

Life Cycle Assessment of Cogeneration Systems Using Raw and Torrefied *Dichrostachys Cinerea* (L.) Wight & Arm. (Marabou).

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Abstract

Purpose This study aims to assess environmentally three different alternatives related to the valorization of *Dichrostachys cinerea* (L.) Wight & Arm. (marabou), identified as an invasive tree, as a feedstock for cogeneration facilities installed in the sugarcane industry in Cuba. The alternatives are (A-1) Electricity generation from marabou in a conventional back-pressure steam turbine cycle, (A-2) Electricity generation from torrefied marabou in a back-pressure steam turbine cycle, and (A-3) Electricity generation from torrefied marabou using extraction-condensing turbines.

Methods SimaPro 9.0.0.35 software was used for the modeling of the inventory, based on different operational parameters. The ReCiPe environmental impact assessment method was used in the hierarchical perspective, assessing 18 impact categories (midpoint), and 3 damage categories (endpoint).

Results and discussion The results demonstrated that A-3 shows the lower environmental impacts (Fine Particulate Matter Formation, Terrestrial Acidification, and Water Consumption) as compared to A-2 and A-1. This performance is explained by a lower normalized marabou consumption (1.85 kg marabou/kWh generated), and lower emissions associated with marabou harvesting, transportation, and processing. The cogeneration stage was the main contributor to the environmental burdens in Water Consumption (100% in A-1; 87% in A-2 and A-3). Marine Ecotoxicity was the impact category with better environmental performance due to the substitution of synthetic mineral fertilizers by ashes produced during combustion. The human health damage category reached the higher impacts on the torrefaction subsystem in the A-3 scenario, representing over 94% of the total environmental burden of the process. PM₁₀, NO₂, and SO₂ contributed the most over this damage category, mainly in marabou combustion, causing injuries in respiratory systems by aspiration of organic compounds.

Conclusions The use of more efficient technology (extraction-condensing steam turbine), using torrefied marabou as feedstock, compared with the previous alternatives, impacts beneficially on the environment. Thus, a combination of marabou torrefaction with cogeneration facilities in sugarcane industries can be considered as an environmental-friendly technology in the Cuban context. The current study results will help decision-makers implement more sustainable policies in the Cuban energy sector, using marabou as feedstock as an attractive bioenergy route pathway.

Statement Of Novelty

This research focuses on the valorization of an invasive tree (*Dichrostachys cinerea* (L.) Wight & Arm., marabou) in sugarcane facilities in Cuba. The potential impact on the environment is evaluated using the LCA approach throughout three different alternatives, taking into account the consideration of using raw marabou and torrefied marabou in the current inefficient technology (back-pressure steam turbine), and in a more efficient technology (extraction-condensing turbine) installed in the cogeneration systems. Besides, the results are useful to potentiate the use of forestry resources (invasives plants), integrated

with cogeneration systems to generate renewable electricity, increasing its impact on the national energy matrix.

Introduction

Cuba is a nation with an energy matrix highly dependent on fossil fuel importation. More than half of the fossil fuels used for energy generation comes from abroad (mainly from Venezuela); thus, national energy security is hindered by the volatility of the prices in the oil market [1]. In particular, the Cuban electricity matrix is supported by liquid and gaseous petroleum derivatives, which are used in centralized and decentralized thermal power plants (81.40%), and in combined cycles (14.10%) with gas turbines using liquefied petroleum [2]. Due to the economic impact on the national economy, the widespread hydrocarbons depletion, and the anthropogenic emissions related to them, a migration towards renewable sources is necessary to increase the country's energy security.

The Perspective development of Renewable Energy Sources (RES) and the efficient use of energy in Cuba, direct actions to change its energy matrix (by 2019, only 5% is based on renewable sources) by migrating to a more renewable one. In this sense, the policy energy targets are to increase the share of biomass in the matrix by 24% to 2030 [3, 4]. Based on this policy, the Cuban government projected to install 19 biomass-based cogeneration plants by 2030. The idea is to install next to sugarcane mills to take advantage of the existing infrastructure for cogeneration currently used by this industry only during the sugarcane harvest period. Currently, there is an installed capacity of about 600 MW of cogeneration plants using sugarcane bagasse as fuel during the industrial period (from December to April). However, these plants are out of service or are operate at very low rates after the harvest period. In addition, most of the installed plants are obsolete or operates at low-efficiency (steam generators coupled with back-pressure steam turbines) [3, 5], which have drawn impacts on human health categories by the emissions of inorganic pollutants [6, 7]. Therefore, the need to modernize the existing cogeneration systems to achieve higher efficiencies is a primary concern [7, 8]. Accordantly, as an alternative, it has been defined in the literature that technologies using extraction-condensing steam turbines could increase the electricity generation by 21.40% compared with the current technologies, producing 140 kWh/t sugarcane [9]. In addition, economic investments for technological improvements are necessary, and a change in operational parameters (increase pressure inside steam generator up to $6.70E+03$ kPa) is considered an attractive option [10].

Besides, the existing cogeneration plants are designed to process mainly sugarcane bagasse as fuel; nevertheless, other lignocellulosic biomass (sugarcane straw, energetic sugarcane, and agricultural harvest residues) could substitute the bagasse during the no-harvesting period [11]. In this sense, Gutiérrez, Eras, Huisingh, Vandecasteele and Hens [11] have highlighted the potentiality of an invasive plant (marabou) for substituting bagasse in the existing cogeneration systems. Therefore, using marabou will shorten the out-of-operation times for cogeneration plants, allowing an increase of 14% of the generation capacity [12].

The *Dichrostachys cinerea* (L.) Wight & Arm. (marabou) is an African origin tree introduced in Cuba in the mid-nineteenth century, which has thorny branches that reach heights between 5-7 meters [13, 14]. The marabou is considered among the 100 most harmful or aggressive invasive species in the country [15], and according to the Cuban National Land Control Centre, about 7% of the national arable land is infested by this tree, hindering agricultural activity and livestock management [16, 17]. Agricultural yield is reported from 37-100 t/ha [18, 19], representing 0.78E+06 GJ as a theoretical energy potential in the country [16].

Currently, there are no industrial applications for marabou, and it is only used as solid fuel at the community level, mainly for cooking, or to produce manufactured charcoal on a small scale [14, 20, 21]. The charcoal production only takes place in isolated areas, producing around 7.70E+04 t/year [22] (half of the total amount corresponds to marabou charcoal), representing a small part of the existing potential. The existing evidence suggests that most of this biomass's characteristics (e.g., heating value, elemental composition, and ashes content) could be considered suitable feedstock for energy purposes [13]. In this regard, Alba, Pérez, Chong and Arteaga [23] measured a lower heating value (LHV) of 16.24 MJ/kg, which is considered similar to other energetic crops (wheat straw (16.53 MJ/kg), poplar (18.50 MJ/kg), german beech (18.80 MJ/kg) [14, 24]). Besides, Fernández, García-Albalá, Andivia, Alaejos, Tapias and Menéndez [13] remarked that the high energy content per unit volume in marabou could produce positive impacts by reducing transportation costs. Abreu [18] studied the ashes content in marabou, obtaining a 3.40% dry basis with high melting temperature (1460 °C), both desirable parameters for thermochemical processes.

Despite its promising properties and availability, the use of marabou has disadvantages associated with its nature, such as high moisture content, hygroscopicity, excess of smock during combustion, low energy density, all of these leading to increased costs for transportation (up to 2.33E-02 \$/MJ km [25]), and auto-ignition risks during storage [26, 27]. Accordingly, pretreatment processes are needed to reduce the disadvantages mentioned above, making torrefaction one of the most attractive solutions.

The torrefaction has several technical benefits such as (i) the torrefied biomass is a non-biodegradable and hydrophobic solid, with higher energy density and grindability than the original biomass, (ii) the process has high energy efficiency, and (iii) it requires lower investment costs as compared to other technical alternatives (pyrolysis or gasification) [28]. The main applications for torrefied biomass are large-scale power production, industrial and residential heating, especially in developing countries [29, 30].

