Techno-Economic Analysis of Vinasse Treatment Alternatives Through Process Simulation: A Case Study of Cuban Distillery

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Abstract

Purpose

Vinasse is one of the organic industrial effluents with major polluting effect. The objective of this work was to perform a techno-economic assessment of vinasses treatment alternatives for valorization of this waste through process simulation with Aspen Hysys v10.0.

Methods

Four alternatives were studied: (A_1) incineration and electricity generation, (A_2) desalinization, (A_3) anaerobic digestion and electricity generation and (A_4) drying. The selected packages for the evaluation and prediction of properties were: Lee-Kesler-Plöcker and NBS Steam, NRTL-Ideal, Peng-Robinson-Stryjer-Vera and NBS Steam and NRTL-Ideal respectively; the validation in these cases was carried out with data reported in the literature. The economic evaluation was carried according to the changes that each alternative determines in each one of the elements of effective cash flow comparing with the actual condition.

Results

With the alternative A_1, fertilizers ashes are obtained removing all the residual and the energy generation. By the alternative A_2, fertilizers salts and desalinate vinasses (for animal food) were obtained. By the alternative A_3, energy is generated from biogas. By the alternative A_4, dry vinasse is obtained which is used as fertilizer and animal food.

Conclusion

The polluting effect of the vinasse can be reduced with the proposed treatment alternatives. It was showed that the alternatives are feasible, being the alternative A_1 the best, with a NPV of $ 1.29 MMUSD, IRR 25.5% and DPBP 2.7 years. Process simulation are a valuable supporting tool when making decisions in investment projects for valorization of vinasse from the ethanol industry.

Statement Of Novelty

The process simulation in Aspen Hysys of several vinasse treatment alternatives as a strategy for reducing the environmental impact caused by this waste, was developed in order to evaluate and compare its techno-economic feasibility. Furthermore, the validation of the proposed simulation models for vinasse treatment on a real industrial plant was carried out. As a result, a more rigorous and valuable simulation was obtained as supporting tool for decision making when evaluating the implementation of these technologies in ethanol industry. This work focuses on offering alternatives to obtain value-added

products from a polluting effluent and demonstrate that electricity, fertilizers and animal food production coupled to ethanol plants are promising opportunities for the valorization of vinasse, for Cuba and others countries.

Introduction

Vinasse is an effluent from the alcoholic distillation process, with a high organic load, unpleasant smell, dark brown color, high potassium salinity and high acidity. Vinasse is the main negative environmental impact from the alcohol industry [1]. The treatment and final waste disposal from this industry, as well as the energy reduction and water consumption, constitute one of the main premises in the management of the ethanol production process.

To achieve an integrated and sustainable alcohol industry, with greater efficiency, it is required to study alternatives for vinasse's treatment. Vinasse should not be considered only as a pollutant. A common mistake has been not to regard its potential as a by-product of ethanol production, with an economic and social effect, limiting the analysis to improving the disposal of the residual [2, 3].

Vinasse treatment methods can be classified into physicochemical and biological [4]. The most common alternatives for the treatment and final arrangement of vinasses on an industrial scale are: anaerobic digestion, concentration and incineration, composting and fertirrigation. There are researches that suggested desalination and drying of concentrated vinasse as attractive alternatives for the integral use of this residual [5-7].

Anaerobic digestion is considered a method of biodegradation of organic waste with great potential. It is an accelerated and optimized reproduction of the natural cycle of decomposition of organic matter in the absence of molecular oxygen, highly applicable for the treatment of vinasse, being used for the production of biogas [8-10].

The incineration of vinasse is used as secondary treatment to the concentration of vinasse up to 60-65 ºBrix [11, 12]. With this technology, potassium ashes, marketable as fertilizer are obtained. Also, the generation of energy and the reduction of residuals can be obtained. It can be considered a cleaner technology.

The vinasse desalination process remove the salts present in the previously treated vinasse by physical-chemical or biological means, recovering 85% of the potassium [5].

For vinasse drying, the concentrated liquid vinasse are sent to a hot air dryer, to obtain a powder with low humidity, feasible to be used in the field as fertilizer, burned in boilers as a fuel with low heating value (LHV) or in the formulation of livestock feed [6, 7].

The study of vinasse treatment technologies using process simulation has been approached by different authors. In this sense, the use of simulators provides a vision of the behavior of a real process, which is particularly useful in complex systems with interaction of several variables.

Simulation is a basic tool in process engineering, essential in the development of better designs, automation, control and optimization [13]. It can be defined as the use of a mathematical model to generate a description of the state of a system [14], once a simulation model has been developed and validated; the behavior of the plant can be studied and effects of changes in the process parameters can be considered without affecting the real system [15, 16]; therefore, its implementation in the study and evaluation of alternatives for the treatment of vinasse from distilleries is of great importance.

The objective of this work is to carry out a technical-economic study of four vinasse treatment alternatives that reduce its organic load or rise a value-added, by means of process simulation.

Materials And Methods

A Cuban distillery actual case is used to evaluate different alternatives for vinasse's treatment. The distillery produced 30,000 L/d of ethanol and generated 17,860 kg/h of liquid vinasse (7 ºBrix). Vinasse is concentrated up to 35 and 60 ºBrix for this study, producing 2,684 kg/h of concentrated vinasse (35 ºBrix) and 1,748 kg/h with 60 ºBrix. For steam generation, 347 kg/h of PCM 1400 crude oil are consumed with LHV 41.87 MJ/kg.

Process Simulation

The Aspen Hysys v 10.0 simulator was used for the simulation of the vinasse treatment alternatives. This simulation tool has been widely used in the industry for: research, development, simulation and design. It is used as an engineering platform to model systems such as gas processing, cryogenic facilities, chemical and refining processes, etc. [17, 18].

Selecting Components and Property Packages

The selection of the components for vinasse's simulation was carried out using representative components according to data reported in the literature [11]. Three composition were used, according to the simulated vinasse. Tables 1–3 present the components used to simulate the vinasses. Hypothetical components were added to represent salts, impurities and cysteine.

