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Process simulation and techno-economic assessment of vinasse-to-biogas in Cuba: Deterministic and uncertainty analysis

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ABSTRACT

This paper presents a process simulation model in Aspen Plus® and a techno-economic assessment for the anaerobic digestion of Cuban sugarcane vinasses considering three scenarios for biogas application: electricity production (S_1), biomethane as vehicle fuel (S_2), and biomethane for gas grid injection (S_3). From the simulation model, non-significant differences (p_value $\geq$ 0.1779) between experimental and simulation results were found. S_1 showed the best economic performance among the assessed biogas applications. From the sensitivity analysis, the mean electricity price leading to a net present value of zero for S_1 was 90 USD/MWh, while for S_2 and S_3 the mean incentive required was 0.33 USD/$m^3_{biomethane}$ and 0.67 USD/$m^3_{biomethane}$, respectively. The uncertainty analysis showed a chance for investment failure in S_1 less than 10%, whereas for S_2 and S_3 it ranged between 31–37%. The minimum scale required (milling and distillery capacities, ethanol yield) for getting profits from biomethane projects was targeted at 10,800 t_{cane}/day, 108 $m^3_{ethanol}$/d at 10 $L_{ethanol}/t_{cane}$, respectively. To this end, Cuban plants should significantly increase their average capacities; otherwise, a centralized biomethane production by limiting the number of biomethane plants to one or two per province could be implemented.

1. Introduction

Renewable energies such as biogas can be produced from a wide diversity of organic materials through a biological process such as anaerobic digestion (AD). Biogas technology in Cuba focuses on the in-situ treatment of organic waste in rural areas such as cattle and swine manure, and wastewaters (municipal and industrial) to reduce environmental pollution. However, the Cuban government has a commitment to promote policies that increase the energy generation from biogas by utilizing residues from the sugar-ethanol industry (e.g. vinasses) (Sagastume Gutiérrez et al., 2020). Vinasse is a by-product obtained after the distillation of fermented cane molasses, with a generation rate between 9 and 20 L per liter of distilled ethanol (Wilkie et al., 2000). Theoretically, 18 Nm^3 of biogas (~60 — 65% of methane) can be produced from 1 m^3 of treated vinasse (Chanfon and Lorenzo, 2014). Cuban distilleries generate about 2,835,000 m^3 of vinasse per year, represent-

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ing a potential to produce 51,030,000 Nm^3 biogas per year. Assuming that 1-Nm^3 of biogas can produce ~22 MJ of energy (Barrera et al., 2013), Cuba has the potential to produce about 310 GWh per year of heat and electricity from vinasse, representing 1.5% of the total Cuban energy demand in 2019 (ONEI, 2019). Nevertheless, more than 60% of the vinasses produced in Cuba are directly applied to the sugar cane cultivation or disposed into oxidation lagoons causing soil salinization (de Oliveira et al., 2013) and uncontrolled methane and carbon dioxide emissions to the atmosphere. Vinasse is a dark color liquid with pH values between 3.5 — 5.0 and sulfate content between 1.3–3.45 $kg_{sulfate}/m^3$ (Barrera et al., 2013; Khanal, 2008). Its composition depends on several factors such as harvesting season, raw materials, agricultural practices, fermentation feedstock (e.g., sugarcane juice or sugarcane molasses) (Moraes et al., 2015). In general, it is characterized by high organic content with chemical oxygen demand (COD) ranging from 50 to 150 kg/m^3 (España-Gamboa et al., 2011), making it a suitable substrate for biogas production. The energetic value of the produced biogas (6.5 — 10 kWh/Nm^3), the organic matter reduction, and the production of biofertilizers are the main drivers for using AD as vinasses treatment. In this regard, the government is willing to support policies that contribute to expanding biogas application from the sugar and ethanol industry. The energy matrix in Cuba depends on fossil fuels and, in rural areas, biogas is used only for cooking. However, biogas can replace fossil fuels by its combustion in combined heat and power generation systems, and, if upgraded (methane content >97%, v/v), it can be injected into the natural gas grid or used as a transportation fuel (O'Shea et al., 2017).

Process simulation and techno-economic analysis (TEA) are key tools to assess different industrialization potentials of a biogas plant from the feedstock to the final biogas applications. In this way, predicting and optimizing the whole process can be performed by minimizing experimental efforts and consuming less time and money (Lovato et al., 2017). Previous works on process simulation for biogas production have been focused on the biological stage of the process (Lorenzo-Llanes et al., 2020; Rajendran et al., 2014), while others have only paid attention to the biogas upgrading process (Lovato et al., 2017; Xu et al., 2015). In addition to the process simulation, the financial assessment of biogas projects must be considered for final decisions. TEA has been widely used on AD, exploring different pretreatment methods for complex materials, biogas upgrading technologies, electricity, and heat generation (López et al., 2020; Rotunno et al., 2017). In the context of the AD of sugarcane vinasses, the TEA has been used to assess different alkalinization strategies (Fuess et al., 2017), full-scale digestion plants with phase separation (i.e., acidification for biogas-H_2 and methanization for biogas-CH_4) (Fuess et al., 2017, 2018), the potential impacts for replacing fossil fuel and natural gas (Silva Neto and Gallo, 2021), and the impacts of different factors on the profitability of the process and biogas application (Fuess and Zaiat, 2018). The majority of the contributions in this field have been performed under Brazilian conditions.

In Cuba, Chanfon and Lorenzo (2014) evaluated different alternatives for vinasses treatment focused on waste valorization routes (e.g., biogas and yeast production); however, no biogas conversion alternatives were considered. The environmental and techno-economic performance of the anaerobic digestion of pretreated and co-digested press mud (plus vinasse) along with a combined heat and power system as biogas final used has been recently assessed (López et al., 2020). Nevertheless, biogas upgrading to biomethane as a vehicle fuels or gas grid injection was not considered. In this regard, a stage-by-stage process simulation model and TEA for the anaerobic conversion of Cuban vinasses into cleaner and more sustainable fuels (i.e., biogas and biomethane) has not yet been reported.

Moreover, most of the studies analyzing the economic profitability of vinasse-to-biogas applications use deterministic models with fixed inputs (Junqueira et al., 2016; Leme and Seabra, 2017; Moraes et al., 2015). Nevertheless, the economic performance of a biogas-to-X application can be significantly affected by uncertainties in the market conditions. Misleading conclusions can be drawn from comparing different biogas applications when uncertainties over the economic criteria have not been considered. Based on this background, this study aims to contribute to the existing literature through the following objectives: (i) To develop a step-by-step process simulation model for the anaerobic digestion of vinasses including biogas cleaning and upgrading using Aspen Plus®, (ii) To assess the economic viability of three pathways for final biogas applications: electricity generation potential (S_1), biomethane to vehicle fuel (S_2) and biomethane to the national gas grid (S_3) by using both, deterministic and stochastic simulation (Monte Carlo). This study will provide the first insight for investment decisions in the Cuban sugar-ethanol industry, helping to move the country toward a low-carbon, cleaner, and more sustainable economy.

2. Methods and model details

In this work, a process simulation model was developed in Aspen Plus® v9.0 for the anaerobic digestion of vinasses. A techno-economic analysis considering three different biogas applications (i.e., electricity production in combined heat and power (CHP) system (S_1), biomethane as a vehicle fuel (S_2), and biomethane for gas grid injection (S_3)) was also carried out. As pointed out, all three alternatives comprised the same biogas plant, as shown in Fig. 1. The system's performance (i.e., biogas production + application) was assessed based on the material and energy balances obtained from the simulation results. A detailed explanation of the model validation can be found in the supplementary material.

2.1. *Simulation model for anaerobic digestion*

2.1.1. *Vinasse composition and component list*

Vinasse composition used in the simulation was based on the average value from all distilleries (San José, Santa Cruz del Norte, and H. Molina) in the province of Mayabeque, Cuba. The total production from the three facilities is 145 $m^3{}_{ethanol}/d$, being the vinasse generation rate just over 16 $L_{vinasse}/L_{ethanol}$ with an average COD ~50 kg/m^3 (COD_{real}, Table S1 in supplementary materials) (Noa-Bolaño et al., 2020). Vinasse's characterization from the H. Molina distillery is closer to the average values from these facilities, being selected as a model for the simulation. The composition of the vinasses was calculated based on the concentration ranges reported by Janke et al. (2015) in order to create a list of components that could be handled in Aspen Plus. The COD of the vinasse stream ($COD_{calculated}$) was calculated by mean of the Aspen Property Set CODMX. The vinasse stream created in Aspen was checked in terms of COD to ensure the accuracy of the results downstream (mean relative error between real COD and calculated COD ~4%). The vinasse characterization used for the AD process simulation is presented in supplementary materials (Table S1).