Adams, Shirley and McManus [31] compared the raw biomass's environmental behavior and the torrefied biomass in a global approach. They demonstrated that torrefied material has environmental benefits when compared to raw biomass. Even when this communication was very explicit, the energy cogeneration unit was not considered and the modeling processes used were off-site. Abreu, Conesa, Pedretti and Romero [32] modeled the simultaneous pyrolysis and combustion of marabou, providing kinetic parameters and valuable data to design a thermo-decomposition processing system. The same

author, Abreu [18], made characterization of raw and torrefied marabou through thermogravimetric analysis, demonstrating the advantages of the torrefaction as a fuel. The analysis showed a beneficial impact when temperatures increase, reducing the pollutant emissions compared to raw marabou in 26 and 36%, respectively. However, the author focused the analysis on general issues, and no details of the overall process are given.

Pedroso and Kaltschmitt [14] analyzed the characteristics of marabou as an energy source, obtaining low levels of combustion gases emitted to the atmosphere (CO_2 , H_2O , CO , NO_2 , SO_2 , O_2 , and Hydrocarbons (HC)) compared with other forestry biomass. In this case, the authors evaluated the main substances emitted, but with no Life Cycle Assessment (LCA) approach. Gutiérrez, Eras, Hens and Vandecasteele [3] evaluated the alternative using marabou combustion for electricity generation in an upgraded biomass-based power generation out of the industrial period in sugarcane mills, focusing the study mainly on saving greenhouse gases (GHG) emissions ($1.80\text{E}+04 \text{ ktCO}_2\text{eq/year}$).

Therefore, this study aims to assess the environmental burdens associated with electricity generation using raw or torrefied marabou as a substitute for bagasse in sugarcane mills cogeneration systems. Several scenarios were compared from the life cycle perspective.

Materials And Methods

According to the International Standard Organization (ISO) [33], the LCA methodology is implemented to compare the environmental performance of three scenarios of cogeneration systems using marabou. The scenarios are (i) direct marabou combustion (assuming back-pressure steam turbine to generate electricity), (ii) torrefied marabou with back-pressure steam turbines, and (iii) torrefied marabou with extraction-condensing turbines. In this case, the existing cogeneration facilities in the sugarcane mills can also be used for marabou with minor modifications.

Simapro software version 9.0.0.35 [34] was selected for the environmental modeling of these scenarios. The ReCiPe hierarchical perspective method (midpoint and endpoint) is used [35] for quantification of the environmental impacts [31, 36, 37]. In this sense, the following impact categories were assessed: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Ionizing Radiation (IR), Ozone Formation, Human Health (OFHH), Fine Particulate Matter Formation (FPMF), Ozone Formation, Terrestrial Ecotoxicity (OZTE), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TE), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET), Human Carcinogenic Toxicity (HCT), Human Non-Carcinogenic Toxicity (HNCT), Land Use (LU), Mineral Resource Scarcity (MRS), Fossil Resource Scarcity (FRS), and Water Consumption (WC). Besides, these impact categories are grouped into three damage categories: Human health, Ecosystem, and Resources.

Goal and scope definition

The present study aims to compare the environmental performance of three scenarios for electricity generation from marabou in a cogeneration plant installed within a Cuban sugarcane mill. The Uruguay

Enterprise (Jatibonico municipality, Cuba), was used as a reference as it has a cogeneration technology that can be used as a model for other industries throughout the country. Moreover, this plant has a standard milling operation of up to 4600 t_{sugarcane}/day, a stable sugarcane supply chain, close to the complimentary feedstock supply areas, and connected to the National Electricity Grid.

Functional unit and system boundaries

The function unit for all scenarios was 1 kWh of electricity produced in a cogeneration plant. The system boundaries (Fig. 1) are defined using a cradle-to-gate perspective, including the harvesting and processing of biomass, thermal pretreatment by torrefaction, mechanical densification via pelletization, and electricity cogeneration. Electricity distribution and consumption are excluded.

Description of the systems under study

The Uruguay Enterprise (Lat: 21.93° and Lon: -79.17°, 65.98 meters above sea level) is located in the center of Cuba (Jatibonico municipality). This factory processes sugarcane during ~135 days/year, with a bulk capacity of 6.00E+04 tons of sugar per year. The mill includes a bagasse-fueled cogeneration plant with 16 MWh of capacity, allowing a self-sufficient energy balance. However, in the non-harvesting period, the cogeneration system is partially operated, which gives space for using other fuels to maintain electricity production. Below, there are three scenarios for using marabou as a substitute for bagasse in this cogeneration system.

Electricity generation from direct marabou combustion in back-pressure steam turbines (A-1): This scenario considers the direct combustion of marabou in the biomass steam generator to produce steam, further fed to a back-pressure steam turbine to generate electricity according to Fig. 1 (See red dashed lines). In this case, marabou harvest, transportation, steam generation, and electricity generation stages are considered. As the marabou is an invasive species, it does not require forest management, land preparation, consumption of herbicides, pesticides, insecticides, or chemical fertilizers [32, 38]. In consequence, the resource consumption and emissions are only related to marabou harvesting and transportation. The marabou yield was assumed to be 37 t/ha [18], where the regeneration period ranges between 3-7 years [32, 39]. This process is performed mechanically using self-propelled biomass harvester BMH480 Kangaroo, which has the primary objective of cutting and marabou particle reduction in sizes up to 80 mm [40]. These particle sizes allow the biomass feeding to the steam generator using the existing facilities without further modifications.

Three supply areas (SA-1, SA-2, and SA-3) with an average 70 km round trip were modeled (Fig. 2). These areas were selected according to the existing transport infrastructure [41], and by optimizing the distances (supported by Google Earth) between fields and the cogeneration plant [16]. The raw material (bulk density of 283 kg/m³) [42] is transported from the supply area to the industry by diesel-fueled trucks (Kamaz, loading capacity 8.00E+03 kg). The marabou harvest and transportation from the supply area to the industry are considered the same for three scenarios; thus, forest yield and distance from harvest site to industry were assumed the same for all the scenarios.

The industrial subsystem includes steam and electricity generation stages. The chopped marabou is introduced into the steam generation stage in the sugarcane mill (cogeneration system). The purpose of the cogeneration system in a sugarcane mill is to produce electricity and steam for self-consumption, being the electricity surplus exported to the National Grid [43, 44]. The electricity generation stage uses back-pressure steam turbines with efficiencies below 18% [45], reducing the electricity surplus sent to the National Grid. Besides, the low-pressure steam is delivered to the sugar production process for juice concentration, heating and evaporation. In this case, the residual steam (low-pressure steam, 7.32E-03 kgf/cm² [46]) is a co-product.

After marabou combustion, the ashes formed are rich in phosphorous [14]; thus, they are considered as an avoided product in substitution of synthetic mineral fertilizer (triple superphosphate [41]). The process scheme includes Retal model 45 (four units) steam generators and a Modified German model EKE 80 unit (Table 1). An average steam generation rate of 4.53 kg steam/kg torrefied marabou pellet was assumed [47].

The industry has electricity generators model P-4-20/2TK (three units) and Allen 4000 (one unit). The consumption of water in the steam generation stage is equivalent to the steam produced affected by a numerical factor that takes into account the needs of the generation capacity of the industry and the losses produced (20%) [48-50]. Depending on the conditions of the primary engines, it is assumed a 3% loss in the generation of steam and 2% in the conversion of direct steam to exhaust [48, 49].

Table 1. Operational parameters of the steam generation and turbogeneration stage [7].

Parameter	Model/value	
Steam generation	Retal 45	Modified German EKE 80
Steam pressure (kPa)	1.82E+03	2.83E+03
Efficiency (%)	80	87
Production (kg/s)	12.50	22.22
Turbogeneration	Russian P-4-20/2TK	English Allen 4000
Power (kWh)	4.00E+03	4.00E+03
Steam pressure (kPa)	1.77E+03	1.77E+03
Index of steam consumed (kg steam/ kWh)	10.62	11.50

Electricity generation from torrefied marabou in back-pressure steam turbines (A-2): The major differences of this scenario concerning A-1 are related to the inclusion of a torrefaction stage previous to the cogeneration system. The harvest, transportation, torrefaction, and electricity generation stages were surrounded by broken lines in the study (Fig. 1), identifying it as A-2.