Table 1 Mass composition for a 7 ºBrix vinasse

Component	Composition (%)	Component	Composition (%)
H_2O	93.00	Propionic acid ($C_3H_6O_2$)	0.01
Sucrose ($C_{12}H_{22}O_{11}$)	1.31	Butyric acid ($C_4H_8O_2$)	0.02
Glucose ($C_6H_{12}O_6$)*	4.50	Cysteine ($C_3H_6NO_2S$)	0.09
Ethanol (C_2H_5OH)	0.41	K_2O	0.31
Impurities	0.03	Na_2O	0.07
Glycerol ($C_3H_8O_3$)	0.08	CaO	0.13
Acetic acid ($C_2H_4O_2$)	0.03	MgO	0.01

* Includes glucose + fructose composition

Table 2 Mass composition for a 35 ºBrix vinasse

Component	Composition (%)	Component	Composition (%)
H_2O	65.00	Propionic acid ($C_3H_6O_2$)	0.01
Sucrose ($C_{12}H_{22}O_{11}$)	3.54	Butyric acid ($C_4H_8O_2$)	0.01
Glucose ($C_6H_{12}O_6$)*	23.76	Cysteine ($C_3H_6NO_2S$)	1.85
Ethanol (C_2H_5OH)	3.95	K_2O	0.53
Impurities	0.07	Na_2O	1.00
Glycerol ($C_3H_8O_3$)	0.01	CaO	0.27

* It includes glucose + fructose composition

Table 3 Mass composition for a 60 ºBrix vinasse

Component	Composition (%)	Component	Composition (%)
H_2O	40.00	K_2O	7.00
Sucrose ($C_{12}H_{22}O_{11}$)	8.50	Na_2O	0.80
Glucose ($C_6H_{12}O_6$)*	40.05	CaO	3.50
Impurities	0.09	MgO	0.06

* It includes glucose + fructose composition

To simulate the crude oil (PCM 1 400), the components were selected as reported by Cruz et al. [19].

For properties estimation according to the operating conditions, the property packages selected were shown in Table 4.

Table 4 Property package selected for the alternatives

Alternative	Property package
Incineration of concentrated vinasse and electricity generation (A_1)	Lee-Kesler-Plöcker[a] NBS Steam
Desalination of concentrated vinasse (A_2)	NRTL-Ideal
Anaerobic digestion of vinasse and generation of electricity (A_3)	Peng-Robinson-Stryjer-Vera (PRSV)[b] NBS Steam
Drying of concentrated vinasse (A_4)	NRTL-Ideal

[a] Most accurate general method for estimating the properties of nonpolar substances and mixtures.

[b] It is an extension of Peng-Robinson for moderately non-ideal systems. It was selected due to the presence of gases at low pressures.

Selection of calculation modules and operating conditions

To create the simulation models, the appropriate modules were selected for each operation involved in the process.

A_1. Incineration of Concentrated Vinasse and Electricity Generation

This alternative consists of incinerating the concentrated vinasse at 60 ºBrix [7, 11, 20] with a mass ratio of 20-80% with crude oil in a boiler to take advantage of the energy released as a result of combustion in the steam generation. This steam produce electricity in the steam turbines.

The conception of the steam generator and its auxiliary equipment was carried out based on the model proposed by Palacios-Bereche [21]. The Tank module was used to represent the furnace (Furnace) and the deaerator (Deaerator). The Heat exchanger module was used for the boiler (Boiler) without pressure drop in the tubes and shell (ΔP = 0 kPa). It was also used to simulate the rest of the auxiliary equipment of the steam generator: the air preheater (Preheater), the superheater (Superheater), both no pressure drop in tubes and shell (ΔP = 0 kPa) and the economizer to preheat the feed water to the boiler (Economizer) with no pressure drop in the shell (ΔP = 0 kPa). The Set module (SET-I) was used to determine the relationship between the concentrated vinasse flow and the feed crude flow (multiplier: 0.2). The Adjust module (ADJ-I) was used to adjust the temperature of the Atmospheric gases stream (160 °C) and manipulate the mass flow of atmospheric air.

The steam distribution system was simulated using the modules: Valve for the reduction pressure valves of the steam line (VR-16/15, VR-15/7 and VR-7/0.5), Tee for the splitting of flow in the steam line (Distributor 1.5 MPa, Distributor 0.7 MPa and Distributor 50 kPa). For the crude heating was used the module Tee like simulation artifice to represent the crude tank (Crude tank), Heater for the simulation of the electric heater of the crude (Electric Heater) and the Heat exchanger to simulate the crude heaters (Crude heater and Crude heater 2).

The electricity generation stage was simulated using several modules. The Expander module (Stage 1 and Stage 2) was used to simulate the two-stage extraction-condensation turbine; the Mixer modules (MIX-I and Desuperheater) to represent the total work produced in the turbine stages and the desuperheater simulation respectively; the Tee module (TEE-I) to divide the steam flow towards the desuperheater and the second stage of electricity generation; a Heat exchanger for the condensation of the low pressure steam (Condenser) with no pressure drop in tubes and shell (ΔP = 0 kPa) and also the Pump module (P-Water) was used to represent the water pump to the desuperheater, with an adiabatic efficiency (70%) supplied as data.

The water temperature at the economizer outlet was set according to Palacios-Bereche [21]. The direct steam conditions were selected taking into account several authors [11, 20, 22]. The isentropic efficiency of the turbine was selected according to Palacios-Bereche [21]: Stage 1: 80.6% and Stage 2: 86.2%. Several authors [11, 21] state that the mechanical efficiency of the turbogenerator equal to 98.2% and the electrical 97.6%, which was taken into account to evaluate electrical and mechanical losses. To estimate steam generator losses, the Spreadsheet module (GV Losses) was used.

The chemical reactions used in the simulation correspond to the combustion of crude oil and vinasse. The reactions involved in the process were inserted into the Furnace module. For crude oil, reactions were reported by Cruz et al. [19]. A 98% conversion was set to consider losses due to incomplete combustion due to mechanical causes [21]. Table 5 shows the chemical combustion reactions of vinasse.

Table 5 Chemical reactions of combustion of concentrated vinasse at 60 ºBrix

Module	Reactions	Limiting Component	Conversion (%)
Furnace	$C_{12}H_{22}O_{11} + 12\ O_2 \rightarrow 12\ CO_2 + 11\ H_2O$	$C_{12}H_{22}O_{11}$	98
	$0{,}5\ C_6H_{12}O_6 + 3\ O_2 \rightarrow 3\ CO_2 + 3\ H_2O$	$C_6H_{12}O_6$	

The simulation model for this alternative is illustrated in Fig. 1.

