Keywords: biogas, gasification, exergy, anaerobic digestion, energy integration

1. Introduction

Biomass is an important source of renewable energy that may help reduce fossil fuel dependency and CO₂ emissions, especially in countries such as Brazil with a large biomass potential. In recent years, biofuels have accounted for almost 70% of renewable energy production in the world [1] and biomass was responsible for 25.5% of Brazilian domestic energy supply [2]. This contribution could be boosted further if undesired biorefinery wastes were converted into valuable energy products. This way, energy consumption and greenhouse gas emissions at biomass processing plants could be reduced along with waste disposal costs and environmental impact. In Brazil, for example, bagasse and vinasse are the main residues of the sugarcane industry, which is, in turn, the major source of bioenergy in the country [2]. Normally, bagasse is used to provide combined heat and power for sugarcane mills, whereas vinasse is typically used as an alternative fertilizer in sugarcane crops [3]. Although they are well established procedures in industry, these practices are

still fairly inefficient and could be replaced by improved energy conversion processes [4, 5].

In the biomass waste conversion context, gasification and anaerobic digestion are prominent research topics among the available technological routes [6]. These technologies together could lead to higher energy conversion and production yields [7] and reduced sizes for treatment plants [8]. Previous studies have already investigated the use of lignocellulosic biomass for synthetic natural gas [9], hydrogen and electricity production [10], highlighting the importance of energy integration to highly efficient plant designs. For sugarcane residues, some examples of conversion routes are: bagasse gasification [5] and enzymatic hydrolysis [7] to increase, respectively, power or ethanol production; and vinasse anaerobic digestion to deliver additional electricity [11] or biomethane [12] to the market. However, while different options have been already proposed for each biomass waste, there is a lack of studies dedicated to analyzing the performance of waste upgrade systems using both resources (bagasse and vinasse). Thus, this paper presents a thermodynamic evaluation of possible processes combining anaerobic digestion and gasification to capitalize vinasse and residual bagasse from biorefineries by using a system-

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atic approach of energy integration and exergy analysis.

2. Process description

Fig. 1 shows the production routes proposed and analyzed in this paper, while Fig. 2 shows the detailed superstructure for each chemical process unit, as well as, the energy resources and the integrated utility systems. The optimized systems were designed to be self-sufficient in terms of power and heat supply, by using purified syngas or vinasse-derived biomethane (or both) as fuels. For each desired final product (methane, hydrogen or electricity), the process was optimized by using two different utility solutions (Rankine or combined cycle based cogeneration plant), totaling six optimized cases in this study. As can be observed in Fig. 2, apart from the steam and combined power cycles, other integrated energy technologies are: furnaces, a cooling tower and a vapor-compression refrigeration system. In addition, the quantity of residues generated by an average sugarcane ethanol distillery was estimated to be 474 m³/h of vinasse (31.5 gCOD/l) and 7.4 kg/s of residual bagasse [2, 7, 13]. Methane and hydrogen final concentration were set as 97%mol CH₄ and 99%mol H₂.

2.1. Vinasse conversion: biomethane and hydrogen production units

The vinasse separated in the ethanol distillation column is at temperatures higher than ambient (60 °C) and presents a low pH (3.75-5) [2], which are not close to ideal conditions for anaerobic bacteria cultures. Thus, vinasse must be first cooled and mixed with a recycled digester effluent (15:1 effluent to influent flow ratio) [14] for temperature and pH correction. Mesophilic anaerobic digestion (35 °C) is conducted in an upflow anaerobic sludge blanket (UASB) reactor, as widely practiced in vinasse treatment plants [15]. The treated vinasse is temporarily stored in lagoons for distribution to sugarcane crops (fertirrigation) by means of channels, diesel-fueled pumps or special trucks. On the other hand, biogas is desulfurized using a cold sodium hydroxide solution (10g NaOH/L; 15 °C) in order to avoid corrosion in downstream equipment. The caustic solution flow rate is adjusted to guarantee maximum output H₂S concentration (200 ppmv). The remaining biogas impurities, mainly CO₂ and H₂O, are physically absorbed by using a Selexol process to achieve commercial specifications. This technology consists of a high pressure column absorber (30 bar, 25 °C) using a mixture of dimethyl ethers of polyethylene glycol (DEPG). The rich solution is partially regenerated by releasing the CO₂ gas at lower pressures (1 bar) and higher temperatures (60 °C). The purged gas may still contain a portion of methane and, thus, it has to be burned to avoid environmental damage.

In the hydrogen via vinasse unit, biomethane is depressurized (20 bar) to enhance the production of a H₂ and CO rich mixture by using steam reforming. The highly endothermic steam reforming reaction requires temperatures well above

700 °C. To avoid excessive formation of carbon that could affect the performance and lifetime of the catalyst, the molar steam to methane ratio is set at 3 [16]. Two sequential high (390 °C) and low (212 °C) temperature shift reactors are used to increase hydrogen concentration through the water-shift exothermic reaction. In this step, the hydrogen rich mixture is intercooled by using a heat recovery system in order to control the maximum attainable reaction temperature [17]. The additional CO₂ produced is removed by using physical absorption and pressure swing adsorption (PSA) systems. Finally, the purified hydrogen is compressed (200 bar) with intercooling for commercialization.