The marabou torrefaction scheme is based on the general diagram proposed by Bergman and Kiel [51], which involved the torrefaction, cooling, and densification stages (Fig. 1). Torrefaction is a thermochemical treatment method for converting lignocellulosic biomass usually operated between 200-300 °C, at low heating rates (<50 °C/min) under conditions of an oxygen-depleted atmosphere. The main product of torrefaction is a dark solid with improved fuel properties [29, 52-55]. The elemental composition considered here for raw and torrefied marabou is presented in Table 2.

Table 2. The elementary composition of raw and torrefied marabou (% dry basis) [18, 56].

Element	Raw marabou	Torrefied marabou	Reference
C	49.42	52.06	Abreu [18]
H	6.12	6.19	Abreu [18]
N	0.79	1.61	Abreu [18]
O	40.24	40.12	Abreu [18]
S	0.05	0.02	Shoulaifar [56]

The marabou moisture was measured experimentally, which is 11% of dry basis [41]; thus, the drying stage is unnecessary [57].

The energy requirements are provided by raw marabou combustion (5.30% of the biomass input to the plant) [18] and by the recirculation of non-condensable gases in the reactor with temperatures above 180 °C (torr-gas). Nitrogen is not considered in the inventory to achieve free-oxygen conditions inside the torrefaction stage. These gases pass through a heat exchange unit (tube and shell) countercurrent for heating, and after that, this stream is redirected back into the torrefaction stage (temperatures above 280 °C). The fluidized bed torrefaction technology was considered [58, 59]. The composition of sulfur in torrefied marabou decreases by 35% related to the initial marabou composition [56]. The moisture at the exit of the torrefaction stage is 3.50% [18] and there is no mass loss by dragging. For the cooling operation, the screw technology was considered using countercurrent water as a cooling medium. It is assumed not torrefied mass losses in the cooling stage; however, the cooling medium (water at room temperature, 25 °C), was replaced every five hours (5%) due to deterioration and leaks in the system (See Fig. 1).

The densification process is carried out to compact the biomass into pellets, increasing the final volumetric density between 1.03-1.28E+02 kg/m³ [60], improving its handling and transportation [61, 62]. The electricity demand is self-supplied. The main parameters considered in the torrefaction stage are presented below (Table 3).

Table 3. Parameters considered in the torrefaction stage.

Parameter	Value	Reference
LHV _{Marabou} (MJ/kg)	19.14	Alba, Pérez, Chong and Arteaga [23]
HHV* _{Torrefied marabou} (MJ/kg)	21.23	Alba, Pérez, Chong and Arteaga [23]
Temperature (°C)	280	Abreu [18]
Time (min)	60	Abreu [18]
Mass yield (%)	70	Bergman, Boersma, Zwart and Kiel [29]
Energy yield (%)	86	Alba [41]

*HHV: high heating value

Electricity generation from torrefied marabou in extraction-condensing turbines (A-3): The stages considered in this scenario are the same as A-2; the main difference is related to the inefficient technology (back-pressure steam turbine) is substituted by a more efficient technology (extraction-condensing turbine). The extraction-condensing turbine is considered the most established configuration for cogeneration systems in the bagasse-based cogeneration stage in the sugar industry [63]. The steam generator pressure used as a base case or this system is fixed at 6.70E+04 kPa (high-pressure system) considering local projects and the design characteristics of the existing facilities [64-66]. After fulfilling the minimum steam demand, the excess steam passes through the condenser unit to generate surplus electricity. The flow-through cylinder at low pressure is equal to the permissible to maintain the safe operation of the cylinder (this minimum was assumed 5% of the nominal capacity of the cylinder). The operating parameters for the steam generation and turbogeneration stages are shown in Table 4. Despite considering two high-pressure water regenerative heaters and one deaerator (increase in the thermodynamic efficiency cycle) in the steam generation scheme, their input/outputs are out of the inventory.

The increase of thermodynamic cycle efficiency with the elevation of operational parameters is a well-established process. However, it implies an increase in capital costs in the cogeneration stage, reaching 2.20E+03 USD/kWe [66]. The analysis is related to a technical (capacity and scale factor) and economical (Net Present Value and Internal Rate of Return) assessment. As the technical factors increase, a beneficial impact on the economy is expected, but additional economic studies are necessary.

Table 4. Operational parameters of the steam generation and the turbogeneration stage considers for A-3.

Parameter	Value	Reference
Steam generator		
Steam pressure (kPa)	6.70E+03	Rubio, Rubio and Roque [66]
Efficiency (%)	88	Rubio, Rubio and Roque [66]
Production (kg/s)	22.22	Rubio, Rubio and Roque [66]
Turbogenerator		
Power (kWh)	1.70E+04	Río [67]
Steam extraction pressure (kPa)	2.20E+02	Río [67]
Index of steam consumed (kg steam/kWh)	6.75	Río [67]

Allocation approach

Following ISO-14040 [33], the allocation should be avoided whenever is possible, extending the system's limits to include additional functions related to co-products (valorizing co-products). In the studied system, steam and electricity generation stages are characterized as multi-products systems. For both cases, the extension of system boundaries was applied. Electricity is identified as the main product in the electricity generation stage; meanwhile, the steam flow energy is considered a substitute for the steam production process from fossil-fuel-based (fuel oil). Combustion ash from raw marabou and torrefied marabou combustion is assumed to be a substitute for synthetic phosphorus mineral fertilizer (triple superphosphate, as P2O5) and is considered an avoided product [14, 68, 69].

Life cycle inventory analysis (LCI)

The inventory analysis involves compiling and quantifying inputs/outputs for the product system [33]. Considering the allocation principles, the central assumptions previously described, the mass and energy balances, information available in bibliographic sources, and provided by the Cuban sugar industry to ensure data reliability and validity, was obtained the life cycle inventory. Infrastructure was excluded from this study. Table 5 shows the inventory for the present study (FU: 1kWh). The marabou harvester considered is the self-propelled biomass harvester BMH480 Kangaroo (diesel-fueled) [70], and the exhaust gas emissions are composed of CO₂, NO₂, HC, CO, and PM<10 [71, 72]. The consumption of diesel in the transportation stage is modeled on the data provided by Prinoth [70] and EPA [71]. The specification of this engine is referred to by Caterpillar [73] and the emissions by EPA [74]. Transportation is carried out in all scenarios using Kamaz trucks (diesel-fueled), model 5320 at total capacity (8.00E+03 kg) with a fuel consumption index of 2.40-6.00 L/km (empty-full capacity) [75]. The emissions evaluated in the internal combustion engines of these vehicles are CO₂, CO, volatile organic compounds (VOC), NO₂, SO₂, and PM<10 [72, 76]. For this scenario, the data were gathered from a previous study [41]. The gases from biomass combustion are considered emissions and their compositions are modeled using the methodology proposed by Basu [77].

Table 5. Primary inventory per functional unit (1 kWh of electricity produced in a cogeneration plant using marabou as feedstock).

Inputs/outputs	Scenarios			Unit	Reference
	A-1	A-2	A-3		
Knows outputs to technosphere (Products and co-products)					
Electricity	1.00	1.00	1.00	kWh	Functional unit
Steam	10.17	10.17	6.46	kg	PérezGil, Moya and Domínguez [7]
Knows outputs to technosphere. Avoided product					
Triple superphosphate, as P ₂ O ₅	2.44E-12	1.33E-09	9.92E-11	kg	Pedroso and Kaltschmitt [14]; PérezGil, Moya and Domínguez [7]
Knows inputs from nature (resources)					
Marabou	4.69	3.49	1.85	kg	Alba [41]
Air	30.14	18.05	7.77	kg	Johnson, Mollenhauer and Tschöke [78]; Basu [77]
Water	13.39	14.20	7.76	kg	Baloh and Wittwer [50]; Espinosa, Machado, Reymond, Carrillo and Priadko [48]; Rein [49]
Land occupation	1.26	0.94	0.50	m ² /year	Abreu [18]
Knows inputs from technosphere (materials/fuels)					
Diesel	0.21	0.15	7.93E-02	kWh	Bruzos, Frómeta and Mirabent [75]
Knows inputs from technosphere (electricity/heat)					
Electricity, pellets	0.13	0.48	0.26	kWh	Arteaga, Vega, Rodríguez, Flores, Zaror and Ledón [58], Kaliyan and Morey [79], PérezGil, Moya and Domínguez [7]
Emissions to air					
CO ₂ , fossil	0.33	0.24	0.13	kg	Mollenhauer and Tschöke [72]; Clean-Air-Institute [76]
SO ₂	7.33E-02	5.24E-02	2.77E-02	kg	Johnson, Mollenhauer and Tschöke [78]; Basu [77]; Clean-Air-Institute