A_2. Desalination of Concentrated Vinasse

The model proposed by Pérez and Garrido [23] was used to simulate alternative A_2. Concentrated vinasse at 60 °Brix and 90 °C is added to a stirred tank with jacketed and cooling medium. Ammonium sulfate is added to this tank to promote the precipitation of salts. Later it goes to the centrifuge where the separation of the salts (rich in sodium and potassium) and a desalinated liquid stream occurs.

The modules for the simulation were: Set (SET-S) was used to determine the relationship between the flow of concentrated vinasse and the flow of aqueous ammonium sulfate (multiplier: 0.036), Tank that was used for the simulation of the reactor (Reactor), Cooler (CoolerR) was used to simulate the reactor cooling system, where the pressure drop (ΔP = 0 kPa) was supplied as data. A Simple Solid Separator was used to represent the centrifuge (Centrifuge) with a pressure drop (ΔP = 0 kPa) and the separation ratio for the streams (solids in liquids: 0.1, since the separation efficiency reported by Pérez and Garrido [23] is 90%, solids in steam: 0 and liquid at the bottom: 0). In the ADJ-DS module the controlled variable was the mass concentration of ammonium sulfate (30%) and in the case of the ADJ-AE the controlled variable was the temperature of the Mix stream (35 °C).

For the simulation of the alternative, a new component was included: ammonia (NH_3). The precipitated salts were simulated as hypothetical components. Table 6 shows the hypothetical solid compounds inserted for the alternative simulation.

Table 6 Hypothetical solid compounds

Compound	Chemical formula	Molar mass (kg/kmol)	Density (kg/m^3)
Ammonium sulfate	$(NH_4)_2SO_4$	132.14	1,770
Sodium sulfate	Na_2SO_4	142.04	2,660
Potassium sulfate	K_2SO_4	174.26	2,660

The chemical reactions used in the simulation are shown in Table 7.

Table 7 Chemical reactions that occur in alternative A_2

Module	Reactions	Limiting Component	Conversion (%)
Reactor	$Na_2O + (NH_4)_2SO_4 \rightarrow Na_2SO_4 + 2\ NH_3 + H_2O$	Na_2O	5.75
	$K_2O + (NH_4)_2SO_4 \rightarrow K_2SO_4 + 2\ NH_3 + H_2O$	K_2O	10

Fig. 2 shows the simulation model obtained for this alternative.

A_3. Anaerobic Digestion of Vinasse and Electricity Generation

For the simulation of anaerobic digestion, thermophilic conditions were selected [24]. The vinasse that comes out of the liquor column is cooled with water in a cooler up to 55 °C, since it is the temperature with the highest microbial growth and methane productivity under the selected conditions [24, 25]. Subsequently, the cooled vinasse goes to the biodigester, where biogas and treated vinasse are obtained. The biogas obtained, once desulfurized, is used in the generation of steam and electricity. For steam generation, the model presented in alternative A_1 [21] was used.

The amount of biomass produced at the exit of the biodigester can be considered negligible [7, 26]. According to Longati et al. [26], a part of the treated vinasse is recirculated to the biodigester, at a rate of 0.5.

To simulate this alternative, different modules were used. Conversion reactor was used for anaerobic digester simulation (Anaerobic Biodigester), the Heat exchanger module was used to simulate the vinasse cooler (Cooler) with no pressure drop in tubes and shell (ΔP = 0 kPa), the Split was used to simulate the flow division at the exit of the biodigester (TEE-101) with a separation ratio of 0.5, the Compressor module (Compressor) for the compression of the biogas and the Component Splitter module was used to simulate the desulfurization of the biogas (Desulfurizer). A value of 0.999 was supplied for the separation fraction of H_2S in the H_2S stream in correspondence with the recommended concentration in the biogas (0.1% H_2S) for its use as fuel [27] and 0.09 for the CO_2 that is lost in the process. Inlet and outlet pressure conditions were selected based on Lorenzo [27].

For the steam and electricity generation stages, the simulation was developed as alternative A_1 in some areas. In this case, the direct steam passes to the turbogenerator (Stage 1), a part passes a reduction pressure valve VR-15/7 and continue to feed the deaerator. The other part of the steam is expanded in the second stage (Stage 2) in order to generate more electricity.

Table 8 shows the components selected for the simulation of the alternative.

Table 8 Components inserted for the simulation of alternative A_3

Component	Chemical formula	Component	Chemical formula
Propionic acid	$C_3H_6O_2$	Hydrogen sulfide	H_2S
Butyric acid	$C_4H_8O_2$	Methane	CH_4
Ammonia	NH_3	Sulfur dioxide	SO_2

The chemical reactions (Table 9) for the biodigester simulation represents four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Biogas combustion reactions for the steam generation stage are considered.

Table 9 Chemical reactions that occur in the anaerobic digestion and steam generation stages

Module	Reactions	Limiting Component	Conversion (%)	Reference
Anaerobic biodigester	Hydrolysis			
	$C_{12}H_{22}O_{11} + H_2O \rightarrow 2\ C_6H_{12}O_6$	$C_{12}H_{22}O_{11}$	90	[16]
	Acidogenesis			
	$C_6H_{12}O_6 + 2\ H_2O \rightarrow 2\ C_2H_4O_2 + 2\ CO_2 + 4\ H_2$	$C_6H_{12}O_6$	95	-
	$C_3H_8O_3 \rightarrow C_3H_6O_2 + H_2O$	$C_3H_8O_3$	99	[28]
	$C_3H_6NO_2S + 2\ H_2O \rightarrow C_2H_4O_2 + NH_3 + CO_2 + 0.5\ H_2 + H_2S$	$C_3H_6NO_2S$	100	-
	Acetogenesis			
	$C_2H_5OH + H_2O \rightarrow C_2H_4O_2 + 2\ H_2$	C_2H_5OH	90	-
	$2\ CO_2 + 4\ H_2 \rightarrow C_2H_4O_2 + 2\ H_2O$	CO_2	100	-
	$C_3H_6O_2 + 2\ H_2O \rightarrow C_2H_4O_2 + CO_2 + 3\ H_2$	$C_3H_6O_2$	100	-
	$C_4H_8O_2 + 2\ H_2O \rightarrow 2\ C_2H_4O_2 + 2\ H_2$	$C_4H_8O_2$	100	-
	Methanogenesis			
	$2\ C_2H_5OH + CO_2 \rightarrow 2\ C_2H_4O_2 + CH_4$	C_2H_5OH	100	-
	$C_2H_4O_2 \rightarrow CH_4 + CO_2$	$C_2H_4O_2$	79	-
	$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$	H_2	99	[28]
Furnace	Combustion			
	$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$	CH_4	98	[29]
	$H_2 + 0.5\ O_2 \rightarrow H_2O$	H_2	98	[29]
	$H_2S + 1{,}5\ O_2 \rightarrow SO_2 + H_2O$	H_2S	98	[29]

Fig. 3 shows the simulation model obtained.