2.2. Bagasse conversion: Gasification, Biomethane and Hydrogen production units

The bagasse as-received from the sugarcane mill has a high moisture content (50%) which must be reduced to less than 10% in a rotary dryer that consumes power and heat provided by the utility systems and recovers heat from the gasifier flue gas [18]. Bagasse is also chipped in an energy intensive process that may require between 1-3% of the total energy (lower heating value basis) in the consumed biomass [19]. The bagasse ultimate composition is set at 46.70% C, 6.02% H, 44.95% O, 0.17% N, 0.02% S and 2.14% ash, whereas proximate analysis is considered as 50% moisture (as-received), 14.32% fixed carbon, 83.54% volatile substances, and ash in balance [20]. The Battelle Columbus Laboratory (BCL) indirect gasifier at atmospheric pressure avoids dilution with nitrogen of the syngas produced, as the combustion and gasification processes occur in a separate double column system (Fig. 2) [21]. Steam is used as the gasification medium (steam-to-biomass mass ratio 0.75), whereas combustion – with air – of a fraction of the char produced in the bagasse pyrolysis step supplies the heat required by the endothermic drying, pyrolysis and gasification reactions. After the syngas produced exits the gasifier, the tar produced is subjected to thermal catalytic cracking. The syngas is cooled to 400 °C, scrubbed with water to remove impurities that may affect downstream equipment and then compressed to 30 bar. At this point, the purified syngas can be converted to either hydrogen-rich syngas or electricity and heat. As it still contains high levels of CO, a water gas shift conversion (analogous to that described for hydrogen production via vinasse) helps increase the hydrogen content, simultaneously producing more CO₂. On the other hand, this is not necessary for the sake of power production and represents an additional source of steam demand and irreversibility.

The production of pure hydrogen by using biomass gasification shares some similar processes with biomethane conversion in the vinasse route, namely, Selexol and PSA purification steps and multistage hydrogen compression. On the other hand, when methane production is intended, a portion of CO₂ is removed from the syngas to obtain the desired proportion of hydrogen per carbon for use in methanation. This process consists in the conversion of hydrogen,

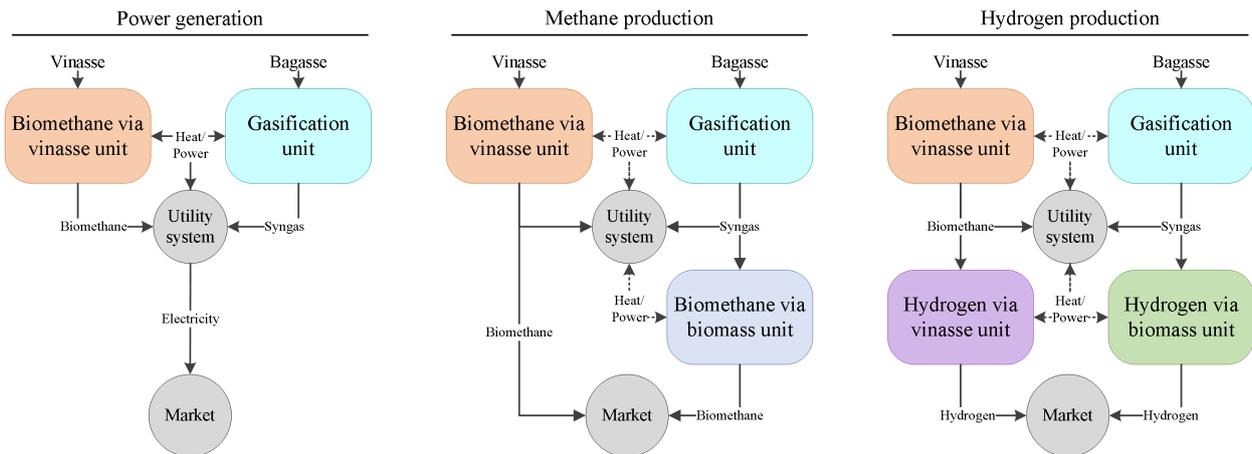


Figure 1: Production routes proposed for electricity, methane and hydrogen

CO and CO₂ into methane and water in three sequential reactor beds [22, 23]. The methanation reactions are exothermic and, therefore, an interbed heat recovery system is required to avoid rapid catalyst deterioration. For instance, the first methanator bed uses a recycle stream combined with intercooling in order to maintain the maximum temperature below 700 °C. As a result, the gas mixture produced has a high methane concentration ($\geq 97\%$), which is sent to a temperature swing adsorption system to reduce its humidity to commercial standards.

3. Methodology

Mass, energy and exergy balances for the unit operations of the studied cases are carried out in Aspen Plus software as well as by means of a Matlab integration routine to compute the mass balance in the anaerobic digestion model [24]. The exergy analysis and energy integration process are used to assess the performance and suggest possible improvements for each production route. A detailed model description is presented in the following sections.

3.1. Process modeling

The composition of vinasse was estimated based on the experimental observations of Barrera et al. [14] with general components (e.g. sugars, lipids, inert, etc.) modeled as commonly observed chemical substances (e.g. glucose, linoleic acid, lignin, etc.) [4]. The thermophysical properties of this effluent mixture were calculated using the Non-Random Two-Liquid model (NRTL). Fertilization was assumed as a black box model with specific diesel consumption of 0.19 L per m³ of vinasse transported, based on previous studies [25, 26]. The anaerobic reactor was modeled as a continuous ideally stirred-tank reactor using the Anaerobic Digestion Model N^o1 (ADM1) [27], a generic kinetic model for anaerobic digestion, with modifications and parameters adapted for sugarcane ethanol vinasse [28]. Moreover, the inlet vinasse temperature was calculated considering the reactor heat loss, esti-

mated by using average heat transfer coefficients [29] and a constant process temperature (35 °C).

