Evaluation of environmental sustainability of biorefinery and incineration with energy recovery based on life cycle assessment

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Supplementary Material

Nomenclature

A	outside area of an equipment with an L/D ratio of 3 and a factor of free head space in the bioreactor
A_{bottom}	bottom area
A_{side}	side area
A_{top}	top area
BBL	barrels
BRF	biorefinery
CCCPP	combined cycle cogeneration power plant
c_p	specific heat capacity
D	tank diameter
DC	developed country
DCBe	dichlorobenzene equivalent
DingC	developing country
E	enzymes
ES	environmental sustainability
ESP	electrostatic fly ash precipitator
$f_{conditioning}$	is a factor that reflects any increase of the m_{FU} by dilution, pH and alkalinity adjustment
Fn	factor of normalization, used to calculate the NPEI from PEI
FP	fine particle
FU	functional unit
FW	fermented wastes
FWEc	freshwater ecotoxicity
FWEu	freshwater eutrophication
GBAER	Environmental Biotechnology and Renewable Energies Group
GHG	greenhouse gas effect
GW	global warming
H	hydrogen
HCT	human carcinogenic toxicity
HNCT	human non-carcinogenic toxicity
IER	incineration with energy recovery
L	tank height
Let N	number of FU/d
L/D	height per diameter
LCA	life cycle assessment
LCI	life cycle inventory
LU	land use

M	methane
m'_a	actual mass flowrate in the equipment or process, based on Γ_{FU} and variations due to conditioning, material additions, and removals/degradation
m_a	actual mass after the m_{FU} has been modified by conditioning, other
ME	marine ecotoxicity
MEu	Marine eutrophication
m_{FU}	mass associated to the Functional Unit
MSW	municipal solid waste
N	number of functional units per day
N_{EVT}	N° of NPEI in REFT higher than EVT, or equivalently, No of NPEI in EVT that are lower than the corresponding NPEI in REFT
NN	bionanobioparticles
NPEI	normalized potential environmental impact
N_{REFT}	N° of NPEI in EVT higher than REFT, or equivalently, No of NPEI in REFT that are lower than the corresponding NPEI in EVT
NSCR	non-selective catalytic reduction
NSCR	non-selective catalytic reduction
OFH	ozone formation, human health
OFMSW	organic fraction of municipal solid waste
OFTE	ozone formation terrestrial ecosystems
PEI	potential environmental impact
PET	terephthalate - polyethylene
PHA	polyhydroxyalkanoate
P_{mixing}	power consumed by the recirculation pump, in W,
POI	photochemical ozone impact
Q	heat load in actual (scaled) conditions
q_{FU}	heat load per functional unit
S	saccharified liquors
SCR	selective catalytic reduction
SM	supplementary material
SMR	scarcity of mineral resources
SOD	Stratospheric ozone depletion
StB	Scum-to-Biodiesel technology
t	1 day time of operation, in seconds, i.e., 86400 sec/d
TA	terrestrial acidification
T_{amb}	is the ambient (or environment) temperature, K or ^oC,
T_H	is the operation temperature in the bioreactor, K or ^oC,
T_i	is an intermediate temperature of the feedstock
TIC	total investment cost
TS	total solids
U	unit load of environmental impact per person and per year (in units of the characterization environmental impact times yr per person)
U	in heat transfer issues, U represents the overall heat transfer coefficient, typically in W/(m*K)
UOW	urban organic waste
VAPs	value added products

VOA	volatile organic acids
$\forall_{geometric}$	geometric volume of a bioreactor or tank
$\forall_{w}$	working volume of a bioreactor or tank
$\forall'$	volumetric flowrate, typically in m^3/s or m^3/d
$\forall'_{recirculation}$	recirculation volumetric flowrate
$\forall'_{feed}$	feed volumetric rate
WC	water consumption
WWTP	wastewater treatment plant
Y	generic yield, in mass of a product or amount energy per entering unit
$Y_{H2/FU}$	example of Y, in mass of hydrogen harvested per functional unit

Greek characters

α	sum of the normalized environmental impacts of a given technology, in (person*yr/FU)
α_R	recirculation ratio, $\alpha_R = \forall'_{recirculation}/\forall'_{feed}$
β	Power intensity of mixing, $P_{mixing}/\forall$
Γ	Capacity
Γ_a	Actual capacity of a process or stage in a biorefinery, in terms of actual mass fed, t/d or kg/h
Γ_{FU}	Capacity of a process or stage in a biorefinery, in terms of functional unit mass fed, t/d or kg/h
γ	Specific investment cost, in USD/t waste or biomass fed
Δ	increase or decrease of the magnitude
ΔH^o	standard enthalpy change (of evaporation, combustion, or reaction, etc.)
ΔP	total head of a pump expressed in pressure units, Nt/m^2
δ	correction for the different dry matter contents
ε_{FU}	Electricity flow per FU, in kWh/FU
η	efficiency
η_{pump}	efficiency of the pump (hydraulic efficienty, decimal number between 0 and 1)
η_{motor}	efficiency of the electrical motor (decimal number between 0 and 1)
θ	mass retention time of a continuous process in steady state, typically in d
θ_{batch}	incubation time in a batch process
ρ	is the density of m_a, in kg/m^3 or t/m^3
σ	GBAER sustainability index related to the quantitative comparison of the environmental sustainability between two technologies,
ξ	Complexity of the biorefinery, low 1 to 2 bioenergy or products, degree 2.5; medium or moderate 3 to 5 bioenergies or products, degree 5.5: high 6 or higher bioenergies or products, degree 9; degrees normalized in a scale 1 to 10
τ	GBAER sustainability index related to the restrictions to the environmental sustainability in the comparison of two technologies
ϕ	correction for different reference flows

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Annex S1. LCI SimaPro from Biorefinery HMEZS-NN

2 **Table S1.1. LCI Biorefinery HMEZS-NN (1/6) Sima PRO** (PRé, 2019).

OFMSW	1000	kg			
Input	**Quantity**	**Unit**	**F l o w**	**Database**	**Observations**
Paper waste	400	kg	-	-	According to Escamilla-Alvarado et al. (2017)
Organic waste	600	kg	-	-	

STAGE FORSU conditionation	3250 kg				
Input	**Quantity**	**Unit**	**Flow**	**Database**	**Observations**
OFMSW	1000	kg		Created	
Wastewater	2123.47	kg	Tap water {RoW}| tap water production, conventional treatment | Cut-off, U	Ecoinvent 3	This must be placed in Outputs known to the technosphere. Products avoided, since using Wastewater avoids the use of tap water.
P2O5	55.5	kg	Phosphate ore	-	Contained in P2O5, possibly the Quantity of mineral/salt is triple, depending on the phosphate chemical species and the impurities.
NaHCO3	71.03	kg	Sodium bicarbonate {RoW}| soda production, solvay process | Cut-off, U	Ecoinvent 3	
Electricity	4.44	kWh	Electricity, high voltage {MX}| production mix | Cut-off, U	Ecoinvent 3	This Electricity is what is required for do the mixing
Mixing plant	0.65	kg	Industrial machine, heavy, unspecified {GLO}| market for | Cut-off, U	Ecoinvent 3	This was adjusted to what was marked for the process Plaster Mixing {RoW}processing/Cut-off,U

STAGE H

Solids production (FW)	3161.14	kg	Fermented waste. This stream will have a split and 40% enters Stage M, while 60% enters AOV and SOLV extraction.
Biogas production H	88.86	kg	Biogas with H2. This current will enter the BG-H purification stage as is. The allocation should be 30%, but perhaps the allocation by price raises the allocation value since H2 is more expensive than a stream of fermented semisolids.

Input	**Quantity**	**Unit**		**Database**	**Observations**
Electricity	4.42	kWh	Electricity, high voltage {MX}| production mix | Cut-off, U	Ecoinvent 3	It is energy due to mixing and pumping. Taken from conditioning but should be reviewed.
Heat	420.5	MJ	Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U	Ecoinvent 3	It represents 60% recovery for the Heat sensitive and is used to preheat the feed to the H reactor.
Anaerobic digestion plant	2.71E-06	p	Anaerobic digestion plant, for biowaste {GLO}| market for | Cut-off, U	Ecoinvent 3	
Machine operation time	0.5722	h	Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| machine operation, diesel, >= 74.57 kW, low load factor | Cut-off, U	Ecoinvent 3	
Output	**Quantity**	**Unit**		**Database**	**Observations**
Carbon dioxide, biogenic	0.59	kg	Carbon dioxide, biogenic	-	
Dinitrogen monoxide	0.0544	kg	Dinitrogen monoxide	-	
Hydrogen sulfide	0.1456	kg	Hydrogen sulfide	-	
Hydrogen	1.08E-04	kg	Hydrogen	-	
Ammonium, ion	1.51E-04	kg	Ammonium, ion	-	
Nitrate	4.83E-03	kg	Nitrate	-	
Nitrite	1.51E-04	kg	Nitrite	-	
Nitrogen, organic bound	1.09E-07	kg	Nitrogen, organic bound	-	
Phosphorus	1.14E-04	kg	Phosphorus	-	
Wastewater	2.00E-02	m^3	Wastewater, average {RoW}| market for wastewater, average | Cut-off, U	Ecoinvent 3	

Table S1.1. (cont.) LCI Biorefinery HMEZS-NN (2/6)

Biogas purification H (Hydrogen 99%) 1.71 kg

Some data were taken from a Purification plant methane at 96% Methane, 96% by volume {RoW}| biogas purification to methane 96 vol-% | "Cut-U"

Input	Quantity	Unit		Database	Observations
Purification plant	1.85E-08	p	Chemical factory, organics {GLO}| market for	Cut-off, U	Ecoinvent 3	It is calculated based on the Quantity of biogas that enters and according to the methane purification model.
Electricity	22.93	kWh	Electricity, high voltage {MX}| production mix	Cut-off, U	Ecoinvent 3	Alternating current, high voltage, Mexican conditions. Required for purification with the adsorption method by alternating pressure changes.
Output	**Quantity**	**Unit**		**Database**	**Observations**
Carbon dioxide	78.36	kg	Dioxide carbon	-	It could be biogenic CO2 because it comes from biomass.
Hydrogen sulfide	0.95	kg	Hydrogen sulfide	-	

Electricity production (PEM)

40.25 kWh Electricity, low voltaje

Input	Quantity	Unit		Database	Observations
Fuel cell	2.33	p	Fuel cell, polymer electrolyte membrane, 2kW electrical, future {RoW}| production	Cut-off, U	Ecoinvent 3	It was calculated based on an ecoinvent PEM adjusted to our process
Membrane maintaintment	3.26E-03	p	Maintenance, polymer electrolyte membrane fuel cell, 2kW electrical {RoW}| maintenance, polymer electrolyte membrane fuel 2cell 2kW electrical	Cut-off, U	Ecoinvent 3	Idem
Plant storage	1.64E-04	p	Storage, 650 l mini CHP plant {RoW}| production	Cut-off, U		
Output	**Quantity**	**Unit**		**Database**	**Observations**
Carbon monoxide	4.79E-04	kg	Carbon monoxide, biogenic	-	
Hydrogen	1.12E-03	kg	Hydrogen	-	
Nitrogen oxides	3.65E-04	kg	Nitrogen oxides	-	
NMVOC	8.41E-05	kg	NMVOC, non-methane volatile organic compounds, unspecified origin	-	
Particles	5.59E-08	kg	Particulates, < 2.5 um	-	

STAGE M

Biogás production M 133.74 kg

This current will enter Stage BG-M purification and production of electrical energy as is. The mass allowance should be 3%.

Input	Quantity	Unit		Database	Observations
Electricity	8.84	kWh	Electricity, high voltage {MX}| production mix	Cut-off, U	Ecoinvent 3	It is energy due to mixing and pumping. Taken from conditioning
Heat	70.42	MJ	Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler modulating >100kW	Cut-off, U	Ecoinvent 3	It represents 60% recovery of sensible heat and is used to preheat the feed to reactor H. In addition, it includes heat lost to the environment in the reactor and auxiliary facilities.
Anaerobic digestion plant	9.50E-07	p	Anaerobic digestion plant, for biowaste {GLO}| market for	Cut-off, U	Ecoinvent	
Machine operation time	0.2	h	Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| machine operation, diesel, >= 74.57 kW, low load factor	Cut-off, U	Ecoinvent 3	
Output	**Quantity**	**Unit**		**Database**	**Observations**
Digested solids (DW)	200	kg	Municipal solid waste {RoW}| treatment of, sanitary landfill	Cut-off, U	Ecoinvent 3	This stream can be sent to an external compost plant and share impacts
Wastewater (licor)	932.7	kg	Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste wat		This current can be sent to conditioning
Dinitrogen monoxide	0.0191	kg	Dinitrogen monoxide	-	
Hydrogen sulfide	0.051	kg	Hydrogen sulfide	-	
Methane, biogenic	5.75E-01	kg	Methane, biogenic	-	
Ammonium, ion	5.28E-05	kg	Ammonium, ion	-	
Nitrate	1.69E-03	kg	Nitrate	-	
Nitrite	5.28E-5	kg	Nitrite	-	
Nitrogen, organic	6.20E-05	kg	Nitrogen, organic bound	-	
Phosphorus	4.01E-05	kg	Phosphorus	-	
Wastewater	7.00E-03	m^3	Wastewater, average {RoW}| market for wastewater, average	Cut-off, U	Ecoinvent 3	

Table S1.1. (cont.) LCI Biorefinery HMEZS-NN (3/6)

Purificación biogás M (Metano 96%) 49.86 kg

Some data was taken from a Purification plant methane at 96%. Methane, 96% by volume {RoW}| biogas purification to methane 96 vol-% | Cut-off, U.

Input	Quantity	Unit		Database	Observations
Purification plant	3.22E-10	p	Chemical factory, organics {GLO}| market for	Cut-off, U	Ecoinvent 3	It was calculated according to the Quantity that enters purification taking the Ecoinvent proxy as a model.
Electricity	36.58	kWh	Electricity, high voltage {MX}| production mix	Cut-off, U	Ecoinvent 3	Alternating current, high voltage, Mexican conditions.
Output	**Quantity**	**Unit**		**Database**	**Observations**
Carbon dioxide	69.51	kg	Dioxide carbon	-	It could be biogenic CO2 because it comes from biomass.
Hydrogen sulfide	0.74	kg	Hydrogen sulfide	-	

Electricity production CCCPP	407.31 kWh	
Heat production CCCPP	681.51 MJ	

Input	Quantity	Unit		Database
Cooling wáter	24.69	m^3	Water, cooling, unspecified natural origin, RoW	-
Planta de ciclo combinado	7.74E-04	p	Gas power plant, combined cycle, 400MW electrical {GLO}| market for	Cut-off, U	Ecoinvent
Soft wáter	23.23	kg	Water, completely softened, from decarbonised water, at user {GLO}| market for	Cut-off, U	Ecoinvent
Decarbonised wáter	773.76	kg	Water, decarbonised, at user {GLO}| market for	Cut-off, U	Ecoinvent
Output	**Quantity**	**Unit**		**Database**
Acenaphthene	3.07E-09	kg	Acenaphthene	-
Acetaldehyde	3.10E-06	kg	Acetaldehyde	-
Acetic acid	4.69E-04	kg	Acetic acid	-
Arsenic	1.60E-07	kg	Arsenic	-
Benzene	3.49E-06	kg	Benzene	-
Benzo(a)pyrene	1.92E-10	kg	Benzo(a)pyrene	-
Beryllium	9.56E-09	kg	Beryllium	-
Butane	3.58E-03	kg	Butane	-
Cadmium	8.74E-07	kg	Cadmium	-
Carbon dioxide, biogenic	206.77	kg	Carbon dioxide, biogenic	-
Carbon monoxide, biogenic	8.52E-03	kg	Carbon monoxide, biogenic	-
Chromium	1.11E-06	kg	Chromium	-
Chromium	6.66E-08	kg	Chromium	-
Dinitrogen monoxide	3.79E-03	kg	Dinitrogen monoxide	-
Ethane	9.66E-03	kg	Ethane	-
Formaldehyde	1.25E-04	kg	Formaldehyde	-
Hexane	3.07E-03	kg	Hexane	-
Lead	3.98E-07	kg	Lead	-
Manganese	3.03E-07	kg	Manganese	-
Mercury	2.66E-08	kg	Mercury	-
Methane, biogenic	3.76E-03	kg	Methane, biogenic	-
Nickel	1.67E-06	kg	Nickel	-
Nitrogen oxides	0.09874	kg	Nitrogen oxides	-
Polycyclic aromatic hydrocarbons	3.10E-05	kg	PAH, polycyclic aromatic hydrocarbons	-
Particulates, < 2.5 um	1.90E-03	kg	Particulates, < 2.5 um	-
Pentane	4.46E-03	kg	Pentane	-
Propane	2.73E-03	kg	Propane	-
Propionic acid	5.65E-06	kg	Propionic acid	
Selenium	1.90E-08	kg	Selenium	-
Sulfur dioxide	2.21E-03	kg	Sulfur dioxide	-
Toluene	5.82E-06	kg	Toluene	-
Water/m3	0.407	m^3	Water/m3	-
Water, RoW	25.01	m^3	Water, RoW	-
Waste (torre de enfriamiento)	3.90E-03	kg	Residue from cooling tower {RoW}| market for residue from cooling tower	Cut-off, U	Ecoinvent 3

Table S1.1. (cont.) LCI Biorefinery HMEZS-NN (4/6)

STAGE Extraction of VOA and SOLV

AOV y SOLV Extracted fermented solids (eFW)

38.04 kg 90% is assigned for economic value

1858.82 kg Extracted Fermented Waste will be distributed in Stage Z (2/3) and Stage S (1/3) of the BRF (10%)

Input	Quantity	Unit		Database	Observations
Solvent for extraction	1.164	kg	4-methyl-2-pentanone {RoW}| production | Cut-off, U	Ecoinvent 3	Solvent for extraction
Electricity	0.56	kWh	Electricity, high voltage {MX}| production mix | Cut-off, U	Ecoinvent 3	
Heat	97.56	MJ	Heat, central or small-scale, natural gas {RoW}| heat production, natural gas, at boiler modulating <100kW | Cut-off, U	Ecoinvent 3	
Output	**Quantity**	**Unit**		**Database**	**Observations**
Esteamating solvent	1.164	kg	4-Methyl-2-pentanone	-	IK must be a ketone with 6 carbons. It seems like a very large emission, it was based on the assumption of 1% solvent loss in each reuse. Collect information and see if the percentage of solvent loss can be lowered.

STAGE Z

Concentrado enzimático	1087.56	kg	Financial allocation approx. concentrates have great added value (90%)		Proxi for Peptane
Sólidos referementados (rFW)	816.96	kg	Refermented solids. They will enter Stage S saccharification. (10%)		Autoclave for esterilization
Input	**Quantity**	**Unit**		**Database**	**Observations**
Urea	3.144	kg	Urea, as N {RoW}| production | Cut-off, U	Ecoinvent 3	Ultrafiltración
Ammonium sulfate NH_4SO_4	14.671	kg	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Cut-off, U	Ecoinvent 3	There is no sensible Heat because the Input currents are warm and the reactor operates at 30 °C, it is Heat from losses to the air during the period of batch fermentation.
Sodium phosphate Na_3PO_4	20.958	kg	Sodium phosphate {RoW}| production | Cut-off, U	Ecoinvent 3	Losses to the environment during sterilization.
Calcium chloride CaCl2	3.144	kg	Calcium chloride {RoW}| soda production, solvay process | Cut-off, U	Ecoinvent 3	Sensitive heat in sterilization to heat the culture medium, 80% heat recovery is assumed with the hot effluent from the sterilizer and continuous sterilization with efficient equipment that allows a 20% reduction. additional Heat required.
Sulfato de magnesio $MgSO_4$	3.144	kg	Magnesium sulfate {RoW}| production | Cut-off, U	Ecoinvent 3	
Peptane	10.479	kg	Protein feed, 100% crude {GLO}| skimmed milk, from cow milk to generic market for protein feed | Cut-off, U	Ecoinvent 3	
Tween 80	10.479	kg	Non-ionic surfactant {GLO}| non-ionic surfactant production, ethylene oxide derivate | Cut-off, U	Ecoinvent 3	This current may be deducted if it is recirculated in the BRF. 50% of filtrates recirculated from the Z process itself? Another destination of this current is to the WWTP, but it will depend on the WWTP having fewer direct discharge impacts to bodies. aquatic receptors.
Tap wáter	10412.68	kg	Tap water {RoW}| tap water production, conventional treatment | Cut-off, U	Ecoinvent 3	
Iron sulfate	0.01	kg	Iron sulfate {RoW}| production | Cut-off, U	Ecoinvent 3	
Manganese sulfate	0.001	kg	Manganese sulfate {GLO}| production | Cut-off, U	Ecoinvent 3	
Monosulfato de zinc	0.001	kg	Zinc monosulfate {RoW}| production | Cut-off, U	Ecoinvent 3	
Electricity	0.609	kWh	Electricity, high voltage {MX}| production mix | Cut-off, U	Ecoinvent 3	
Electricity	47.81	kWh	Electricity, high voltage {MX}| production mix | Cut-off, U	Ecoinvent 3	
Electricity	31.97	kWh	Electricity, high voltage {MX}| production mix | Cut-off, U	Ecoinvent 3	
Heat	59.15	MJ	Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U	Ecoinvent 3	
Heat	2.8	MJ	Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U	Ecoinvent 3	
Heat	646.02	MJ	Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U	Ecoinvent 3	
Output	**Quantity**	**Unit**		**Database**	
Carbon dioxide	19.08	kg	Carbon dioxide	-	
Wastewater (licor)	9794.4	kg	Waste water	-	

Table S1.1.(cont.) LCI Biorefinery HMEZS-NN (5/6)