All the components present in the simulation model were considered conventional according to Aspen classification, except proteins and carbohydrates, which were assumed to be solids. For complex compounds such as proteins, cellulose, hemicellulose, and lignin, missing properties were estimated according to the literature (e.g., molecular weight, solid heat of formation, solid molar volume, solid heat capacity) (Wooley and Putsche, 1996). Amino acids, such as arginine, histidine, proline, and cysteine, were taken from Rajendran et al. (2014). Lipids were considered as triolein and tripalmate, while proteins were classified as soluble and insoluble, being insoluble protein considered as casein (Rajendran et al., 2014; Ramsay and Pullammanappallil, 2001). Other compounds such as glycerol, lactic acid, and phenols, although relevant, were not considered because of the lack of data about its concentration in Cuban sugarcane vinasses. However, glycerol was included

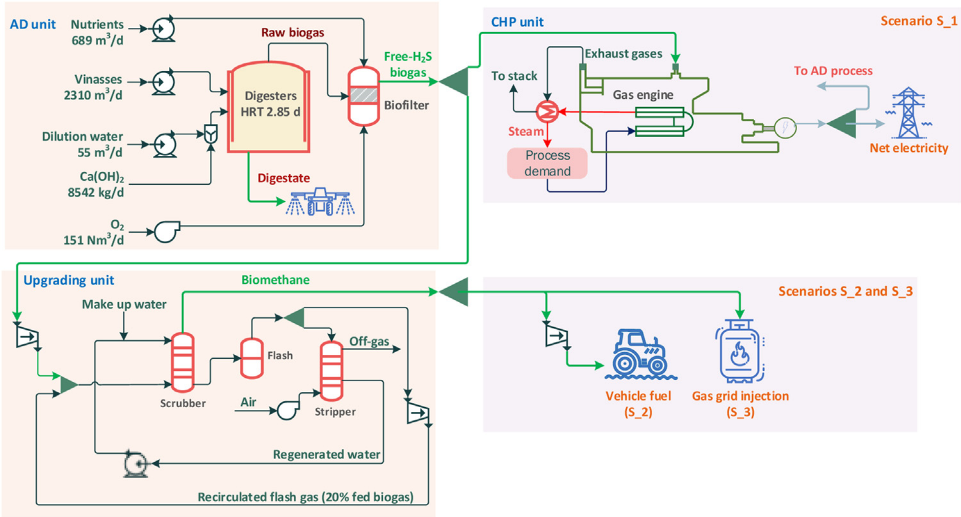

Fig. 1 – Process flow diagram of three different biogas applications.

in the reaction sets (i.e., hydrolysis and acidogenic) presented in the supplementary materials (Table S2).

2.1.2. *Anaerobic digestion of vinasse*

The AD of vinasses was modeled in a stage-by-stage (i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis) sequence, where chemical and gas–liquid equilibrium reactions were also considered. The model is based on the previous work performed by Rajendran et al. (2014) with the inclusion of sulfate reduction reactions. The NRTL (Non-Random Two-Liquid model) method was used for the estimation of the thermodynamic properties, allowing the calculations of gas–liquid systems based on activity coefficients and mole fractions (Rajendran et al., 2014). The simulation model was divided into two reaction sets (R-1 and R-2). Set R-1 considered the hydrolysis step, while set R-2 the remaining reactions in the AD process (i.e., acidogenesis, acetogenesis, and methanogenesis). Set R-1 was modeled in an RStoic module (HIDROLIS) taking into account the extent of the reactions from reactants into products of the main components present in the vinasses (Table S2 in supplementary materials), while reaction set R-2 was kinetically modeled in the RCSTR module (KINETIC) (Rajendran et al., 2014).

A modification from previous models was considered in set R-2 by including the sulfate reduction process (Lorenzo-Llanes et al., 2020). For each reaction in R-2, the kinetic parameters were calculated in different calculator blocks through Fortran subroutines. Inhibition effects (i.e., hydrogen, acetic acid, pH) (Angelidaki et al., 1993; Batstone et al., 2002) were included within each calculator block in R-2. The inhibition by low pH was considered in the acidogenesis and acetogenesis phases, while low and high pH was considered in the methanogenesis stage. The limits for low and high pH inhibition were set to 6 and 8.5 respectively (Angelidaki et al., 1993). The range of thermophilic temperatures (55 °C) for modeling the AD of the vinasse has been selected for two fundamental reasons: (1) The vinasses leave the ethanol distillation tower between 95 and 104 °C, reducing the cooling water consumption, and (2) higher organic loading rate (>20 kg_{COD}/m^3d) can be applied (Fuess and Garcia, 2017). All the reactions' stoichiometry can be found in the supplementary materials, while the kinetic parameters have been reported elsewhere (Lorenzo-Llanes et al., 2020; Rajendran et al., 2014). The reactors size was calculated based on the organic loading rate of 20 kg_{COD}/m^3d, with a total residence time of 2.85 days. Due to the acidic characteristics of vinasses, calcium hydroxide (85%) was added as neutralizing at a rate of 3.7 kg per m^3 of vinasse (Barrera et al., 2016). Temperature was kept constant at thermophilic conditions (55 °C).

2.2. *Biogas desulfurization*

For all common biogas application (e.g., CHP, biomethane production), hydrogen sulfide removal is considered to avoid corrosion issues downstream. Owing to the high-strength sulfate characteristics in vinasses, considerable amounts of hydrogen sulfide can be produced by sulfate reducing bacteria (Barrera et al., 2013). Thus, for CHP systems using gas engines, hydrogen sulfide level should be kept below 100 ppm, while lower levels up to 4 ppm are required for gas grid applications (Kapoor et al., 2019). In this work, ex-situ biofilters with immobilized microorganism have been used for the biogas desulfurization (≥98% hydrogen sulfide removal efficiency) (Koonaphapdeelert et al., 2020; Wasajja et al., 2020).

Three modules (i.e., Calculator block, two-outlet component separator, and stoichiometry reactor) were used during the biofilter simulation. A Fortran subroutine was implemented in the Calculator block based on the method described by Sinnott and Towler (2019) for packing tower design, and previously applied to a biofilter design by Koonaphapdeelert et al. (2020). The outlet hydrogen sulfide concentration downstream the biofilter was settled at 20 ppm, yielding a removal efficiency of ~98%. The biofilter model assumed that: (i) the space velocity was equal to 50 h^{-1}, (ii) the diameter of the biofilter ranged between 1.5–2.5 m, (iii) plastic Pall rings as packing material, (iv) volumetric flows of oxygen and nutrients (as water) were considered as 2% (v/v) of the biogas flow, respectively (Koonaphapdeelert et al., 2020).

A height to diameter ratio of the column between 2.5–5 was used as stop criteria during the first iterative loop. In the final calculation loop, the flooding condition was checked by comparing the flooding velocity with the actual biogas mass flow rate per unit of cross-sectional area (Koonaphapdeelert et al., 2020). Once the design procedure has converged, the components are separated into two streams (top and bottom) via the two-outlet separator module. The top (cleaned biogas) was sent to the water removing stage where it is first compressed and later cooled down to remove excess moisture. The former was simulated as a two-outlet component separator. The bottom (water + oxygen + removed hydrogen sulfide) was sent to a stoichiometry reactor to simulate hydrogen sulfide oxidation to elemental sulfur as in actual biofilter. Detailed information of the mathematical model for the biofilter (Tables S3 and S4) as well as the process simulation flowsheet of the vinasses AD (Fig. S1) can be found in the supplementary materials.