In the desulfurization unit, the process mass balance is estimated using a rate-based model and a set of chemical reactions involving electrochemical and gas-liquid interactions [30, 31]. Since this process involves ionic substances, the Electrolyte Non-Random Two-Liquid model (ELECNRTL) was used to calculate the thermophysical properties. On the other hand, the Perturbed-Chain Statistical Associating Fluid Theory (PC-SAFT) is used to model the physical absorption of CO₂ with DEPGs [32]. In the remaining simulated components (e.g. methanation, PSA, gasification, etc.), the Peng-Robinson EOS with Boston-Mathias modifications is used. Gasification is modeled as composed of sequential drying, pyrolysis, reduction and combustion processes. In order to estimate the actual yield rates of hydrogen, CO, CO₂, methane, tar, char and water in the pyrolysis reaction step, empirical correlations reported in the literature as a function of temperature were used [33]. The tar and methane produced, typically underestimated via the non-stoichiometric equilibrium methods, is adjusted with a set of approach-to-equilibrium temperatures to reflect the actual syngas composition of the gasifier [34]. Thermodynamic equilibrium is also used to model the steam reforming (with temperature approach correction), water shift and methanation reactors and flare combustor. Moreover, an air to fuel ratio of 1.5 times the stoichiometric proportion is considered for purification purge gas combustion.

Pumps and compressors were modeled based on fixed isentropic efficiencies of, respectively, 60% and 80%. Pressure swing adsorption is simplified as a black-box model assuming a hydrogen recovery efficiency of 80% mol, based on previous works [16]. As a simplification, the adsorption systems consumptions are assumed too small in terms of the overall system and the temperature swing adsorption was assumed as lossless. Furthermore, pressure and heat losses are not considered in any process, except for the anaerobic reactor.

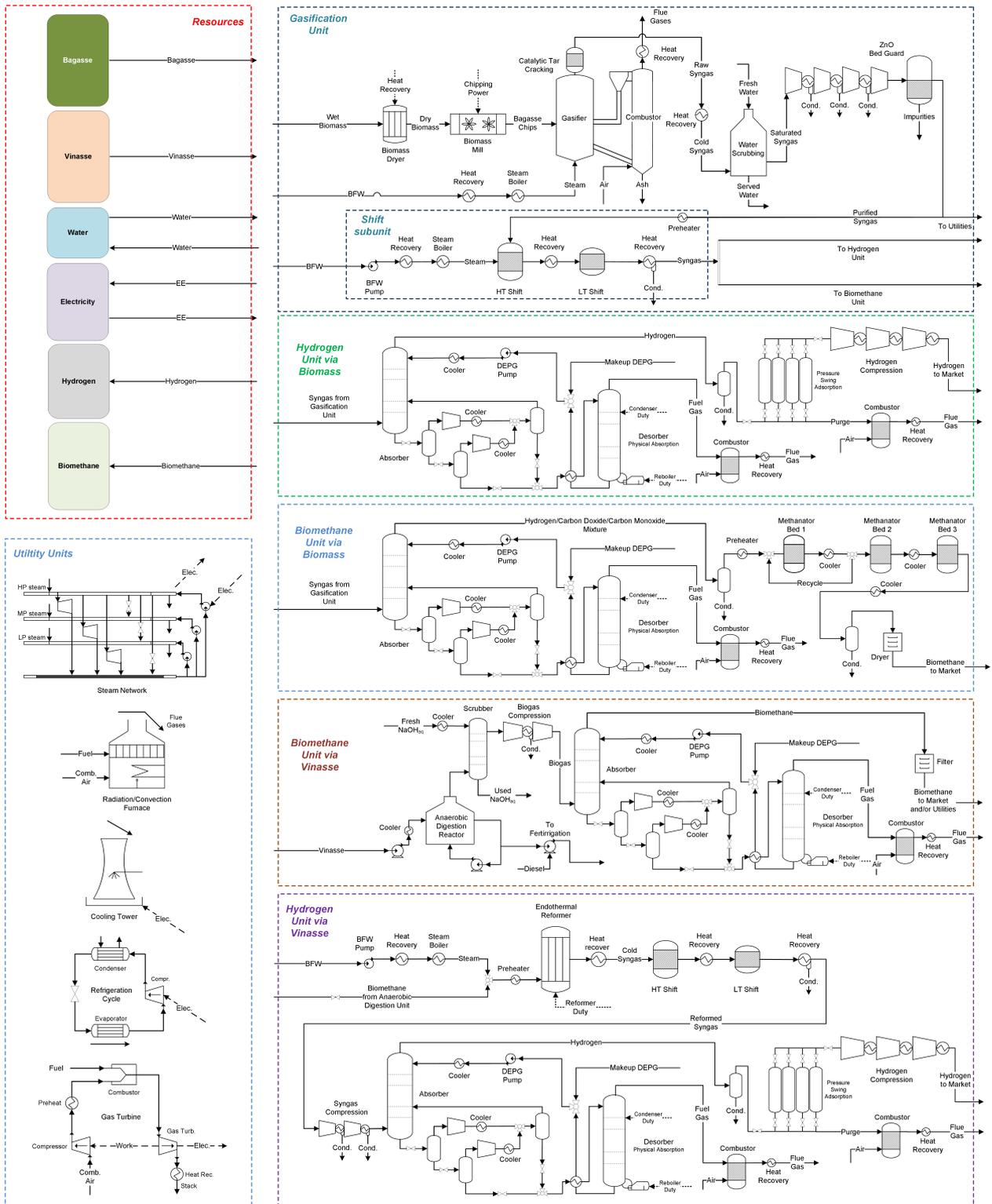


Figure 2: Detailed superstructure of the various biofuel production routes

3.2. Energy integration and operating cost minimization

The energy integration analysis is performed by using the OSMOSE Lua platform developed by the IPSE group at EPFL, Switzerland [35]. This tool is used to determine the most suitable utility systems and their operating conditions, which satisfy the minimum energy requirement (MER) with the lowest resource consumption and optimal operating cost (water consumption, vinasse and bagasse). This computational framework manages the data transfer with the Aspen Plus software and builds the mixed integer linear programming (MILP) problem described in the Equations (1-5) which minimizes the operating cost of the chemical plant [36] while satisfying the constraints of the MER problem. In other words, the optimization problem consists of finding the load factor (f^ω) of each utility unit that minimizes the operational cost function (objective function) given by Equation 1:

$$\min_{f^\omega, y^\omega, R_r} [(f^\omega \dot{B}^{CH} c)_{\text{vinasse}} + (f^\omega \dot{B}^{CH} c)_{\text{bagasse}} + (f^\omega \dot{V} c)_{\text{water}} - (f^\omega \dot{B}^{CH} c)_{\text{biofuel or electricity}}] t_{op} \quad (1)$$

Subject to the following constraints:

$$\sum_{\omega=1}^{N_\omega} f^\omega q_r^\omega + \sum_{i=1}^N Q_{i,r} + R_{r+1} - R_r = 0 \quad \forall r = 1 \dots N \quad (2)$$

$$\sum_{\omega=1}^{N_\omega} f^\omega W^\omega + W_{in} - W_{exp} = 0 \quad (3)$$

$$f_{min}^\omega y^\omega \leq f^\omega \leq f_{max}^\omega y^\omega \quad \forall \omega = 1 \dots N_\omega \quad (4)$$

$$R_1 = 0, R_{N_r+1} = 0, R_r \geq 0 \quad (5)$$

Where, \dot{B}^{CH} and c stands, respectively, for the chemical exergy flow rate and cost of the feedstock consumed or prices of marketable fuels and electricity produced; while \dot{V} and t_{op} are the amount of water consumed and the operational time. Furthermore, Q and R are, respectively, the heat flow and cascade heat flow; and N_ω is the number of different units in the set of utility systems.

Additional equations for the mass and energy balances on each stream layer (water, feedstock, fuels, electricity), along with the equations for modeling each one of the various energy technologies, are also included in the optimization problem. The optimal utility set is determined by calculating the integer variables (y_ω) associated to the existence or absence of a given utility unit and the corresponding continuous load factor (f_ω) of the selected utility systems. Representative Brazilian market costs for water (3.03 EUR/m³), vinasse (0.0006 EUR/kWh), and bagasse (0.0056 EUR/kWh) consumed, as well as the selling prices of hydrogen (0.072 EUR/kWh), biomethane (0.032 EUR/kWh) and electricity (0.06 EUR/kWh) produced are taken from literature [36–38].

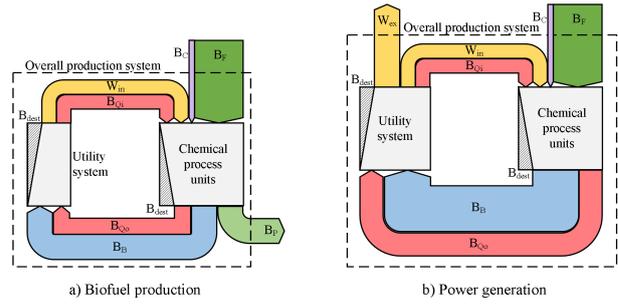


Figure 3: Grassman diagram for biofuel (a) and electricity (b) production routes

3.3. Exergy analysis

Vinasse chemical exergy is estimated based on its theoretical chemical organic demand (ThCOD) concentration, as proposed by Nakashima and Oliveira Junior [4] based on early studies of Tai, Matsushide and Goda [39]. Assuming that ThCOD and experimental chemical organic demand (COD) are approximately equal, the chemical exergy of vinasse organic material ($b_{org. \text{vinasse}}^{CH}$) can be estimated based on the reported COD concentrations according to Equation 6.

$$b_{org. \text{vinasse}}^{CH} = 14.56 \text{ ThCOD} \quad (6)$$

Bagasse lower heating value (LHV) is estimated based on correlations by Channiwala and Parikh [40], whereas the ratio of the specific chemical exergy to the LHV is calculated by means of correlations for solid fuels with given atomic C, H, O, N composition [41]. Furthermore, the specific chemical exergy of diesel fuel was considered as 44.85 MJ/kg [42].

Figure 3 briefly depicts the control volume adopted to perform the exergy balance for the analyzed biofuels and electricity production routes. As can be observed, the chemical process units consume exergy from the external feedstock (B_F) and chemicals (B_C) streams, as well as the power (W_{in}) and the heating or cooling demands (B_{Qi}) to deliver biofuel (B_P) or electricity (W_{ex}) to the market. The chemical process units also supply heat exergy to the heat recovery section of the utility systems (B_{Qo}) in order to energetically integrate the chemical plant, while reducing the amount of fuel consumed. This fact notwithstanding, a portion of the produced biofuel (B_B , purified syngas or biomethane from vinasse) must still be used to supply the balance of exergy for the chemical process plant. It must be noticed that, in this analysis, all the irreversibility generated via the heat exchanger network and the power generation systems is allocated to the utility systems. This simplifies the exergy analysis, since the heating or cooling exergy requirements (B_{Qi} and B_{Qo}) can be easily calculated based on the knowledge of the exergy balance of each part of the process equipment (e.g. heat exchangers, endothermic reactors, etc.). Otherwise, a detailed design of the utility system would be necessary in the initial stages of the overall plant design.