STAGE S (acid sacarification)					
Hydrolyzed (HL)	515.31	kg	They are the hydrolysates that will enter the succinic acid production process.		
Input	**Quantity**	**Unit**		**Database**	**Observations**
Sodium hydroxide (NaOH)	20.7	kg	Sodium hydroxide (50% NaOH), production mix/RER Mass	Agri-footprint	
Hydrochloric acid (HCl)	55	kg	Hydrochloric acid, without water, in 30% solution state {RoW}| hydrochloric acid production, from the reaction of hy	Ecoinvent 3	
Electricity	36.69	kWh	Electricity, high voltage {MX}| production mix | Cut-off, U		
Heat	44.63	MJ	Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U		
Output	**Quantity**	**Unit**		**Database**	**Observations**
Waste (non valuable) (HW)	180	kg	Municipal solid waste {RoW}| treatment of, sanitary landfill | Cut-off, U	Ecoinvent 3	Goes to a landfill
STAGE NN Category _NN-Bioparticle production					
NN-Bioparticles	39.74	kg	The bioparticles produced here will be fed to the nanobioparticles production process	NA	
NN-Biogas M1	9.745	kg	This biogas involves which biogas purification NN-Purificacion Biogas M		
Input	**Quantity**	**Unit**	**o**	**Database**	**Observations**
Activated carbon	3.78E+01	kg	Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	Ecoinvent 3	
Anaerobic digestion plant for source waste Biological	7.242	p	Anaerobic digestion plant, for biowaste {GLO}| market for | Cut-off, U	Ecoinvent 3	REVISAR, parece un número excesivo de piezas; 4.34E-9 p ????
Heavy machine operation time	0.01581056	h	Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| market for | Cut-off, U	Ecoinvent 3	
Electricity	0.75	kw h	Electricity, high voltage {MX}| production mix | Cut-off, U	Ecoinvent 3	Replaced by indigenous electrical energy. Electricity required for feed pumping and recirculation in the reactor fluidized bed anaerobic
Heat	1.84	MJ	Heat, central or small-scale, natural gas {RoW}| heat production, natural gas, at boiler modulating <100kW | Cut- off, U	Ecoinvent 3	Reactor heating and auxiliaries for compensate heat losses to the environment
Output producto evitado	**Quantity**	**Unit**		**Database**	**Observations**
Potable water to feed the reactor is replaced by municipal wastewater	707.43	kg	Tap water {RoW}| tap water production, conventional treatment | Cut-off, U	Ecoinvent 3	This current will be replaced by recirculation of internal flows of the BRF such as source Z, effluent from this same process, anaerobic effluent from NN-nanobioparticles production
Output	**Quantity**	**Unit**		**Database**	**Observations**
Carbon dioxide, biogenic	0.02	kg	Carbon dioxide, biogenic	-	Biogas leakM
Dinitrogen monoxide N2O	1.48E-03	kg	Dinitrogen monoxide	-	Biogas leakM
Hydrogen sulfide	0.004	kg	Hydrogen sulfide	-	Biogas leakM
Methane,biogenic	4.54E-02	kg	Methane, biogenic	-	Biogas leakM
Ammonium ion-Hidric emisión	4.17E-06	kg	Ammonium, ion	-	Emissions to water bodies
Nitrate-Hidric emisión	1.33E-04	kg	Nitrate	-	Emissions to water bodies
Nitrite-Hidric emisión	4.17E-06	kg	Nitrite	-	Emissions to water bodies
Organic Nitrogen-Hidric emisión	4.89E-06	kg	Nitrogen, organic bound	-	Emissions to water bodies
Phosphorus-Hidric emisión	3.16E-06	kg	Phosphorus	-	Emissions to water bodies
Wastewater (treatment)	3.04E-01	m^3	Wastewater, from residence {RoW}| treatment of, capacity 1.1E10l/year | Cut-off, U		
Wastewater (treatment)	6.00E-04	m^3	Wastewater, average {RoW}| market for wastewater, average | Cut-off, U	Ecoinvent 3	

Table S1.1. (cont.) LCI Biorefinery HMEZS-NN (6/6)

Category _NN-Nanobioparticle production					
NN-Biogas M2	2.11	kg	This biogas involves which biogas purification NN-Purificacion Biogas M		
NN-Nanobioparticles	40.36	kg	Nanobioparticles are a product for sale to the market by biorestoration companies. acuíferos yde tratamiento de efluetnes tóxicos		
Input	**Quantity**	**Unit**	**Flow**	**Database**	**Observations**
Commercial ferric chloride	2.41E+01	kg	Iron (III) chloride, without water, in 40% solution state {RoW}| iron (III) chloride production, product in 40% solution state | Cut-off, U	Ecoinvent 3	
Planta de digestión anaerobia para waste de origen biológico	1.49E-08	p	Anaerobic digestion plant, for biowaste {GLO}| market for | Cut-off, U	Ecoinvent 3	
Heavy machine operation time	0.003	h	Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| market for | Cut-off, U	Ecoinvent 3	
Electricity	3,65	kw h	Electricity, high voltage {MX}| production mix | Cut-off, U	Ecoinvent 3	Alternating current, high voltage, Mexican conditions. Replaced by indigenous E of the BRF
Heat	0.21	MJ	Heat, central or small-scale, natural gas {RoW}| heat production, natural gas, at boiler modulating <100kW | Cut- off, U	Ecoinvent 3	Energy of fossil origin. It was replaced by Heat indigenous to the BRF
Output	**Quantity**	**Unit**	**Flow**	**Database**	**Observations**
Carbon dioxide, biogenic	5.87E-03	kg	Carbon dioxide, biogenic	-	Biogas leakM
Oxido de dinitrogeno	2.95E-04	kg	Dinitrogen monoxide	-	Biogas leakM
Hydrogen sulfide	0.00079	kg	Hydrogen sulfide	-	Biogas leakM
Methane,biogenic	9.02E-03	kg	Methane, biogenic	-	Biogas leakM
Ammonium ion-Hidric emission	8.28E-07	kg	Ammonium, ion	-	Emissions to water bodies
Nitrate-Hidric emission	2.65E-05	kg	Nitrate	-	Emissions to water bodies
Nitrite-Hidric emission	8.28E-07	kg	Nitrite	-	Emissions to water bodies
Organic Nitrogen-Hidric emision	9.73E-07	kg	Nitrogen, organic bound	-	Emissions to water bodies
Phosphorus-Hidric emission	6.28E-07	kg	Phosphorus	-	Emissions to water bodies
Wastewater (treatment)	0.23573	m^3	Wastewater, from residence {RoW}| treatment of, capacity 1.1E10l/year | Cut-off, U	Ecoinvent 3	Output (treatment); zero discharge because the anaerobic effluent from this process is recirculated partly in this same process and partly in the NN-bioparticles process, so it is null discharge
Wastewater (treatment)	1.32E-04	m^3	Wastewater, average {RoW}| market for wastewater, average | Cut-off, U	Ecoinvent 3	Output (treatment)
Category NN-Biogas purification M					
NN-methane at purity 96%	5.24	kg	biogas with 96% methane content, will be fed to NN energy co-generation		
Input	**Quantity**	**Unit**	**Flow**	**Database**	**Observations**
Global average chemical plant contribution, recommended	3.38E-11	p	Chemical factory, organics {GLO}| market for | Cut-off, U	Ecoinvent 3	It was calculated based on a global averaged chemical compound factory, adjusted for the number of pieces in our case.
Methane purification process from biogas	6.91E+00	m^3	Methane, 96% by volume modif2 HP para CH4{RoW}| biogas purification to methane 96 vol-% | Cut-off, U	Ecoinvent 3	Ecoinvent proxi process
Electricity to power process compressors etc.	2.41E+00	kWh	Electricity, high voltage {MX}| production mix | Cut-off, U		
Output	**Quantity**	**Unit**	**Flow**	**Database**	**Observations**
Carbon dioxide, biogenic	5.75E+00	kg	Carbon dioxide, biogenic	-	Emission to the atmosphere
H2S	8.00E-02	kg	Hydrogen sulfide	-	Emission to the atmosphere
H2O steam	7.90E-01	kg	Water	-	Emission to the atmosphere
Category NN-Energy from methane					
Electricity high and medium voltage	42.8	kWh	High and medium voltage electricity obtained by cogeneration in a combined cycle plant, using biogenic methane		
Heat	70.04		Heat obtained by cogeneration in a combined cycle plant, using biogenic methane		
Input	**Quantity**	**Unit**	**Flow**	**Database**	**Observations**
Piped drinking water for boiler water replacement and cooling	1.05	kg	Tap water {RoW}| tap water production, conventional treatment | Cut-off, U	Ecoinvent 3.0	
Proxy process for E, S, Emissions from electricityt production in CCCPP	42.8	kw h	Electricity, high voltage CCCPP modif1 HP {RoW}| heat and power co-generation, natural gas, combined cycle p	Ecoinvent 3.0	
Proxy process for E, S, Emissions from Heat production in CCCPP	7.00E+01	MJ	Heat, district or industrial, natural gas modif1 HP {RoW}| heat and power co-generation, natural gas, combined c	Ecoinvent 3.0	
Output	**Quantity**	**Unit**	**Flow**	**Database**	**Observations**
Exits are nested in proxy processes					

References

Poggi-Varaldo, H.M. (2019). *Análisis de Ciclo de Vida de una biorrefinería que procesa la fracción orgánica de residuos urbanos y produce bioenergías, ácidos orgánicos, enzimas, y nanobiopartículas*. LCA of a biorefinery that processes the organic fraction of municipal solid waste and and produces bioenergies, organic acids, enzymes, and bionanobioparticles. Final Report to approve the Diploma on Life Cycle Analysis of CADIS A.C.

Annex S2. Life Cycle Inventory IER

Table S2.1. Life Cycle Inventory IER (1/7)

Products	Amount	Unit	Remarks		
Electricity	393	kWh	20% allocation		
Heat	5653	MJ	30% allocation		
Input	**Cantidad**	**Unit**	**Flow**	**Data base**	**Remarks**
OFMSW	1000	kg	-	Creado	400 kg paper waste, 600 kg organic waste (Escamilla-Alvarado et al., 2017)
Oxygen	950.00	kg	-	Eoinvent 3	Oxygen from ambient air needed to combust and oxidise this waste. Net demand, i.e. without O2 leaving the plant in flue gas uncombusted. (Tchoubanouglous & Kreith, 2002)
Ammonia	0.996	kg	Ammonia, liquid {RER}| market for | Cut-off, U	Ecoinvent 3	Input to DeNOx stage (100% NH3).
Cationic resin	5.746E-04	kg	Cationic resin {RER}| market for cationic resin | Cut-off, U	Ecoinvent 3	Auxilliary input for mercury removal in filter ash treatment (FLUWA).
Cement	9.808	kg	Cement, unspecified {CH}| market for cement, unspecified | Cut-off, U	Ecoinvent 3	Cement required for solidification of landfilled residual material.
Chemical, inorganic	0.135	kg	Chemical, inorganic {GLO}| market for chemicals, inorganic | Cut-off, U	Ecoinvent 3	Auxilliary inputs for the wastewater treatment stage of the incinerator plant. Proxy for Polyelectrolyte.
Chemical, organic	1.041E-03	kg	Chemical, organic {GLO}| market for | Cut-off, U	Ecoinvent 3	Auxilliary inputs for the wastewater treatment stage of the incinerator plant. Proxy for (pure) Trisodium-trimercapto-s-triazine (CAS 17766-26-6), used as 15% diluted solution, aka TMT15.
Chromium oxide	1.274E-03	kg	Chromium oxide, flakes {GLO}| market for | Cut-off, U	Ecoinvent 3	Input to DeNOx stage. Active component in SCR catalyst (vanadium pentoxide, V2O5), here approximated with the available chromium trioxide.
Heat, natural gas	186.294	MJ	Heat, district or industrial, natural gas {CH}| market for heat, district or industrial, natural gas | Cut-off, U	Ecoinvent 3	Input to DeNOx stage, to heat up flue gas in low-dust SCR.
Hydrochloric acid 30%	0.715	kg	Hydrochloric acid, without water, in 30% solution state {RER}| market for | Cut-off, U	Ecoinvent 3	Auxilliary inputs for the wastewater treatment stage of the incinerator plant.
Hydrogen peroxide 50%	1.730	kg	Hydrogen peroxide, without water, in 50% solution state {RER}| market for hydrogen peroxide, without water, in 50% solution state | Cut-off, U	Ecoinvent 3	Auxilliary oxidising agent for filter ash treatment (FLUWA).
Iron (III) chloride 40%	0.002	kg	Iron (III) chloride, without water, in 40% solution state {GLO}| market for | Cut-off, U	Ecoinvent 3	Auxilliary inputs for the wastewater treatment stage of the incinerator plant.
Metalliferous hydroxide sludge	-5.381	kg	Metalliferous hydroxide sludge {GLO}| metalliferous hydroxide sludge, Recycled Content cut-off | Cut-off, U	Ecoinvent 3	Metalliferous hydroxide sludge from filter ash leaching (FLUWA).
Municipal waste incineration facility	4.643E-07	p	Municipal waste incineration facility {CH}| construction | Cut-off, U	Ecoinvent 3	Demands per kilogram waste.

Table S2.1. (cont.) Life Cycle Inventory IER (2/7)

Input	Quantity	Unit	Flow	Data base	Observations
Process-specific burdens, residual material landfill	48.889	kg	Process-specific burdens, residual material landfill {CH}| market for process-specific burdens, residual material landfill | Cut-off, U	Ecoinvent 3	Mass-specific expenditures required for landfilling of incineration residues.
Process-specific burdens, slag landfill	264.938	kg	Process-specific burdens, slag landfill {CH}| market for process-specific burdens, slag landfill | Cut-off, U	Ecoinvent 3	Mass-specific expenditures required for landfilling of bottom ash.
Quicklime, milled, packed	2.563	kg	Quicklime, milled, packed {RER}| market for quicklime, milled, packed | Cut-off, U	Ecoinvent 3	Auxilliary inputs for the flue gas treatment stage of the incinerator plant.
Residual material landfill	1.019E-07	p	Residual material landfill {CH}| construction | Cut-off, U	Ecoinvent 3	Landfill infrastructure required for landfilling of incineration residues.
Slag landfill	4.710E-07	p	Slag landfill {CH}| construction | Cut-off, U	Ecoinvent 3	Auxilliary inputs for the flue gas treatment stage of the incinerator plant, and partially in the filter ash treatment (FLUWA).
Sodium hydroxide 50%	2.007	kg	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	Ecoinvent 3	Input to DeNOx stage (TiO2 catalyst carrier)
Titanium dioxide	0.062	kg	Titanium dioxide {RER}| market for | Cut-off, U	Ecoinvent 3	Transport services to transport incineration residues to landfills and filter ash to external treatments (FLUWA).
Transport, freight, lorry, unspecified	12.125	tkm	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	Ecoinvent 3	Landfill infrastructure required for landfilling of bottom ash.
Water, decarbonised, at user	1595.590	kg	Water, decarbonised, at user {GLO}| market for | Cut-off, U	Ecoinvent 3	Incinerator process water used in flue gas scrubber stage.
Output (Emissions to air)	**Quantity**	**Unit**	**Flow**	**Data base**	**Observations**
Aluminium	6.600E-05	kg	Aluminium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Ammonia	5.857E-03	kg	Ammonia	Ecoinvent 3	Nitrogen species emitted to air after DeNOx stage.
Arsenic	1.269E-04	kg	Arsenic	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Benzene	3.864E-04	kg	Benzene	Ecoinvent 3	Incomplete combustion product emitted to air.
Benzene, hexachloro-	8.080E-07	kg	Benzene, hexachloro-	Ecoinvent 3	Incomplete combustion product emitted to air.
Benzene, pentachloro-	2.042E-06	kg	Benzene, pentachloro-	Ecoinvent 3	Incomplete combustion product emitted to air.
Benzo(a)pyrene	8.599E-09	kg	Benzo(a)pyrene	Ecoinvent 3	Incomplete combustion product emitted to air.
Bromine	2.427E-05	kg	Bromine	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Cadmium	5.697E-07	kg	Cadmium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Calcium	1.389	kg	Calcium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Carbon dioxide, biogenic	118	kg	Carbon dioxide, biogenic	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Carbon monoxide, biogenic	0.657	kg	Carbon monoxide, biogenic	Ecoinvent 3	Incomplete combustion product emitted to air.
Chromium	5.66E-05	kg	Chromium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.

Table S2.1. (cont.) Life Cycle Inventory IER (3/7)

Output (Emissions to air)	Quantity	Unit	Flow	Data base	Observations
Cobalt	7.36E-05	kg	Cobalt	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Copper	1.34E-05	kg	Copper	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Cyanide	0.104	kg	Cyanide	Ecoinvent 3	Nitrogen species emitted to air after DeNOx stage.
Dinitrogen monoxide	0.483	kg	Dinitrogen monoxide	Ecoinvent 3	Nitrogen species emitted to air after DeNOx stage.
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	6.18E-10	kg	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Ecoinvent 3	Incomplete combustion product emitted to air.
Heat, waste	2614.749	MJ	Heat, waste	Creado	Waste heat generated from heating value of this waste plus any electricity required to process it. Tchoubanouglous & Kreith, 2002)
Hydrogen chloride	1.85E-02	kg	Hydrogen chloride	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Hydrogen fluoride	1.09E-02	kg	Hydrogen fluoride	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Iodine	2.47E-07	kg	Iodine	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Iron	8.71E-06	kg	Iron	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Lead	1.24E-05	kg	Lead	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Magnesium	2.41E-02	kg	Magnesium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Manganese	6.65E-06	kg	Manganese	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Mercury	2.25E-05	kg	Mercury	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Methane, biogenic	5.80E-03	kg	Methane, biogenic	Ecoinvent 3	Incomplete combustion product emitted to air.
Molybdenum	4.26E-06	kg	Molybdenum	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Nickel	5.51E-05	kg	Nickel	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Nitrogen oxides	1.855	kg	Nitrogen oxides	Ecoinvent 3	Sum of fuel-Nox and thermal-NOx emitted to air after DeNOx stage.
NMVOC	1.76E-02	kg	NMVOC, non-methane volatile organic compounds, unspecified origin	Ecoinvent 3	Incomplete combustion product emitted to air.
Particulates, < 2.5 um	4.61E-02	kg	Particulates, < 2.5 um	Ecoinvent 3	Incomplete combustion product emitted to air.
Particulates, > 2.5 um, and < 10um	2.32E-04	kg	Particulates, > 2.5 um, and < 10um	Ecoinvent 3	Incomplete combustion product emitted to air.
Phenol, pentachloro-	1.68E-07	kg	Phenol, pentachloro-	Ecoinvent 3	Incomplete combustion product emitted to air.
Phosphorus	9.30E-03	kg	Phosphorus	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Potassium	1.40E-01	kg	Potassium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Selenium	4.83E-05	kg	Selenium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Silicon	5.04E-04	kg	Silicon	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.

Table S2.1. (cont.) Life Cycle Inventory IER (4/7)

Output (Emissions to air)	Quantity	Unit	Flow	Data base	Observations
Sodium	9.97E-02	kg	Sodium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Sulfur dioxide	1.03E-01	kg	Sulfur dioxide	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Tin	4.23E-08	kg	Tin	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Toluene	7.73E-04	kg	Toluene	Ecoinvent 3	Incomplete combustion product emitted to air.
Vanadium	5.15E-04	kg	Vanadium	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Water/m3	12.580	m^3	Water/m3	Ecoinvent 3	Water vapour from waste humidity, hydrogen oxidation and part of the process water.
Zinc	3.16E-04	kg	Zinc	Ecoinvent 3	Emission to air from waste composition and transfer coefficients.
Output (Emissions to water)	**Quantity**	**Unit**	**Flow**	**Data base**	**Observations**
Aluminium	6.01E-03	kg	Aluminium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Aluminium	62.489	kg	Aluminium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Antimony	7.50E-06	kg	Antimony	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Antimony	4.08E-06	kg	Antimony	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Arsenic	9.87E-03	kg	Arsenic	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Arsenic	6.51E-03	kg	Arsenic	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
BOD5, Biological Oxygen Demand	3.188	kg	BOD5, Biological Oxygen Demand	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
BOD5, Biological Oxygen Demand	0.978	kg	BOD5, Biological Oxygen Demand	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Boron	0.068	kg	Boron	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Boron	8.59E-04	kg	Boron	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Bromine	4.51E-02	kg	Bromine	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Bromine	2.52E-03	kg	Bromine	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Cadmium	1.99E-07	kg	Cadmium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Cadmium	1.79E-04	kg	Cadmium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Calcium	149.869	kg	Calcium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Calcium	3.173	kg	Calcium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Chloride	27.515	kg	Chloride	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Chloride	4.080	kg	Chloride	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Chromium	8.41E-06	kg	Chromium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.

Table S2.1. (cont.) Life Cycle Inventory IER (5/7)

Output (Emissions to water)	Quantity	Unit	Flow	Data base	Observations
Chromium VI	3.69E-03	kg	Chromium VI	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Chromium VI	1.07E-03	kg	Chromium VI	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Cobalt	6.73E-06	kg	Cobalt	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Cobalt	3.55E-02	kg	Cobalt	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
COD	1.000	kg	COD, Chemical Oxygen Demand	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
COD	9.746	kg	COD, Chemical Oxygen Demand	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Copper	0.137	kg	Copper	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Copper	1.26E-05	kg	Copper	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
DOC	3.857	kg	DOC, Dissolved Organic Carbon	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
DOC	0.436	kg	DOC, Dissolved Organic Carbon	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Fluoride	1.081	kg	Fluoride	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Fluoride	0.471	kg	Fluoride	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Iodide	4.34E-04	kg	Iodide	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Iron	2.492	kg	Iron	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Iron	1.02E-04	kg	Iron	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Lead	1.02E-05	kg	Lead	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Lead	0.106	kg	Lead	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Magnesium	21.270	kg	Magnesium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Magnesium	0.173	kg	Magnesium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Manganese	4.36E-06	kg	Manganese	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Manganese	2.77E-02	kg	Manganese	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Mercury	1.19E-04	kg	Mercury	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Mercury	3.02E-06	kg	Mercury	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Molybdenum	5.39E-04	kg	Molybdenum	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Molybdenum	2.50E-03	kg	Molybdenum	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Nickel	4.33E-02	kg	Nickel	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.

Table S2.1. (cont.) Life Cycle Inventory IER (6/7)

Output (Emissions to water)	Quantity	Unit	Flow	Data base	Observations
Nickel	2.97E-05	kg	Nickel	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Nitrate	0.416	kg	Nitrate	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Nitrate	1.162	kg	Nitrate	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Phosphate	0.014	kg	Phosphate	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Phosphate	0.823	kg	Phosphate	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Potassium	20.339	kg	Potassium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Potassium	7.686	kg	Potassium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Selenium	8.06E-04	kg	Selenium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Selenium	3.11E-03	kg	Selenium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Silicon	23.909	kg	Silicon	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Silicon	0.077	kg	Silicon	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Sodium	7.951	kg	Sodium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Sodium	3.998	kg	Sodium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Sulfate	4.962	kg	Sulfate	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Sulfate	29.030	kg	Sulfate	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Thallium	9.16E-06	kg	Thallium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Thallium	1.53E-08	kg	Thallium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Tin	4.30E-02	kg	Tin	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Tin	5.85E-05	kg	Tin	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
TOC, Total Organic Carbon	0.436	kg	TOC, Total Organic Carbon	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
TOC, Total Organic Carbon	3.857	kg	TOC, Total Organic Carbon	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Vanadium	3.57E-05	kg	Vanadium	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.
Vanadium	9.49E-03	kg	Vanadium	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Water, CH	2.695	m^3	Water, CH	Ecoinvent 3	Process water released to surface water.
Zinc	0.212	kg	Zinc	Ecoinvent 3	Long-term emissions from landfilling of incineration residues.
Zinc	2.89E-05	kg	Zinc	Ecoinvent 3	Emissions to water from waste composition and transfer coefficients in incinerator and landfills.

Table S2.1. (cont.) Life Cycle Inventory IER (7/7)

Output (Emissions to soil)	Quantity	Unit	Flow	Data base	Observations
Slags	32.670	kg	Slags	Creado	(Tchoubanouglous & Kreith, 2002)
Fly ash	3.200	kg	Fly ash	Creado	(Tchoubanouglous & Kreith, 2002)
Output (Waste for treatment)	**Quantity**	**Unit**	**Flow**	**Data base**	**Observations**
Spent activated carbon with mercury	6.05E-04	kg	Spent activated carbon with mercury {GLO}| market for | Cut-off, U	Ecoinvent 3	Spent ion exchanger charged with mercury, from FLUWA filter ash treatment, approximated here with Spent activated carbon with mercury, deposited undergound in a polyethylene Big Bag.
Waste cement, hydrated	24.522	kg	Waste cement, hydrated {CH}| market for waste cement, hydrated | Cut-off, U	Ecoinvent 3	Hydrated cement output for solidification of landfilled residual material.

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Annex S3. Calculation procedures for incineration with energy recovery

S3.1. Combustion products

Below are the calculations carried out to calculate CO_2; they were performed in accordance with Tchobanoglous and Kreith (2002), Neuwahl, et al. (2019), Tchobanoglous et al. (1977) .