A_4. Drying of Concentrated Vinasse

The vinasse concentrated at 35 ^{o}Brix goes to a hot air dryer where concentrated vinasse is obtained in powder [30], which is used as fertilizer. The humidity of the vinasse is reduced to values between 1-8% [6, 7].

For the simulation of this alternative, different modules were used. Compressor was used to simulate the hot air fan (Main Fan) and the air coming out of the cyclone (Exhaust air fan), Heater was chosen to simulate the air heater (Heater) where the pressure drop (ΔP = 0 kPa) was supplied as data.

The Component splitter module was used for the simulation of part of the body of the hot air dryer (Dryer). The data given in this module were: separation ratio of water in the cold air stream of 97% and for the air component 100%; for stream dry vinasse 95% was inserted for salts. For the simulation of the dryer cyclone, the Cyclone module was selected.

The simulation model for this alternative at shown in Fig. 4.

Economic Analysis

The total investment cost was calculated based on delivered-equipment cost Peters' method [31] with the factors adjusted by Petrides [32]. All purchase costs were adjusted by capacity and considering the inflation factor by mean of the six-tenths rule and the Marshall & Swift Equipment Cost Index [33].

The selling prices and costs used to determine income and expenses are shown in Table 10. As a modification analysis is carried out, only the changes that each alternative determines in each of the elements of the cash flow with respect to the base case were considered. What is related to previous technology or equipment was not taken into account.

Table 10 Prices and costs used

Selling prices	Value	Cost	Value
Spirit (USD/L)	0.62	Crude (USD/hL)	33.63
Electricity (USD/kWh)	0.16	Electricity (USD/kWh)	0.1842
Fertilizer ash (USD/t)	221.83	Water (USD/m^3)	0.11
Fertilizer salts (USD/t)	150.52		
Animal feed (desalinated vinasse) (USD/t)	100		
Dry vinasse (USD/t)	17.50		

For the analysis, dynamic economic indicators were calculated: net present value (NPV), internal rate of return (IRR), payback period of capital (PBP), payback period of discounted capital (DPBP), return on investment (ROI) and updated rate of return (RNPV). For the calculation, the following indices were considered as reported for the Cuban sugar industry: a tax rate of 35%, an interest rate of 12%, a project life of five years and a useful lifetime of the equipment of 10 years. It was also considered an operation time equal to 300 days per year.

Results And Discussion

Technical-environmental Analysis

Tables 11–15 show the results obtained from the simulation and validation of the four alternatives. The simulation models showed an absolute relative error for all simulated alternatives less than 10%, which has been considered as high accuracy model [34].

A_1. Incineration of Concentrated Vinasse and Electricity Generation

Table 11 presents the results obtained from alternative A_1.

Table 11 Results of alternative A_1

Parameter	Aspen Hysys
Crude oil consumption (kg/h)	349.7
Losses in the boiler steam (kJ/h)	$-8.245 \cdot 10^5$
Ashes (kg/h)	198.6
Generated electricity (kWh)	Stage 1: 460.3
	Stage 2: 170.6
	Total: 630.9
Electrical losses in the turbo generator (kWh)	15.14
Mechanical losses in the turbo generator (kWh)	11.36
Power consumed by the air fan (kW)	21.97
Combustion gas temperature (ºC)	943.6
Stack gas temperature (ºC)	160
Power consumed by the feed water pump to the boiler steam (kW)	13.18
Power consumed by the tempering water pump (kW)	0.20
Feed water to deaerator (kg/h)	4,852
Tempering water (kg/h)	350.8
Total condensates (kg/h)	Condensed turbo: 1,995
	Condensed crude: 150
	Condensed crude 2: 10.08
	Total: 2,155

The electricity generated, by a similar capacity distillery (30,000 L/d), is 625 kWh, according to Ramaiah and collaborators [35], so the result obtained in the model differs from the one reported by 0.94%. Noa et al. [11] propose an electricity production of 632 kWh; compared with the result calculated in the simulator, a relative error of 0.17% is obtained. These authors also propose a fuel consumption of 349.6 kg/h, value that differs by 0.03% from that obtained with the alternative A_1 model.

Regarding the electricity generation index by mass flow of steam generated (kWh/kg), the one obtained in the simulator was 0.087, similar to that reported by various authors [35, 36]: 0.081 and 0.089 respectively; and slightly higher than that stated (0.061) by Alappat [37].

The temperature of the combustion gases (943.6 ºC) is within the interval reported (850-950 ºC) by Schfopf and Erbino [38] for this type of system. The temperature of the chimney gases (160 ºC) is within the range referred to (155-165 ºC) by Palacios-Bereche [21] and differs by 1.9% from that stated (157 ºC) by Noa et al. [11]. This obtained temperature shows the use of energy achieved in the auxiliary equipment of the steam generator.

The ashes obtained present 61.62% by mass of potassium, so the high concentration of this mineral proves its usefulness as a fertilizer or for use in its formulation.

The distillery's steam demand (4,400 kg/h) and electricity (119 MWh/campaign) are supplied. The costs for the electricity purchase in the plant are reduced, in addition to income from the sale to the national electricity system of 154 MWh per campaign.

Another positive environmental effect is the recovery of the condensates as feed water to the boiler, since it is possible to reduce the consumption of treated water by 3,780 m^3/year. With the use of concentrated vinasse at 60 ºBrix as fuel, the consumption of crude oil is reduced by 184 t/year, equivalent to 62,567 USD/year.

Regarding the emission of combustion gases, although the consumption of crude oil is reduced, CO_2 emissions to the atmosphere increase with the application of the mixture of vinasse-crude oil as fuel; this is due to the contribution of organic carbon from the vinasse.

As vinasse is a by-product of sugar cane, the CO_2 emitted during its combustion is part of that absorbed by the plant during its development. Sugarcane plantations have been shown to act as absorbent areas, which, through chemical reactions, absorb carbon dioxide (CO_2) from the air and expel it as oxygen [39-41].

Fig. 5 shows the behavior of the emissions for alternative A_1 comparing with the real case study.