					[76]
Water	2.80	1.41	0.68	kg	Johnson, Mollenhauer and Tschöke [78]; Basu [77]
N ₂	20.61	13.88	6.72	kg	Johnson, Mollenhauer and Tschöke [78]; Basu [77]
O ₂	1.17	1.52	0.34	kg	Johnson, Mollenhauer and Tschöke [78]; Basu [77]
CO	9.38E-04	6.98E-04	3.70E-04	kg	Johnson, Mollenhauer and Tschöke [78]; Basu [77]; Clean-Air-Institute [76]
VOC	1.78E-04	1.33E-04	7.05E-05	kg	Johnson, Mollenhauer and Tschöke [78]; Clean-Air-Institute [76]
NO ₂	1.68E-03	1.25E-03	6.63E-04	kg	Johnson, Mollenhauer and Tschöke [78]; Clean-Air-Institute [76]
HC	2.50E-08	1.86E-08	9.88E-09	kg	Johnson, Mollenhauer and Tschöke [78]
PM <10 µm	3.77E-04	2.55E-04	1.34E-04	kg	Johnson, Mollenhauer and Tschöke [78], Arteaga, Vega, Rodríguez, Flores, Zaror and Ledón [58]; Koppejan and Van Loo [80]; Clean-Air-Institute [76]
Emissions to water					
Water	-	8.74E-02	4.54E-02	kg	Alba [41]
Emissions to soil					
Cr	4.96E-06	2.69E-06	1.40E-06	kg	Pedroso and Kaltschmitt [14]
Co	8.12E-07	4.41E-07	2.29E-07	kg	Pedroso and Kaltschmitt [14]
Fe	1.64E-07	8.93E-08	4.64E-08	kg	Pedroso and Kaltschmitt [14]
K	3.19E-09	1.73E-09	9.02E-10	kg	Pedroso and Kaltschmitt [14]
Cu	1.08E-03	5.86E-04	3.05E-04	kg	Pedroso and Kaltschmitt [14]
Li	3.04E-07	1.66E-07	8.61E-08	kg	Pedroso and Kaltschmitt [14]
Mg	1.48E-08	8.06E-09	4.19E-09	kg	Pedroso and Kaltschmitt [14]
Mn	3.59E-	1.95E-	1.01E-	kg	Pedroso and Kaltschmitt [14]

	05	05	05		
Mo	1.06E-05	5.81E-06	3.02E-06	kg	Pedroso and Kaltschmitt [14]
Ni	3.92E-07	2.13E-07	1.11E-07	kg	Pedroso and Kaltschmitt [14]
Si	2.90E-08	1.58E-08	8.21E-09	kg	Pedroso and Kaltschmitt [14]
Sr	1.39E-04	7.57E-05	3.94E-05	kg	Pedroso and Kaltschmitt [14]
Na	2.17E-06	1.18E-06	6.13E-07	kg	Pedroso and Kaltschmitt [14]
Zn	4.14E-09	2.25E-09	1.17E-09	kg	Pedroso and Kaltschmitt [14]
P	5.39E-05	2.93E-05	1.52E-05	kg	Pedroso and Kaltschmitt [14]
S	1.21E-04	6.59E-05	3.42E-05	kg	Pedroso and Kaltschmitt [14]

Results And Discussion

As shown in Fig. 3, FPMF, TA, LU, and WC are the impact categories with harmful burdens for all scenarios. The rest of the categories depicted favorable impacts owing to the environmental benefits of steam and ash. Steam and ash are avoiding impacts from two dimensions. First, the marabou-derived steam reduces the impacts of the steam produced from fossil fuels (fuel-oil in centralized and decentralized thermal power plants), while the ash (avoided product) will reduce the impacts associated with chemical fertilizers (triple superphosphate, as P_2O_5) production chain.

Electricity generation from torrefied marabou pellets in extraction-condensing turbines (A-3) presented the lower environmental impacts in almost all impact categories due to its lower marabou consumption (1.85 kg/kWh), decreasing by 153% and 88% concerning A-1 (4.69 kg/kWh), and A-2 (3.49 kg/kWh), respectively (See Table 5). This performance also implies lower resource (fossil fuel) requirements during all energy-supply chains, particularly in lower land occupation and biomass transport requirements; consequently, lower pollutants emitted to air. Otherwise, A-3 presented the lowest environmental impacts in FPMF due to its higher efficiency reduced the specific particulate matter emissions by 43% (A-2) and 64% (A-1). In addition, the highest efficiency of A-3 is also translated into lower TA impacts due to this generation cycle requires lower amounts of marabou per kWh generated. In A-3 scenario, a lower water/electricity generated index (7.76 kg/kWh) is associated with lower environmental damage, justifying the impact over WC impact category.

The low biomass demand for A-3 can be justified by higher burner efficiency when torrefied biomass is used than raw marabou, which is also related to biomass energy content. Accordingly, the torrefied marabou presented higher LHV (19.14 MJ/kg) than raw marabou (16.24 MJ/kg). Additionally, the cogeneration system used in A-3 is more efficient (extraction-condensing turbine), generating 1.31-2.57 times higher electricity (kWh) per kg of steam than A-2 and A-1 (back-pressure steam turbines). This performance also implies a reduction of water consumption for steam generation, being approximately 42% for A-1 and 45% for A-2.

LU and WC impact categories depicted a different environmental pattern than the others mentioned above. For both impact categories, A-2 shown a higher score than A-1 but lower than A-3. A-2 showed an increment in the harmful impact of 230% compared to A-3 and 392% compared with A-1 (Fig. 3). The higher impacts on LU for A-2 is related to the electricity consumption from lignocellulosic biomass, flow with the higher harmful contribution. The consumption of lignocellulosic biomass to generate electricity is associated with soil damage and species loss due to its use to obtain lignocellulosic feedstock. This behavior is caused by the intensive forest occupation necessary for wood chips harvesting to generate electricity [81]. It is referred that the agricultural stage (mainly cultivation) dominated LU over 95% except in Agricultural land occupation, and the rest belongs to the industrial stage [37].

It is described the beneficial impact of marabou as an invasive tree with energy purposes compared to energy crops over the soil, like this tree is required to avoid erosion and degradation of the area with the maintenance of organic matter [82-84]. Agricultural yield and biomass heating value influence are the leading causes of this performance. Compared with other energy crops, such as *Salix miyabeana* (50-72 dry t/ha [85]), *Casuarina equisetifolia* (9.63 dry t/ha [86]), *Leucaena leucocephala* (33.82 dry t/ha [87]), and *Gliricidia sepium* (8.13 dry t/ha [87]), marabou showed high agricultural yield (up to 89 dry t/ha [19]).

Regarding biomass heating value, marabou exhibit an LHV of 16.24 MJ/kg [23], lower compared with *Casuarina equisetifolia* (18.49 MJ/kg [88]), but higher compared with *Salix miyabeana* (up to 10.01 MJ/kg [85]), and *Leucaena leucocephala* (14.30 MJ/kg [87]). *Gliricidia sepium* (16.10 MJ/kg [87]) presented a similar value. Evidence suggests that an increase in biomass LHV impacts LU beneficially due to the low land requirement per energy unit [89] and the low moisture content in marabou. McNamee, Adams, McManus, Dooley, Darvell, Williams and Jones [90] suggested LU is proportional with a caloric value of biomass, but this behavior is minimized by increasing the caloric content of torrefied biomass itself. For that reason, LU needs to be optimized to be competitive with other typical energy crops, considering the limitation of this resource.