2.3. *Scenarios for biogas utilization*

2.3.1. *CHP system (S_1)*

CHP systems based on gas engines use the engine generator along with heat exchangers for heat recovery. The gas engine simulation was based on the TCG-2020_V20 model from MWM (MWM, 2020). Process simulation of the CHP system comprised of a combination of Aspen unit operation models (e.g., compressor, turbine, heat exchangers, chemical reactor) along with manipulator modules (i.e., design specification). The property method selected for the engine cycle simulation was the Redlich-Kwong-Soave with the alpha function of Boston-Mathias (RKS-BM), which has been recommended for combustion processes and electricity generation plants (Alfonso-Cardero et al., 2020; Aspen Technology, 2017).

The biogas is first mixed with the preheated air before being compressed up to a compression ratio equal to 12.5. Air flow was manipulated to meet the performance of the engine in terms of electrical efficiency. The gas mixture is fed into the combustion chamber, modeled as an RGibbs reactor, where the heat duty (manipulated variable) is calculated iteratively by using a design specification (outlet turbine temperature, 700 K). The pressure drops assumed in the combustion chamber was 5%, like typical values in actual combustion chambers. The calculated heat duty was assumed to be equal to the heat recovered in the engine circuit (i.e., oil circuit, water jacket), plus the heat losses. Combustion gases are expanded in the turbine until a pressure of 6 kPa is reached, keeping the isentropic efficiency equal to 85%. Low-pressure steam (i.e., saturated at 253 kPa) was considered to meet part of the heating load in the ethanol production (process demand in Fig. 1) by heat recovering from exhaust gases. The exhaust gas temperature was fixed at 453 K following the manufacturer recommendations. Fig. S2 (supplementary materials) shows the process simulation flowsheet for the CHP system.

2.3.2. *Biomethane production and utilization (S_2 and S_3)*

Scenarios S_2 and S_3 explore the utilization of upgraded biogas (biomethane) as vehicle fuel and for its injection into the natural gas grid, respectively. Water scrubbing is the cheapest, environmental friendly and widely used method (Angelidaki et al., 2018; Sun et al., 2015) for biogas upgrading. It is a mature technology accounting for nearly 41% share in the biogas upgrading industry (Kapoor et al., 2019). Based on these facts, water scrubbing was chosen as the upgrading technology for biomethane production in the present study. Simulation of the upgrading unit comprised three main steps (i.e., absorption, flash separation and desorption). The property package selected was the electrolyte-NRTL (ELECNRTL) which has shown good agreement with experimental data over a wide range of pressures and temperatures (Cozma et al., 2013).

The absorption and desorption towers were modeled using the Aspen Plus rigorous model for multistage vapor-liquid separation (RadFrac). The number of equilibrium stages was determined iteratively until the CH_4 composition requirement (>97%) in the biomethane was met. The two-outlet model for vapor-liquid (Flash-2) was used for the flash drum modeling. Before entering the absorber, the biogas is pressurized up to a target pressure. Subsequently, it is cooled down until a temperature ~298 K is reached. Biogas is then injected into the absorber via the bottom side of the tower, flowing towards the counter-current flow of the water, which is fed from the top of the absorption tower (Bauer et al., 2013). The produced biomethane is released from the top of the scrubber, while a CO_2-rich water is obtained from the bottom. The by-product liquid is sent to a flash separator, where a certain amount of the released gas (20%–30% based on biogas volumetric flow) is recirculated to the scrubber (Bauer et al., 2013). The CO_2-rich solvent from the flash separation is regenerated in the desorption tower at atmospheric pressure, leading to the removal of CO_2, H_2S, and other gases. The desorption process is modeled by air stripping. The regenerated water from the bottom of the desorption tower is then recirculated to the scrubber. Besides, a Calculator block was settled to fix the makeup water to consider the water losses in the process. The number of equilibrium stages in the absorption and desorption towers were settled as design specifications to meet the biomethane and regenerated water purities. Table S5 shows the operating conditions considered in the upgrading unit as well as the equipment specifications. Fig. S3 (Supplementary Materials) shows the process simulation flowsheet of the upgrading system.

2.4. *Economic assessment for biogas utilization*

Based on material and energy balances from the Aspen model, the economic performance of each alternative for biogas utilization was carried out. The capital expenses (CAPEX) were calculated based on five areas: (I) AD plant, (II) CHP system (gas engines), (III) biogas upgrading (water scrubbing), (IV) biomethane compression, and (V) biomethane distribution. For each area, direct and indirect costs along with working capital were calculated as a function of the equipment costs (Smith, 2016). Depending on the use of biogas, the total investment was calculated as the sum of the above areas as follows: electricity generation (S_1, I + II), biomethane as vehicle fuel (S_2, I + III + IV), biomethane for gas grid injection (S_3, I + III + V). All purchase costs were adjusted by capacity and considering the inflation factor by mean of the six-tenths rule and the CE index (Chemical Engineering Plant Cost Index, CEPCI) (Sinnott and Towler, 2019). The investment cost of the AD plant was based on a 3600 m^3 UASB digester (Obaya et al., 2005), while the biofilter was scaled-up from 80 m^3/h of biogas (Tomàs et al., 2009). The investment cost of the biomethane compressor in (IV) was calculated from the regressed cost line, according to Pasini et al. (2019).

Revenues and operating costs (OPEX) also resulted from the material and energy balances from the Aspen model. Only in scenario 1, the surplus electricity was sold to the national grid. The sale of the sludge from UASB digesters, the effluent for fertirrigation, and the carbon credits are common revenues in all scenarios. The utility costs were assumed as 140 USD/MWh and 0.25 USD/m^3 for electricity and water, respectively (López et al., 2020).

The cost of chemicals used in the neutralization stage (i.e., $Ca(OH)_2$) was assumed as 150 USD per ton (López et al., 2020). In this work, $Ca(OH)_2$ was assumed as alkalizing agent as this is the current chemical used in Heriberto Duquesne Biogas plant (the only one in Cuba) located in Villa Clara, and previ-

Table 1 – Inputs for the economic assessment of the three-biogas utilization alternatives (S_1, S_2 and S_3).

Assumptions	Scenarios			References
	S_1	S_2	S_3	
Digester [USD]	700,161	700,161	700,161	Obaya et al. (2005)
Biofilter [USD]	58,240	58,240	58,240	Tomàs et al. (2009)
Upgrading unit [USD/Nm^3 biogas/h]		1,700	1,700	Kapoor et al. (2019)
Total CHP Plant [USD/kW]	2,008			Darrow et al. (2017)
Underground lines [USD/km]		56,000	56,000	Cucchiella and D'Adamo (2016)
Installing-distribution pipes [USD/km]		168,000	168,000	de Oliveira et al. (2013)
Electricity selling price [USD/MWh]	140	–	–	López et al. (2020)
Tax rate [%]	34	34	34	Longati et al. (2019)
Depreciation period [years]	10	10	10	López et al. (2020)
Depreciation rate [%]	10	10	10	López et al. (2020)

ously considered by López et al. (2020) and Barrera et al. (2016). Moreover, lime is the cheapest option compared to NaOH or $NaHCO_3$ (Fuess et al., 2017) and does not increase the Ca^{2+} toxicity through precipitation of Ca^{2+} as a $CaCO_3$ (Khanal, 2008). It should be pointed out that lime use can cause scaling problems in the bioreactor affecting the long-term economic profitability of the plant (Ghanavati, 2018; Khanal, 2008), however, this was not the case considered in the present work.

The biomethane selling price was assumed as 0.3 USD/m^3 (Cucchiella and D'Adamo, 2016) according to the natural gas prices in Europe and quoting EUR/USD equal to 1.12 based on June 2020 (Bloomberg, 2020). In scenario 2, an incentive of 0.36 USD/Nm^3 of biomethane was assumed, while in scenario 3 the incentive comprised the biomethane selling price at twice of the market price of natural gas (Cucchiella and D'Adamo, 2016). A maximum distance of 5 km was assumed for the refueling stations and gas pipes in scenarios 2 and 3.

The lifetime considered was 20 years with an interest rate of 11%. It was also considered an operation time equal to 270 days per year, typical period in Cuban distilleries. Table 1 shows the main assumptions considered for the economic evaluation of the three considered scenarios. The economic performance of the investment was based on dynamic indicators such as the net present value (NPV), the internal rate of return (IRR), and the payback period (PBP). The full list of all considerations made for the economic evaluation can be found in supplementary materials (Tables S9 and S10).