Net O_2 should be taken

O_2 = 908 kg O_2 net / 1000 kg $_{ORFMSW}$

$(32 kg\ O_2 / mol\ O_2)/(12 kg\ C /mol\ C)= 2.66$

$(301\ of\ C)\ (32\ kg\ O_2 / mol\ O_2)/(12 kg\ C /mol\ C)+ (301 kg\ of\ C)= 1101.66 kg\ CO_2$

S3.2. Mass balance

The energy consumption of the incineration plant is related to the calorific value of the waste and the volume of combustion gases generated (Buekens, 2013)

Below in table S3.2.1. The typical composition of organic solid waste in Mexico and its energy content are shown.

Table S3.2.1. Composition and energy content of organic solid waste in Mexico, typical characteristics (percentage by weight, wet basis)

Composition	OFMSW kg	Inert waste** %	Dry weght kg	Energy ** BTU/lb	Energy kJ/kg	Total energy kJ
Food waste	423	5	274.9	2,000	4,652	1967386.62
Wood	21	1.5	13.9	8,000	18,608	399141.6
Garden waste	155	4.5	100.8	2,800	6,513	1010135.28
Cartón	205	6	133.1	7,000	16,282	3333739.5
Paper	195	5	126.9	7,200	16,747	3270728.16
Total	1000		649.7			9,981,131.16

*INEGI data, 2017

**Typical energy content of waste at discharge (Tchobanoglus *et al.,*1993; Ref: INEGI, 2017 and Tchobanoglous and Kreith, 2002)

S3.3. Theoretical air requirements

The amount of air required for the combustion of the OFMSW was determined. The oxygen necessary for the oxidation of carbon, hydrogen and sulfur contained in the

OFMSW was calculated (Table S3.3.1.) according to the combustion reactions presented below (Tchobanoglous and Kreith, 2002):

Carbon: $(C + O_2 \rightarrow CO_2) \rightarrow$ *11.52 kg of dry air /kg C burnt* (S3.3.0a)

Hidrogen: $\left(2H + O_2 \rightarrow 2H_2O\right) \rightarrow 34.56$ *kg of dry air /kg H burnt* (S3.3.0b)

Sulfur: $\left(S + O_2 \rightarrow SO_2\right) \rightarrow 4.31$ *kg of dry air /kg S burnt* (S3.3.0c)

Dry air was assumed to contain: 23.15% weight of O2. Therefore, the corresponding quantities of dry air required to oxidize 1 kg of coal, 1 kg of hydrogen and 1 kg of sulfur are (Eqs. S3.3.1.- S3.3.4.) below:

$(PMO_2/PA_j)/*(100/p_j) = m_{j\ dry\ air}$ (kg)/kg rusty or burnt element (S3.3.1), j = C, H, ó S

where = $m_{j\ dry\ air}$ is the mass (in kg) of dry air required to burn 1 kg of element $_j$; PM O_2 is 32 kg; PA_j is the atomic weight of the element C, or S, or H; p_j is the percentage proportion of element $_j$ in the dry OFMSW.

Carbon: [(32 kg de O_2 / 12 kg de C) (1 / 0.2315)] =

11.52 *kg of dry air /kg of C* (S3.3.2.)

Hydrogen: [(32 kg de O_2 / 4 kg de H_2) (1 / 0.2315)] =

34.56 *kg of dry air /kg of* H_2 (S3.3.3)

Sulfur: [(32 kg de O_2 / 32.1 kg de S) (1 / 0.2315)] =

4.31 *kg of dry air /kg of S* (S3.3.4)

In Table S3.3.1. dry mass is shown (m_j, $_j$ = C, H, S) of each element in a dry OFMSW functional unit (650 kg m_j)

Each row was calculated as follows

$m_j = m_{OFMSW}*(p/100)$ (S3.3.5)

where m_j is the dry mass of each element in kg, m_{OFMSW} of the m_j de OFMSW in kg, p was defined as Eq. (S3.3.1)

Table S3.3.1. Weight of the elements that make up the dry OFMSW

Element	Peso seco, en base decimal	Peso seco, en base porcentual (b.s.) (%) w/w	Kg elemento en 650 kg OFMSW dry
Carbon	0.4630	46.30	300.82
Hidrogen	0.0615	6.15	39.95
Oxígen	0.4046	40.46	262.84
Nitrogen	0.0175	1.75	11.38
Sulfur	0.0030	0.30	1.94
Ash	0.0503	5.03	32.67
Total		99.99	649.60

References: Own elaboration (Tchobanoglous and Kreith, 2002)

Table S3.3.2. shows the mass in kg of dry air required by the mass of each element in 650 kg of dry OFMSW. Each of the first 3 rows is calculated as follows:

$m_{airj} = mj^* m_{j\ dry\ air}$ (S3.3.6),

where m_{airj} is the mass of dry air (in kg) required to oxidize the mass of element $_j$ present in 650 kg of dry OFMSW;

Table S3.3.2. Theoretical air requirements for combustion of 650 kg dry OFMSW

Element	Required air kg
Carbon	3465.44
Hydrogen	1380.58
Sulfur	8.36
Total theoretical dry air	4854.37
Total air (100% excess)	4854.37[a]
Humidity (1%)	48.54
Air recirculation (20%)	1951.46[b]
Total air required	7805.82

References: own elaboration based on data from Tchobanoglous and Kreith (2002)
[a]. air excess of 100% of the theoretically required, as recommended by Tchobanoglous and Kreith (2002) and Neuwahl *et al*. (2019).
[b] air recirculation is 20 % (Tchobanoglous and Kreith, 2002; Neuwahl *et al*., 2019)

The mass of air required, considering the excess of 100% of the theoretical quantity, totals 7805.82 kg air as it comes. This is required to burn 650 kg of dry OFMSW.
Let $m\mu_{OFMSW}$ be the number of moles of air required for the combustion of 100 kg of OFMSW. Then,

$$m\mu_{OFMSW} = m_{rar} / PM_{air} * 100/650 \quad \text{(S3.3.7)}$$

then,

m_{rar} = required air mass m_{rar} =

$$= (7805.82 \text{ kg}_{rar} / 28.7 \text{ kg air/ mol air})(100/650) = 41.84 \text{ moles}_{rar} \quad \text{(S3.3.8)}$$

3.3.1.Oxygen required

According to the data presented in table S3.3.2. calculations of the required oxygen were carried out.

For this, the PM of the air is assumed to be 28.7 kg / kmol, composition of the air in oxygen volume fraction 0.2069. The behavior of ideal gases is assumed, so the volume of the fractions can be taken as mole fractions and be equal to the volume percentages divided by 100 (Tchobanoglous and Kreith, 2002).

$$\mu O_2 \text{ (moles } O_2 / 1000 \text{ kg}_{OFMSW\ dry}) = m_{atr} (100/650) \quad \text{(S3.3.1.1a)}$$

$$\mu O_2 \text{ (moles } O_2 / 1000 \text{ kg}_{OFMSW\ dry}) =$$

$$= 41.84 \text{ moles}_{atr} / 1000 \text{ kg}_{OFMSW\ dry} (0.2069 \text{ moles de } O_2) =$$

$$= 8.66 \text{ mol } O_2 / 1000 \text{ kg}_{OFMSW\ dry} \quad \text{(S3.3.1.1b)}$$

To calculate the mass of O_2

ω = kg of oxigen

$$\omega = (\text{kg } O_2 / 1000 \text{ kg}_{OFMSW\ dry}) * PM\ O_2 (\text{kg } O_2 / \text{mol } O_2) * (650\ _{OFMSW\ dry} / 100 \text{ kg}_{OFMSW\ dry}) \quad \text{(S3.3.1.2a)}$$

$$\omega = 8.66 \text{ mol } O_2 / 100 \text{ kg}_{OFMSW\ dry} (32\ O_2 \text{ kg } O_2 / \text{ mol } O_2) (650\ _{OFMSW\ dry} / 100 \text{ kg}_{OFMSW\ dry})$$

(S3.3.1.2b)

ω = 1170.83 kg O_2 / 1000 kg $_{OFMSW}$ (S3.3.1.2c)

To calculate the net O_2, 262 kg of O_2 (Table S3.3.2.) of the OFMSW must be subtracted from the kg of O_2 required for the combustion of 1000 kg OFMSW, i.e.

1170.83 kg O_2 / 1000 kg $_{OFMSW}$ - 262 kg de O_2 (650 $_{OFMSW\ dry}$ / 1000 kg) =

= 908 kg O_2 netos / 1000 kg $_{OFMSW}$ (S3.3.1.3)

3.3.2. Combustion products

Below are the calculations carried out to calculate CO_2, these calculations were carried out in accordance with Tchobanoglous and Kreith, 2002.

Net O_2 should be taken

O_2 = 908 kg O_2 netos / 1000 kg $_{OFMSW}$

(32 kg O_2 / mol O_2)/(12 kg C /mol C)=

=2.66 (301 kg de C) (32 kg O_2 / mol O_2)/(12 kg C /mol C)+ (301 kg de C) =

=1101.66 kg CO_2 (S3.3.2.1)

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Annex S4. Emissions technological adequacy factors

The technological suitability factors were calculated for those emissions of greatest environmental importance for IER technology. The permissibility factors were calculated in accordance with the emission limits established by the corresponding regulations in Europe and Mexico (Table S4.1.). These factors were calculated according to European Environmental Agency (2022)(European Enegy Agency, 2022) and with NOM-047-SEMARNAT-2014

Table S4.1. Emissions technological adequacy factors

Component	Emission limit (mg/m^3)		Permissibility factor
	Europ	Mexico	
CO	12.50	63.00	5.04
SO_2	20.00	80.00	4.00
Hg	0.01	0.07	7.00
Dioxins and furans	0.05	0.20	4.00
			5.00

Ref: EEA, 2022; SEMARNAT, 2014

Annex S5. Data quality

Table S5.1. BRF data quality

Data used in every stage/ process	Integrity	Coherence
Stage (H) includes compliment, hydrogenic bioreactor, biogas purification H and electric generation in fuel cells with protonic exchange membrane		
Materials	Good (95% mín, criteriosde corte	Good
Electric Energy consumption	Good	Good
Termic charge generation	Good	Good
Electric Energy generation	Good	Good
Termic charge generation	Good	Good
Products	Good	Good
Emisions	Regular	Regular
Waste treatment	Regular	Regular
Stage (M), includes metanogenic bioreactor, Biogas purification M and co-generation of electricity, and heat in combined cycle potential plant	Good	Good
Materials	Good	Good
Electric Energy consumption	Good	Good
Termic charge generation	Good	Good
Electric Energy generation	Good	Good
Termic charge generation	Good	Good
Products	Good	Good
Emisions	Regular	Regular
Waste treatment	Regular	Regular
Acid organic extraction stage; includes liquid-liquid extraction with acid organic solvent and reuse by destillation		
Materials	Good	Good
Electric energy consumption	Regular	Regular
Termic charge consumption	Regular	Regular
Electric energy generated	NA	NA
Termic energy generated	NA	NA
Products	Good	Good
Emisions	Regular	Regular
Waste treatment	Regular	Regular
Enzyme production stage (Z); includes enzyme biological production, cellulolytic and xylanolytic and ultrafiltration to produce ezimatic concetrated		

Table S5.1. (cont.) Biorefinery data quality

Data used in every stage/ process	Integrity	Coherence
Materials	Regular	Regular
Electric Energy consumption	Good	Good
Termic charge consumption	Good	Good
Electric Energy generated	NA	NA
Termic charge generated	NA	NA
Products	Good	Good
Emisions	Regular	Regular
Waste treatment	Regular	Regular
Scarification stage (S); includes acid hidrolysis of fermented solids (previamente extraídos), neutralization, and activated carbón adsoption to remove inhibitor of downstream posible fermentations.		
Materials	Very Good	Very Good
Electric Energy consumption	Good	Good
Termic charge consumption	Good	Good
Electric Energy generated	NA	NA
Termic charge generated	NA	NA
Products	Very Good	Very Good
Emisions	Regular	Regular
Waste treatment	Regular	Regular
Nanobioparticles production stage (NN); includes biorreactor 1 to produce biogas (M) and bioparticles, bioreactor 2 to produce biogas M and nanobioparticless, biogás purification M, and heat and electricity co-generation by purified methane combustion.		
Materials	Very Good	Very Good
Electric Energy consumption	Good	Good
Termic charge consumption	Good	Good
Electric Energy generated	Good	Good
Termic charge generated	Good	Good
Products	Good	Good
Emisions	Regular	Regular
Waste treatment	Regular	Regular

Table S5.2. Data quality analysis IER

Stage	Data	Year	Geography	Technology	Precision	Integrity	Represintivaness	Reproducibility	Coherence	Resources	Incertitude
Obtention of OFSWM	Rasw material (Organic waste and paper)	2021	Switzerland	NA	Good	high	Good	✓	✓	Waste generation report (Mexico City)	Low
Grate incinators	Heat production	2021	N/A	N/A	Good	high	Good	✓	✓	Calculations according to the process Tchoubanouglous & Kreith, 2002	Low
	Combustion gas production	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
ESP Fly ash	Water, aire and soild emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
Wet flue gas cleaning system	Air and water emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
SNCR	Water emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
SCR- high dust	Air and water emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
SCR-low dust	Air and water emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
Sistem DeNOX-polvo	Air and water emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
Treatment ash filter (FLUWA)	Soild and wáter emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
Separación Iron rest separation in the slag	Soild and wáter emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
Gross efficiency electric technology	Electricity consumption	2021	N/A	N/A	Good	high	Good	✓	✓	Calculations according to the process Tchoubanouglous & Kreith, 2002	Low
	Air and water emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low
Gross efficiency heat technology	Heat consumption	2021	N/A	N/A	Good	high	Good	✓	✓	Calculations according to the process Tchoubanouglous & Kreith, 2002	Low
	Air and water emisions	2006-2018	Switzerland	Modern	Good	high	Good	✓	✓	Ecoinvent	Low

NOTAS: SNCR: sistema of non-selective catalytic reduction, ESP: Electrostatic precipator, SCR: sistema of selective catalytic reduction.

Reference: Own elaboration with Ecoinvent proxy data “Biowaste {CH}| treatment of, municipal incineration with fly ash extraction”, ISO 14044, 2006; Tchobanoglous & Kreith, 2002.

Annex S6
Table S6.1. Impact category description

Impact category	Indicators
Global warming (GWP) Kg CO_2e	Greenhouse emisions increase
Ionizing radiation (IRP) kBq Co-60e	Absorbed dose increase
Fossil resource scarcity kg oil e	Natural fossil resources decrease
Ozone formation, Terrestrial ecosystems kg NO_X e	Tropospheric ozone increase
Ozone formation, Human health kg NO_X e	Tropospheric ozone ingest increase by population
Stratospheric ozone depletion Kg CFC-11 e	Stratospheric ozone depletion
Fine particulate matter formation kg $PM_{2.5}$ e	Particulate matter 2.5 inhalation increase by population
Human carcinogenic toxicity kg 1,4-DCBe	Cancer incidence risk increase
Human non-carcinogenic toxicity kg 1,4-DCB e	Incidence risk increase in non-carcinogenic diseases
Terrestrial ecotoxicity kg 1,4-DCB e	Natural soilds risk weigthed increase
Ecotoxicidad al agua dulce kg 1,4-DCBe	Fresh water risk weighted increase
Land use m^2 a crop e	Soild surfance utilization with food chains or biodiversity damage potential
Mineral resource scarcity kg Cue	Natural non-fossil resources decrease
Water consumption m^3	Water resources consumption

References: Based in Huijbregts *et al.*, 2017

In Table S6.3. the corresponding normalization factors are shown for EDIP, 1997 in Stranddorf et al. 2005 and used to obtain the corresponding PEIs reported by Turconi et al. (2011) and Fruergaard and Astrup (2011).

Table S6.3. Normalization factors for EDIP, 1997

Impact categories	Unit	Normalizaction factor EDIP 1997
Global warming	kg CO_2eq/person/year	8.70E+03
Ozone depletion	kg CFC11eq/person/year	0.2
Acidification	kg SO_2eq/person/year	124
Nutrient enrichment	kg NO_3 eq/person/year	298
Human tox via air	m^3air/capita/year	9.18E+09
Human tox via soil	m^3soil/capita/year	3.10E+02
Human tox via water	m^3water/capita/year	5.90E+04
Photochemical ozone formation	kg C_2H_4eq/person/year	20
Ecotoxicity, water,acute	m^3water/capita/year	4.80E+04
Ecotoxicity, water, chronic	m^3water/capita/year	4.70E+05
Ecotoxicity, soil, chronic	m^3soil/capita/year	3.00E+04

Annex 7. Obtaining NPEI = PEI/U, where U = unit load of environmental impact per person and per year

S7.1. Definition and equations for determining NPEIs

Normalization is a useful tool for the interpretation of impact analysis results and for better understanding the relative environmental significance of impacts across categories, as it allows identifying the most relevant impact categories, life cycle stages, process and resource consumptions, or emissions. Normalization factors help to interpret the scores for each impact category, converting them into a fraction of the system impact of a reference situation (e.g. the global system as presented in this study). (Sala et al., 2017) Currently, the level of harmonization between the basic approaches used to obtain data can still be improved. Therefore, a systematic collection of more detailed and accurate data associated with the global emission profile and resource use is always needed, thus ensuring consistency of assumptions and extrapolations. (Sala et al., 2017)

In order to normalize the PEI obtained, the equations Eq. S7.1 – S7.4 described below were generated.

process of conversion $PEI_j \longrightarrow NPEI_j$

$$[PEI_j] = \frac{[Impact\ j\ (PCTB)]}{FU} \qquad [S7.1]$$

where

The square brackets indicate the units of the variable inside the brackets

[PCTB] = physicochemical toxic biological unit of the characterization impact

FU= functional unit.,

For instance, a characterization impact of global warming of the IER analyzed in our article would be 120 kg $CO2e/FU_{OFMSW}$

Then we define the concept of unitary load of contribution to impact j per person per year $[U_j]$ = [Impact (PCTB)]/(person * yr).

Therefore, we can normalize by dividing the PEI_j by U_j

$$NPEIj = PEIj/Uj \qquad [S7.2]$$

Let us adopt the notation φ(X) for stating “the units of the magnitude X.”

Therefore, the units of NPEIj can be written as φ(NPEIj), and

$$\varphi(NPEIj) = \frac{\varphi(PEI_j)}{\varphi(Uj)} = \frac{\frac{PCBT_j}{FU}}{\frac{PCTB}{person*yr}} = \frac{person*yr}{FU} \qquad [S7.3]$$

The researchers involved in the development of SimaPro used the inverse of U_j which they called the normalization factor $F_{n,j}$; the latter has inverse units, that is,

$$U_j = 1/ F_{n,j} \qquad [S7.4]$$

and

$$\varphi (F_{n,j}) = person*year / \varphi(PEI_j) = person*year/PCBT \qquad [S7.5]$$

The values of U_j (or N_j as it is called in the ReCiPe method) and the normalization factors $F_{n,j}$ and their corresponding units are shown in Tables S7.1 and S7.2 below

Therefore, equivalently

$NPEI_j = PEI_j * F_{n,j}$ [S7.6]

$$\varphi(NPEIj) = (PEI_j) * \varphi(F_{n,j}) = \frac{PCBT}{FU} * \frac{person*yr}{PCBT} = \frac{person*yr}{FU} \quad \text{[S7.7]}$$

The units of all the $NPEI_j$ are the same, that is, (person * yr) /FU
When comparing options where they all have the same FU, then it can be omitted.
If the FUs are different, then the characterization impacts have to be harmonized to a common base FU before doing any calculations and comparison.
The main conclusion is that this normalization process allows the NPEIj to be comparable within each category j, and between categories j,k, and that they can be added and that they can be divided

Next, the normalized impact index (α) of a technology or process was defined as the sum of the 18 normalized potential impacts

$$\alpha = \sum_{j=1}^{18} NPEI_j \quad \text{[S7.8]}$$

where NPEIj represents the normalized potential environmental impact; j is the subscript representing the j-ésimo impact.
Therefore, when α is higher, then sustainability is lower.
Thus, the sum of the NPEI makes it possible to compare the environmental impacts between different technologies, and from this concept, the GBAER environmental sustainability indices were generated. The requisite of same or harmonized FU is mandatory.

S7.2. Tables with unit loads and normalization factors ReCiPe and Simapro

Table S7.1. Unit environmental loads and characterization factors from National Institute for Public Health and the Environment (2024). ReCiPe reports 2016. Normalization factors.

Impact category	Units of the environmental impact[a]	Unit load (U or N) [units of the environmental impact type/(person*year)][b]	Normalization factor (F_n) [(person*year)/units of the environmental impact type][c]
Global warming	kg CO_2 e per person in 2010	7.99E+03	0.0001252
Stratospheric ozone depletion	kg CFC11 e per person in 2010	6.00E-02	16.7
Ionizing radiation	kBq Co-60 emitted to air e per person in 2010	4.80E+02	0.00208
Ozone formation, Human health	kg NO_x e per person in 2010	2.06E+01	0.0486
Fine particulate matter formation	kg PM2.5 e per person in 2010	2.56E+01	0.0391
Ozone formation, Terrestrial ecosystems	kg NO_x e per person in 2010	1.77E+01	0.0563
Terrestrial acidification	kg SO2 e per person in 2010	4.10E+01	0.0244
Freshwater eutrophication	kg P to freshwater e per person in 2010	6.50E-01	1.54
Marine eutrophication	kg N to marine water equivalents per person in 2010	4.62E+00	0.217
Terrestrial ecotoxicity	kg 1,4-DCB e emitted to industrial soil per person in 2010	1.52E+04	0.000965
Freshwater ecotoxicity	kg 1,4-DCB e emitted to freshwater per person in 2010	2.52E+01	0.815
Marine ecotoxicity	kg 1,4-DCB e emitted to seawater per person in 2010	4.34E+01	0.969
Human carcinogenic toxicity	kg 1,4-DCB e emitted to urban air per person in 2010	1.03E+01	0.361
Human non-carcinogenic toxicity	kg 1,4-DCB e emitted to urban air per person in 2010	3.13E+04	0.00671
Land use	m^2e annual crop per person in 2010	6.17E+03	0.000162
Mineral resource scarcity	kg Cu e per person in 2010	1.20E+05	0.00000833
Fossil resource scarcity	kg oil e per person in 2010	569.90	0.00102
Water consumption	m^3 consumed per person in 2010	2.67E+02	0.00375

[a] The actual units of a concrete environmental impact category in an LCA project are the physical/chemical/biological/toxicological (PCBT) units of the impact per Functional Unit

[b] The unit load is given in [units of the environmental impact type/(person*yr] where the 'units of the environmental impact type' means the PCBT units. For example the unit environmental load would have the units 'kg of CO2 eq. /(person*yr)'.

[c] The normalization factor units are the inverse of the unit environmental load.

Table S7.2. Unit environmental loads and normalization factors from ratios NPEI/PEI by Simapro.