Regarding WC, A-2 performed the worst environmental profile, showing an increment in the harmful impact by 7% compared to A-1, and 48% compared with A-3 (Fig. 3). The significant impact of WC on biomass cogeneration systems is well known since liquid consumption is not considered in biomass agricultural activities [91, 92]. The cogeneration system showed the higher impacts for all scenarios (100% in A-1 and up to 87% in A-2, and A-3), linked directly to freshwater input for steam generation. The

rest corresponds to cooling water after the torrefaction stage, which is necessary to avoid torrefied biomass auto-combustion and improve its handling in further stages.

A-1 consumed 6% less water than A-2, due to the consideration of the combustion of raw marabou without the torrefaction stages, including the cooling stage. The efficient technology (extraction-condensing turbines) plays an important role in reducing water consumption compared to A-2 (back-pressure steam turbines) by 46%. This result is supported by an increase of 22% in steam generation and a reduction by 31% of the steam consumption index (kg steam/kWh), reducing marabou consumption per electricity generated. This performance involves a reduction in land use and diesel consumption in harvest and transportation stages. Besides, a reduction in resource requirements (water and air) is expected. The torrefied marabou cogeneration depicted a better environmental profile than raw marabou cogeneration due to improved energy marabou properties (LHV) and a high-efficient steam power cycle, contributing to reduce the environmental burdens.

Wang, Lei, Yang, Li, Qi, Xin, He, Ajayebi and Yan [37] showed significantly impacted water depletion even when decreasing energy consumption in briquette fuel production compared to other scenarios. Besides, Guerra, Coleta, Arruda, Silva and Kulay [93] affirmed that implementing a reheat-regenerative steam power cycle at $6.70E+03$ kPa could decrease the water consumption by 18% compared to the conventional steam power cycle at working at the same pressure. In this regard, importance should be remarked to an efficient water supply system to reduce the water consumption of biomass-based cogeneration systems.

Normalized midpoint results for the three scenarios are displayed in Fig. 4. The negative values of impact categories mean an environmental benefit, and it is associated with avoided products. Furthermore, while more negative is the impact values, higher are the benefits. Based on that, the A-1 registered the best environmental performance on ecotoxicities (terrestrial, freshwater and marine), human toxicity (carcinogenic and non-carcinogenic) and fossil resources scarcity (FRS). In this case, MET depicted the best environmental performance due to inorganic mineral fertilizer substitution by ashes from the marabou combustion process, avoiding the emissions of heavy metals to the ocean (mostly cobalt, copper, manganese, molybdenum, and zinc). In this case, A-1 depicted a higher beneficial impact than A-2 (12%) and A-3 (66%), justified by substituting steam generated by centralized and decentralized thermal power plants and triple superphosphate. These results suggest that the worse alternative from the energy efficiency perspective presented the higher environmental benefit.

Nevertheless, these results would be confusing because it expected a better environmental profile for a more energy-efficient alternative. Accordantly, the methodological assumptions made in the present study, particularly the substitute process of ashes (triple superphosphate), significantly influenced the environmental performance. A-3 in all impact categories reported the lower beneficial environmental impacts. More detailed results about the impact categories with harmful impacts are described below.

The most significant contributions to TA are associated with the emissions of inorganics (SO_2 (97%); NO_2 (2.20%), and to a lesser extent VOC (0.23%)). The emitted gases in marabou and torrefied marabou

combustion followed by diesel combustion presented the main environmental burdens. This is related to SO₂ emissions, caused mainly by the presence of sulfide in marabou and torrefied marabou (assumed 5.00E-02 kg and 1.75E-02 kg for marabou and torrefied marabou, respectively) [94]. Similar results have been found by Wang, Lei, Yang, Li, Qi, Xin, He, Ajayebi and Yan [37], where higher impacts are reported on TA related to the industrial stage.

Sulfur content in biomass is related to the sowing site, the genetic material used, the interaction between the environment and the genotype, arranging, and age [95]. Despite the influence in sulfurous emissions, the sulfur content in marabou indicates that it can be used in the cogeneration process, saving more than 90% of SO₂ emissions than coal-burning [96]. This suggests that sulfur composition in biomass is critical for reducing global SO₂ emissions in cogeneration systems. Furthermore, positive impacts are achieved when biomass torrefaction is considered, releasing smaller amounts of sulfur [97].

Despite the beneficial role of ashes on soil, improving nutrient cycling, and avoiding mineral fertilizers consumption [98], soil pH changes could be expected. This performance is closely related to high Ca, K, Mg, and P in ash concentration, leading to increased soil pH concentration [99], impacting harmfully in basic lands, and reducing metal availability [100].

According to the emissions of NO₂, transportation is the primary source. A combination of sulfide and nitrogen emissions could increase the forest's probability of acid rains, raising tree mortality [101, 102]. However, these substances may impact the soil depending on its status, neutralized by buffer reactions [103].

A-1 showed the worst environmental performance, with an increment in the harmful impact of 87% and 183% compared to A-2 and A-3, respectively. The cogeneration, harvesting and transportation stages are critical in this impact category. The highest environmental impacts are associated with particulate matter emissions from biomass combustion and liquid fuel combustion (diesel) [104]. However, the cogeneration stage contributed the most over this impact category, presenting almost 97% of the total. The rest of the stages made negligible contributions. This result is supported by PérezGil, Moya and Domínguez [7], who affirmed that particulate matter in bagasse cogeneration systems is one of the most significant harmful impacts on the environment. Similar results have also been reported by Proto, Bacenetti, Macri and Zimbalatti [105], and Pfeffer, Schuck and Breuer [106]. The evidence suggests that the increase in caloric value between A-1 and the scenarios using torrefied marabou as feedstock (A-2 and A-3), has a beneficial effect on this impact category, reducing more than 7% the emission on particulate matter. In addition, reducing particulate matter emission is related to compacted biomass [107]. Special attention needs to be focused on the technology used and the operational conditions [108], applying strategies oriented to optimizing the biomass combustion process with exhaust gas cleaning processes.

Analysis of the LCI by damage categories

ReCiPe allows converting midpoints to endpoints simplifying the interpretation of the LCA results. Endpoint impact categories or damage categories "Human health", "Ecosystem" and "Resources" were analyzed. According to the previous analysis, the environmental impacts of A-3 as the best scenario were evaluated, quantified according to the single score (mPt) for the damage categories. For a better understanding and considering the stages in Fig. 1, an arrangement by subsystems was made at this point: agricultural subsystem includes harvesting and transportation stages, torrefaction subsystem includes torrefaction, cooling, densification stages, and cogeneration subsystem includes steam and electricity generation stages (Fig. 5).

The electricity generation using torrefied marabou in torrefaction subsystem contributes to the higher environmental burdens to Human health, showing impacts over 94% of the total of this subsystem. The emissions of PM_{<10}, NO₂, and SO₂ affect the most over this damage category, mainly in torrefied marabou combustion, an issue discussed above, causing injuries in respiratory systems by aspiration of organic compounds [7]. However, it is affirmed that despite the high emissions of these pollutants, large-scale electricity generation plants produce proportionally less environmental impact compared to conventional wood stoves and open fireplaces [108].

Ecosystems were identified as a second affected damage category negatively, with a contribution of 6% to the torrefaction subsystem. TA impacts the most over this damage category due to the emissions of SO₂ and NO₂. Meanwhile, the negligible environmental contribution on Resources damage is despited for torrefaction subsystem.

There are reported beneficial impacts of the cogeneration subsystem on the Human health damage category (87%). This performance is due to the steam generated using renewable sources and delivered to process evaluated as an avoided product. Similar behavior is depicted for the ecosystem damagen category, influenced strongly by the valorization of combustion ashes, replacing synthetic inorganic mineral fertilizer. Diesel consumption contributes the most to Human Health (67%) and Resources (27%) in the agricultural subsystem, caused by the use of fossil fuel and its relation to anthropogenic emissions (CO₂, CO, COV, NO₂, SO₂, and PM_{<10}).

The torrefaction subsystem presented the most remarkable environmental burdens, being the Human health the highest score. The cogeneration subsystem has a beneficial performance in all damage categories, mainly by substituting steam produced with fossil fuels by renewable energy and the valorization of combusted ashes.