The exergy efficiency of the chemical process units, the utility system and the overall plant shown in Figure 3 can be

calculated as the ratio of useful output-to-total input exergy flows for each sub-system, according to Equations 7, 8 and 9.

$$\eta_{\text{process units}}^{\text{chemical}} = \frac{B_P + B_B + B_{Qo}}{B_F + B_{Qi} + W_{in} + B_C} \quad (7)$$

$$\eta_{\text{system}}^{\text{utility}} = \frac{B_{Qo} + W_{in} + W_{ex}}{B_{Qo} + B_B} \quad (8)$$

$$\eta_{\text{system}}^{\text{overall}} = \frac{B_P + W_{ex}}{B_F + B_C} \quad (9)$$

4. Results and discussion

Fig. 4 shows the exergy consumption and production breakdown for each one of the units shown in Fig. 2. It is noteworthy that the gasification unit analysis was separated into two parts, since the water gas shift process is only used for the production of biofuels. As can be seen from Fig. 4, the larger fraction of exergy consumption (98-76%) is related with biomass chemical exergy (vinasse, bagasse, methane and syngas) and the two highest productions of irreversibilities (27% and 58%) are present in the primary units. In the biomethane via vinasse unit, the vinasse high concentration of organic material inert to bacterial activity represents a substantial exergy loss (50% of discarded vinasse). Furthermore, water, minerals and sludge present in the discarded vinasse were not considered as products in this analysis, which could substantially increase the unit exergy efficiency (18%). As for the gasification unit, a significant part of the exergy of the biomass has to be internally consumed in syngas production, which significantly reduces the produced gas.

On the other hand, the biomass-derived biomethane and hydrogen units attained the two highest exergy efficiencies, 94% and 85%, respectively. The biomass biomethane unit efficiency is attributed to the reduced amount of CO₂ separation, since a portion is to be converted in the methanator, and the absence of the adsorption process, which reduces the exergy loss. As for the hydrogen via biomass unit, there are few sources of irreversibilities, mainly related with purge gas from purification processes and its subsequent combustion (flare), since the unit mainly consists of purification processes with low exergy consumption.

In the process units analyzed, heat appears as the second largest exergy consumption and an important side-product, specially in those with highly endothermic (gasification and steam reform) and/or exothermic (combustion, water gas shift and methanation) reactions. In this way, the efficiency of the heat recovery system can have a major impact on the usefulness of the heat produced and, consequently, on overall production system efficiency. For example, although the hydrogen production units from either biogas or biomass have similar exergy efficiencies (84% and 85%, respectively), the former is much more dependent on the usefulness of the heat produced than the latter. In other words, the exergy efficiency of the overall system could be compromised were it not for the rational use of the available waste heat.

Finally, in this analysis, electricity appears as a small exergy expense (1-3%) in comparison to other exergy consumption sources.

The main exergy consumption and production highlights for each analyzed case are summarized in Table 1. It can be observed that the biomass route delivers more goods to the market, since vinasse is not completely converted in anaerobic digestion, as shown in Fig. 4 and previously discussed. This discrepancy decreases in the methane production cases, since anaerobic digestion directly transforms vinasse in methane, while the bagasse route relies on additional energy conversion processes. In general, the use of a combined cycle increases the amount of exported products (80% for electricity and 6-7% for biofuels) due to its higher efficiency and, consequently, lower fuel consumption. However, this difference may not be justifiable for biofuel production considering the additional investment cost of a gas turbine and related equipment. Nevertheless, hydrogen offers an advantageous financial return per unit of product, with utilities fuel consumption similar to the methane production scenarios option, in spite of the need of further reaction steps, due to the increased exergy being delivered to the heat recovery system.

Interestingly, most biofuel production routes use purified syngas as utilities fuel to minimize production costs. Since the dominant variable in the optimization problem is the product exergy flow (biofuel or electricity), the choice of syngas as the utility fuel is due to the lower fuel consumption per unit of product present in the conversion paths that use vinasse as input. Table 2 shows the ratio of fuel, heat and power consumed per product for each route. In the methane production case, for example, each kW of methane requires 1.23 kW of syngas or 1 kW of vinasse-derived biomethane. Thus, it is coherent to prioritize the production route that has the higher potential to deliver more goods to the market, in order to minimize the production costs. Nonetheless, this may change according to the efficiency of the utility system and the exergy consumptions of the chemical process unit, as can be seen for the hydrogen production case with a Rankine cycle based utility system. Although more hydrogen could be produced from vinasse-derived biomethane, this would require substantially more power and heat than by using syngas (see Table 2). Thus, even if there is a gain on product per fuel yield by prioritizing the vinasse route for hydrogen production, there is also a penalty related to the increased consumption of fuel in the utility system.