Impact category	Units of the environmental impact[a]	Unit load (U or N) [units of the environmental impact type/(person*year]b	Normalización WReCiPe 2016 Midpont (H) V1.03 World (2010)H (Fn) [(person*year)/units of the environmental impact type]c
Global warming	kg CO_2 e	7.99E+03	0.0001252
Stratospheric ozone depletion	kg CFC11 e	6.00E-02	16.7
Ionizing radiation	kBq Co-60 e	4.80E+02	0.00208
Ozone formation, Human health	kg NOx e	2.06E+01	0.0486
Fine particulate matter formation	kg PM2.5 e	2.56E+01	0.0391
Ozone formation, Terrestrial ecosystems	kg NOx e	1.77E+01	0.0563
Terrestrial acidification	kg SO2 e	4.10E+01	0.0244
Freshwater eutrophication	kg P e	6.50E-01	1.54
Marine eutrophication	kg N e	4.62E+00	0.217
Terrestrial ecotoxicity	kg 1,4-DCB e	1.52E+04	0.000965
Freshwater ecotoxicity	kg 1,4-DCB e	2.52E+01	0.815
Marine ecotoxicity	kg 1,4-DCB e	4.34E+01	0.969
Human carcinogenic toxicity	kg 1,4-DCB e	1.03E+01	0.361
Human non-carcinogenic toxicity	kg 1,4-DCB e	3.13E+04	0.00671
Land use	m^2e annual crop	6.17E+03	0.000162
Mineral resource scarcity	kg Cu e	1.20E+05	0.00000833
Fossil resource scarcity	kg oil e	569.90	0.00102
Water consumption	m^3	2.67E+02	0.00375

[a] The actual units of a concrete environmental impact category in an LCA project are the physical/chemical/biological/toxicological (PCBT) units of the impact per Functional Unit

[b] The unit load is given in [units of the environmental impact type/(person*yr) where the 'units of the environmental impact type' means the PCBT units. For example the unit environmental load would have the units 'kg of CO2 eq. /(person*yr)'.

[c] The normalization factor units are the inverse of the unit environmental load.

References

National Institute for Public Health and the Environment (2024). ReCiPe reports 2016. Normalization factors.

Sala, S., et al. (201). Indicators for environmental sustainability. In Life Cycle Assessment: Theory and Practice In: *Encyclopedia of Life Support Systems (EOLSS*) pp. 491-516.

Annex S8. Environmental sustainability metrics based on potential normalized environmental impacts. GBAER environmental sustainability indices

The environmental sustainability indices α, σ and τ (Equations S8.1 – S8.3) were developed in the GBAER in order to compare between different technologies and determine their environmental sustainability. These indices allow analyzing the results obtained by the SimaPro software and positioning the technologies in a σ-τ plane (Fig. S8.1), to facilitate their comparison (Yáñez-Vergara, 2022; Sierra-Gachuz *et al.,* 2022).

$$\alpha = \sum_{j=1}^{i=18} \mathrm{NPEIj} \qquad \text{(S8.1)}$$

where
NPEI= Normalized potential environment impact

Let us assume the following scenario:
It is wanted to compare the environmental sustainability of an existing, conventional technology that is known as the 'reference' technology (subscript $_{REFT}$) with that of new or under evaluation technology (subscript $_{EVT}$) (Sierra-Gachuz et al., 2022)
It is convenient to define the variable σ as below

$$\sigma = \log\left[\frac{(\alpha_{\mathrm{REFT}})}{(\alpha_{\mathrm{EVT}})}\right] \qquad \text{(S8.2)}$$

where

α_{REFT}= α of the REFT

α_{EVT} = α of the EVT
REFT= Reference technology
EVT= Evaluated technology

The variable τ is defined below

$$\tau = \log\left[\frac{(\mathrm{N_{EVT}} + 1)}{(\mathrm{N_{REFT}} + 1)}\right] \qquad \text{(S8.3)}$$

where N_{EVT}: N° of NPEI in REFT higher than EVT, or equivalently, No of NPEI in EVT that are lower than the corresponding NPEI in REFT, and
N_{REFT}: N° of NPEI in EVT higher than REFT, or equivalently, No of NPEI in REFT that are lower than the corresponding NPEI in EVT

The sum of 1 in the numerator and denominator of Eq S8.3 avoids particular cases of indetermination of log (0/D) or log (N/0)

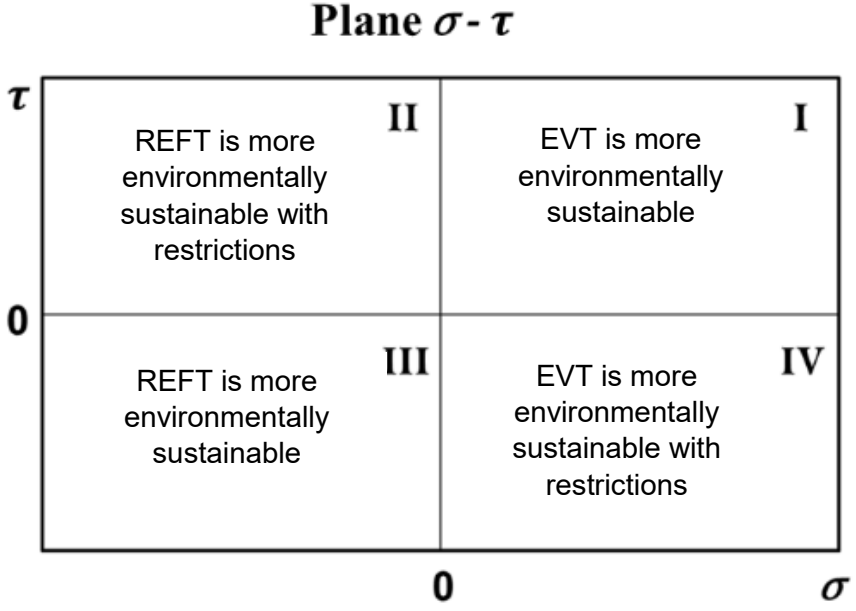


Fig. S8.1. Plane σ- τ

The plane σ - τ shown in Fig. S8.1. allows us to locate the variables σ and τ as one point P within on the plane and compare between different technologies and determine their environmental sustainability according to the P position ; (I) the evaluated technology is more environmentally sustainable; (II) reference technology is more environmentally sustainable with restrictions; (III) reference technology is more environmentally sustainable; and (IV) Technology evaluated is more environmentally sustainable with restrictions.

"With Restrictions" means that the number of NPEIs of the less sustainable technology, which are lower than the corresponding NPEIs of the second technology, can be higher than half of the total number of NPEIs (i.e., higher than 9). In spite of this feature, the magnitudes of the NPEIs are such that the overall alpha of the α less sustainable technology is the highest. In practical terms, the restrictions point out to

further work optimizing and improving sustainabilities of particular niches of the more sustainability technology.

In our case, the evaluated technology is BRF whereas the reference technology is IER. This is because the Mexico City's authorities decided to place an order for the construction and operation of a mega incinerator that would provide thermal treatment to nearly 12'0000 t/d of MSW in 2017. Table S8.1. summarizes the information required for the calculations of the metrics sigma and tau in our work. Fig. S8.2 shows the position of the point P with coordinates (sigma, tau) for our particular sustainability evaluation of BRF and IER of OFMSW

Table S8.1. Summary of sustainability metrics calculation

α_{BRF}	α_{IER}	σ	N_{EVT}	N_{REFT}	τ
40.7251	179.113	log(179.113/40.7251)= 0.6433	6	12	Log[(6+1)/(12+1)] = -0.2688

Therefore, the point P(0.6433, -0.2688) that represents the sustainability comparison is located in the Quadrant IV. It means that our BRF is more sustainable (with restrictions) than the IER.

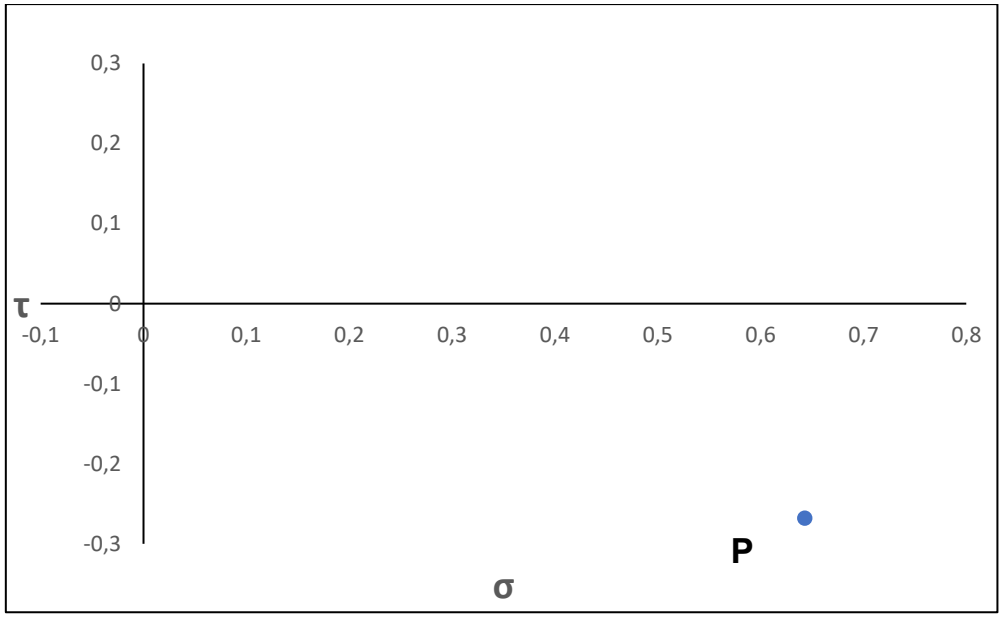


Figure S8.2. Position of the point P(sigma,tau) that represents the result of the sustainability evaluation between BRF and IER in our work.

Annex S9. Proxies of relevant processes for BRF techonology

In this annex we show the most relevant proxies for BRF technology taken from Ecoinvent (2019) SimaPro. The relevant emissions or processes can be identified in red or green.

Table S9.1. Proxi "Sodium phosphate {RoW}| production | Cut-off, U"

Products			
Sodium phosphate {RoW}| production | Cut-off, U	1	kg	100
Resources			
Water, unspecified natural origin, RoW	in water	0.000931	m3
Materials/fuels			
Chemical factory, organics {GLO}| market for | Cut-off, U	4E-10	p	Reg. normal
Heat, district or industrial, natural gas {CA-QC}| market for | Cut-off, U	0.00419097	MJ	Reg. normal
Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.24080903	MJ	Reg. normal
Heat, district or industrial, other than natural gas {CA-QC}| market for | Cut-off, U	0.00017533	MJ	Reg. normal
Heat, district or industrial, other than natural gas {RoW}| market for | Cut-off, U	0.39282467	MJ	Reg. normal
Nitrogen, liquid {RoW}| market for | Cut-off, U	0.019	kg	Reg. normal
Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for | Cut-off, U	0.99	kg	Reg. normal
Soda ash, light, crystalline, heptahydrate {GLO}| market for | Cut-off, U	0.737	kg	Reg. normal
Electricity/heat			
Emissions to air			
Carbon dioxide, fossil	high. pop.	0.967	kg
Nitrogen, atmospheric		0.019	kg
Water/m3		0.00019086	m3
Emissions to wáter			
Water, RoW		0.00074015	m3

Table S9.2. Phosphoric acid, industrial grade, without water, in 85% solution state {RER}| purification of wet-process phosphoric acid to industrial grade, product in 85% solution state | Cut-off, U

Products			
Phosphoric acid, industrial grade, without water, in 85% solution state {RER}| purification of wet-process phosphoric acid to industrial grade, product in 85% solution state	Cut-off, U	1	kg	100
Avoided products			
Resources			
Water, cooling, unspecified natural origin, RER	in water	0.12275	m3
Water, well, RER	in water	0.004311	m3
Materials/fuels			
Chemical factory, organics {RER}| construction	Cut-off, U	4.7E-10	p	Reg. normal
Heat, district or industrial, natural gas {RER}| market group for	Cut-off, U	0.372	MJ	Reg. normal
Heat, district or industrial, other than natural gas {RER}| market group for	Cut-off, U	0.372	MJ	Reg. normal
Isopropanol {RER}| market for isopropanol	Cut-off, U	0.007	kg	Reg. normal
Phosphoric acid, fertiliser grade, without water, in 70% solution state {GLO}| market for	Cut-off, U	1.02	kg	Reg. normal
Quicklime, milled, loose {CH}| market for quicklime, milled, loose	Cut-off, U	0.108	kg	Reg. normal
Sodium hydroxide, without water, in 50% solution state {GLO}| market for	Cut-off, U	0.026	kg	Reg. normal
Sulfuric acid {RER}| market for sulfuric acid	Cut-off, U	0.129	kg	Reg. normal
Water, deionised, from tap water, at user {CH}| market for water, deionised, from tap water, at user	Cut-off, U	0.00111607	kg	Reg. normal
Water, deionised, from tap water, at user {Europe without Switzerland}| market for water, deionised, from tap water, at user	Cut-off, U	1.08888393	kg	Reg. normal
Electricity/heat			

Emissions to air			
Water/m3		0.04940197	m3
Emissions to wáter			
Fluoride		0.0014	kg
Sodium		0.0017	kg
Water, RER		0.07874904	m3
Waste to treatment			
H3PO4 purification residue {GLO}| market for | Cut-off, U			
Spent solvent mixture {CH}| market for spent solvent mixture | Cut-off, U			
Spent solvent mixture {Europe without Switzerland}| market for spent solvent mixture | Cut-off, U			

Table S9.3. Proxi: "H3PO4 purification residue {RoW}| treatment of H3PO4 purification residue, residual material landfill | Cut-off, U"

Waste treatment			
H3PO4 purification residue {RoW}| treatment of H3PO4 purification residue, residual material landfill | Cut-off, U	1	kg	
Avoided products			
Resources			
Materials/fuels			
Cement, unspecified {Europe without Switzerland}| market for cement, unspecified | Cut-off, U	0.03754	kg	Reg. normal
Cement, unspecified {RoW}| market for cement, unspecified | Cut-off, U	0.36246	kg	Reg. normal
Process-specific burdens, residual material landfill {Europe without Switzerland}| market for process-specific burdens, residual material landfill | Cut-off, U	0.282874	kg	Reg. normal
Process-specific burdens, residual material landfill {RoW}| market for process-specific burdens, residual material landfill | Cut-off, U	0.717126	kg	Reg. normal
Residual material landfill {GLO}| market for | Cut-off, U	2.08E-09	p	Reg. normal
Emissions to wáter			
Aluminium	River	1.39E-06	kg
Aluminium	groundwater, long-term	0.00083	kg
Arsenic	groundwater, long-term	4.89E-14	kg
Arsenic	River	4.89E-05	kg
Cadmium	groundwater, long-term	4.82E-07	kg
Cadmium	River	8.05E-10	kg

Calcium	River	4.13E-05	kg
Calcium	groundwater, long-term	0.02476	kg
Chromium VI	groundwater, long-term	0.000292	kg
Chromium VI	River	9.24E-05	kg
Copper	River	1.21E-08	kg
Copper	groundwater, long-term	7.28E-06	kg
Fluoride	River	0.002612	kg
Fluoride	groundwater, long-term	0.045578	kg
Iron	groundwater, long-term	2.8E-05	kg
Iron	River	4.68E-08	kg
Lead	River	1.21E-10	kg
Lead	groundwater, long-term	7.26E-08	kg
Magnesium	groundwater, long-term	0.001032	kg
Magnesium	River	1.72E-06	kg
Manganese	groundwater, long-term	5.2E-07	kg
Manganese	River	8.69E-10	kg
Mercury	River	3.74E-11	kg
Nickel	River	1.44E-07	kg
Nickel	groundwater, long-term	8.62E-05	kg
Phosphate	River	1.75E-05	kg

Phosphate	groundwater, long-term	0.010512	kg
Silicon	groundwater, long-term	0.028582	kg
Silicon	River	6.44E-05	kg
Sulfate	River	0.062028	kg
Sulfate	groundwater, long-term	0.51611	kg
Vanadium	groundwater, long-term	0.000698	kg
Vanadium	River	2.23E-06	kg
Zinc	River	2.72E-08	kg
Zinc	groundwater, long-term	1.63E-05	kg
Emissions to soil			
Final waste flows			
Non material emissions			
Social issues			
Economic issues			

Table S9.4. Proxi "Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U"

Materials/fuels	Amount	Units
	1.000	kg
Electricity, medium voltage {AU}| market for | Cut-off, U	0.022	kWh
Electricity, medium voltage {NZ}| market for electricity, medium voltage | Cut-off, U	0.004	kWh
Electricity, medium voltage {RAF}| market group for | Cut-off, U	0.072	kWh
Electricity, medium voltage {RAS}| market group for | Cut-off, U	1.027	kWh
Electricity, medium voltage {RLA}| market group for | Cut-off, U	0.138	kWh
Electricity, medium voltage {RNA}| market group for | Cut-off, U	0.482	kWh
Electricity, medium voltage {RoW}| market for | Cut-off, U	0.000	kWh
Electricity, medium voltage {RU}| market for | Cut-off, U	0.097	kWh
Total	1.842	kWh
Hard coal {AU}| market for | Cut-off, U	0.192	kg
Hard coal {CN}| market for | Cut-off, U	1.335	kg
Hard coal {ID}| market for | Cut-off, U	0.189	kg
Hard coal {IN}| market for hard coal | Cut-off, U	0.313	kg
Hard coal {RLA}| market for | Cut-off, U	0.045	kg
Hard coal {RNA}| market for | Cut-off, U	0.281	kg
Hard coal {RoW}| market for | Cut-off, U	0.416	kg
Hard coal {RU}| market for | Cut-off, U	0.147	kg
Hard coal {ZA}| market for | Cut-off, U	0.082	kg
Heat, district or industrial, natural gas {CA-QC}| market for | Cut-off, U	0.228	MJ
Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	13.072	MJ
Industrial furnace, coal, 1-10MW {GLO}| market for | Cut-off, U	3.21E-08	p
Water, completely softened, from decarbonised water, at user {GLO}| market for | Cut-off, U	12.434	kg
Emissions to air		
	6.18E-04	kg
Antimony	9.13E-08	kg
Arsenic	1.46E-06	kg
Barium	7.28E-06	kg
Benzene	2.89E-05	kg
Benzo(a)pyrene	5.78E-10	kg
Beryllium	7.28E-08	kg
Boron	2.74E-05	kg
Bromine	5.48E-07	kg
Cadmium	9.13E-08	kg
Calcium	7.28E-05	kg
Carbon dioxide, fossil	5.289	kg
Carbon monoxide, fossil	0.006	kg

Table S9.4. (Cont.) Proxi "Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U" (Ecoinvent, 2019)

Emision	Amount	Units
Selenium	5.48E-07	kg
Silicon	9.13E-04	kg
Sodium	3.65E-05	kg
Strontium	1.10E-05	kg
Sulfur dioxide	2.89E-02	kg
Thallium	9.13E-08	kg
Thorium	1.10E-07	kg
Thorium-228	3.18E-04	kBq
Thorium-232	2.02E-04	kBq
Tin	3.65E-08	kg
Titanium	2.19E-05	kg
Toluene	5.78E-06	kg
Uranium	1.46E-07	kg
Uranium-238	5.78E-04	kBq
Vanadium	2.19E-06	kg
Water/m3	1.87E-03	m3
Xylene	5.78E-06	kg
Zinc	1.83E-07	kg
Emissions to wáter		
Water, RoW	0.011	m3
Waste to treatment		
Hard coal ash {RoW}| market for hard coal ash | Cut-off, U	0.168	kg

Table S9.5. Proxi Treatment of coal mining waste proxi "Spoil from hard coal mining {GLO}| treatment of, in surface

Waste treatment	Amount	Units
Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	1.00E+00	Kg
Emissions to water		
Aluminium	1.42E-07	Kg
Aluminium	8.51E-05	Kg
Antimony	1.13E-10	Kg
Antimony	6.36E-08	Kg
Arsenic	1.08E-09	Kg
Arsenic	6.24E-07	Kg
Barium	6.04E-09	Kg
Barium	3.62E-06	Kg
Beryllium	4.38E-10	Kg
Beryllium	2.62E-07	Kg
Cadmium	1.07E-07	Kg
Cadmium	1.78E-10	Kg
Calcium	3.17E-03	Kg
Calcium	5.64E-05	Kg
Chloride	4.30E-04	Kg
Chloride	1.47E-05	Kg
Chromium VI	2.28E-09	Kg
Chromium VI	1.34E-06	Kg
Cobalt	7.05E-09	Kg
Cobalt	3.47E-06	Kg
Copper	1.80E-06	Kg
Copper	3.70E-09	Kg
Fluoride	1.71E-06	Kg
Fluoride	1.49E-07	Kg
Iron	4.72E-07	Kg
Iron	2.83E-04	Kg
Lead	1.05E-10	Kg
Lead	6.27E-08	Kg
Magnesium	1.76E-03	Kg
Magnesium	2.25E-05	Kg
Manganese	1.41E-04	Kg
Manganese	1.07E-06	Kg
Mercury	1.20E-10	Kg
Mercury	4.85E-08	Kg
Molybdenum	1.58E-09	Kg

Table S9.5. (Cont.) Proxi Treatment of coal mining waste proxi "Spoil from hard coal mining {GLO}| treatment of, in surface

Waste	Amount	Units
Molybdenum	8.26E-07	Kg
Nickel	1.60E-05	Kg
Nickel	3.97E-08	Kg
Nitrate	1.86E-04	Kg
Nitrate	2.77E-06	Kg
Phosphate	5.51E-04	Kg
Phosphate	7.89E-05	Kg
Potassium	2.23E-06	Kg
Potassium	1.20E-03	Kg
Scandium	3.38E-07	Kg
Scandium	5.87E-10	Kg
Selenium	5.56E-07	Kg
Selenium	1.71E-09	Kg
Silicon	2.83E-06	Kg
Silicon	1.69E-03	Kg
Silver	3.04E-09	Kg
Silver	4.99E-10	Kg
Sodium	1.92E-03	Kg
Sodium	6.34E-06	Kg
Strontium	6.13E-05	Kg
Strontium	5.94E-07	Kg
Sulfate	1.42E-02	Kg
Sulfate	2.92E-04	Kg
Thallium	2.53E-11	Kg
Thallium	1.52E-08	Kg
Tin	3.43E-11	Kg
Tin	2.05E-08	Kg
Titanium	2.65E-09	Kg
Titanium	1.59E-06	Kg
Tungsten	2.10E-08	Kg
Tungsten	5.35E-11	Kg
Vanadium	6.99E-07	Kg
Vanadium	1.18E-09	Kg
Zinc	3.17E-08	Kg
Zinc	1.90E-05	Kg

Table S9.6. Proxi "Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U" l " Ecotoxicidad al agua dulce, y agua marina, etapa NN

Waste treatment	Amount	Units
Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	1.00E+00	Kg
Emissions to water		
Aluminium	1.42E-07	Kg
Aluminium	8.51E-05	Kg
Antimony	1.13E-10	Kg
Antimony	6.36E-08	Kg
Arsenic	1.08E-09	Kg
Arsenic	6.24E-07	Kg
Barium	6.04E-09	Kg
Barium	3.62E-06	Kg
Beryllium	4.38E-10	Kg
Beryllium	2.62E-07	Kg
Cadmium	1.07E-07	Kg
Cadmium	1.78E-10	Kg
Calcium	3.17E-03	Kg
Calcium	5.64E-05	Kg
Chloride	4.30E-04	Kg
Chloride	1.47E-05	Kg
Chromium VI	2.28E-09	Kg
Chromium VI	1.34E-06	Kg
Cobalt	7.05E-09	Kg
Cobalt	3.47E-06	Kg
Copper	1.80E-06	Kg
Copper	3.70E-09	Kg
Fluoride	1.71E-06	Kg
Fluoride	1.49E-07	Kg
Iron	4.72E-07	Kg
Iron	2.83E-04	Kg
Lead	1.05E-10	Kg
Lead	6.27E-08	Kg
Magnesium	1.76E-03	Kg
Magnesium	2.25E-05	Kg
Manganese	1.41E-04	Kg
Manganese	1.07E-06	Kg
Mercury	1.20E-10	Kg
Mercury	4.85E-08	Kg
Molybdenum	1.58E-09	Kg

Waste	Amount	Units
Molybdenum	8.26E-07	Kg
Nickel	1.60E-05	Kg

Nickel	3.97E-08	Kg
Nitrate	1.86E-04	Kg
Nitrate	2.77E-06	Kg
Phosphate	5.51E-04	Kg
Phosphate	7.89E-05	Kg
Potassium	2.23E-06	Kg
Potassium	1.20E-03	Kg
Scandium	3.38E-07	Kg
Scandium	5.87E-10	Kg
Selenium	5.56E-07	Kg
Selenium	1.71E-09	Kg
Silicon	2.83E-06	Kg
Silicon	1.69E-03	Kg
Silver	3.04E-09	Kg
Silver	4.99E-10	Kg
Sodium	1.92E-03	Kg
Sodium	6.34E-06	Kg
Strontium	6.13E-05	Kg
Strontium	5.94E-07	Kg
Sulfate	1.42E-02	Kg
Sulfate	2.92E-04	Kg
Thallium	2.53E-11	Kg
Thallium	1.52E-08	Kg
Tin	3.43E-11	Kg
Tin	2.05E-08	Kg
Titanium	2.65E-09	Kg
Titanium	1.59E-06	Kg
Tungsten	2.10E-08	Kg
Tungsten	5.35E-11	Kg
Vanadium	6.99E-07	Kg
Vanadium	1.18E-09	Kg
Zinc	3.17E-08	Kg
Zinc	1.90E-05	Kg

Table S9.7. Proxi "Spoil from lignite mining {GLO}| treatment of, in surface landfill | Ecotoxicidad al agua dulce etapa Z.