Limitation of the present study

The main limitations of the current study are presented below:

- i. Emission factors to air from biomass combustion are associated with impact categories, so a variation of these implies significant impacts on the environmental profile. The air emission factors for cogeneration are considered equals for both studied technologies (back-pressure steam turbine

and extraction-condensing turbine). In this study, the PM₁₀ emission factor for marabou and torrefied marabou combustion was considered the same (3.92E-06 kg/MJ biomass), and referred by Arteaga, Vega, Rodríguez, Flores, Zaror and Ledón [58]. However, lower impacts are expected in Fine Particulate Matter Formation, since studies carried out by Mitchell, Lea-Langton, Jones, Williams, Layden and Johnson [109] suggested that biomass torrefaction generates fewer impacts in approximately 40% than raw biomass. This is caused by the difference in the soot formation mechanism of raw marabou and torrefied marabou.

- ii. Sugarcane mills produce with improvements in agricultural yield, a sugarcane bagasse surplus of around 37% [3], which blended with marabou, a reduction in fuel-oil consumption be reduced to generate electricity from the National Grid. The present study was considered the only marabou fuel in back-pressure steam turbines and extraction-condensing steam turbines as leading cogeneration technologies. These technologies use as typical fuel sugarcane bagasse. However, the marabou and bagasse blend could be an attractive alternative to increase electricity generation during the non-harvesting period. Studies reported by Sanchez [110] highlighted the benefits of marabou and bagasse co-combustion, in particular, avoiding some technical issues such as reduction in burning efficiency, slag deposition in steam generation stage, and increase in fuel compactness. Besides, the substitution of bagasse use reported a decrease in harmful impacts to impact categories, such as fossil fuels, climate change, and respiratory effects of inorganics compounds. This behavior is due to the associated effects of extraction, processing, and consumption of fossil fuels (diesel) [7]. Eutrophication/acidification impact categories also could be improved due to the fertilizer and pesticide reduction in the agricultural subsystem.
- iii. The energy source in torrefaction (raw marabou combustion) could play an essential role in reducing emissions associated with biomass combustion. Global warming potential is identified as the impact category that benefited the most from using renewable sources. A study developed by Christoforou and Fokaidis [111] affirmed that replacing raw biomass with solar energy could reduce by 17% the potential global warming emissions (CO₂ equivalent/t biomass).
- iv. Electricity consumption in torrefied marabou densification implies around 40% of the total electricity consumption. A decrease in the environmental impacts is expected when a reduction in densification occurs. Li, Mupondwa, Panigrahi, Tabil and Adapa [112] analyzed different electricity consumption in the pelletizing process of torrefied biomass. The authors obtained a better environmental performance for freshwater aquatic ecotoxicity (35%), and photochemical oxidation (22%) when electricity input is reduced by 40%.
- v. Energy advantages are reported by Abreu [18] when parameters like residence time and temperature increase for marabou torrefaction. In that study, a carbon mass fraction of 0.67 was obtained for temperature and residence time of 290 °C and 120 min (the present study was evaluated at 280 °C and 60), which means a higher caloric value, but a considerable total mass reduction (leaving torrefaction stage as volatile gas). However, McNamee, Adams, McManus, Dooley, Darvell, Williams and Jones [90] showed beneficial impacts on climate change when temperature increases by 9.65%, reducing total emissions by 20% (gCO₂ equivalent/MJ electricity). Severe torrefaction conditions

have to be assessed in further studies due to their impacts on land requirements and transportation costs.

Conclusion

Marabou could be considered as an alternative to increasing energy cogeneration in a renewable way. The present study gives detailed results about the environmental profiles of different scenarios in the electricity cogeneration process from marabou in the Cuban sugarcane industry. Generally, for electricity cogeneration in sugarcane mills from marabou, cradle-to-gate environmental impacts are negatively affected by Terrestrial Acidification, Fine Particulate Matter Formation, Land Use, and Water Consumption relative significance. The first score was relatively the most harmful for all scenarios, followed by Fine Particulate Matter Formation, which was the impacts attributable to the emission of NO₂, SO₂, and PM_{<10} in all subsystems in the study. The rest of the impact categories impact beneficial. A-1 performed the worst in Fine Particulate Matter Formation and Terrestrial Acidification; however, the better environmental performance was beneficial except in Global Warming, Ionizing Radiation, and Fossil Resource Scarcity. In Land Use and Water Consumption, A-2 was a higher harmful impact. Despite A-3 has the worst performance in beneficial impact categories, it shows better performance in harmful impact categories. Marabou cogeneration stage was the main contributor to the environmental burdens in Water Consumption (100% in A-1; 87% in A-2 and A-3). Via damage categories analysis, Human health damage category reached the higher impacts on the torrefaction subsystem in A-3 scenario, representing over 94% of the total environmental burden of the process. PM_{<10}, NO₂, and SO₂ contributed the most over this damage category, mainly in marabou combustion, causing injuries in respiratory systems by aspiration of organic compounds. Beneficial impacts are reported on the cogeneration subsystem due to the steam and ash valorization, considered both as avoided products. These results can be considered to support the Cuban government's projections for electricity generation using marabou as fuel.

Declarations

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Authors' contributions Yasmani Alba-Reyes: Investigation-writing-original draft preparation. Maylier Pérez-Gil: Writing-original draft preparation-supervision-reviewing. Ernesto L. Barrera: Writing-reviewing. Yannay Casas-Ledón: Supervision-reviewing. Luis E. Arteaga-Pérez: Conceptualization-supervision-reviewing.

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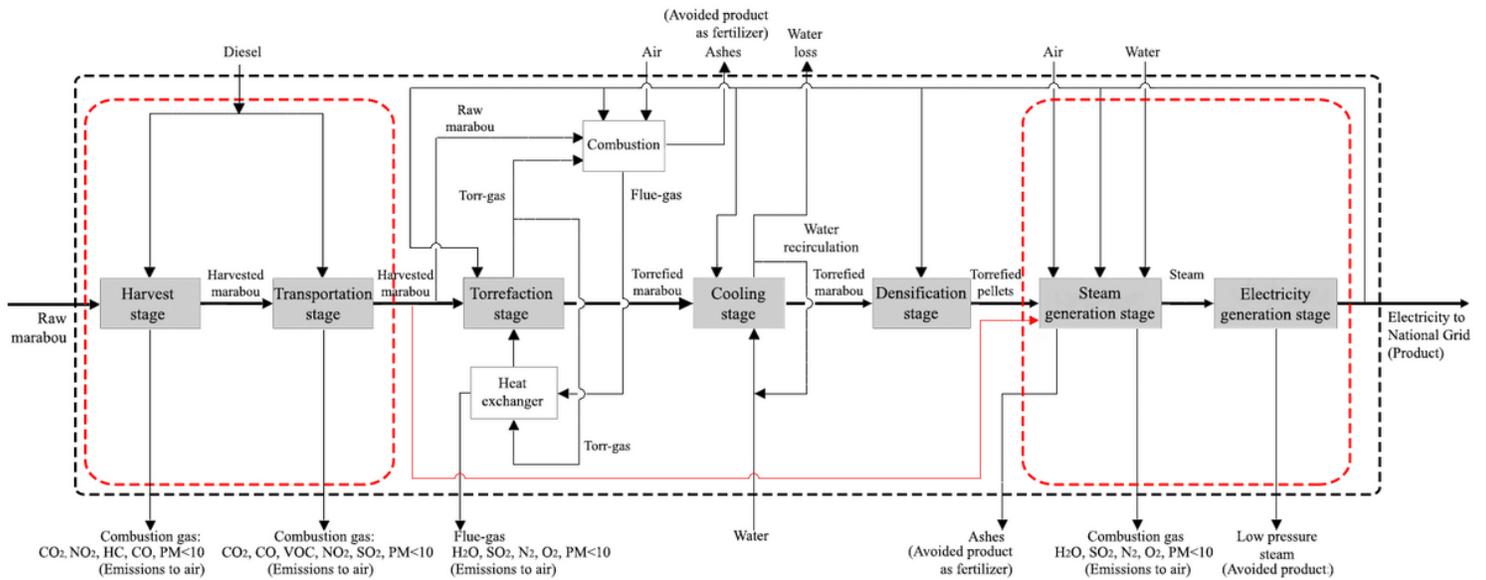
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Figures



A-1: Considered only Harvest, Transportation, Steam and Electricity generation stages (back-pressure steam turbine)

A-2: Considered Harvest, Transportation, Torrefaction, Cooling, Densification, Steam and Electricity generation stages (back-pressure steam turbine)

A-3: Considered all stages as same as A-2, only Steam and Electricity generation stages change operational parameters (extraction-condensing turbine)

Figure 1

System boundaries for the cogeneration from marabou in a sugarcane mill.