In the following, the exergy efficiency and the exergy destruction breakdown of the various production routes for biofuels and electricity, related in Table 1, are presented in Fig. 5 and 6. It can be observed that higher overall exergy efficiencies (blue bars), Fig. 5 are obtained for the biofuel production routes, whereas the exergy destruction rates are concentrated in the gasification, anaerobic digestion and utility system units. Although the chemical process units have similar efficiencies for each case (52-57%), overall system efficiency varies substantially with the type of exported product (10-44%). The best performance scenario is found for

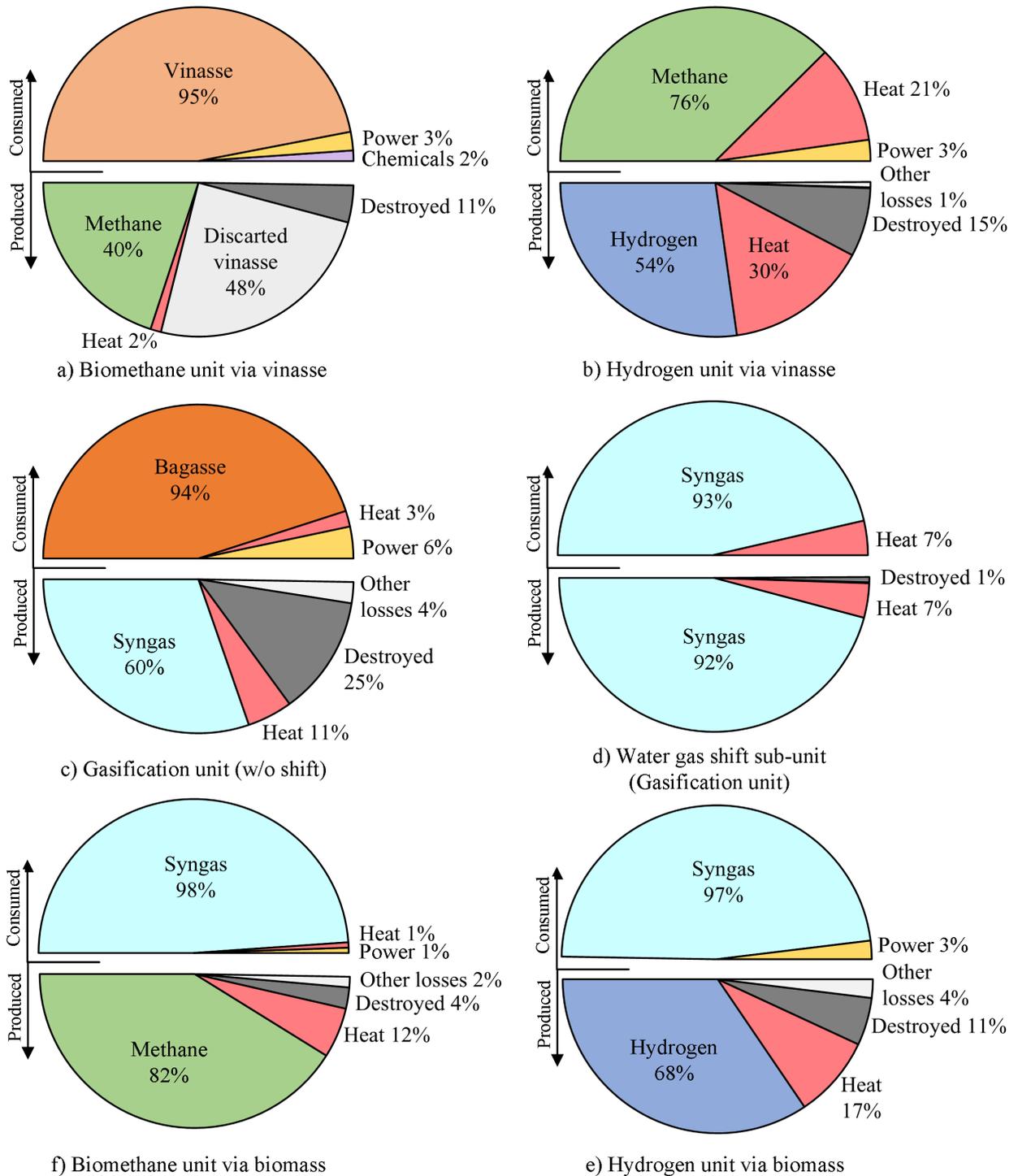


Figure 4: Exergy consumption and production breakdown for each chemical process unit

Table 1: Exergy consumption and production highlights for each product and power generation system

Simulated cases						
Parameters	Electricity	Rankine	Methane	Rankine	Hydrogen	Rankine
Utility system fuel (exergy)	Combined cycle All purified syngas and biomethane (76.2 MW)	Rankine All purified syngas and biomethane (76.2 MW)	Combined cycle 110 kmol/h of purified syngas (6.9 MW)	Rankine 188 kmol/h of purified syngas (11.8 MW)	Combined cycle 116 kmol/h of purified syngas (7.3 MW)	Rankine 46 kmol/h of biomethane (10.7 MW)
Exported product from biomass route	16 MW	9.3 MW	144 kmol/h	127 kmol/h	405 kmol/h	478 kmol/h
Exported product from vinasse route	9.6 MW	5.6 MW	122 kmol/h	122 kmol/h	291 kmol/h	182 kmol/h
Total product exergy	25.6 MW	14.9 MW	62.3 MW	58.2 MW	48.2 MW	45.7 MW
Estimated revenues	803 EUR/h	289 EUR/h	1569 EUR/h	1438 EUR/h	2990 EUR/h	2806 EUR/h

Table 2: Exergy consumption per product ratio for biofuel production units

Exergy ratio	Production route			
	CH_4 from vinasse-derived biomethane	CH_4 from syngas	H_2 from vinasse-derived biomethane	H_2 from syngas
Fuel per product	1 $\frac{kW_{CH_4}}{kW_{CH_4}}$	1.23 $\frac{kW_{syngas}}{kW_{CH_4}}$	1.42 $\frac{kW_{CH_4}}{kW_{H_2}}$	1.43 $\frac{kW_{syngas}}{kW_{H_2}}$
Heat per product	0 $\frac{kW}{kW_{CH_4}}$	0.11 $\frac{kW}{kW_{CH_4}}$	0.38 $\frac{kW}{kW_{H_2}}$	0.12 $\frac{kW}{kW_{H_2}}$
Power per product	0 $\frac{kW}{kW_{CH_4}}$	0.01 $\frac{kW}{kW_{CH_4}}$	0.06 $\frac{kW}{kW_{H_2}}$	0.04 $\frac{kW}{kW_{H_2}}$

methane production by using combined cycle (44%), because its chemical process units are more efficient (as previously discussed and shown by $\eta_{\text{chemical process units}}$ in Fig. 5) and have lower power and heat consumption (Table 2).