Waste treatment	Amount	Unit
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	1.0	Kg
Emissions to water		
Aluminium	7.08E-05	Kg
Aluminium	1.18E-07	Kg
Antimony	9.38E-11	Kg
Antimony	5.35E-08	Kg
Arsenic	8.96E-10	Kg
Arsenic	5.22E-07	Kg
Barium	3.01E-06	kg
Barium	5.03E-09	Kg
Beryllium	3.65E-10	Kg
Beryllium	2.18E-07	Kg
Cadmium	8.88E-08	Kg
Cadmium	1.48E-10	Kg
Calcium	3.18E-03	Kg
Calcium	4.69E-05	Kg
Chloride	4.33E-04	Kg
Chloride	1.23E-05	Kg
Chromium VI	1.90E-09	Kg
Chromium VI	1.12E-06	Kg
Cobalt	3.47E-06	Kg
Cobalt	5.87E-09	Kg
Copper	1.80E-06	Kg
Copper	3.08E-09	Kg
Fluoride	1.25E-07	Kg
Fluoride	1.74E-06	Kg
Iron	2.36E-04	Kg
Iron	3.93E-07	Kg
Lead	5.22E-08	Kg
Lead	8.72E-11	Kg
Magnesium	1.76E-03	Kg
Magnesium	1.87E-05	Kg
Manganese	8.91E-07	Kg
Manganese	1.41E-04	Kg
Mercury	9.99E-11	Kg
Mercury	4.85E-08	Kg
Molybdenum	7.03E-07	Kg
Molybdenum	1.32E-09	kg

Table S9.7. (Cont.) Proxi "Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U" Ecotoxicidad al agua dulce etapa Z.

Product	Amount	Units
Nickel	1.60E-05	Kg
Nickel	3.30E-08	Kg
Nitrate	1.87E-04	Kg
Nitrate	2.31E-06	Kg
Phosphate	5.64E-04	Kg
Phosphate	6.57E-05	Kg
Potassium	1.86E-06	Kg
Potassium	1.02E-03	Kg
Scandium	2.83E-07	Kg
Scandium	4.89E-10	Kg
Selenium	5.08E-07	kg
Selenium	1.42E-09	kg
Silicon	1.41E-03	kg
Silicon	2.36E-06	kg
Silver	4.16E-10	kg
Silver	3.12E-09	kg
Sodium	1.77E-03	kg
Sodium	5.28E-06	kg
Strontium	6.14E-05	kg
Strontium	4.95E-07	kg
Sulfate	1.43E-02	kg
Sulfate	2.43E-04	kg
Thallium	2.11E-11	kg
Thallium	1.26E-08	kg
Tin	1.71E-08	kg
Tin	2.85E-11	kg
Titanium	1.32E-06	kg
Titanium	2.21E-09	kg
Tungsten	4.45E-11	kg
Tungsten	1.86E-08	kg
Vanadium	9.82E-10	kg
Vanadium	5.83E-07	kg
Zinc	2.64E-08	kg
Zinc	1.58E-05	Kg

Annex S10. Characterization impacts for BRF

Annex S10.1. Process contribution results to the human carcinogenic toxicity category of BRF HMEZS-NN technology

In Fig. S10.1. and table S10.1 the results referring to the contribution of processes to the category of human carcinogenic toxicity can be observed.

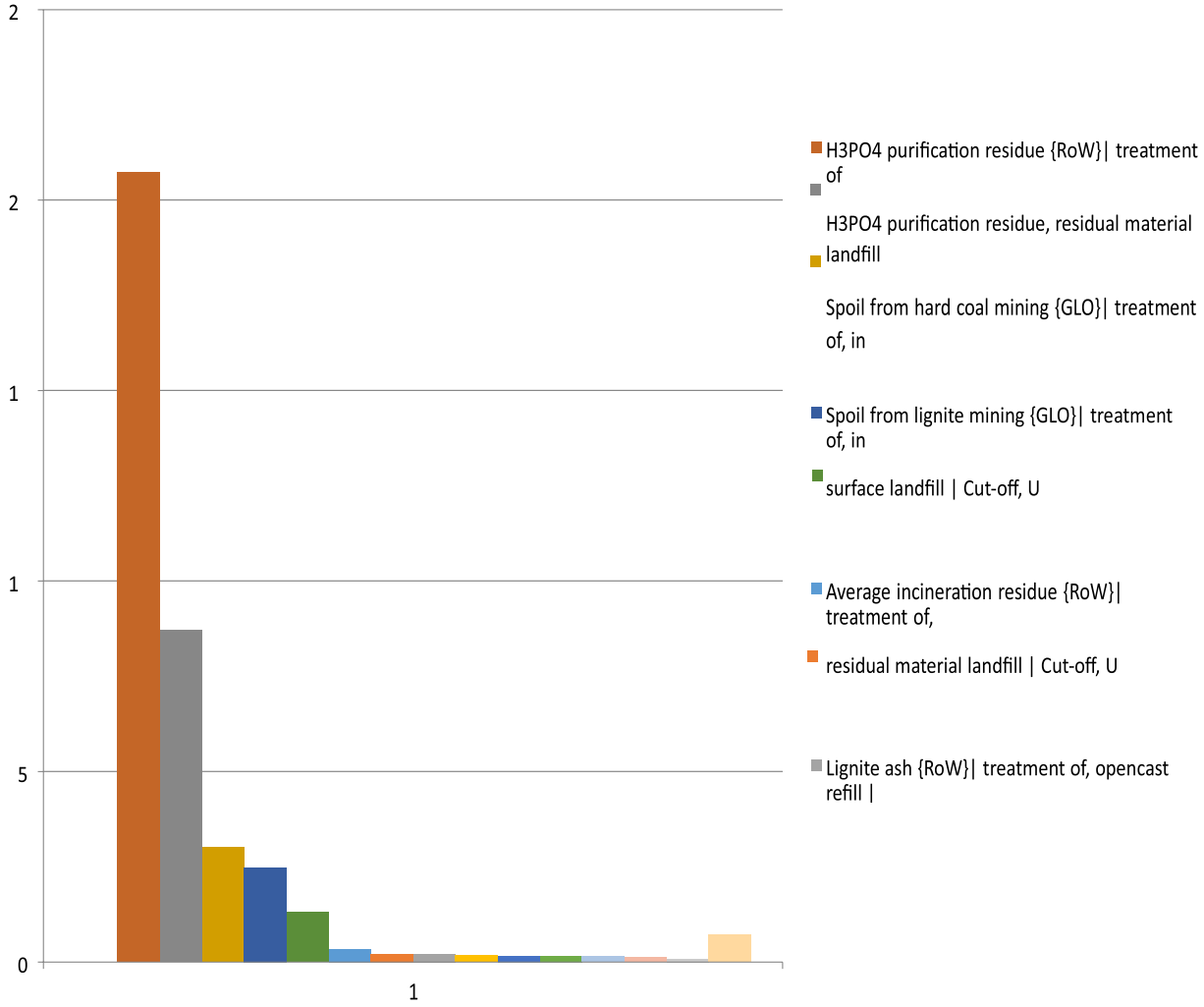


Figure S10.1. General contributions of the HMEZS-NN BRF processes to the human carcinogenic toxicity category

Table S10.1. Contributions of the BRF HMEZS-NN stages to the category Human toxicity of carcinogenic type.

Proceso	Proyecto	Unidad	Total	_BRF-ETAPA EXTRACCION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICACION	_BRF-ETAPA Z
El total de todos los procesos		kg 1,4-DCB	38.5963	0.5961	1.4449	0.4422	10.47	2.509	23.139
Procesos remanentes		kg 1,4-DCB	1.7880	0.0651	0.1591	0.0359	0.43	0.212	0.882
H3PO4 purification residue {RoW}| treatment of H3PO4 purification residue, residual material landfill | Cut-off, U	Ecoinvent 3 - al	kg 1,4-DCB	20.7181	0.0000	0.0002	0.0000	0.00	0.000	20.718
U	Ecoinvent 3 - al	kg 1,4-DCB	8.7146	0.1394	0.8109	0.2323	6.21	0.776	0.550
Hard coal ash {RoW}| treatment of, residual material landfill | Cut-off, U	Ecoinvent 3 - al	kg 1,4-DCB	3.0139	0.0608	0.1162	0.0405	2.02	0.567	0.207
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	Ecoinvent 3 - al	kg 1,4-DCB	2.4902	0.0831	0.2438	0.0982	0.86	0.798	0.407
Coal slurry {GLO}| treatment of, impoundment | Cut-off, U	Ecoinvent 3 - al	kg 1,4-DCB	1.3138	0.0208	0.1140	0.0352	0.94	0.120	0.083
Average incineration residue {RoW}| treatment of, residual material landfill | Cut-off, U	Ecoinvent 3 - al	kg 1,4-DCB	0.3371	0.2252	0.0005	0.0001	0.00	0.027	0.084

In the BRF, the processes are mainly related to the treatment of phosphoric acid residues, which are found in some processes and materials found in the main files (Table S10.1). In the process, 85% of the toxic load and 60% of the total toxic load of the BRF are included (Table S10.1). With the data obtained, it can be assumed that the use of phosphates is related to the process within the conformation of the culture medium of stage Z, or if a production of phosphoric acid and treatment of its waste from stage Z is manifested.

Annex 10.2. Process contribution results to the non-carcinogenic human toxicity category of BRF HMEZS-NN technology

The results referring to the contribution of processes to the category of non-carcinogenic human toxicity are observed in Fig. S10.2. and Table S10.2.

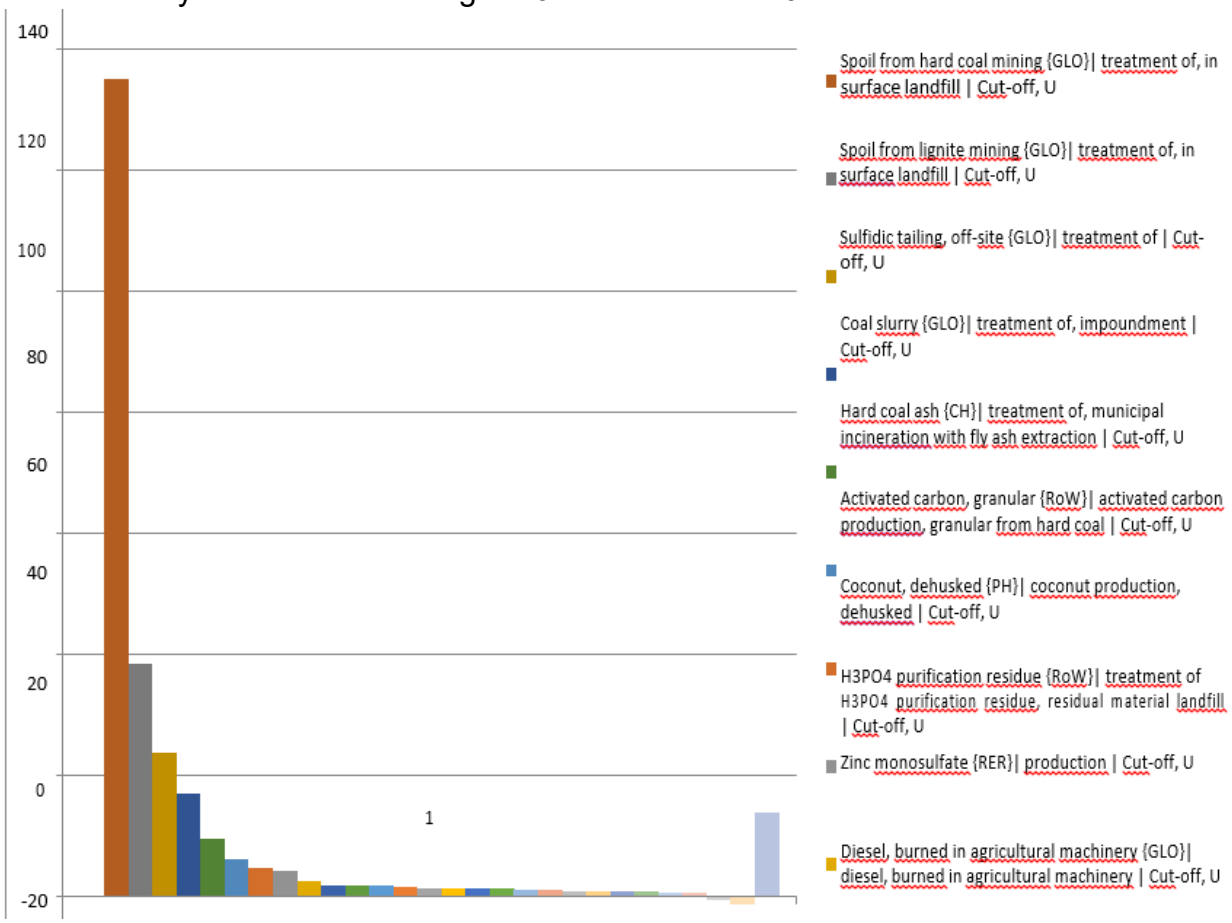


Fig. S10.2. General contributions of the HMEZS-NN BRF processes to the non-carcinogenic human toxicity category

It can be seen in Fig. S10.2. that some of the processes that are linked to coal mining and its multiple treatments are those that have the greatest influence on the category of non-carcinogenic human toxicity.

Table S10.2. Contributions of the HMEZS-NN BRF stages to the non-carcinogenic human toxicity category

Proceso	Unidad	Total	_BRF-ETAPA EXTRACCION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICACION	_BRF-ETAPA Z
El total de todos los procesos	kg 1,4-DCB	271.14	6.03	28.30	8.02	134.22	30.43	64.15
Procesos remanentes	kg 1,4-DCB	8.27	0.45	0.99	0.28	1.60	1.62	3.34
Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB	135.05	2.16	12.57	3.60	96.18	12.02	8.52
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB	38.36	1.28	3.76	1.51	13.26	12.29	6.27
Sulfidic tailing, off-site {GLO}| treatment of | Cut-off, U	kg 1,4-DCB	23.68	0.50	0.55	0.01	0.35	0.25	22.03
Coal slurry {GLO}| treatment of, impoundment | Cut-off, U	kg 1,4-DCB	16.95	0.27	1.47	0.45	12.14	1.55	1.08
Hard coal ash {CH}| treatment of, municipal incineration with fly ash extraction | Cut-off, U	kg 1,4-DCB	9.50	0.27	5.11	1.04	0.69	0.54	1.86
Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	kg 1,4-DCB	6.17	0.00	0.00	0.00	6.17	0.00	0.00
Coconut, dehusked {PH}| coconut production, dehusked | Cut-off, U	kg 1,4-DCB	4.52	0.00	0.00	0.00	0.00	0.00	4.52
H3PO4 purification residue {RoW}| treatment of H3PO4 purification residue, residual material landfill | Cut-off, U	kg 1,4-DCB	4.22	0.00	0.00	0.00	0.00	0.00	4.22
Zinc monosulfate {RER}| production | Cut-off, U	kg 1,4-DCB	2.35	0.00	0.00	0.00	0.00	0.00	2.35

It can be seen in Fig. S10.2 that 80% of the general effect of the BRF is the agglomeration of 4 processes that are in this category and that are non-explicit processes nested in others that have been summoned in the main files. However, it is necessary to corroborate whether coal mining and the treatment of its remains have any link with the production of activated carbon, since it has been observed that it significantly affects several impacts of the NN stage.

The NN stage was the most dominant, followed by the acts of the Z stages which manifest the effects of the process and finally the saccharification process is found.

Annex S10.3. Process contribution results to the marine ecotoxicity category of BRF HMEZS-NN technology

In Fig. S10.3. and Table S10.3 show the results regarding the contribution of processes to marine ecotoxicity.

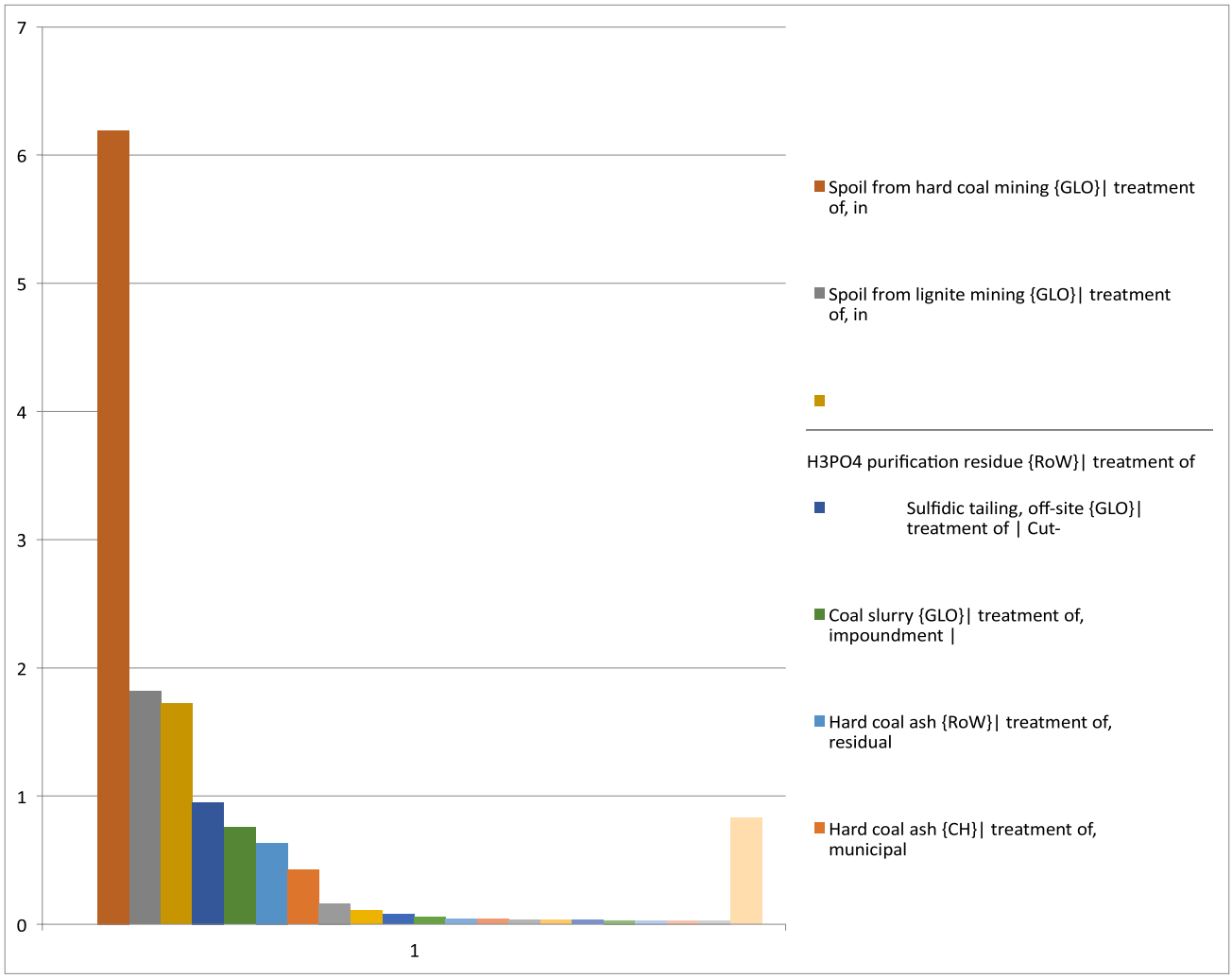


Fig. S10.3. Overall contributions of the BRF HMEZS-NN processes to the category Marine ecotoxicity in kg 1,4-DCBe

It can be seen in Fig. S10.3. that the coal processes and treatment of its waste, linked to the phosphoric acid waste treatment process, dominate the results. That is why they are found preponderantly, in the sense that this subset of processes contributes to multiple categories of toxicity and ecotoxicity impact.

Table S10.3. Contributions of the BRF HMEZS-NN stages to the marine ecotoxicity category: values tabulated in kg 1,4-DCBe

Proceso	Unidad	Total	_BRF-ETAPA EXTRACCION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICACION	_BRF-ETAPA Z
El total de todos los procesos	kg 1,4-DCB	14.039	0.296	1.226	0.342	6.273	1.496	4.407
Procesos remanentes	kg 1,4-DCB	1.110	0.078	0.128	0.029	0.213	0.132	0.530
H3PO4 purification residue {RoW}| treatment of H3PO4 purification residue, residual material landfill | Cut-off, U	kg 1,4-DCB	1.721	0.000	0.000	0.000	0.000	0.000	1.721
Sulfidic tailing, off-site {GLO}| treatment of | Cut-off, U	kg 1,4-DCB	0.954	0.020	0.022	0.000	0.014	0.010	0.887
Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB	6.192	0.099	0.576	0.165	4.410 0.551		0.391
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB	1.815	0.061	0.178	0.072	0.627	0.582	0.296
Steel in car shredder residue {RoW}| treatment of, municipal incineration | Cut-off, U	kg 1,4-DCB	0.163	0.000	0.000	0.000	0.000	0.000	0.163
Hard coal ash {CH}| treatment of, municipal incineration with fly ash extraction | Cut-off, U	kg 1,4-DCB	0.425	0.012	0.229	0.047	0.031	0.024	0.083
Coconut, dehusked {PH}| coconut production, dehusked | Cut-off, U	kg 1,4-DCB	0.079	0.000	0.000	0.000	0.000	0.000	0.079
Coal slurry {GLO}| treatment of, impoundment | Cut-off, U	kg 1,4-DCB	0.756	0.012	0.066	0.020	0.541	0.069	0.048
Hard coal ash {RoW}| treatment of, residual material landfill | Cut-off, U	kg 1,4-DCB	0.633	0.013	0.024	0.009	0.425	0.119	0.043
Phosphoric acid, fertiliser grade, without water, in 70% solution state {RoW}| phosphoric acid production, dihydrate process | Cut-off, U	kg 1,4-DCB	0.039	0.000	0.000	0.000	0.000	0.000	0.039
Zinc monosulfate {RER}| production | Cut-off, U	kg 1,4-DCB	0.033	0.000	0.000	0.000	0.000	0.000	0.033
Natural gas, unprocessed, at extraction {GLO}| production | Cut-off, U	kg 1,4-DCB	0.055	0.001	0.003	0.000	0.012	0.007	0.031
Wood preservation, pressure vessel, creosote, outdoor use, ground contact {RoW}| wood preservation, pressure vessel, creosote, outdoor use, ground contact | Cut-off, U	kg 1,4-DCB	0.031	0.000	0.000	0.000	0.000	0.000	0.031
Waste cement, hydrated {RoW}| treatment of, residual material landfill | Cut-off, U	kg 1,4-DCB	0.032	0.000	0.000	0.000	0.000	0.001	0.031

The main contributors to the total impact of marine ecotoxicity are the NN stage, which is found first, and then the Z stage. Between the two, they contribute about 76% of the ecotoxicity, since the NN stage predominates due to the contribution of fill treatment. of global coal mining waste and which are probably involved in the extraction of coal to make activated carbon.