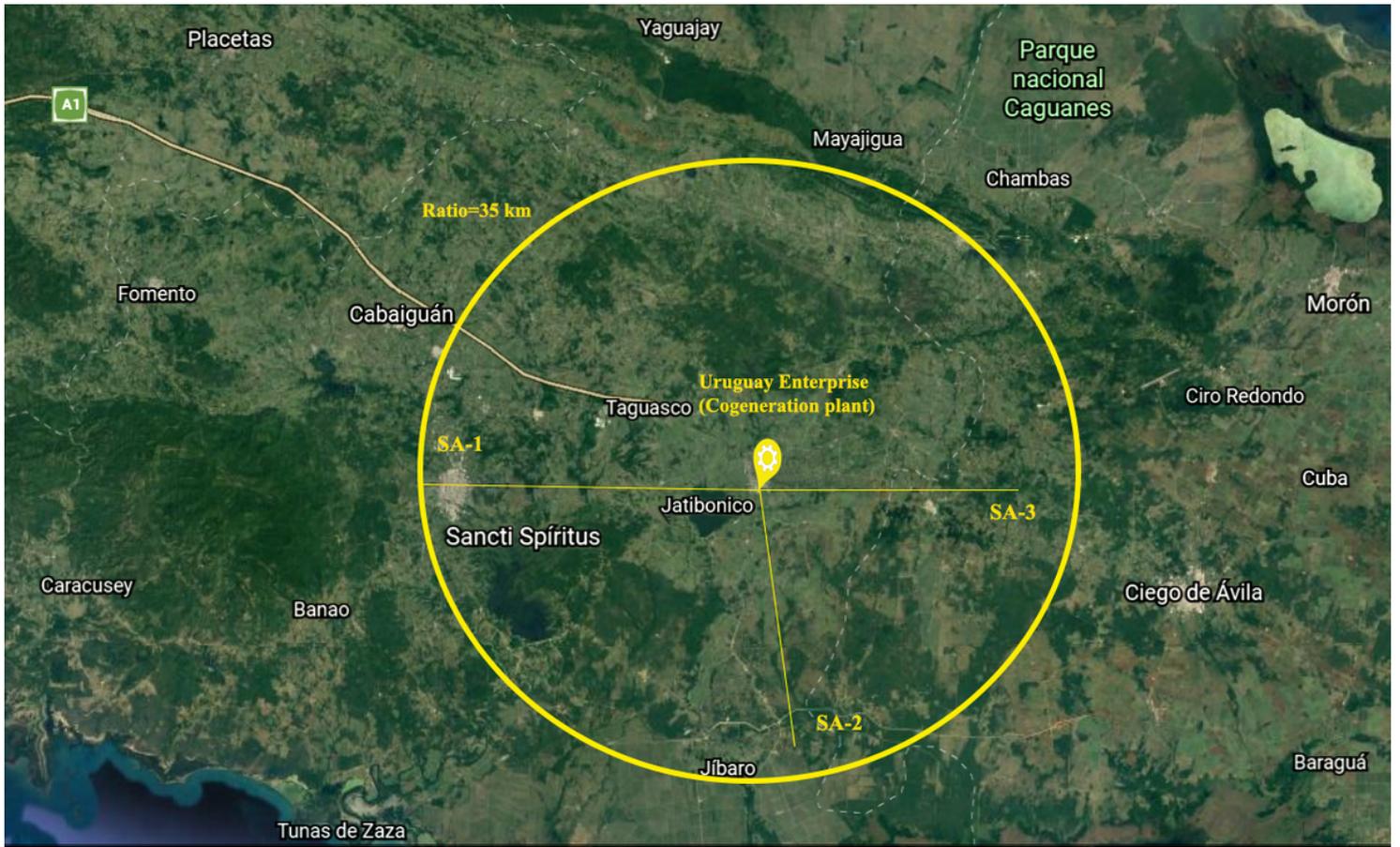


Figure 2

Supply Areas (SA) and the cogeneration plant (Sancti Spiritus province).

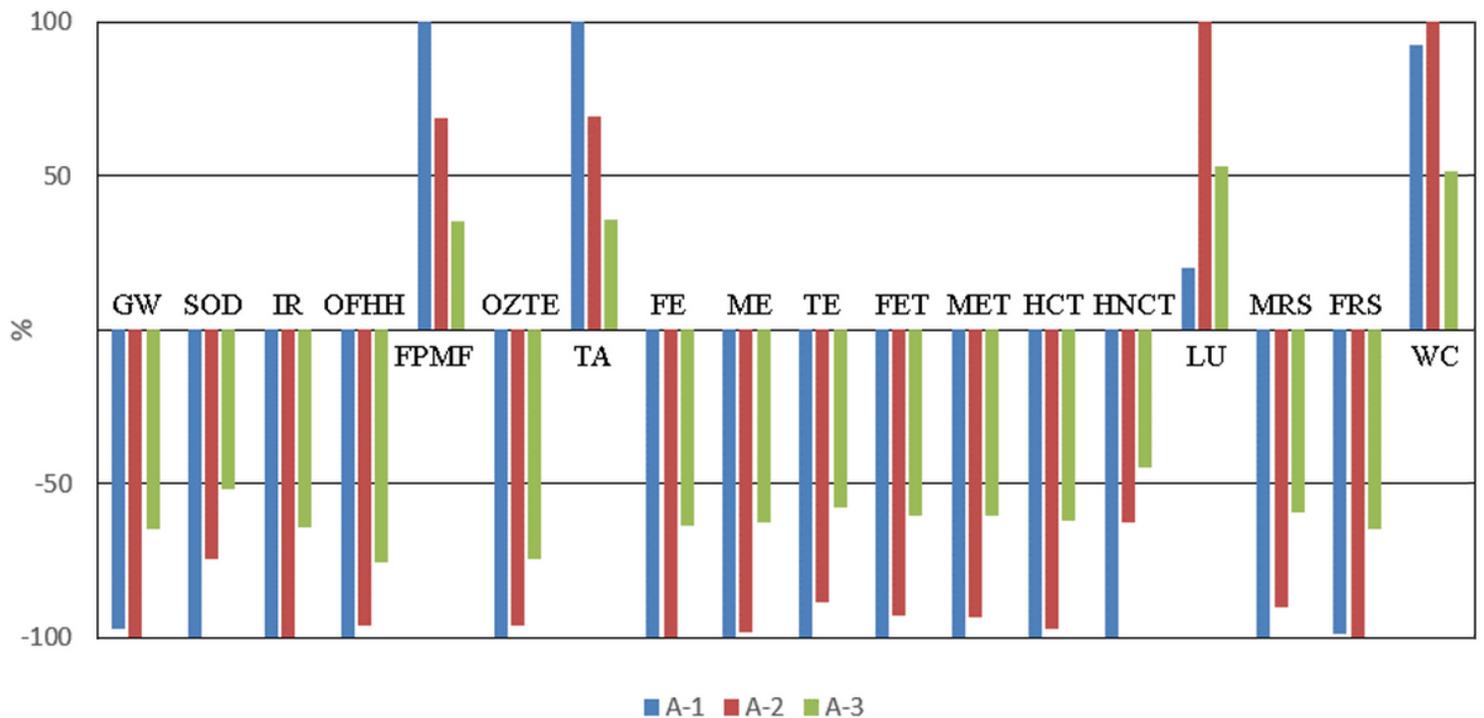


Figure 3

Environmental profile by impact categories/characterization for A-1, A-2, and A-3 scenarios. Global Warming (GW), Stratospheric Ozone Depletion (SOD), Ionizing Radiation (IR), Ozone Formation, Human Health (OFHH), Fine Particulate Matter Formation (FPMF), Ozone Formation, Terrestrial Ecotoxicity (OZTE), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TE), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET), Human Carcinogenic Toxicity (HCT), Human Non-Carcinogenic Toxicity (HNCT), Land Use (LU), Mineral Resource Scarcity (MRS), Fossil Resource Scarcity (FRS), and Water Consumption (WC).