According to the Cuban standard for air quality NC-TS 803 [42] the emissions of gaseous pollutants from this alternative comply with the established values of maximum allowable emissions.

A_2. Desalination of Concentrated Vinasse

With a potassium content of 50.4%, 212.8 kg/h of fertilizer salts are obtained. The desalinated vinasse generated is 1,413 kg/h, which can be used as animal feed or in the production of yeast. The consumption of ammonium sulfate for the precipitation of the salts was 16.95 kg/h.

The validation of the simulation model for alternative A_2 was carried out comparing with data from Pérez and Garrido [23]. The referred data were inserted into the simulation model and the results obtained were compared with those reported by the authors. Validation results for this alternative are shown in Table 12.

Table 12 Comparison of the results of the simulation of alternative A_2

Parameter	**Pérez y Garrido** [23]	**Aspen Hysys**	**Relative error (%)**
Salt concentration in concentrated vinasse at 60 ºBrix (%)	11.37	11.36	0.09
Ammonium sulfate mass flow (kg/h)	4,620	4,618	0.04
Temperature at the tank outlet (ºC)	35	34.92	0.23
Mass flow of desalinated vinasse (kg/h)	115,626	115,500	0.11
Mass flow of salts obtained (kg/h)	17,280	17,400	0.69

As shown in Table 12, a relative error less than 1.0% was obtained (the maximum relative error is 0.69), so the simulation model obtained is verified.

A_3. Anaerobic Digestion of Vinasse and Electricity Generation

For the validation of the simulation model obtained for alternative A_3, obtained and validated results are shown in Tables 13 and 14 for the simulated biogas, respectively.

Table 13 Results obtained from alternative A_3

Parameter	Aspen Hysys
Biogas produced (Nm^3/h)*	890.4
Methane produced (Nm^3/h)*	416.9
COD removal efficiency (%)	77.52
Yield (Nm^3CH_4/COD_r)	0.2518
H_2S removal efficiency (%)	99.9
Losses in the boiler steam (kJ/h)	$-3.248 \cdot 10^5$
Generated electricity (kWh)	Stage 1: 240.5
	Stage 2: 232
	Total: 472.5
Electricity generation index per methane produced (kWh/m^3)	1.134
Stack gas temperature (ºC)	160
Power consumed by air fan (kW)	3.96
Power consumed by the compressor (kW)	24.42
Power consumed by the feed water pump to the boiler steam generator (kW)	7.19
Feed water to deaerator (kg/h)	1,248
Condensates (kg/h)	2,830

* Reported to normal conditions (0 ºC y 101.325 kPa)

Table 14 Validation of the biogas entering the combustion reactor

Composition (% v/v)	Reference	Value	Aspen Hysys	Criterion
CH_4	[43, 44]	50-70	55.31	Complies
	[45, 46]	55-70		Complies
CO_2	[43, 44]	25-50	44.69	Complies
	[45]	27-45		Complies

The COD removal efficiency obtained (77.52%) is within the values reported by several authors [25, 47, 48], ranging between 70-80% for this system. The methane yield under normal conditions is 0.2518

Nm^3CH_4/CODr, a value that is in the range reported by various authors [25, 26, 49-51]: 0.225-0.299 ± 0.066.

The electricity generation index by quantity of methane produced in this study (1,134 kWh/m^3) is higher than that reported by Ramaiah and collaborators [35] (0.54 kWh/m^3) for a similar distillery (30,000 L/d). Lorenzo-Acosta et al. [52] report an index of 1.7 kWh/m^3 for a 50,000 L/d distillery, an index higher than that obtained.

With the implementation of anaerobic digestion of vinasse, the organic load is considerably reduced (~ 78%) and electricity is generated from biogas production. The COD removal achieved shows that it is possible to reduce the environmental pollution caused by the vinasse from distilleries.

In this case, as in alternative A_1, the electricity demand is supplied by generating approximately 204 MWh per campaign, the costs for the purchase are reduced, in addition to generating income from the sale to the SEN of 61 MWh per campaign. The biogas produced, equivalent to 489 kg/h of oil, used in the generation of electricity, allows a crude oil saving of 98.9%, a result similar to that obtained by Pérez [53]. In addition, it is possible to reduce combustion gas emissions by 5,732 t/year (14%).

With this alternative, the specific water consumption of the distillery increases, due to the addition of the cooling water from the vinasse cooler (30.27 m^3/h).

A_4. Drying of Concentrated Vinasse

Results obtained from alternative A_4 are presented in Table 15.

Table 15 Results obtained from alternative A_4

Parameter	Aspen Hysys
Dry vinasse flow (kg/h)	993.4
Evaporated water flow (kg/h)	1,690.6
Dry vinasse temperature (ºC)	98.42
Dry vinasse moisture (%)	5.54
Drying system drive power (kW)	215.8

The drive power of the drying system addressed by Perera [30] is 746 kW for 9.1 m^3/h of concentrated vinasse at 35 ºBrix. Both values are 3.5 times higher than the flow of concentrated vinasse fed and power consumed in the simulation model. Therefore, it can be said that the relationship between the power consumed and the flow of vinasse fed (0.012 kW/kg) in the simulation model of the alternative is similar to that of the reference. According to Perera [30], the relationship between the flow of dry vinasse and that of concentrated vinasse at 35 ºBrix that is fed to the drying system is 0.38 kg/kg, a result that differs by 2.63% from that obtained in the model simulation of alternative A_4. Also in the case of the ratio of evaporated water and fed vinasse, a similar result is obtained (0.6 kg/kg).

The humidity of the dry vinasse obtained (5.54%) is within the interval reported by Irizarri [6] and Morandini and Quaia [7] 1-8%.

Concentrated vinasse drying cause a reduction of the negative environmental impacts and produce a powder, suitable for being used as: fertilizer, fuel with a low heating value or cattle food formulation.

Each of the studied alternatives partially or totally reduces the residual, condition required for an integrated and sustainable industry.

Economic Analysis

The income and expenses of the process were determined as part of the economic analysis. Tables 16 and 17 show the elements of the annual cash flow and the dynamic economic indicators calculated.