As expected, the efficiency of the utility system (brown bars, Fig. 5) is drastically lower for the scenarios of electricity production (only), since it entails a large amount of exergy destroyed in the combustion of all fuel produced by the chemical process plant. Furthermore, the utility system efficiency is higher for hydrogen production since, in these cases, the chemical process unit requires significantly more heat than electricity (see Fig. 4), which is simpler to provide. On the other hand, in the biofuel exportation scenarios, the lion's share of the exergy destruction corresponds to the gasification and anaerobic digestion units, since the fuel consumption in the utility system only needs to balance their internal heat and power demands.

In fact, as can be observed in Fig. 6, the exergy analysis points out that gasification and wastewater (vinasse) treatment offer the most remarkable opportunities for improvement in most cases. For example, vinasse has a high concentration of inert material (related to the anaerobic digestion) that is discarded in the sugarcane crops, thus the reuse of vinasse water or the exploitation of vinasse organic inerts (e.g. concentration and combustion) could significantly reduce the exergy destruction in the routes analyzed. As for gasification, a significant part of the exergy of the biomass has to be internally consumed in syngas production, which significantly reduces the gas produced. Moreover, higher

gasification pressures may lead to reduced power consumption and, consequently, lower exergy destruction in the utility system. Other envisioned possibility include increasing the efficiency of the separation processes to reduce purged gas, which is burned in the proposed designs, or mixing it with byproduct gas to directly produce electricity in gas turbines.

Fig. 7 illustrates the breakdown of power consumed by the chemical processes and other ancillary systems, such as refrigeration and cooling tower, as well as the power supplied by the respective power technologies (gas and steam turbines) in each production route. As can be seen, in agreement with their lower exergy efficiencies, the gasification and the anaerobic digestion processes also present the highest power consumption compared to the same figures for other units (see Fig. 2). Gasification and biomethane via vinasse units include energy intensive processes required for biomass pre-treatment (chipping and vinasse recirculation) as well as several compression steps, due to the close-to-atmospheric operating conditions. Higher gasification pressures may lead to reduced power consumption, provided that pressurized biomass injection does not offset the advantages of pressurized gasification. On the other hand, vinasse recirculation and biogas compression also consume large amounts of power, compared to vapor compression refrigeration or cooling water demands. The reduction of electricity consumption may lead to a smaller utility system and lower internal fuel consumption, which could increase the overall exergy efficiency and revenues of all of the biofuel and electricity production routes. Fig. 7 also highlights that most of