Annex S10.4. Process contribution results for the BRF HMEZS-NN freshwater ecotoxicity category.

In Fig. S10.4. and Table S10.4 the results regarding the contribution of ecotoxicity processes to fresh water are observed.

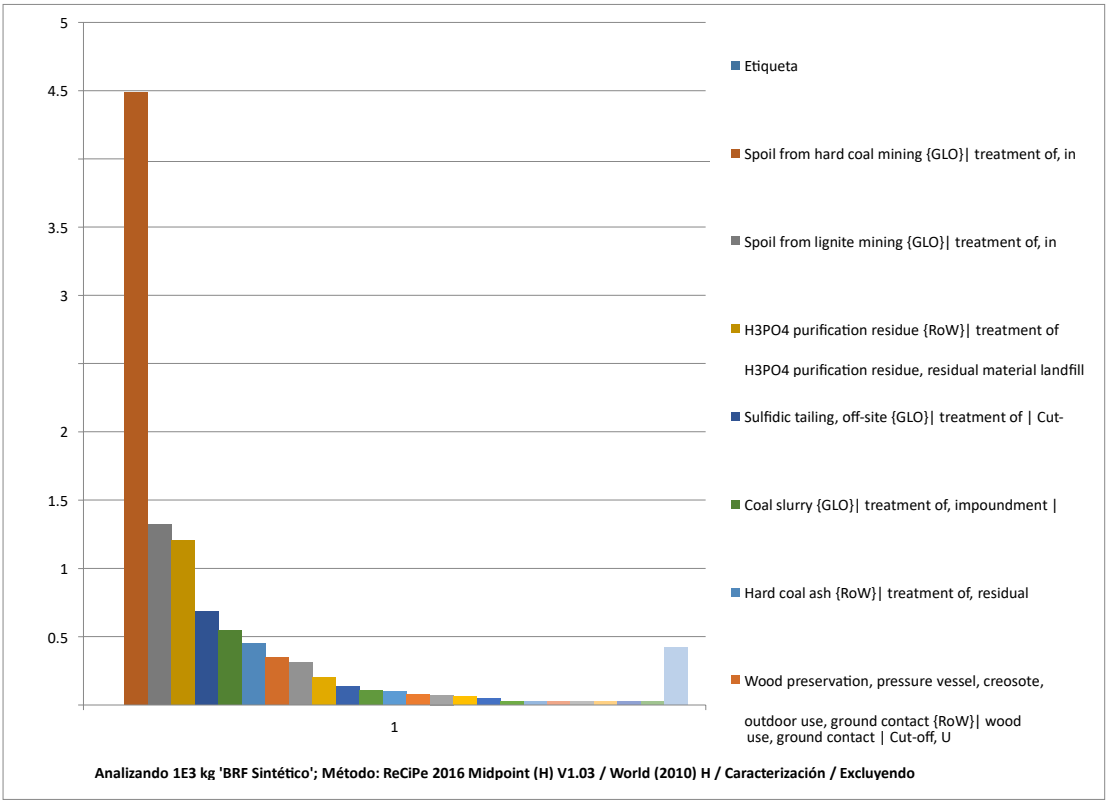


Fig. S10.4. Overall contributions of the HMEZS-NN BRF processes to the freshwater ecotoxicity category, units in kg 1.4 DCBe

Regarding Fig. S10.4 it can be appreciated that some processes linked to coal mining waste are the predominant contribution. Table S10.4. indicates that the processes with the greatest contributions are again NN and Z. In NN, in turn, the processes that are seen as dominant are those of order in relation to the waste from coal mining (hard coal) and lignite, in landfills. For the situation of process Z, the process that appears dominant with respect to the waste caused by the treatment of phosphoric acid that is disposed of in a landfill. This may be caused using phosphate salts in the Z culture medium, or by some tacit materials and processes nested in proxies.

Table S10.4. Contributions of the HMEZS-NN BRF stages to the freshwater ecotoxicity category: values tabulated in 1,4-DCBe

Proceso	Total	BRF-E	BRF-H	BRF-M	BRF-NN	BRF-S	BRF.Z
El total de todos los procesos	10.74	3.63E-01	8.66E-01	2.40E-01	4.49E+00	1.06E+00	3.73E+00
Procesos remanentes	0.54	3.93E-02	6.08E-02	1.05E-02	6.88E-02	4.56E-02	3.18E-01
Ácidos orgánicos y solventes	0.06	6.30E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Extracted fermented waste wb	0.0270	2.70E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coal slurry {GLO}| treatment of, impoundment | Cut-off, U	0.53	8.64E-03	4.75E-02	1.47E-02	3.91E-01	4.99E-02	3.47E-02
Coconut, dehusked {PH}| coconut production, dehusked | Cut-off, U	0.09	5.63E-09	1.67E-06	1.70E-08	4.37E-08	3.62E-08	9.46E-02
H3PO4 purification residue {RoW}| treatment of H3PO4 purification residue, residual material landfill | Cut-off, U	1.20	5.59E-07	8.75E-06	8.12E-07	-3.94E-06	2.51E-06	1.21E+00
Hard coal ash {CH}| treatment of, municipal incineration with fly ash extraction | Cut-off, U	0.31	8.78E-03	1.67E-01	3.41E-02	2.24E-02	1.77E-02	6.07E-02
Hard coal ash {RoW}| treatment of, residual material landfill | Cut-off, U	0.45	9.07E-03	1.73E-02	6.04E-03	3.02E-01	8.47E-02	3.08E-02
Lignite ash {RoW}| treatment of, opencast refill | Cut-off, U	0.08	2.74E-03	6.96E-03	1.83E-03	2.84E-02	2.65E-02	1.23E-02
Natural gas, unprocessed, at extraction {GLO}| production | Cut-off, U	0.04	1.11E-03	2.56E-03	2.42E-04	9.60E-03	5.53E-03	2.50E-02
Non-ionic surfactant {GLO}| non-ionic surfactant production, ethylene oxide derivate | Cut-off, U	0.20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.99E-01
Scrap copper {RoW}| treatment of, municipal incineration | Cut-off, U	0.03	1.40E-04	1.28E-03	1.95E-04	4.59E-03	7.31E-04	2.01E-02
Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	4.48	7.17E-02	4.17E-01	1.20E-01	3.19E+00	3.99E-01	2.83E-01
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	1.32	4.41E-02	1.29E-01	5.21E-02	4.56E-01	4.23E-01	2.16E-01
Steel in car shredder residue {RoW}| treatment of, municipal incineration | Cut-off, U	0.14	1.40E-08	2.54E-06	2.73E-08	7.19E-08	5.95E-08	1.36E-01
Sulfidic tailing, off-site {GLO}| treatment of | Cut-off, U	0.68	1.44E-02	1.58E-02	3.20E-04	1.00E-02	7.36E-03	6.37E-01

Annex S10.5. Process contribution results to BRF terrestrial ecotoxicity category H-M-E-Z-S-NN

Fig. S10.5 and Table S10.5 show the results referring to the contribution of processes to the category of terrestrial ecotoxicity are observed.

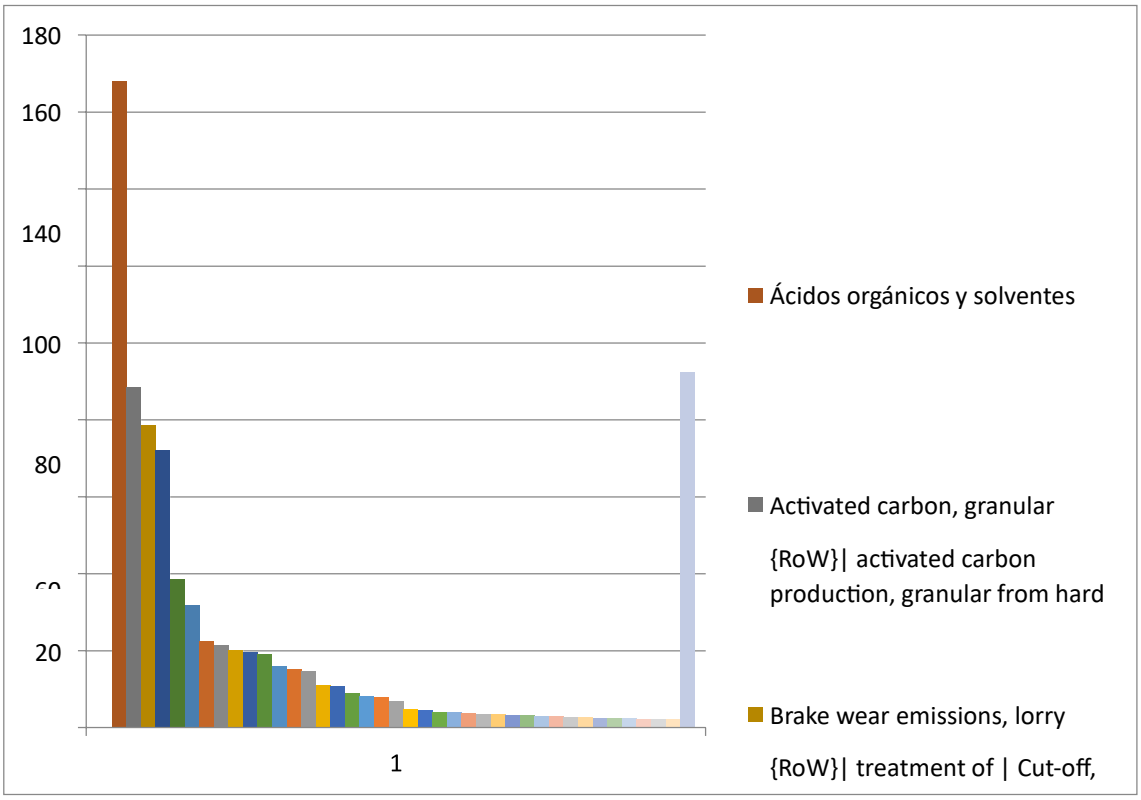


Fig S10.5. Overall contributions of BRF H-M-Z-S-NN processes to the terrestrial ecotoxicity category in units of kg 1.4 DCB e

In Fig. S10.5. and in Table S10.5. 2 processes are presented that predominate in the contribution of this category: the organic acid products and solvents (which are extracted in the extraction process from solids fermented in H), again the activated carbon that is used in NN and in the process Yes respectively. An omitted transportation process that causes emissions due to the consumption of the brakes of transport vehicles is presented in third place.

Table S10.5. Overall contributions of the BRF H-M-Z-S-NN processes to the terrestrial ecotoxicity category in units of kg 1.4 DCB and

Proceso	Total	BRF-E	BRF-H	BRF-M	BRF-NN	BRF-S	BRF-Z
El total de todos los procesos	832.154	272.233	68.499	23.099	153.691	66.062	248.570
Procesos remanentes	92.452	5.683	11.432	4.454	24.696	20.835	25.351
Ácidos orgánicos y solventes	168.017	168.017	0.000	0.000	0.000	0.000	0.000
Activated carbon, granular {RoW}| activated carbon production, granularfrom hard coal | Cut-off, U	88.593	0.000	0.000	0.000	88.593	0.000	0.000
Brake wear emissions, lorry {RoW}| treatment of | Cut-off, U	78.504	4.239	7.478	3.828	9.560	12.496	40.902
Extracted fermented waste wb	72.007	72.007	0.000	0.000	0.000	0.000	0.000
Zinc monosulfate {RER}| production | Cut-off, U	38.716	0.002	0.004	0.001	0.002	0.006	38.702
Brake wear emissions, lorry {RER}| treatment of | Cut-off, U	31.902	1.723	3.039	1.556	3.885	5.078	16.622
Zinc monosulfate {RoW}| production | Cut-off, U	22.436	0.661	0.006	0.001	0.186	0.294	21.287
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	21.319	0.723	14.644	0.026	0.485	0.392	5.049
Sulfuric acid {RoW}| primary zinc production from concentrate | Cut-off, U	20.250	0.615	0.006	0.001	0.173	0.274	19.182
Ammonia, liquid {RoW}| ammonia production, steam reforming, liquid | Cut- off, U	19.668	0.012	0.559	0.007	0.126	0.081	18.883
Ammonium sulfate, as N {GLO}| nickel mine operation, sulfidic ore | Cut-off,U	18.966	0.000	0.000	0.000	0.000	0.000	18.966
Heat, district or industrial, other than natural gas {RoW}| heat production, heavy fuel oil, at industrial furnace 1MW | Cut-off, U	15.991	0.423	11.175	0.019	0.360	0.293	3.720
Ammonia, liquid {RoW}| ammonia production, partial oxidation, liquid | Cut-off, U	15.108	0.009	0.430	0.005	0.097	0.062	14.505
Electricity, high voltage {RoW}| electricity production, oil | Cut-off, U	14.591	0.556	0.665	0.304	5.655	5.473	1.939
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW | Cut-off, U	10.940	0.012	3.445	6.761	0.675	0.006	0.041
Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| machine operation, diesel, >= 74.57 kW, low load factor | Cut-off, U	10.778	0.000	7.505	2.701	0.249	0.323	0.000
Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U	9.074	0.235	0.382	0.099	4.500	0.728	3.130
Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U	8.150	4.396	0.036	0.003	0.028	0.022	3.664
_Acetic acid modif2 HP, without water, in 98% solution state {RoW}| acetic acid production, product in 98% solution state | Cut-off, U	8.024	8.024	0.000	0.000	0.000	0.000	0.000
Electricity, high voltage {SA}| electricity production, oil | Cut-off, U	6.888	0.268	0.315	0.142	2.742	2.640	0.781

Annex S10.6. Process contribution results for the BRF terrestrial acidification category HMEZS-NN

Fig. S10.6 and Table S10.6 show the results referring to the contribution of processes to the terrestrial acidification category.

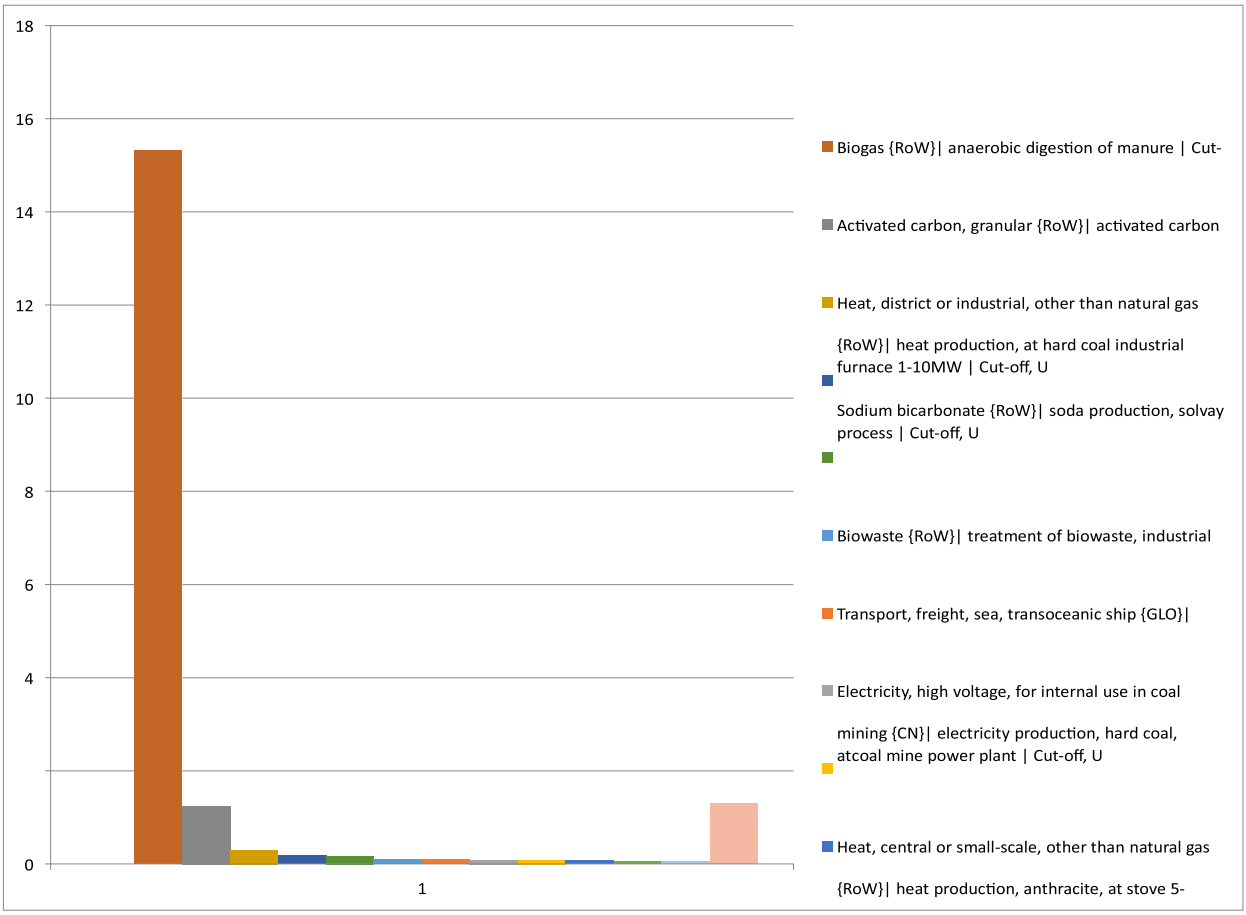


Fig. S10.6. General contributions of the HMEZS-NN BRF processes to the terrestrial acidification category. Units in kg SO2 e

It can be seen in Fig, A10.6. and in Table S10.6. that the processes that contribute the most are related to the methanogenesis/anaerobic digestion that occurs in Process M as in the NN process, contributing 67% of the contribution. Followed by it again is Activated Carbon which is a resource of the NN and S processes. In the first process it is used as a buffer to form the nanobioparticles; It is subsequently used to detoxify those hydrolysates abundant in reducing sugars that have fermentation inhibitors such as phenolic compounds and furans.

Table S10.6. Contributions of the BRF stages HMEZS-NN to the terrestrial acidification category: tabulated values in kg SO_2e

Process	Unidad	Total	_BRF-ETAPA EXTRACCION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICACION	_BRF-ETAPA Z
El total de todos los procesos	kg SO2 e	1.91E+01	1.08E-01	5.40E+00	9.68E+00	2.65E+00	4.23E-01	7.99E-01
Procesos remanentes	kg SO2 e	1.30E+00	4.33E-02	1.30E-01	1.09E-01	3.39E-01	2.49E-01	4.32E-01
Biogas {RoW}| anaerobic digestion of manure | Cut-off, U	kg SO2 e	1.53E+01	5.33E-04	4.84E+00	9.53E+00	9.44E-01	4.78E-03	5.68E-03
Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	kg SO2 e	1.25E+00	0.00E+00	0.00E+00	0.00E+00	1.25E+00	0.00E+00	0.00E+00
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	kg SO2 e	3.00E-01	1.02E-02	2.06E-01	3.66E-04	6.83E-03	5.53E-03	7.11E-02
Sodium bicarbonate {RoW}| soda production, solvay process | Cut-off, U	kg SO2 e	1.88E-01	0.00E+00	1.88E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sulfuric acid {RER}| production | Cut-off, U	kg SO2 e	1.73E-01	3.20E-06	1.78E-05	2.97E-06	6.02E-06	2.53E-05	1.73E-01
Biowaste {RoW}| treatment of biowaste, industrial composting | Cut-off, U	kg SO2 e	9.60E-02	9.16E-10	4.22E-08	2.87E-09	3.86E-09	9.60E-02	5.63E-06
Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U	kg SO2 e	9.10E-02	2.36E-03	3.83E-03	9.98E-04	4.51E-02	7.31E-03	3.14E-02
Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Cut-off, U	kg SO2 e	8.59E-02	1.54E-03	8.77E-03	2.26E-03	5.86E-02	9.44E-03	5.26E-03
Sulfuric acid {RoW}| production | Cut-off, U	kg SO2 e	8.46E-02	2.57E-03	2.33E-05	4.47E-06	7.22E-04	1.14E-03	8.01E-02
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW | Cut-off, U	kg SO2 e	6.61E-02	6.97E-05	2.08E-02	4.09E-02	4.08E-03	3.66E-05	2.46E-04
Electricity mix, AC, consumption mix, at consumer, 1kV - 60kV EU-27 S System - Copied from ELCD	kg SO2 e	4.98E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.98E-02	0.00E+00
Acetone, liquid {RoW}| production | Cut-off, U	kg SO2 e	4.76E-02	4.76E-02	5.86E-07	1.51E-07	2.94E-07	1.80E-07	2.85E-06

Annex 10.7. Process contribution results to freshwater eutrophication category for BRF HMZS-NN

The results of process contributions and BRF stages to the freshwater eutrophication category are shown in Fig. S10.7. and Table S10.7.