2.4.1. *Sensitivity analysis*

Three sensitivity analyses were carried out to identify the parameters that influence the most the investment's economic sustainability. Input parameters were varied by ±25%, ±50%, and ±75% compared to the baseline. In S_1, the electricity selling price, and the cost of $Ca(OH)_2$ were changed, while biomethane selling price changed in S_2 and S_3. Due to the high-power consumption in S_2 and S_3, the cost of electricity was also assessed. The present study can be classified as a Ċlass 5 estimateẅith the CAPEX accuracy ranging from ±30 to ±50% according to the Association for the Advancement of Cost Estimating International (AACE International) (Sinnott and Towler, 2019). The effect of the economy of scale was measured by varying the capacity of the plant for all scenarios. Limiting conditions (NPV = 0) for each alternative were also investigated by changing the electricity selling price in S_1 and the incentive in S_2 and S_3.

2.4.2. *Uncertainty analysis (Monte Carlo simulation)*

The sensitivity analysis is a way to predict the outcome of a decision; nevertheless, it does not consider the probability that those decisions will take place. Instead, a stochastic method like Monte Carlo can be applied. Monte Carlo simulation leads to output variables with its probabilistic distributions, allowing the evaluation of specific results. In this work, Monte Carlo simulation was performed by comprising few steps such as: (i) definition of the probability distribution of variables (assumed as Normal), (ii) generation of a set of variables based on the probability distribution (10,000 random values of electricity selling price and incentives based on mean and standard deviations from the sensitivity analysis) (Lewis, 2005), (iii) generation of the output (as NPV) for the set of values generated in (ii).

3. Results and discussion

3.1. *Model validation and technical analysis*

Table 2 shows the parameters considered during the validation of the AD model, along with the results from the simulation runs at different scales (i.e., pilot and laboratory).

As observed, the methane yield reported was underpredicted by the model in all cases, with a MrE between 10% and 13% for lab scale, and less than 3% in the pilot one, showing a medium accuracy (10%–30%) (Batstone and Keller, 2003). For COD removal and biogas yield, values of MrE ranged between 4% and 16% with maximum deviations corresponding to COD removal; hence, a medium accuracy can be considered. The methane composition in biogas showed a mean absolute relative error (MrE) in all the simulated cases less than 10%, which has been considered as high accuracy model (Batstone and Keller, 2003). Considering the differences in scales, the volume from pilot and laboratory cases (75 m^3 vs. 10 L, respectively), along with the variability of the operating conditions such as organic loading rate, hydraulic retention time, and vinasse flow rate (Table S6, Supplementary materials) rate, hydraulic retention time, and vinasse flow rate (Table S6, Supplementary materials), it is concluded that the model is able to predict the main variables at different scales and conditions.

A statistical evaluation was made to check for significant differences between experimental data and simulated results at each scale (i.e., pilot and laboratory). The ANOVA test showed non-significant differences, leading to p-values higher that 0.05 in all cases (Table 2).

After the AD unit, the simulation process was also developed for the biogas cleaning and upgrading (Tables S7, S8 in supplementary material). The results showed that more than 97% (v/v) of methane was reached in the biomethane stream with losses about 1.72%, in agreement with reported data (Angelidaki et al., 2018; Bauer et al., 2013). Values of 6.38

Table 2 – Simulation results from the anaerobic digestion of vinasses.

Scale	Methane yield [$10^{-3}Nm^3{}_{CH4}/kg_{CODremoved}$]	COD Removal [%]	Biogas yield [$Nm^3{}_{biogas}/m^3{}_{reactor}d$]	Methane [%, v/v]
Pilot[a]				
Literature	310.64	71.80	9.80	60.00
Simulated	303.34	60.55	8.25	59.38
MrE[c]	2.35	15.67	15.86	1.03
Laboratory[e,b]				
Literature	225.70	58.70	3.52	62.20
Simulated	203.29	55.32	3.69	60.05
MrE[c]	9.65	5.76	4.84	3.46
Laboratory[f,b]				
Literature	234.20	60.70	3.88	58.40
Simulated	205.23	51.84	4.36	61.36
MrE[c]	12.37	14.60	12.44	5.07
P-value[d]	0.6704	0.1779	0.9097	0.9619

a Souza et al. (1992).
b Ferraz Júnior et al. (2016).
c MrE, mean relative error.
d p-value > 0.05 (95.0% CI) denote no significant difference between the literature experimental cases and the simulated ones for each response variable.
e Laboratory conditions: HTR = 1.75 days, OLR = 20 kgCOD/m^3·d, Flow rate = 5.85 L/d.
f Laboratory conditions: HTR = 1.42 days, OLR = 25 kgCOD/m^3·d, Flow rate = 7.32 L/d.

Table 3 – Technical results considered in the economic evaluation for each scenario.

Base case outputs	Unit	Scenarios		
		S_1	S_2	S_3
Biogas flow	Nm^3/h	1,245	1,245	1,245
Biogas yield	$m^3{}_{biogas}/m^3{}_{vinasse}$	17	17	17
Biomethane flow	Nm^3/h	–	779	779
Electricity demand AD	$kWh/m^3{}_{biogas}$	0.47	0.47	0.47
Electricity demand upgrading	$kWh/Nm^3{}_{biomethane}$	–	0.24	0.24
Power produced	kW	3,380	–	–
LHV_{biogas}	$MJ/Nm^3{}_{biogas}$	23	23	23
$LHV_{bimethane}$	$MJ/Nm^3{}_{biomethane}$	–	35	35
Gross overall efficiency	%	85	94	94

$kWh/Nm^3{}_{biogas}$ and 9.71 $kWh/Nm^3{}_{biomethane}$ were obtained (Table 3), fitting the typical values reported previously (Kapoor et al., 2019). The electricity consumption indexes obtained (Table 3) for AD and water scrubbing models were in agreement with reported data (i.e. 0.44 $kWh/m^3{}_{biogas}$ (Obaya et al., 2005) and 0.2–0.25 $kWh/Nm^3{}_{biomethane}$ (Bauer et al., 2013; Kapoor et al., 2019)).

The energy inflows and outflows for biogas utilization in each scenario are presented in Fig. 2. In all the cases, the heating value of the cleaned biogas (Table 3) was considered as an energy inflow. Power demand, along with the corresponding losses, are also included for each scenario.

In the CHP scenario (S_1), 43% and 42% of electrical and thermal gross efficiencies were obtained, respectively. These values are in good agreement with the state-of-the-art gas engines fueled with biogas (MWM, 2020). When power demand in the AD stage (~24% of the total power generated) is considered, the net electrical output is reduced to 17.2 GWh, corresponding to a net electrical efficiency of 33% (Fig. 2, S_1). Regarding the heat recovered withing the CHP system (Fig. 2, S_1), about 10% of the steam demand in Cuban distilleries (380 $kg_{steam}/hL_{ethanol}$) (Pérez-Ones, 2011) could be replaced by the biogas maximizing its use as a competitive energy source in the sugar-ethanol industry.

In scenarios S_2 and S_3, the energy outflow comprised the heating value of the produced biomethane. In both cases,

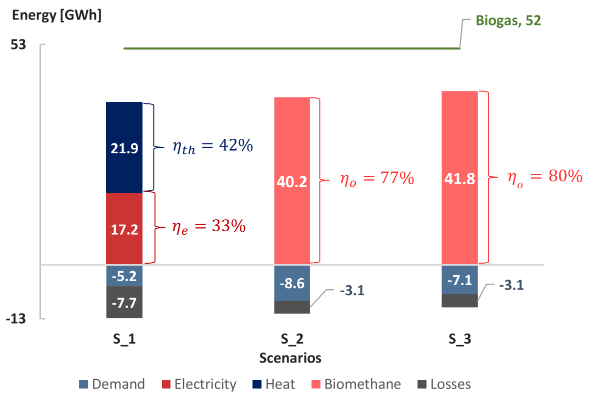

Fig. 2 – Energy flows per year for biogas utilization in the three studied scenarios: CHP (S_1), biomethane for vehicle fuel (S_2) and biomethane for gas grid injection (S_3). % refers to net electrical (η_e), thermal (η_{th}), and overall (η_o).

energy losses were due to non-recovered methane, representing 6% of the energy inflow in the biogas stream. Based on the total energy produced (as biomethane), power demands represented 17% and 14% for S_2 and S_3, respectively. Similar results have been reported for biomethane production using water scrubbing as upgrading technology (Rajendran et al., 2019). The inclusion of power demands in the energy balance leads to net global efficiencies of 77% (S_2) and 80% (S_3) (Fig. 2).