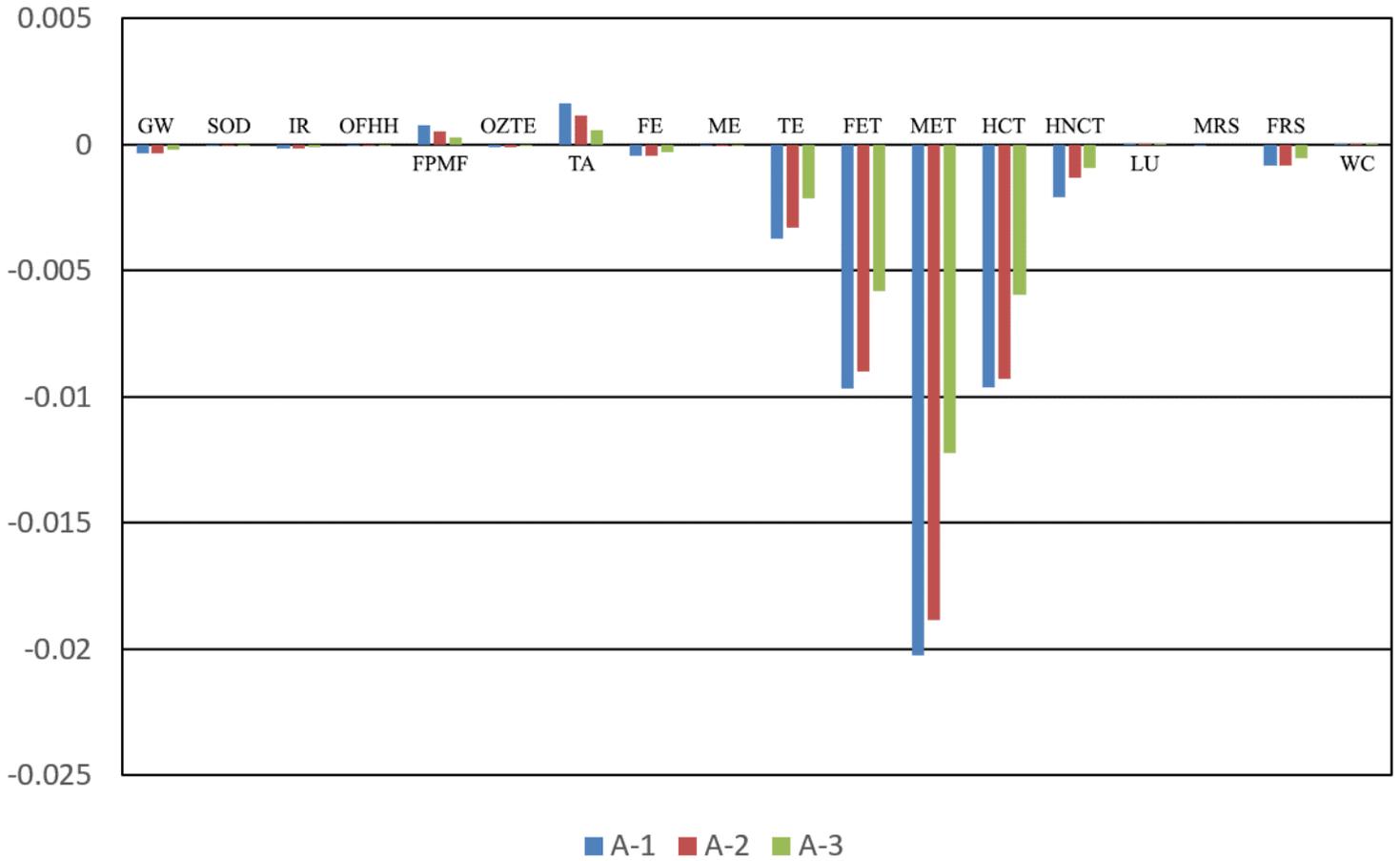


Figure 4

Environmental profile by impact categories (normalization).

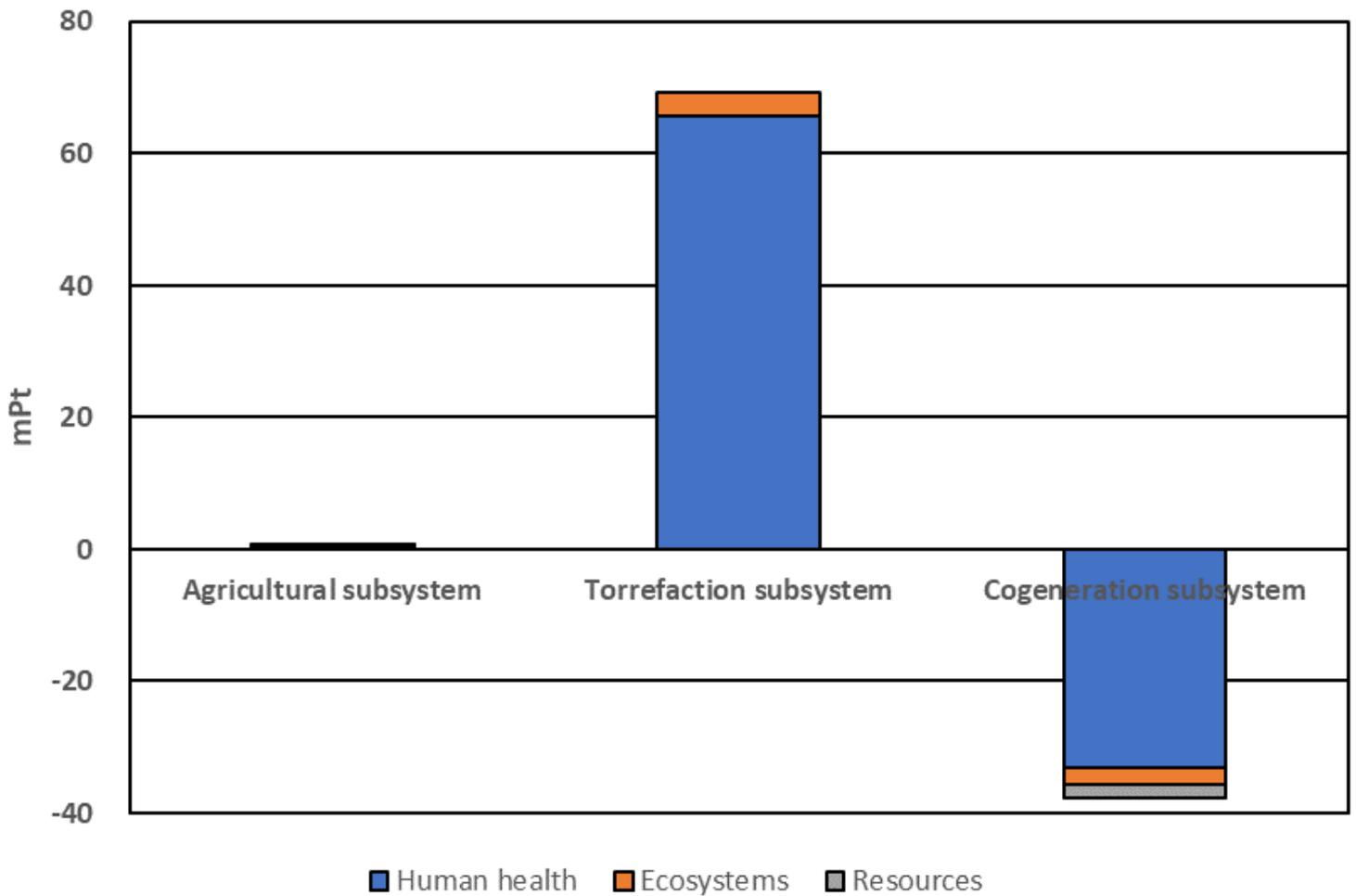


Figure 5

Contribution for each life cycle subsystem (Agricultural, Torrefaction, and Cogeneration subsystems) to total impact by damage categories (single score) in A-3.

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