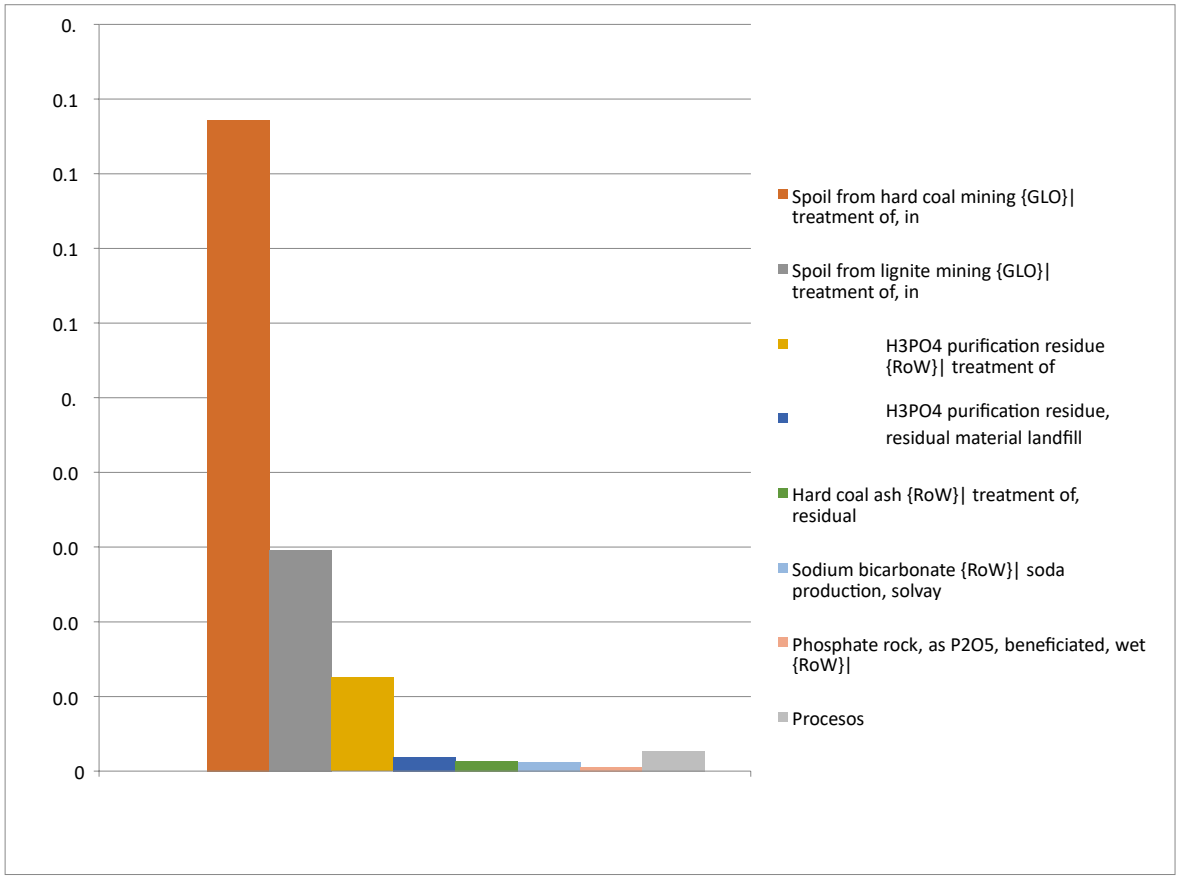


Figure S10.7. Overall contributions of BRF H-M-E-Z-S-NN processes to the Freshwater Eutrophication category. Units in kg Pe

Fig. S10.7. shows that the most relevant contributions deal with the M process as well as the NN process ("Biogas RoW | anaerobic digestion of manure…" method). Followed by Activated Carbon which is a resource of the NN and S processes. In the first process it is used as a buffer to form the nanobio particles; It is subsequently used to detoxify those hydrolysates abundant in reducing sugars that have fermentation inhibitors such as phenolic compounds and furans.

Table S10.7. General contributions of H-M-Z-S-NN BRF processes to the freshwater eutrophication category. Units in kg Pe

Proceso	Unidad	Total	ETAPA EXTRACCION	ETAPAH	ETAPAM	ETAPANN	ETAPA SACARIFICACION	ETAPAZ
El total de todos los procesos	kg P e	2.74E-01	5.78E-03	2.50E-02	7.08E-03	1.47E-01	3.55E-02	5.39E-02
Procesos remanentes	kg P e	4.71E-03	1.34E-04	2.36E-04	6.33E-05	5.38E-04	4.71E-04	3.26E-03
Spoil from hard coal mining {GLO}| treatment of, in surface landfill |Cut-off, U	kg P e	1.74E-01	2.79E-03	1.62E-02	4.65E-03	1.24E-01	1.55E-02	1.10E-02
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg P e	5.93E-02	1.98E-03	5.80E-03	2.34E-03	2.05E-02	1.90E-02	9.68E-03
H3PO4 purification residue {RoW}| treatment of H3PO4 purification residue, residual material landfill | Cut-off, U	kg P e	2.52E-02	1.17E-08	1.83E-07	1.70E-08	-8.22E-08	5.23E-08	2.52E-02
Sulfidic tailing, off-site {GLO}| treatment of | Cut-off, U	kg P e	3.77E-03	7.95E-05	8.71E-05	1.77E-06	5.52E-05	4.05E-05	3.51E-03
Hard coal ash {RoW}| treatment of, residual material landfill | Cut-off, U	kg P e	2.67E-03	5.37E-05	1.03E-04	3.58E-05	1.79E-03	5.02E-04	1.83E-04
Sodium bicarbonate {RoW}| soda production, solvay process | Cut-off, U	kg P e	2.50E-03	0.00E+00	2.50E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Phosphate rock, as P2O5, beneficiated, wet {RoW}| phosphate rock beneficiation, wet | Cut-off, U	kg P e	1.14E-03	4.86E-09	3.53E-08	9.55E-09	2.25E-08	7.40E-09	1.14E-03
Acetone, liquid {RoW}| production | Cut-off, U	kg P e	7.47E-04	7.47E-04	9.19E-09	2.37E-09	4.61E-09	2.82E-09	4.47E-08

Table S10.7. shows that processes M and H have the greatest contributions in the impact classification (50 and 25% respectively).
The stages exhibited in the first place are the NN stage with 50% of the total contribution, unlike the Z stage which is positioned in second place with 20% of the total contribution. In the processes that are related to coal mining waste, the NN stage is clearly found, while for the phosphoric acid purification waste, the Z Stage predominates.

Annex 10.8. Process contribution results to BRF global warming category HMEZS-NN

The results of process contributions and BRF stages to the global warming category are shown in Fig. S10.8. and Table S10.8.

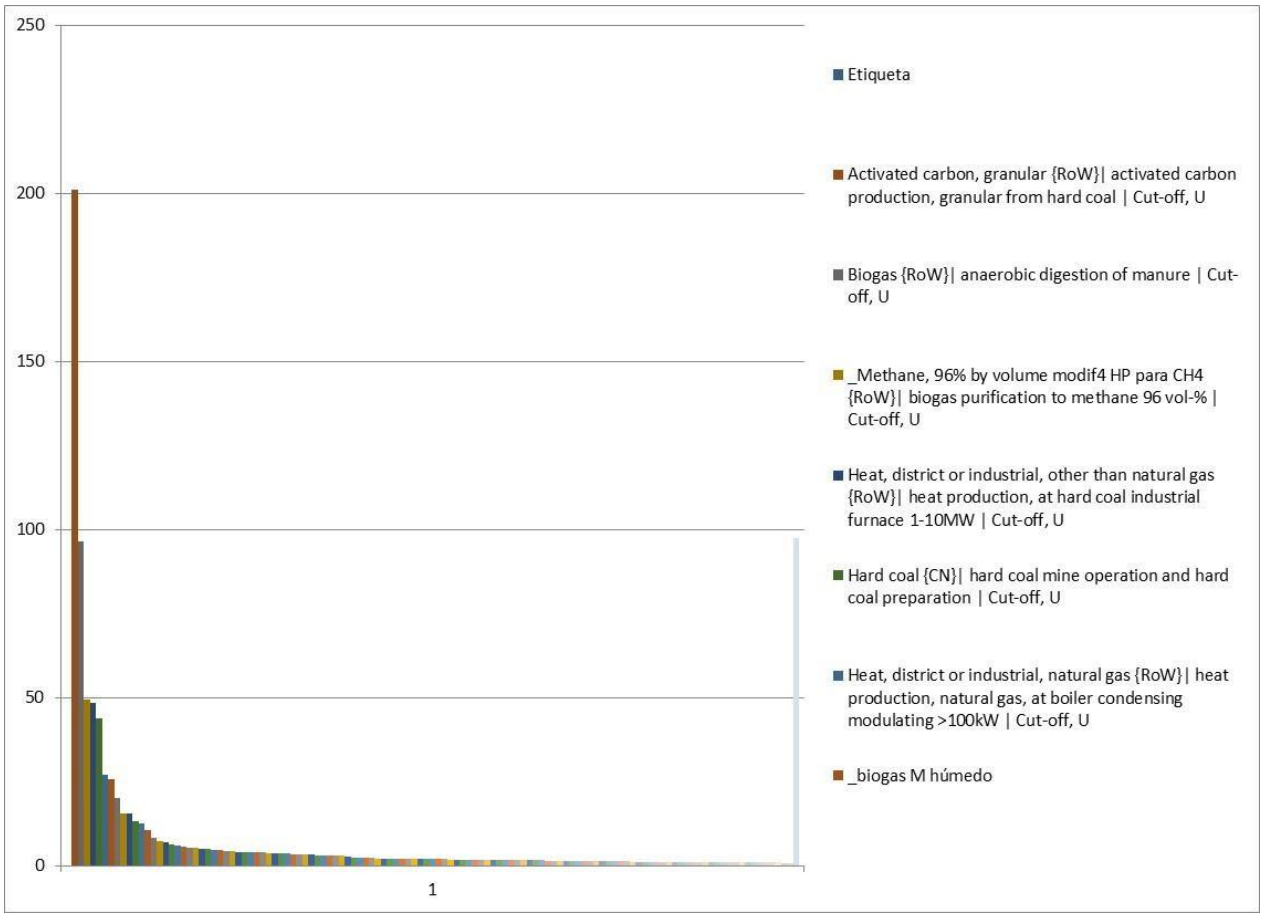


Fig. S10.8. General contributions of processes to the category General contributions of processes to the global warming category of the BRF HMEZS-NN

In table S10.8. and Fig. S10.8. It is observed that the contributing processes at the BRFs level are those associated with the NN stage (consequence of activated carbon and non-explicit proxy processes of its production) and the M stage (Biogas from the anaerobic digestion of agricultural waste in the rest of the world. '; 'wet methanogenic biogas produced in bireactor M'; 'methane purification.

Table S10.8. General contributions of processes to the category General contributions of processes to the global warming category of the BRF HMEZS-NN

Proceso	Unidad	Total	BRF-ETAPA EXTRACCION	BRF-ETAPA H	BRF-ETAPA M	BRF-ETAPA NN	BRF-ETAPA SACARIFICACION	BRF-ETAPA Z
El total de todos los procesos	kg CO2 e	942.43	33.79	126.64	159.73	357.40	94.53	170.34
Procesos remanentes	kg CO2 e	55.46	2.87	5.73	2.69	14.67	9.87	19.62
Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	kg CO2 e	201.10	0.00	0.00	0.00	201.10	0.00	0.00
Biogas {RoW}| anaerobic digestion of manure | Cut-off, U	kg CO2 e	96.67	0.00	30.52	60.12	5.95	0.03	0.04
_Methane, 96% by volume modif4 HP para CH4 {RoW}| biogas purification to methane 96 vol-% | Cut-off, U	kg CO2 e	49.40	0.00	0.00	49.40	0.00	0.00	0.00
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	kg CO2 e	48.39	1.64	33.24	0.06	1.10	0.89	11.46
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	kg CO2 e	43.82	0.79	4.47	1.15	29.91	4.81	2.68
Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler condensing modulating >100kW | Cut-off, U	kg CO2 e	27.04	0.00	0.00	0.00	0.00	2.46	24.58
_biogas M húmedo	kg CO2 e	25.83	0.00	0.00	25.83	0.00	0.00	0.00
Sodium phosphate {RoW}| production | Cut-off, U	kg CO2 e	20.27	0.00	0.00	0.00	0.00	0.00	20.27
Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| machine operation, diesel, >= 74.57 kW, low load factor | Cut-off, U	kg CO2 e	15.67	0.00	10.91	3.93	0.36	0.47	0.00
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW | Cut-off, U	kg CO2 e	15.62	0.02	4.92	9.65	0.96	0.01	0.06
Acetone, liquid {RoW}| production | Cut-off, U	kg CO2 e	13.42	13.42	0.00	0.00	0.00	0.00	0.00
Fermented wastes	kg CO2 e	12.78	0.00	12.78	0.00	0.00	0.00	0.00
Heat, district or industrial, natural gas {RU}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U	kg CO2 e	10.62	0.49	0.11	0.00	6.37	0.04	3.61
Electricity mix, AC, consumption mix, at consumer, 1kV - 60kV EU-27 S System - Copied from ELCD	kg CO2 e	8.33	0.00	0.00	0.00	0.00	8.33	0.00
Ethylene, average {RoW}| production | Cut-off, U	kg CO2 e	7.42	0.00	0.01	0.00	0.00	0.00	7.41
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	kg CO2 e	7.13	0.25	0.17	0.00	0.01	0.01	6.70
Cow milk {RoW}| milk production, from cow | Cut-off, U	kg CO2 e	6.50	0.00	0.00	0.00	0.00	0.00	6.50
Electricity, high voltage {CN-NM}| electricity production, hard coal | Cut-off, U	kg CO2 e	6.19	0.24	0.30	0.13	2.53	2.30	0.70
Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Cut-off, U	kg CO2 e	5.86	0.11	0.60	0.15	4.00	0.64	0.36
Hard coal {RoW}| hard coal mine operation and hard coal preparation | Cut-off, U	kg CO2 e	5.49	0.06	0.07	0.03	4.81	0.23	0.29
Heat, district or industrial, natural gas {RoW}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U	kg CO2 e	5.30	0.24	0.06	0.00	3.18	0.02	1.80
_Methane, 96% by volume modif2 HP para CH4 {RoW}| biogas purification to methane 96 vol-% | Cut-off, U	kg CO2 e	5.23	0.00	0.00	0.00	5.23	0.00	0.00
Ammonia, liquid {RoW}| ammonia production, steam reforming, liquid | Cut-off, U	kg CO2 e	5.19	0.00	0.15	0.00	0.03	0.02	4.99
Electricity, high voltage {CN-SD}| electricity production, hard coal | Cut-off, U	kg CO2 e	4.63	0.18	0.23	0.10	1.89	1.72	0.52
Electricity, high voltage {CN-JS}| electricity production, hard coal | Cut-off, U	kg CO2 e	4.61	0.18	0.23	0.10	1.88	1.71	0.52
Propylene {RoW}| production | Cut-off, U	kg CO2 e	4.27	4.12	0.00	0.00	0.00	0.00	0.14
Hard coal, run-of-mine {IN}| hard coal mine operation | Cut-off, U	kg CO2 e	4.26	0.09	0.40	0.11	2.71	0.65	0.30
Electricity, high voltage {RFC}| electricity production, lignite | Cut-off, U	kg CO2 e	4.25	0.16	0.19	0.09	1.64	1.59	0.58
Electricity, high voltage {RU}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U	kg CO2 e	4.23	0.16	0.22	0.09	1.74	1.53	0.48
Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U	kg CO2 e	4.18	0.11	0.18	0.05	2.07	0.34	1.44

Annex S10.9. Results of process contribution to the category of ozone formation in terrestrial ecosystems of BRF H-M-Z-S-NN

The results of process contributions and BRF stages to the category of ozone formation in terrestrial ecosystems are shown in Fig. S10.9. and Table S10.9.

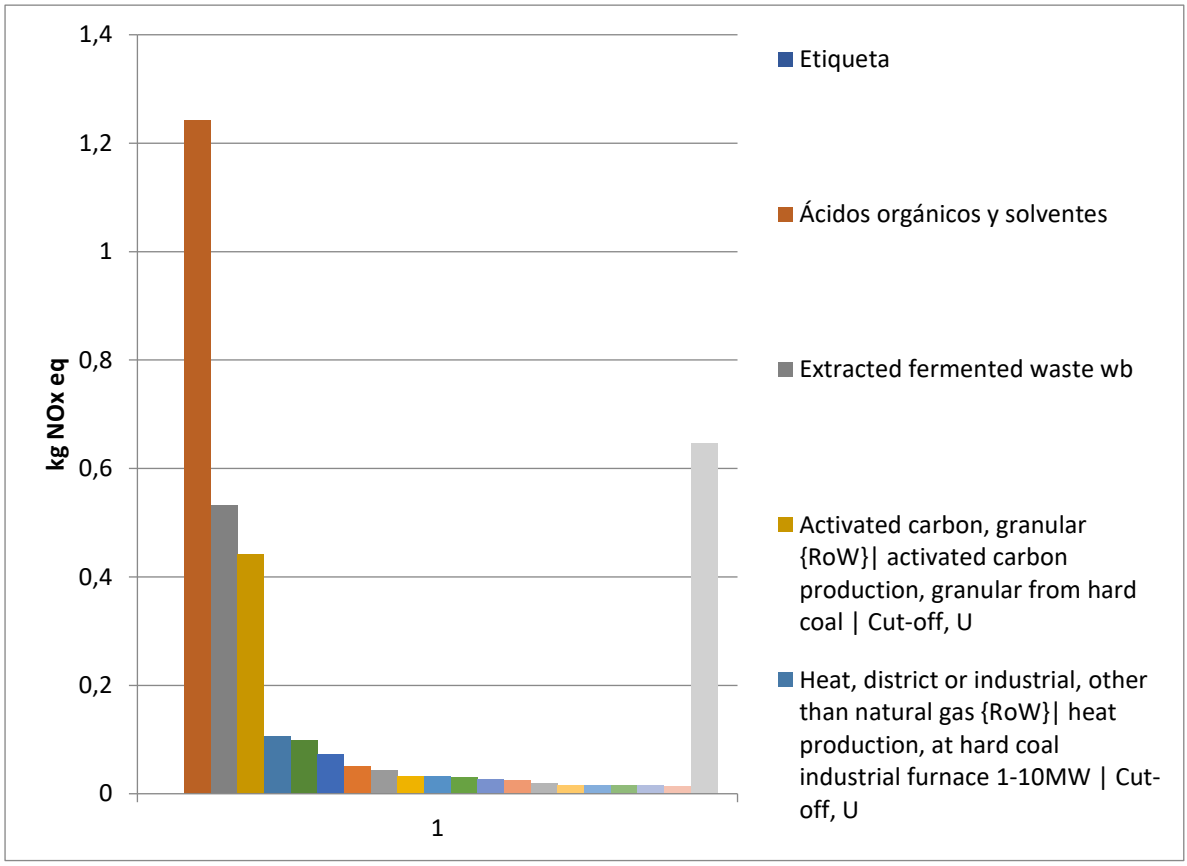


Fig. S10.9. General contributions of BRF H-M-E-Z-S-NN processes to the category Ozone formation in terrestrial ecosystems. Units in kg NOx e

There are 3 processes that predominate in a descending order and they are: Organic acids and solvents', 'Extracted fermented waste', and the production of activated C (Fig. S10.9). In stage E, the first two products are generated (extraction of organic acids and solvents). Providing 60% of the fermented solids that leave bioreactor H and that are subject to liquid-liquid extraction and the extract is distilled to reuse the extraction solvent. While the third process highlights the NN and S stages, which is where activated carbon is used.

Table S10.9. Contributions of the BRF stages H-M-E.Z-S-NN to the category ozone formation in terrestrial ecosystems: tabulated values in kg NOx e

Proceso	Total	_BRF-ETAPA EXTRACCION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICACION	_BRF-ETAPA Z
El total de todos los procesos	3.48E+00	1.91E+00	1.85E-01	1.38E-01	7.53E-01	1.76E-01	3.13E-01
Procesos remanentes	4.07E-01	2.65E-02	4.51E-02	1.17E-02	1.08E-01	9.22E-02	1.24E-01
Ácidos orgánicos y solventes	1.24E+00	1.24E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Extracted fermented waste wb	5.33E-01	5.33E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	4.43E-01	0.00E+00	0.00E+00	0.00E+00	4.43E-01	0.00E+00	0.00E+00
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	1.07E-01	3.61E-03	7.32E-02	1.30E-04	2.42E-03	1.96E-03	2.52E-02
_Electricity, high voltage CCCPP modif1 HP {RoW}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut- off, U	9.92E-02	0.00E+00	0.00E+00	8.98E-02	9.43E-03	0.00E+00	0.00E+00
Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U	7.34E-02	1.90E-03	3.09E-03	8.05E-04	3.64E-02	5.90E-03	2.53E-02
Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| machine operation, diesel, >= 74.57 kW, low load factor | Cut-off, U	5.01E-02	1.65E-11	3.49E-02	1.26E-02	1.16E-03	1.50E-03	9.56E-08
4-methyl-2-pentanone {RoW}| production | Cut-off, U	4.33E-02	4.33E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dodecanol {GLO}| dodecanol production, ziegler process | Cut-off, U	3.29E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.29E-02
Acetone, liquid {RoW}| production | Cut-off, U	3.16E-02	3.16E-02	3.88E-07	1.00E-07	1.95E-07	1.19E-07	1.89E-06
Transport, freight train {RoW}| diesel | Cut-off, U	2.95E-02	1.87E-03	2.04E-03	9.23E-04	8.09E-03	4.93E-03	1.17E-02
Blasting {RoW}| processing | Cut-off, U	2.60E-02	4.13E-04	3.04E-03	6.15E-04	1.58E-02	2.42E-03	3.68E-03
Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Cut-off, U	2.51E-02	4.51E-04	2.56E-03	6.61E-04	1.71E-02	2.76E-03	1.54E-03
Electricity, high voltage {CN-NM}| electricity production, hard coal | Cut-off, U	2.01E-02	7.65E-04	9.90E-04	4.20E-04	8.22E-03	7.46E-03	2.27E-03
Diesel, burned in building machine {GLO}| processing | Cut-off, U	1.63E-02	1.55E-04	2.53E-03	2.48E-04	6.73E-03	1.06E-03	5.52E-03
Transport, freight train {CN}| diesel | Cut-off, U	1.60E-02	2.89E-04	1.63E-03	4.22E-04	1.09E-02	1.78E-03	9.85E-04
Electricity, high voltage {CN-SD}| electricity production, hard coal | Cut-off, U	1.51E-02	5.73E-04	7.41E-04	3.15E-04	6.15E-03	5.59E-03	1.70E-03
Electricity, high voltage {CN-JS}| electricity production, hard coal | Cut-off, U	1.50E-02	5.70E-04	7.38E-04	3.13E-04	6.13E-03	5.56E-03	1.69E-03
Ethylene, average {RoW}| production | Cut-off, U	1.43E-02	1.57E-07	1.02E-05	3.46E-06	1.65E-06	1.07E-06	1.43E-02
Sulfuric acid {RER}| production | Cut-off, U	1.39E-02	2.56E-07	1.42E-06	2.38E-07	4.82E-07	2.03E-06	1.39E-02
Electricity, high voltage {ZA}| electricity production, hard coal, conventional | Cut-off, U	1.35E-02	5.12E-04	7.55E-04	2.90E-04	5.40E-03	5.00E-03	1.55E-03
Blasting {RER}| processing | Cut-off, U	1.29E-02	2.04E-04	1.50E-03	3.04E-04	7.81E-03	1.20E-03	1.89E-03
Acetone, liquid {RoW}| acetone production, from isopropanol | Cut-off, U	1.28E-02	1.28E-02	1.58E-07	4.07E-08	7.93E-08	4.84E-08	7.67E-07
Electricity, high voltage {RoW}| electricity production, oil | Cut-off, U	1.22E-02	4.66E-04	5.58E-04	2.55E-04	4.74E-03	4.59E-03	1.63E-03
Electricity, high voltage {CN-SX}| electricity production, hard coal | Cut-off, U	1.15E-02	4.35E-04	5.63E-04	2.39E-04	4.68E-03	4.25E-03	1.29E-03
Electricity, high voltage {CN-HE}| electricity production, hard coal | Cut-off, U	1.12E-02	4.25E-04	5.50E-04	2.34E-04	4.57E-03	4.15E-03	1.26E-03

Annex S10.10. Results of contribution of processes to the ozone deterioration category in the stratosphere of BRF H-M-E-Z-S-NN

The results of contributions to processes and stages of the BRF to the atmospheric ozone depletion category are shown in Fig. S10.10. and Table S10.10.