These values are slightly higher than the obtained in S_1 (75%, in Fig. 2) in correspondence with Fuess and Zaiat (2018), reflecting a higher energy potential for biomethane. However, if the irreversibilities associated with the final biomethane conversions (i.e., vehicle fuel or natural gas substitution) were included in the global balance, scenario S_1 will remain the more efficient biogas conversion process.

According to the simulation results, the energy potential from the produced biogas was ~1.1 $MWh/m^3_{ethanol}$ (assuming 16 $m^3_{vinasse}/m^3_{ethanol}$), which is slightly higher than the energy potential reported by Tolmasquim (2016) (0.92 $MWh/m^3_{ethanol}$) in Brazil. Differences can be explained by the low ratio of ethanol-to-vinasse (~10 $m^3_{vinasse}/m^3_{ethanol}$) (Fuess and Zaiat, 2018; Moraes et al., 2014) in Brazil compared to Cuba and the LHV obtained in the simulation (23 MJ/Nm^3_{biogas}) compared to lower values reported by Brazilian authors (Moraes et al., 2014). Regarding the mass of sugarcane milled, the energy recovered in the biogas was about 8.36 kWh/t_{cane} (based on 7.6 $L_{ethanol}/t_{cane}$ estimated from Rein (2016)), leading to 3.73 kWh_e/t_{cane}. A wide range of biogas-based electricity per ton of sugarcane milled for annexed distilleries (3.05–15 kWh_e/t_{cane}) has been reported by several authors (Bernal et al., 2017; Fuess and Zaiat, 2018; Moraes et al., 2014). In Cuba, annexed distilleries only process molasses in most facilities; hence, ethanol yields are much lower (~ 7.6 $L_{ethanol}/t_{cane}$) compared to the Brazilian ones (~53 $L_{ethanol}/t_{cane}$) leading to more vinasse to be converted in biogas per ton of sugarcane milled and consequently a higher energy potential. From the above discussion, it is concluded that the simulation model fits well the expected energy output and can be used to explore the potential energy recovery from the biogas plant.

The Cuban potential for fossil-based commodities replacement from the biogas produced through the AD of vinasse was also assessed (Fig. 3a–d). Considering an ethanol yield of 7.6 $L_{ethanol}/t_{cane}$ (baseline in Cuba) and the milling capacities per province (see Fig. S6), the net electricity potential throughout the country was estimated as shown in Fig. 3a. Overall, it would be possible to produce 292 GWh_e, replacing ~2.3% of the fossil-based electricity produced in thermoelectric plants in 2019. If ethanol yields were increased to 10 $L_{ethanol}/t_{cane}$ (Optimistic) and 12.6 $L_{ethanol}/t_{cane}$ (Very optimistic), savings in fossil-based electricity could reach up to 3.8% (Fig. 3b). The electric potential from biogas could contribute to increasing the gross electricity production from sugarcane industry in Cuba (i.e., 37 kWh/t_{cane}) (ONEI, 2019) to 40.73 kWh/t_{cane} (10%), 42 kWh/t_{cane} (13%), and 43.2 kWh/t_{cane} (17%) under the baseline, the optimistic, and the very optimistic ethanol yields, respectively.

The capacity for fossil fuels (i.e., diesel and natural gas) replacement through biomethane applications is shown in Fig. 3c and d. For vehicle fuel application, over $59{\cdot}10^3$ and $92{\cdot}10^3$ tons of oil equivalent (toe) could be annually replaced for ethanol yields of 7.6 $L_{ethanol}/t_{cane}$ and 12.6 $L_{ethanol}/t_{cane}$, respectively. These figures represent savings between 20.2% and 33% of the diesel demand in the transport sector (i.e., 293 376 toe) (ONEI, 2019) (Fig. 3c). Calculations for natural gas replacement were based on its demand for manufactured gas production (i.e., air-methane mixture), assuming a high heating value (HHV) of 25 $MJ/Nm^3_{manufactured\ gas}$ in agreement with the new Cuban standards (Norma Cubana, 2020). Fig. 3d shows that at a very optimistic scenario (12.6 $L_{ethanol}/t_{cane}$), $18{\cdot}10^6$ m^3 of natural gas could be replaced by biomethane, leading to a reduction in the annual demand (i.e., $106{\cdot}10^6$ m^3) of 15.4%.

3.2. Economic assessment

Fig. 4 shows the CAPEX for the individual units (i.e., AD, CHP, water scrubbing, and biomethane compression) comprised within each scenario along with the OPEX. The CAPEX for scenario S_1 was about 17 MMUSD, while for S_2, and S_3 was just under 24 MMUSD. Based on the total volume of vinasse processed per year, scenario S_1 had a CAPEX of ~28 $USD/m^3_{vinasse}$, while ~38 $USD/m^3_{vinasse}$ was obtained for biomethane production scenarios (S_2 and S_3) (Fig. 4). The estimated CAPEX for the AD plant was equal to ~16 $USD/m^3_{vinasse}$ per year, leading to 2.86 $USD/m^3_{vinasse}$ per year (based on equipment cost). An index factor for the equipment cost of 2.80 $USD/m^3_{vinasse}$ per year has been reported in previous works for biogas plants treating vinasse in UASB reactors (Fuess and Zaiat, 2018; Salomon et al., 2011).

Water scrubbing (WS) was the most expensive alternative for biogas conversion accounted for ~54% of CAPEX in scenario S_2 and S_3, while in S_1 the CHP plant led to ~41% of the total investment. A comparison between all scenarios showed that CAPEX for the CHP plant (S_1) was ~46% lower than the WS unit (S_2 and S_3). This fact is of great importance for developing countries like Cuba, where monetary resources are limited, and no incentive programs for biomethane production are established. The main contribution to the OPEX in scenario S_1 was the operation and maintenance cost of the CHP system accounting for 39% of the total, followed by the consumption of $Ca(OH)_2$ (35%). Whereas, in S_2 and S_3 was given by electricity consumption, accounting for 44% and 39%, respectively.

In this work, the net production costs for cleaned biogas and biomethane (i.e., 6.29 $USD/GJ_{HHVbiogas}$ and 4.68 $USD/GJ_{HHVbiogas}$, respectively) were slightly lower than those obtained by Leme and Seabra (2017) (i.e., 7.23 $USD/GJ_{HHVbiogas}$ and 5.53 $USD/GJ_{HHVbiogas}$, respectively). However, the biomethane production cost was in agreement with the value reported by Koonaphapdeelert et al. (2020) (4.44 $USD/GJ_{HHVbiogas}$), which were also checked for different biogas plant capacity (Supplementary material, Fig. S4). Thus, it is possible to conclude that assumptions made are in good agreement with reported data in the literature, allowing the calculation of reliable dynamic parameters (e.g., NPV, IRR, and PBP).

Table 4 shows the economic performance of each biogas application. Overall, scenario S_1 (CHP with electricity selling) showed the best economic performance among the assessed alternatives, with an IRR of 21.1% and a PBP ~7 years. Non-significant differences were observed between biomethane scenarios (S_2 and S_3) with NPV rounding 3.2 million USD and an IRR ~ 13%. Despite S_2 and S_3 resulted profitable, special attention should be paid to the IRR values. These are quite close to the interest rate assumed in this work (11%), resulting in a high risk of investment for the biomethane pathway.