Table 16 Cash flow elements

Cash flow element (USD/año)	Alternative			
	A_1	A_2	A_3	A_4
Annual profit (Aci)	2,617,434	2,084,513	1,931,215	1,404,396
Investment cost (Atc)	3,652,419	2,777,323	3,043,358	2,023,084
Annual amount for taxes (Ait)	882,213	704,025	647,922	472,923
Net profit (Anci)	1,734,939	1,380,489	1,283,293	931,472
Annual depreciation charges (Ad)	96,020	73,014	80,008	53,186

As the alternatives that are analyzed are of income, the cheapest alternative is the one with the highest NPV. Table 17 shows that the alternatives analyzed are economically advantageous, obtaining the greatest benefits in alternative A_1. In all cases the IRR presents values above the rate at which the company can obtain funds (interest rate: 12%) and the ROI is higher than 33%, which denotes that the investments are attractive. In all the alternatives, the investment is recovered through the net profits obtained, in less than four years, demonstrating their great liquidity.

Table 17 Comparison of economic indicators

Indicators	Alternative			
	A_1	A_2	A_3	A_4
NPV (USD)	1,291,782	889,164	272,760	24,800
IRR (%)	25.5	24.3	15.6	12.5
PBP (years)	1.8	1.8	2.2	2.4
DPBP (years)	2.7	2.7	3.3	3.6
ROI (%)	56.4	54.9	45.1	41.8
RNPV (USD/USD)	0.35	0.32	0.09	0.01

As there are several modification alternatives, they may compete between them for the available capital, so the RNPV criterion establishes the order of priority of implementation. The best alternative is incineration, then desalination, followed by anaerobic digestion and then drying.

Finally, a sensitivity analysis of the investment was carried out when total income, total expenses and investment cost change. NPV was considered as a dependent variable and five values of each independent variable were selected, the expected value (0%), the optimistic (+5%) and pessimistic value (-5%) and extreme optimistic (+10%) and pessimistic (-10%) values.

It can be observed (Fig. 6) that the investment will be sensitive to all the independent variables analyzed, but the highest sensitivity appears for the total income, which is the one with the greatest slope.

Conclusions

Four technologies for vinasse treatment were simulated in Aspen Hysys v10.0: (1) concentration and incineration and electricity generation, (2) concentration and desalination, (3) anaerobic digestion and electricity generation, and (4) concentration and drying. The simulation models obtained were validated from the consulted literature and it was found that they adequately reproduce the simulated technologies.

The alternatives cause a reduction of the polluting effect of vinasse and increase its added-value. Incineration of concentrated vinasse makes it possible to generate energy and to obtain potassium fertilizer ashes. Anaerobic digestion allows the generation of energy and reduces COD by approximately 78%. Desalination and drying alternatives provide income from the sale of animal feed and fertilizer products.

The four alternatives are economically feasible. IRRs are obtained higher than the interest rate used and PBP are between 1.8 and 2.4 years. The highest benefits were obtained with alternative A_1, showing a RNPV of 0.35 USD/USD.

The simulation models obtained in this paper represent a valuable supporting tool for decision making when evaluating the implementation of these technologies for vinasse valorization in ethanol industry.

Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Availability of data and material

Not applicable

Code availability

Not applicable

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection, simulation process and results analysis were performed by Arletis Cruz Llerena, Osney Pérez Ones, Lourdes Zumalacárregui de Cárdenas and José Luis Pérez de los Ríos. The first draft of the manuscript was written by Arletis Cruz Llerena and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval

All authors agreed with ethical responsibilities.

Consent to participate

All authors agreed with the manuscript content and its participation.

Consent for publication

All authors approved the version to be published and obtained consent from the responsible authorities at the institute/organization where the work has been carried out and agreed with to submit the manuscript.