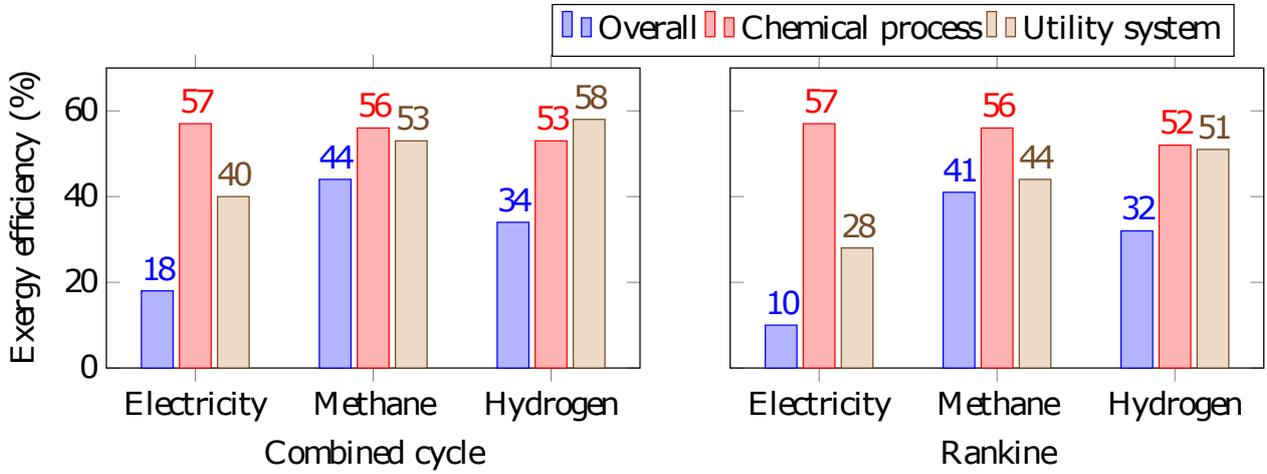


Figure 5: Exergy efficiency for each production route

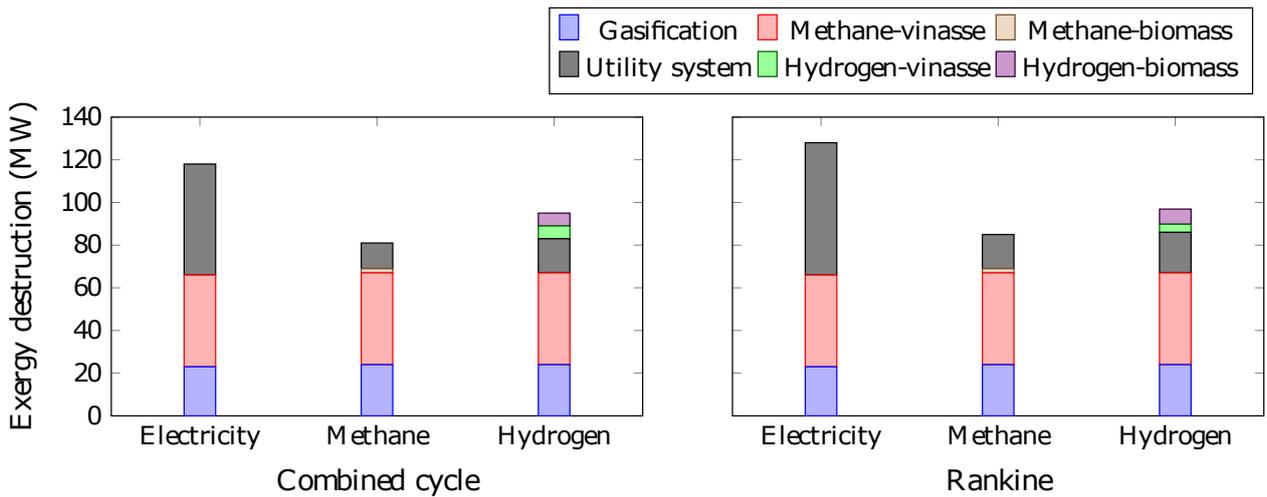


Figure 6: Exergy destruction breakdown for each production route

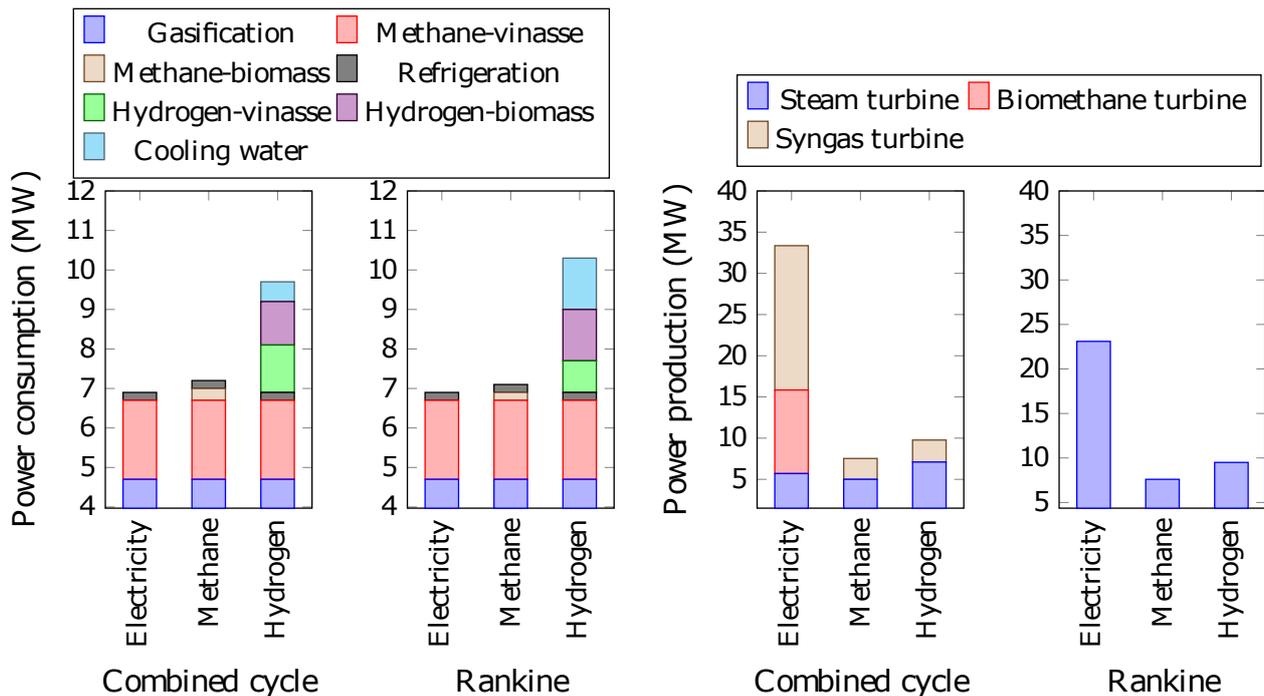


Figure 7: Power consumption and production for each production route

the power production is supplied by the steam turbine, due to the fairly large amount of heat exergy available from the chemical processes and recovered by the steam network.

5. Conclusions

In this work, six scenarios are proposed for upgrading the main sugarcane wastes into added-value products, namely methane, hydrogen and electricity. An exergy analysis and energy integration study was performed to determine the best configuration of chemical processes and utility system parameters to maximize operating revenues while reducing process irreversibilities. Among the studied cases, methane production presented the highest exergy efficiency, due to the lower exergy consumption of the chemical process unit and reduced losses associated with the purge streams from purification steps. However, hydrogen exportation is expected to obtain the highest revenues at competitive efficiencies. The introduction of a combined cycle among the utility systems represented small efficiency gains for biofuel production (2-3% points) compared with electricity generation cases (8% points). Technological improvements associated with reduced power consumption in gasification and wastewater (vinasse) treatment units may substantially increase overall plant efficiency regardless of the production route. Moreover, since anaerobic digestion cannot fully convert the exergy of the vinasse, other processes must be used to reduce losses in wastewater disposal (e.g. concentration, solid separation, etc.).

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