Results from Table 4 are slightly different when compared with similar works published in the literature. For CHP applications, values of IRR ranging from 12% to 18% have been reported (Fuess and Zaiat, 2018; Moraes et al., 2014), which are lower compared with this study. This could be due to differences in the unit prices for revenues and expenses with a high impact on the cash flow (e.g., electricity price, incentives, chemical cost). For instance, the electricity price considered in this work (140 USD/MWh) was higher than the reported range in Brazilian cases (54–77 USD/MWh) (Fuess and Zaiat, 2018;

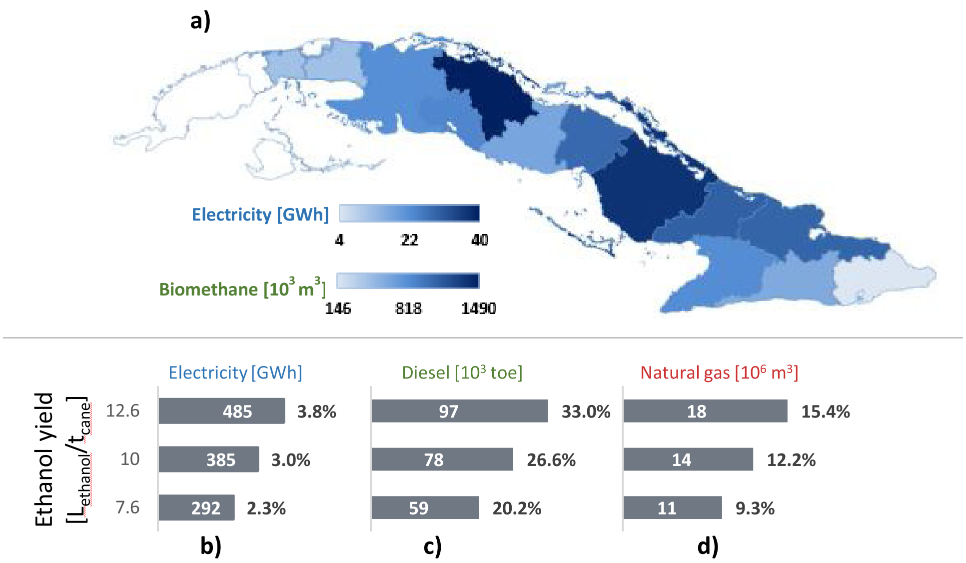

Fig. 3 – Biogas potential from AD of vinasses for fossil-fuel-based commodities replacement in Cuba. Calculations based on sugarcane milling capacities per province at 7.6 $L_{ethanol}/t_{cane}$ (a), electricity produced in thermoelectric plants (b), diesel demand in transport sector (c), and manufactured gas (HHV = 25 MJ/Nm^3) production (d).

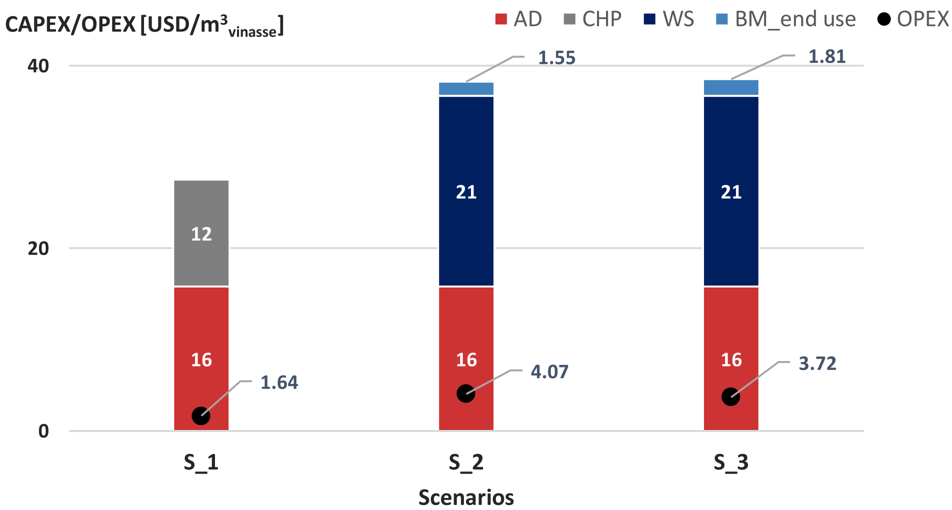

Fig. 4 – CAPEX components and OPEX for each biogas application scenario. AD: anaerobic digestion, WS: water scrubbing, CHP: combined heat and power, BM_use: biomethane compression.

Table 4 – Economic performance for each biogas application.

Scenarios	Incentives	NPV [10^6 USD]	IRR [%]	PBP [Years]
S_1	No	12.17	21.16	6.89
S_2	Yes	3.18	12.98	14.4
S_3	Yes	3.05	12.87	14.6

Moraes et al., 2014), having a positive influence in the cash flow (higher IRR, lower PBP).

Some authors (Junqueira et al., 2016; Moraes et al., 2014) have reported values of IRR between 15% and 17.5% (with PBP ~7 years) for biomethane production from AD of vinasses, being slightly higher than the one obtained in this work (~13% for IRR, Table 4). Assuming the same interest rate and electricity cost as in Moraes et al. (2014), the re-calculated values obtained in the present work (i.e., IRR = 14.6% and PBP = 6.5 years) were in good agreement with those reported by these authors. Likewise, considering the same inputs as in Junqueira et al. (2016) (i.e., length of the gas grid line, electricity price, and interest rate), the model for S_3 yielded an IRR of 14.4% with a PBP of 6.8 years, indicating good accuracy of the economic assumptions made in the present study. Finally, it should be pointed out that S_1 (CHP system) yielded higher profitability levels compared to biomethane production (S_2 and S_3), which is in contrast with previous works (Junqueira et al., 2016; Moraes et al., 2014). This is mainly caused by differences in the economic assumptions which are based on national macroeconomic models (i.e., taxes, interest rate, electricity prices, etc.) as explained so far. For instance, low electricity prices in Brazil compared to those in the present work, lead to a simultaneous reduction in the level of profits in CHP systems and the biomethane production cost (low electricity cost). Hence, a higher net profit from biomethane scenarios is achieved, economically outperforming the electricity generation as has been observed in the Brazilian context.