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Figures

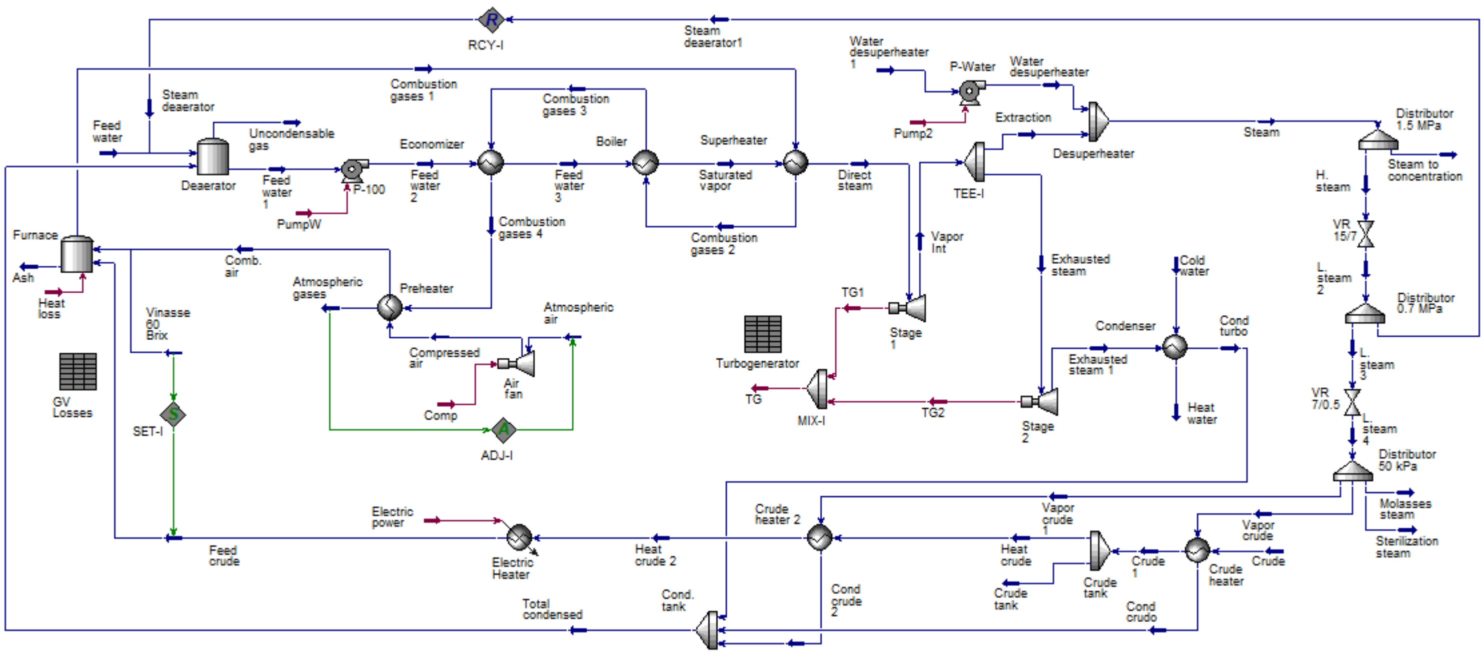

Figure 1

Simulation model of the alternative A_1

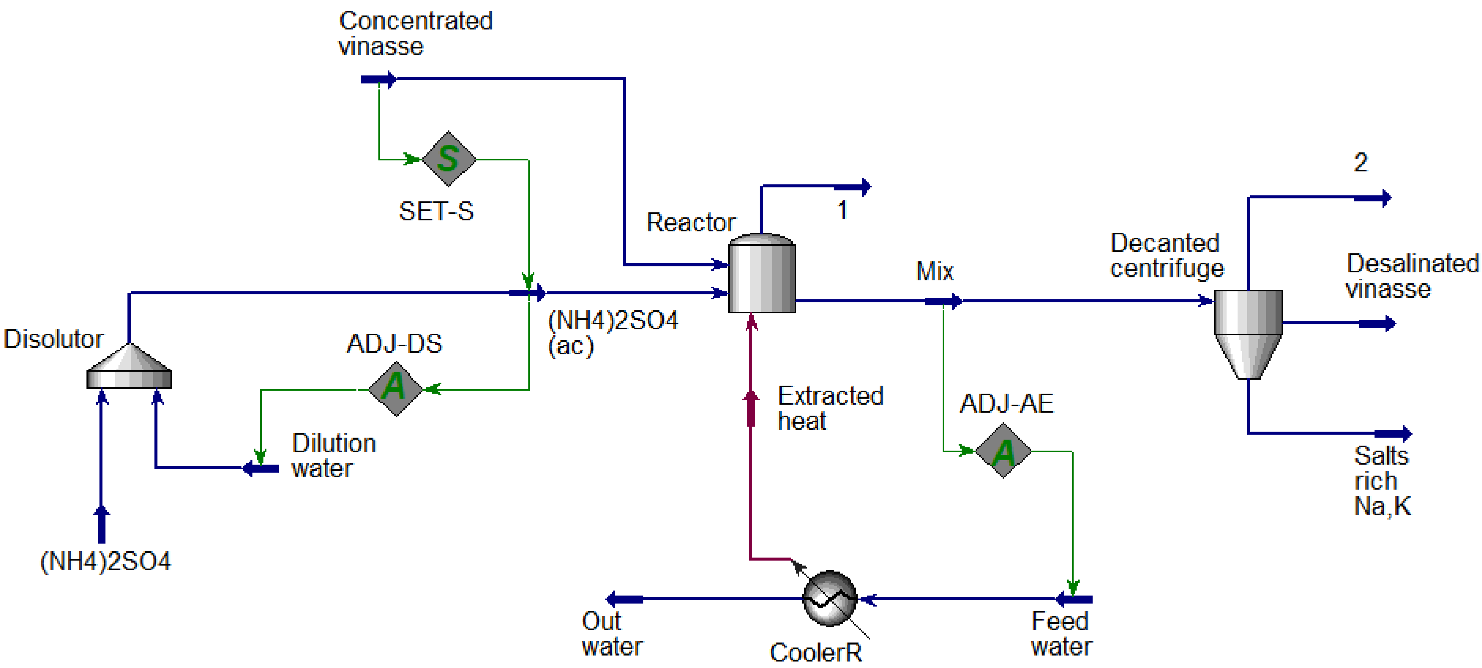

Figure 2

Simulation model of the alternative A_2

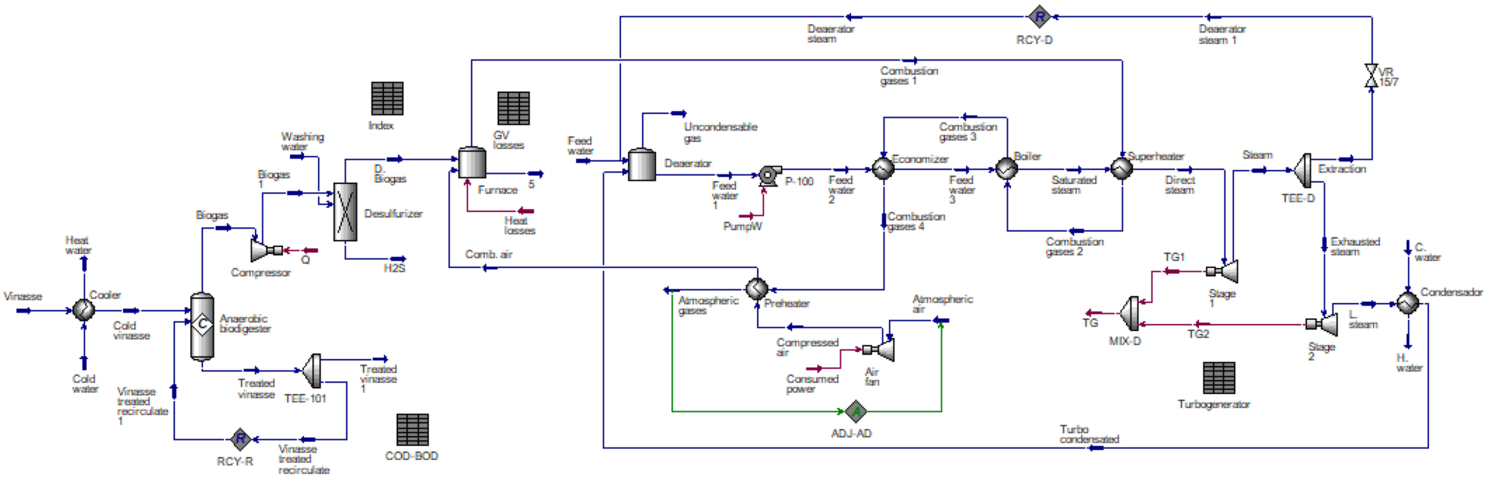

Figure 3

Simulation model of the alternative A_3

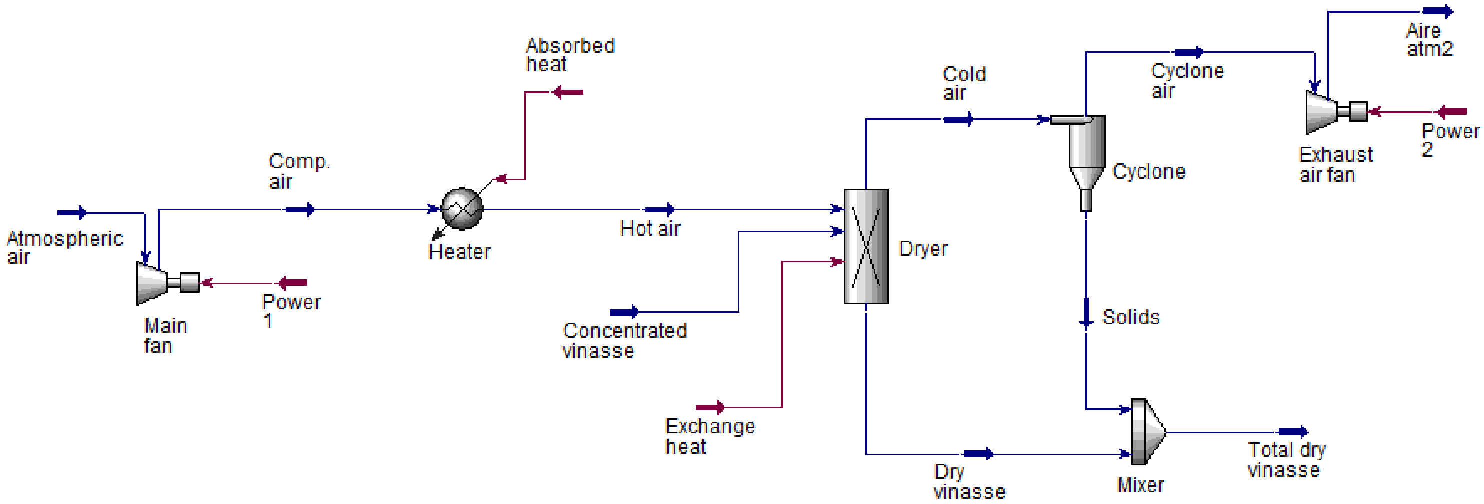