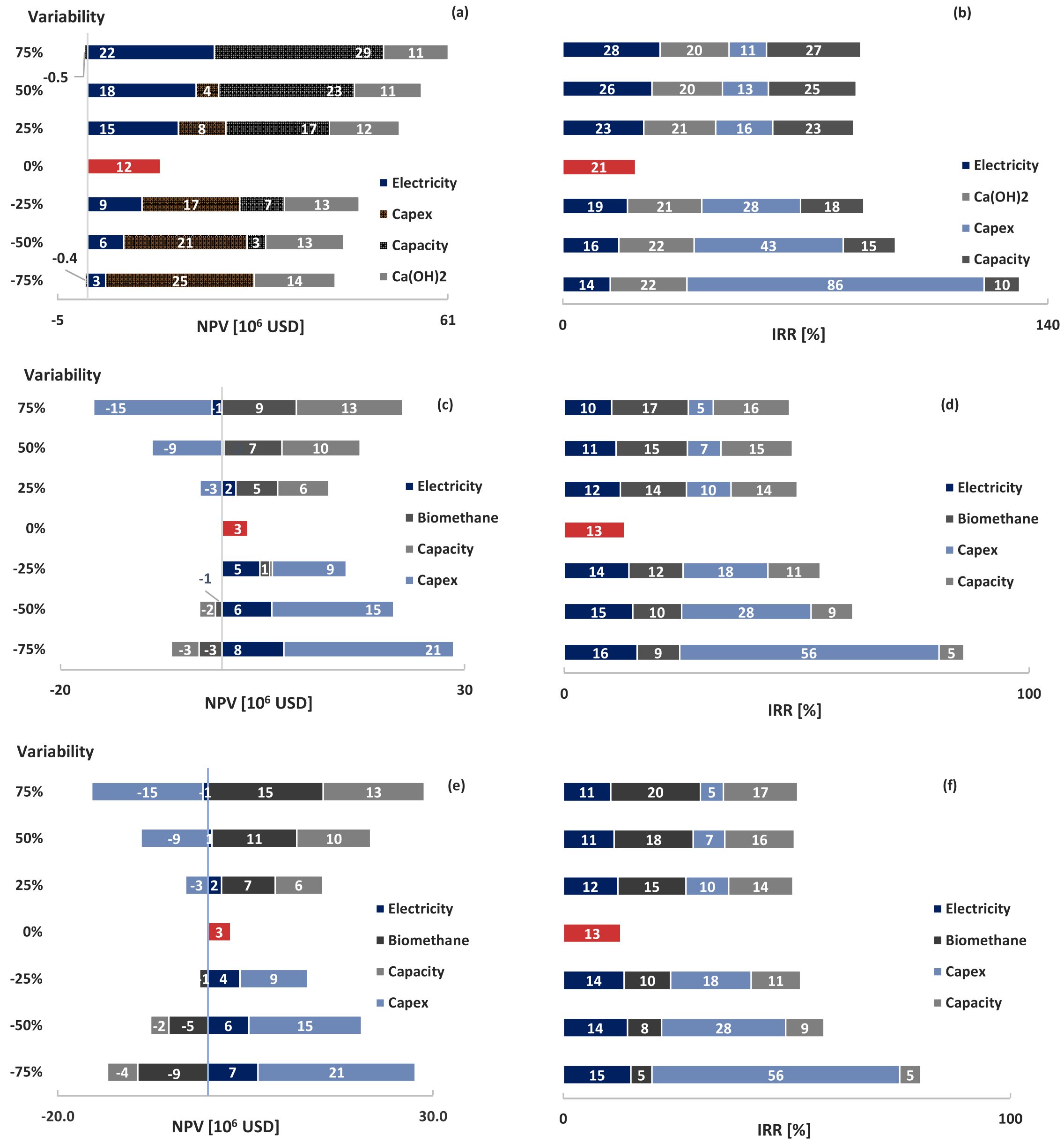

Fig. 5 – Results from the sensitivity analysis for each scenario: S_1, CHP system (a,b); S_2, vehicle fuel (c,d); S_3, gas grid injection (e,f).

3.3. *Sensitivity analysis*

From the baseline scenarios, ±25%, ±50%, and ±75% were considered as the fluctuation ranges in the sensitivity analysis, yielding 72 alternative scenarios. Fig. 5a–f show the impact of sensitivity analysis on the NPV and the IRR. Overall, the profitability of the investment was verified in 74% of the alternative considered. The distribution for positive NPV (accounting 24 cases for each baseline scenario) was 22 (92%), 16 (67%), and 15 (63%) cases for CHP, vehicle fuel, and gas grid injection, respectively.

Fig. 5a and b shows the effect of the economy of scale on the profitability of scenario S_1. An NPV of ~29 MMUSD (130% higher) and an IRR ~27% were obtained when the capacity was increased by 75% compared to the baseline. A vinasse flow around 1155 $m^3{}_{vinasse}$ per day (i.e., -50% baseline capacity) resulted in a non-profitable scenario. Assuming the average Cuban generation rate of 16 $L_{vinasse}/L_{ethanol}$, the equivalent capacity for an ethanol distillery yielding 50% less vinasse than that of the baseline would be around 72 m^3 per day, representing the minimum capacity to get profits. This result could be used for decision-makers to select potential candidates for biogas-based-CHP projects in Cuban distilleries when only vinasse is considered as a substrate. The second major contribution to the discounted cash flow for the CHP application was the CAPEX. For Člass 5 studiesČAPEX are within the range from ±30% to ±50% (Sinnott and Towler, 2019), suggesting that CHP application will remain profitable in the whole range (Fig. 5a and b). According to Fig. 5a, under the worst scenario regarding electricity selling price (drop of 75%), the investment remained profitable; however, the IRR (13.7%) (Fig. 5b) was quite close to the interest rate assumed (11%) for the investment, increasing the risk of the project. No significant effect of $Ca(OH)_2$ cost on the final NPVs and IRRs were obtained over the whole fluctuation range for scenario S_1 (Fig. 5a and b). According to Fuess et al. (2018), alkali addition showed to be significant under specific strategies where high chemical doses are needed. However, because of the lower cost of the $Ca(OH)_2$ (150 USD/t) compared to other alkalizing agents like NaOH (920

USD/t) (Fuess et al., 2018), it is expected less significant effect on process profits than those reported by other authors.

Fig. 5c–f show the performance of the economic indicators for biomethane application scenarios (S_2 and S_3) after the sensitivity analysis. Overall, vehicle fuel and gas grid injection showed the same trend in terms of NPV and IRR. Electricity cost had the lowest effect on NPV compared to the rest of the parameters considered. Drops in electricity cost favored scenario S_2 (i.e., higher NPV) over S_3 as the cost for biomethane compression to meet the vehicle fuel requirements is more power demanding than gas grid injection (Fig. 5c and e). No significant differences were observed in terms of NPV (Fig. 5c and e) and IRR (Fig. 5d and f) between both scenarios when plant capacity was increased. Likewise, a reduction in capacities beyond 50% of the baseline negatively impacted profitability indicators regardless of the biomethane application, limiting the implementation of biomethane programs at large scales to get profits. Previous works (Cucchiella and D'Adamo, 2016; Rajendran et al., 2019) have also shown similar results as those obtained in the present study.

Regarding the biomethane price, scenario S_3 outperformed S_2, yielding a higher NPV (Fig. 5c and e) when the price raised between 25% and 75% of the baseline. However, when the biomethane price dropped between 25% and 75% of the baseline, only one alternative scenario (-25% in S_2) was profitable. The most critical factor that affected the profitability of biomethane applications was the CAPEX. In both scenarios (S_2 and S_3), no profits were obtained when CAPEX was increased beyond 25% of the baseline (Fig. 5c and e), suggesting that special attention should be paid to CAPEX since, as a Class 5 study, it is possible to get values ±30% and ±50% (Sinnott and Towler, 2019) those in the baseline.

The electricity selling price in S_1 and the incentive for S_2 and S_3 were also evaluated by varying the most significant factors identified above, until an NPV = 0 was obtained. For S_1, variations of plant capacity and CAPEX yielded an electricity-selling price ranging between 26 and 157 USD/MWh (mean of 90 USD/MWh and standard deviation of 52 USD/MWh). In S_2, variations in the biomethane price, plant capacity, and CAPEX led to an incentive required for vehicle fuel between 0.011 and 0.9 $USD/m^3_{biomethane}$ (mean of 0.33 $USD/m^3_{biomethane}$ and standard deviation of 0.23 $USD/m^3_{biomethane}$). Likewise, the incentive required for gas grid injection varied from 0.31 to 1.35 $USD/m^3_{biomethane}$ (mean of 0.67 $USD/m^3_{biomethane}$ and a standard deviation of 0.3 $USD/m^3_{biomethane}$). These results were used as input for the uncertainty assessment through the Monte Carlo simulation.

3.4. *Uncertainty analysis*

For the sensitivity analysis to yield meaningful results, the impact of uncertainty should be considered. A Monte Carlo simulation was performed to assess the effect of uncertainty of electricity selling price (in S_1) and the incentive (in S_2 and S_3) on the NPV. The normal distribution assumption was checked for each assessed variable based on the skew coefficient (Lewis, 2005). Skew coefficients close to 0.5 were obtained for electricity selling price (0.0453) and incentive for S_2 (0.312) and S_3 (0.585), respectively. Additionally, an Anderson–Darling Goodness of Fit test was implemented in R package to test normality (see supplementary materials). From the p-values obtained for the uncertainty variables (i.e., electricity selling price (0.8961), incentive in S_2 (0.3347), and incentive in S_3 (0.267)) it was concluded that there is not sufficient evidence to reject the null hypothesis of the test. Hence, normal distribution provides a reasonable approximation of the distribution of uncertainty encompassing variable changes.