Figure 4

Simulation model of the alternative A_4

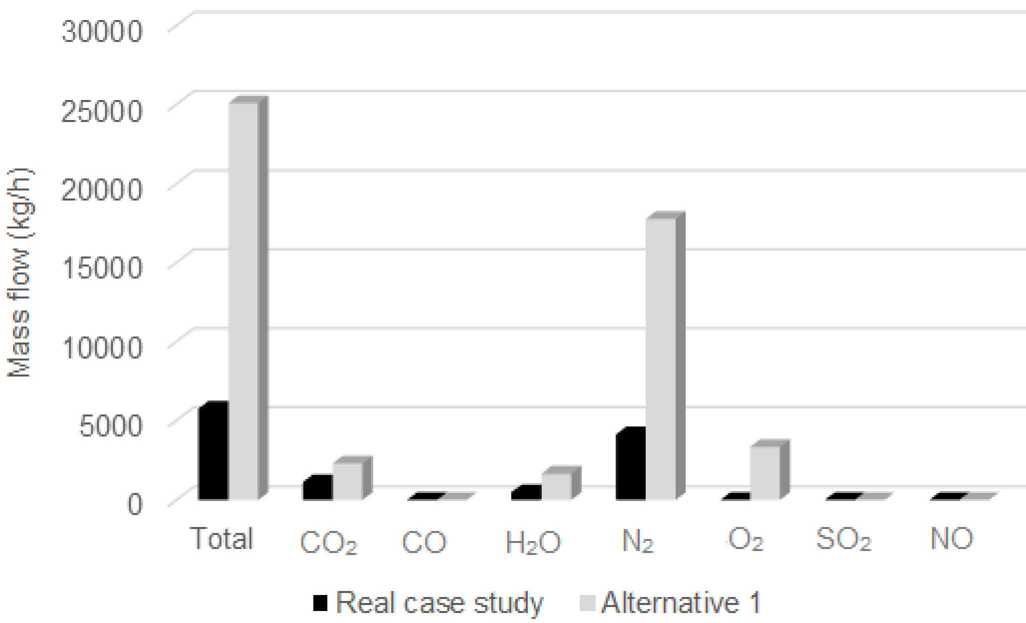

Figure 5

Comparison of emissions from alternative A_1 with respect to the real case study. (a) Mass flows (b) Mass composition

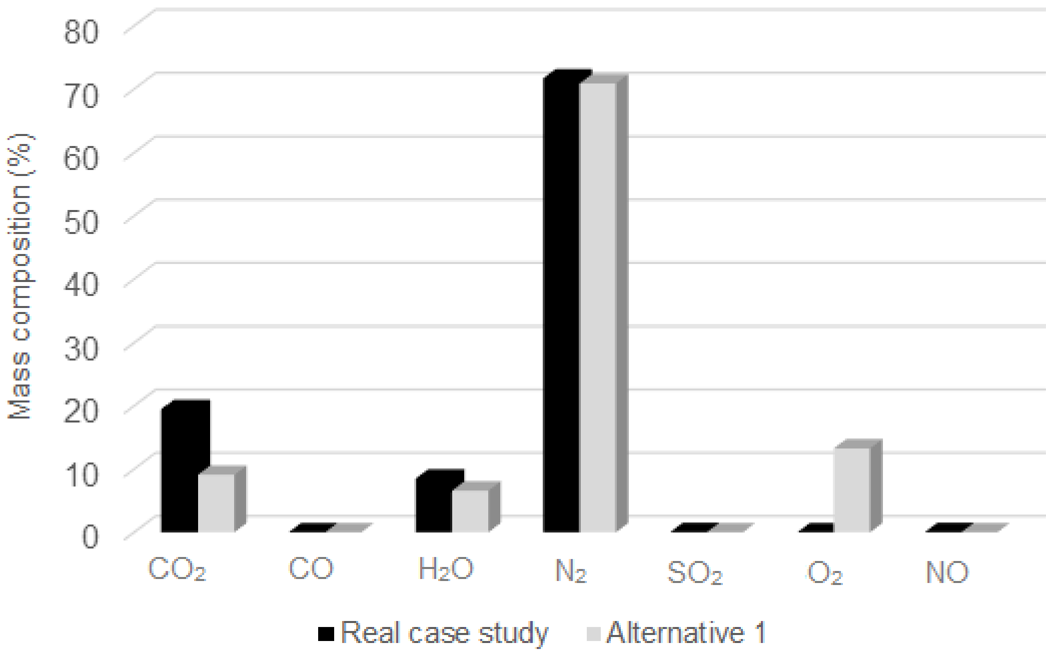

Figure 6

Sensitivity analysis of the investment of alternative A_1

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