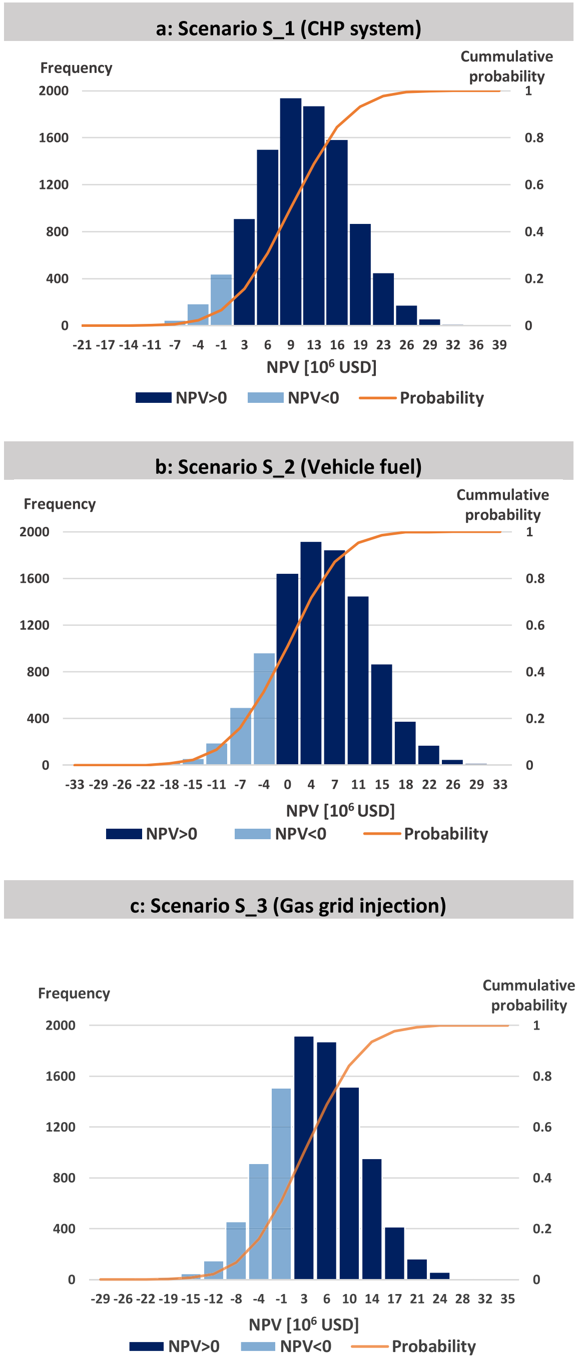

Fig. 6 – Uncertainty analysis on NPV for biogas application under the three studied scenarios obtained by Monte Carlo simulation.

Fig. 6a–c shows the frequency distribution of NPV occurring during the total number of trials simulated (i.e., 10,000) for each scenario. The probability of losing money (i.e., NPV < 0) was calculated for each scenario. For the CHP application, the average NPV was ~9.5 MMUSD with a 95% confidence interval ranging from 9.08 to 9.92 MMUSD. Fig. 6a shows that CHP application resulted in a low-risk investment compared to S_2 and S_3, with a chance of losing money ranging between 7.5% and 9.5% throughout the range of electricity selling price considered. Assuming a cut-off value of 35 USD/MWh (i.e., -75% compared to the baseline price in the deterministic analysis), the chance to get a higher selling price was ~92% according to the probability distribution, reducing the chance to get low profits (supplementary materials, Fig. S5).

For biomethane applications, similar trends between vehicle fuel (S_2) and gas grid injection (S_3) were observed. In both cases, the chance of losing money ranged between 31% and 37% (Fig. 6 b and c), significantly increasing the risk of investment compared to CHP application. For vehicle fuel application, the mean NPV was ~3.30 MMUSD with a 95% confidence interval between 2.96 and 3.43 MMUSD, while the gas grid injection scenario showed a mean NPV ~2.96 MMUSD (10% lower than the vehicle fuel scenario) with a 95% confidence interval ranging from 2.82 to 3.10 MMUSD. Cut-off values were analyzed for biomethane applications to test the probability of getting profits under a wide range of alternatives (i.e., changes in biomethane prices, CAPEX, and plant capacities). For S_2, the probability to get an incentive higher than 0.7 USD/$m^3_{biomethane}$ (cut-off value) was about 6%. Whereas, in S_3, an incentive higher than 1.06 USD/$m^3_{biomethane}$ (cut-off value) had a probability of 10% (Fig. S5 in supplementary material). These results showed the low chance to get profits under critical scenarios (e.g., low biomethane prices, high CAPEX, low capacities) for biomethane application compared to the CHP systems. In this regard, it is evident that biogas utilization for electricity production in Cuba from the sugar-ethanol industry has a better chance to be implemented. Nevertheless, with the development of new policies, supported by specific financial agreements between the government and potential investors, it is possible the implementation of national biomethane program.

3.5. *Targeting the minimum plant capacities for biomethane-to-vehicle fuel in the sugar-ethanol industry*

A driving force to boost biomethane projects is fuel replacement during cane harvest and transportation using dual-fuel machinery (e.g., trucks, harvester). Even if incentives were available, it is important to determine the milling capacities that meet the biomethane production levels required. The results showed that a minimum milling capacity of 9 000 t_{cane}/d is required for getting profits at the highest ethanol yield (12.6 $L_{ethanol}/t_{cane}$) considered. Under these conditions, an annexed distillery of 108 $m^3_{ethanol}$/d is also needed (Table S12 in supplementary materials). At the current Cuban capacities (i.e., milling and distillery), these scenarios cannot be carried out for almost the total of mills in the country since it would not be economically feasible.

Fig. 7 shows the biomethane production from the AD of vinasses and its demand in dual-fuel engines as a function of the distillery capacity (only profitable scenarios in Table S12). It is shown that the lower the ethanol yield, the higher the biomethane consumption is required as more cane should be harvested and transported to meet the ethanol production from the distillery. Likewise, a minimum yield of 10 $L_{ethanol}/t_{cane}$ (i.e., Medium_yield) is required to produce enough biomethane for satisfying fuel-substitution in the dual-fuel engines independently of the distillery capacity (Fig. 7). Hence, ethanol yields lower than 10 $L_{ethanol}/t_{cane}$ are not technically feasible (i.e., biomethane demand is not met) when vehicle fuel replacement for cane harvesting and transportation are considered. To meet the full techno-economic feasibility, ethanol yields above 10 $L_{ethanol}/t_{cane}$, milling capacities between 10,800 and 25,000 t_{cane}/d, and ethanol production from 108 to 250 $m^3_{ethanol}$/d are required.

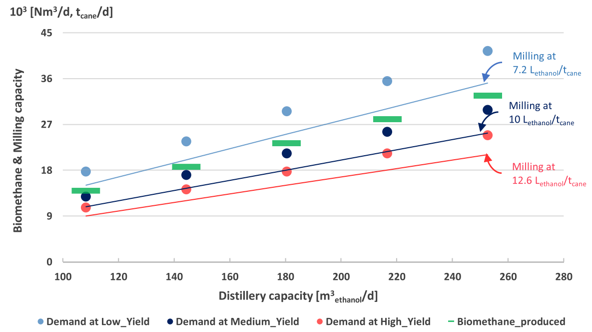

Fig. 7 – Biomethane consumption in dual-fuel machinery and milling capacities required as function of distillery capacity (Based on Energy Substitution Ratios: Harvesting (60%), Transportation (45%) (da Silva Neto et al., 2020). Lines represent milling capacities at different ethanol yields in $L_{ethanol}/t_{cane}$.

Currently, milling capacities in Cuban sugarcane factories are by far lower than those mentioned above. However, total capacities throughout the different provinces are between 10,300 to 31,390 t_{cane}/d with an expansion projected in ~30% by 2024 (Fig. S6 in supplementary materials). Hence, it is possible to centralized biomethane production by limiting the number of biomethane plants to one or two per province. In this scenario, biomethane production from the anaerobic digestion of vinasses could be a source of profits and fuel replacement for a modernized Cuban sugar-ethanol industry.

4. Conclusions

The present study explored the Cuban sugar-ethanol industry diversification by assessing the techno-economic feasibility of vinasse-to-biogas and its utilization for electricity generation, biomethane-to-vehicle fuel, and biomethane-to-gas grid injection. The process simulation model implemented in Aspen Plus® yielded results in good agreement with experimental and pilot-scale data. At the baseline conditions, all the scenarios assessed were profitable, with electricity production in CHP system economically outperforming the biomethane applications. The uncertainty analysis revealed the high risk of getting profits under a wide range of conditions for both biomethane scenarios (vehicle fuel and gas grid injection) compared to electricity production. The chance to get an incentive higher than 0.7 USD/$m^3_{biomethane}$ (cut-off value) for vehicle fuel scenario was 6%, while for gas grid injection an incentive greater than 1.06 USD/$m^3_{biomethane}$ had a chance ~10%. The methodology applied in the present work also allowed targeting the minimum plant capacities for sugarcane mills and distilleries for vinasse-to-biomethane projects aiming at fuel replacement in the Cuban sugar-ethanol industry. These results provide crucial information for decision-makers in Cuba interested in the development of an indigenous biomethane industry.

Formatting of funding sources

None declare.

Conflict of interest

None declare.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cherd.2021.02.031.

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