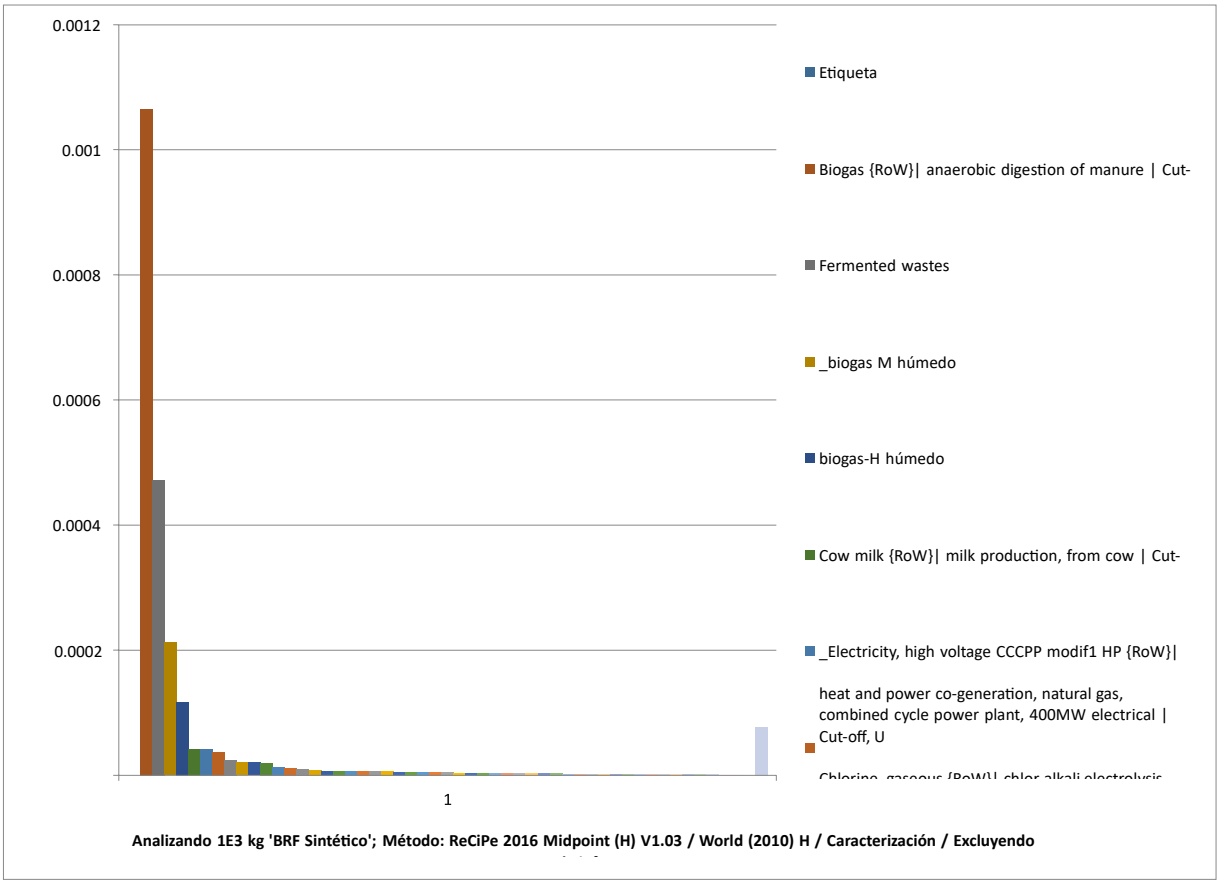


Fig S10.10. Overall contributions of H-M-Z-S-NN BRF processes to the Stratospheric Ozone Deterioration category. Units in kg CFC11 e

In Fig.S10.10 and Table S10.10. the “Biogas RoW| process is shown anaerobic digestion of manure | Cut-off, U” that are found in the proxi that represents the methanogenic digestion in the M process, as well as the processes of a smaller methanogenic scale of the NN process (it only collects 45% of the impact of the category.

Table S10.10. Contributions of BRF stages H-M-Z-S-NN to the category Stratospheric ozone depletion: tabulated values in kg CFC11 e

Proceso	Unidad	Total	_BRF-ETAPA EXTRACCIO N	_BRF-ETA PAH	_BRF-ETA PAM	_BRF-ETAP ANN	_BRF-ETAPA SACARIFICACION	_BRF-ETA PAZ
El total de todos los procesos	kg CFC11 e	2.33E-03	4.48E-06	9.54E-04	9.24E-04	1.69E-04	8.82E-05	1.87E-04
Procesos remanentes	kg CFC11 e	7.81E-05	2.35E-06	7.07E-06	2.17E-06	2.28E-05	1.83E-05	2.54E-05
Biogas {RoW}| anaerobic digestion of manure | Cut-off, U	kg CFC11 e	1.07E-03	3.71E-08	3.37E-04	6.63E-04	6.56E-05	3.33E-07	3.95E-07
Fermented wastes	kg CFC11 e	4.72E-04	0.00E+00	4.72E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
_biogas M húmedo	kg CFC11 e	2.12E-04	0.00E+00	0.00E+00	2.12E-04	0.00E+00	0.00E+00	0.00E+00
biogas-H húmedo	kg CFC11 e	1.18E-04	0.00E+00	1.18E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cow milk {RoW}| milk production, from cow | Cut-off, U	kg CFC11 e	4.25E-05	1.87E-23	3.15E-23	7.95E-24	2.88E-22	2.84E-23	4.25E-05
_Electricity, high voltage CCCPP modif1 HP {RoW}| heat and power co-generation,natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	kg CFC11 e	4.18E-05	0.00E+00	0.00E+00	3.78E-05	3.97E-06	0.00E+00	0.00E+00
Chlorine, gaseous {RoW}| chlor-alkali electrolysis, membrane cell | Cut-off, U	kg CFC11 e	3.75E-05	4.68E-10	7.84E-10	2.94E-10	9.66E-06	2.78E-05	9.61E-09
Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	kg CFC11 e	2.40E-05	0.00E+00	0.00E+00	0.00E+00	2.40E-05	0.00E+00	0.00E+00
Alfalfa-grass silage {RoW}| alfalfa/grass silage production | Cut-off, U	kg CFC11 e	2.04E-05	8.98E-24	1.51E-23	3.82E-24	1.38E-22	1.37E-23	2.04E-05
Coconut, dehusked {PH}| coconut production, dehusked | Cut-off, U	kg CFC11 e	2.03E-05	1.21E-12	3.58E-10	3.65E-12	9.40E-12	7.79E-12	2.03E-05
Biowaste {RoW}| treatment of biowaste, industrial composting | Cut-off, U	kg CFC11 e	1.93E-05	1.84E-13	8.45E-12	5.74E-13	7.73E-13	1.93E-05	1.13E-09
NN-Bioparticles	kg CFC11 e	1.30E-05	0.00E+00	0.00E+00	0.00E+00	1.30E-05	0.00E+00	0.00E+00
Nitric acid, without water, in 50% solution state {RER}| nitric acid production, product in 50% solution state | Cut-off, U	kg CFC11 e	1.24E-05	7.97E-08	6.00E-07	1.21E-07	2.99E-06	4.72E-07	8.10E-06
Nitric acid, without water, in 50% solution state {RoW}| nitric acid production, product in 50% solution state | Cut-off, U	kg CFC11 e	9.91E-06	6.62E-08	5.05E-07	1.01E-07	2.48E-06	3.91E-07	6.37E-06
Coconut, dehusked {ID}| coconut production, dehusked | Cut-off, U	kg CFC11 e	8.01E-06	4.77E-13	1.41E-10	1.44E-12	3.70E-12	3.07E-12	8.01E-06
Electricity, high voltage {RU}| market for | Cut-off, U	kg CFC11 e	7.69E-06	2.87E-07	4.07E-07	1.68E-07	3.17E-06	2.78E-06	8.74E-07
Coconut, dehusked {RoW}| coconut production, dehusked | Cut-off, U	kg CFC11 e	6.69E-06	3.98E-13	1.18E-10	1.20E-12	3.09E-12	2.56E-12	6.69E-06
Electricity, high voltage {MX}| market for | Cut-off, U	kg CFC11 e	6.58E-06	7.37E-08	4.79E-06	3.98E-08	7.39E-07	7.26E-07	2.15E-07
Chlorine, gaseous {RoW}| chlor-alkali electrolysis, diaphragm cell | Cut-off, U	kg CFC11 e	6.54E-06	1.03E-10	1.50E-10	4.13E-11	3.80E-08	6.50E-06	2.23E-09
Hay {RoW}| production | Cut-off, U	kg CFC11 e	6.48E-06	2.85E-24	4.81E-24	1.21E-24	4.40E-23	4.34E-24	6.48E-06
Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| machine operation, diesel, >= 74.57 kW, low load factor | Cut-off, U	kg CFC11 e	6.46E-06	2.13E-15	4.50E-06	1.62E-06	1.49E-07	1.94E-07	1.23E-11
Petroleum {RoW}| petroleum and gas production, on-shore | Cut-off, U	kg CFC11 e	5.79E-06	1.44E-07	1.63E-06	5.40E-07	8.85E-07	5.71E-07	2.03E-06
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	kg CFC11 e	5.78E-06	1.96E-07	3.97E-06	7.04E-09	1.31E-07	1.06E-07	1.37E-06
Transport, pipeline, long distance, natural gas {RU}| processing | Cut-off, U	kg CFC11 e	5.63E-06	1.97E-07	1.34E-07	2.76E-08	1.98E-06	4.57E-07	2.84E-06
Maize silage {RoW}| production | Cut-off, U	kg CFC11 e	5.48E-06	2.41E-24	4.07E-24	1.03E-24	3.72E-23	3.67E-24	5.48E-06

Annex S10.11. Results of contribution of processes to the ozone deterioration category in the stratosphere of BRF H-M-E-Z-S-NN

The results of process contributions and BRF stages to the ozone formation and human health category are shown in Fig. S10.11. and Table S10.11

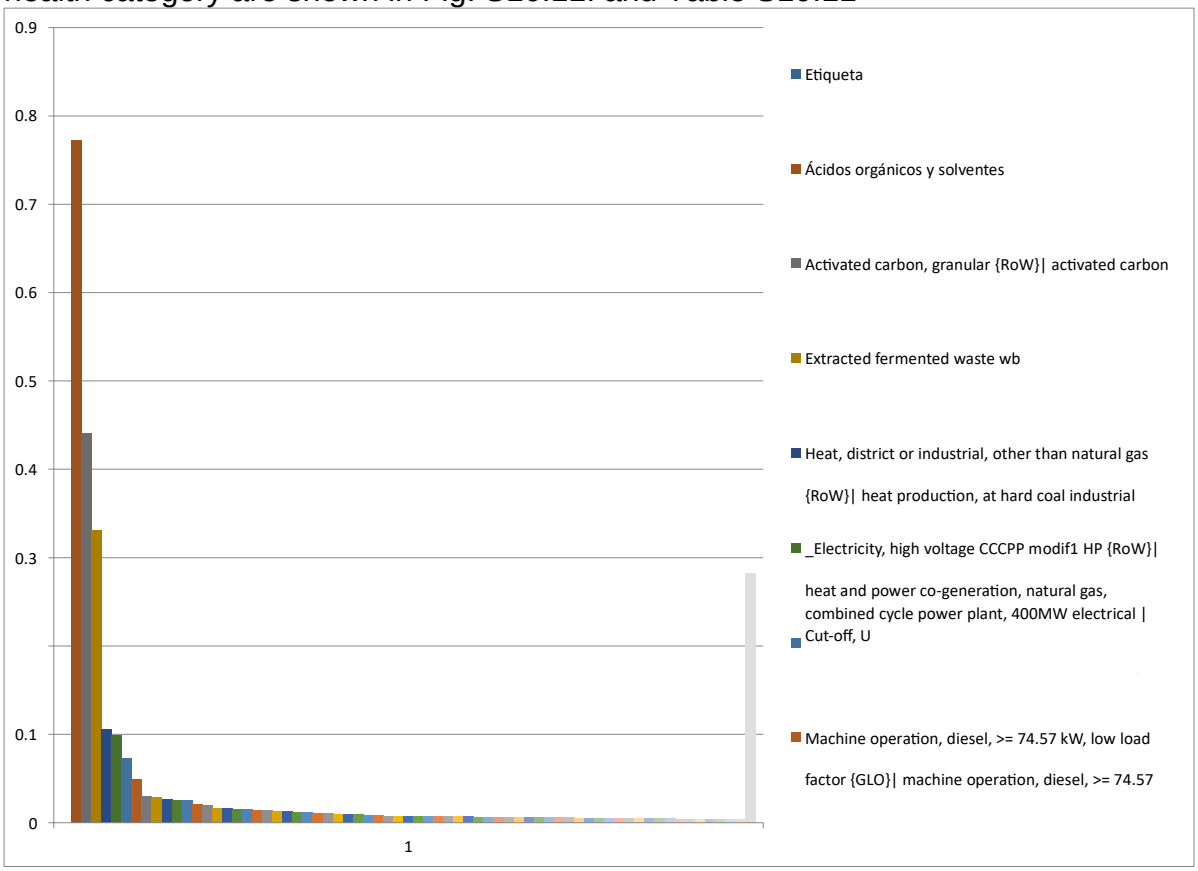


Fig. S10.11. Overall contributions of BRF H-M-Z-S-NN processes to the Ozone Formation and Human Health category. Units in kg NOx e

In Fig. S10.11. and Table S10.11.the contribution of the separation process of organic acids and low MW solvents is shown, where the obtaining by solvent (L/L) and the distillation of the solvent to be reused stand out as unique executions (the solvent used is methyl isobutyl ketone).

Table S10.11. Contributions of BRF stages H-M-Z-S-NN to the category Ozone formation and human health: tabulated values in kg NOx e

Proceso	Proyecto	Unidad	Total	BRF Sintético	_BRF-ETAPA EXTRAC-CION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICACION	_BRF-ETAPA Z
El total de todos los procesos		kg NOxeq	2.74E+00	0.00E+00	1.21E+00	1.82E-01	1.37E-01	7.48E-01	1.74E-01	2.91E-01
Procesos remanentes		kg NOxeq	2.82E-01	0.00E+00	1.78E-02	3.36E-02	8.73E-03	7.33E-02	5.75E-02	9.10E-02
Ácidos orgánicos ysolventes	HMSZNN	kg NOxeq	7.73E-01	0.00E+00	7.73E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	Ecoinvent 3 - allocation, cut-off byclassification - unit	kg NOxeq	4.40E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.40E-01	0.00E+00	0.00E+00
Extracted fermented waste wb	_HMSZNN	kg NOxeq	3.31E-01	0.00E+00	3.31E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	Ecoinvent 3 - allocation, cut-off byclassification - unit	kg NOxeq	1.06E-01	0.00E+00	3.59E-03	7.28E-02	1.29E-04	2.41E-03	1.95E-03	2.51E-02
_Electricity, high voltage CCCPP modif1 HP {RoW}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	_HMSZNN	kg NOxeq	9.92E-02	0.00E+00	0.00E+00	0.00E+00	8.98E-02	9.43E-03	0.00E+00	0.00E+00
Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U	Ecoinvent 3 - allocation, cut-off byclassification - unit	kg NOxeq	7.31E-02	0.00E+00	1.89E-03	3.07E-03	8.01E-04	3.62E-02	5.86E-03	2.52E-02
Machine operation, diesel, >= 74.57 kW, low load factor {GLO}| machine operation, diesel, >= 74.57 kW, low load factor | Cut-off, U	"	kg NOxeq	4.94E-02	0.00E+00	1.63E-11	3.44E-02	1.24E-02	1.14E-03	1.48E-03	9.42E-08
Acetone, liquid {RoW}| production | Cut-off, U	"	kg NOxeq	2.93E-02	0.00E+00	2.93E-02	3.61E-07	9.29E-08	1.81E-07	1.11E-07	1.75E-06
Transport, freight train {RoW}| diesel | Cut-off, U	"	kg NOxeq	2.92E-02	0.00E+00	1.86E-03	2.02E-03	9.14E-04	8.01E-03	4.88E-03	1.16E-02
4-methyl-2-pentanone {RoW}| production | Cut-off, U	"	kg NOxeq	2.69E-02	0.00E+00	2.69E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Blasting {RoW}| processing | Cut-off, U	"	kg NOxeq	2.55E-02	0.00E+00	4.05E-04	2.98E-03	6.04E-04	1.55E-02	2.38E-03	3.61E-03
Electricity, high voltage, for internal use in coal mining {CN}| electricityproduction, hard coal, at coal mine power plant | Cut-off, U	"	kg NOxeq	2.51E-02	0.00E+00	4.51E-04	2.56E-03	6.61E-04	1.71E-02	2.76E-03	1.54E-03
Dodecanol {GLO}| dodecanol production, ziegler process | Cut-off, U	"	kg NOxeq	2.04E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E-02
Electricity, high voltage {CN-NM}| electricityproduction, hard coal | Cut-off, U	"	kg NOxeq	2.01E-02	0.00E+00	7.65E-04	9.89E-04	4.20E-04	8.21E-03	7.46E-03	2.26E-03
Diesel, burned in building machine {GLO}| processing | Cut-off, U	"	kg NOxeq	1.60E-02	0.00E+00	1.53E-04	2.50E-03	2.45E-04	6.65E-03	1.05E-03	5.46E-03
Transport, freight train {CN}| diesel | Cut-off, U	"	kg NOxeq	1.58E-02	0.00E+00	2.86E-04	1.61E-03	4.18E-04	1.08E-02	1.76E-03	9.75E-04
Electricity, high voltage {CN-SD}| electricityproduction, hard coal | Cut-off, U	"	kg NOxeq	1.51E-02	0.00E+00	5.73E-04	7.41E-04	3.15E-04	6.15E-03	5.59E-03	1.70E-03
Electricity, high voltage {CN-JS}| electricityproduction, hard coal | Cut-off, U	"	kg NOxeq	1.50E-02	0.00E+00	5.70E-04	7.38E-04	3.13E-04	6.12E-03	5.56E-03	1.69E-03
Sulfuric acid {RER}| production | Cut-off, U	"	kg NOxeq	1.39E-02	0.00E+00	2.56E-07	1.42E-06	2.38E-07	4.82E-07	2.03E-06	1.39E-02
Electricity, high voltage {ZA}| electricityproduction, hard coal, conventional | Cut-off, U	"	kg NOxeq	1.35E-02	0.00E+00	5.12E-04	7.55E-04	2.90E-04	5.40E-03	5.00E-03	1.55E-03
Ethylene, average {RoW}| production | Cut-off, U	"	kg NOxeq	1.31E-02	0.00E+00	1.44E-07	9.32E-06	3.17E-06	1.52E-06	9.84E-07	1.31E-02
Blasting {RER}| processing | Cut-off, U	"	kg NOxeq	1.27E-02	0.00E+00	2.00E-04	1.47E-03	2.98E-04	7.66E-03	1.18E-03	1.85E-03
Electricity, high voltage {RoW}| electricityproduction, oil | Cut-off, U	"	kg NOxeq	1.22E-02	0.00E+00	4.66E-04	5.57E-04	2.55E-04	4.74E-03	4.59E-03	1.63E-03
Electricity, high voltage {CN-SX}| electricity production, hard coal | Cut-off, U	"	kg NOxeq	1.14E-02	0.00E+00	4.35E-04	5.63E-04	2.39E-04	4.67E-03	4.25E-03	1.29E-03
Electricity, high voltage {CN-HE}| electricity production, hard coal | Cut-off, U	"	kg NOxeq	1.12E-02	0.00E+00	4.25E-04	5.50E-04	2.34E-04	4.57E-03	4.15E-03	1.26E-03

Annex 10.12. Results of contribution of processes to the category of ozone deterioration in the stratosphere of BRF H-M-Z-S-NN

The results of contributions to processes and stages of the BRF to the category ozone decay to the stratosphere are shown in Fig. S10.12. and Table S10.12.

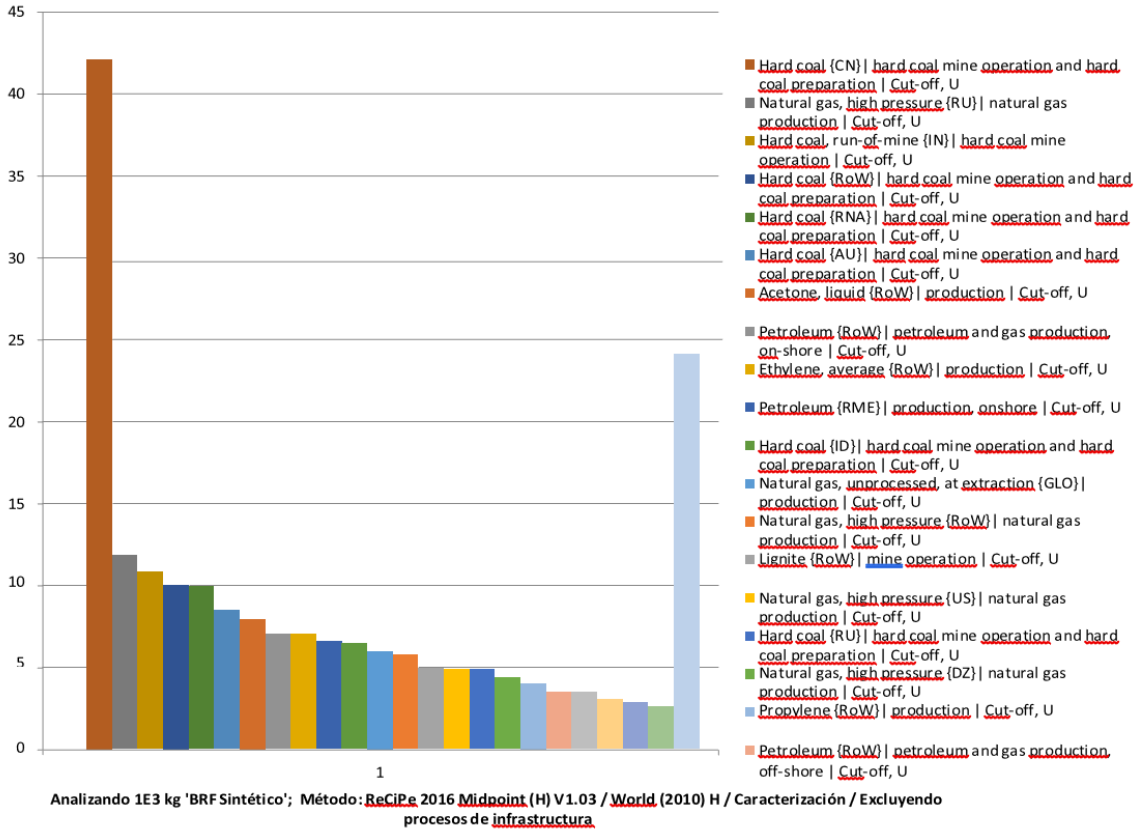


Fig. S10.12. General contributions of BRF H-M-E-Z-S-NN processes to the fossil resource scarcity category. Units in kg of crude oil e.

The contributions of particular processes to the impact classification Scarcity of fossil resources are presented in Figure S10.12, on the other hand, the detailed impacts by processes are compiled in Table S10.12.

Table S10.12. Contributions of BRF H-M-E-Z-S-NN stages to the Fossil Resource Scarcity classification. Kg of crude oil e.

Proceso	Unidad	Total	_BRF-ETAPA EXTRACCION	_BRF-ETAPA ETAPA H	_BRF-M	_BRF-ETAPA NN	SACARIFI-CACION	_BRF-ETAPA Z
El total de todos los procesos	kg oil e	202.98	16.91	18.11	5.27	86.85	24.03	51.83
Procesos remanentes	kg oil e	20.19	1.44	2.15	0.60	4.85	3.43	7.70
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	kg oil e	42.10	0.76	4.30	1.11	28.73	4.63	2.58
Natural gas, high pressure {RU}| natural gas production | Cut-off, U	kg oil e	11.84	0.42	0.27	0.06	4.44	1.02	5.63
Hard coal, run-of-mine {IN}| hard coal mine operation | Cut-off, U	kg oil e	10.87	0.23	1.01	0.28	6.92	1.67	0.76
Hard coal {RoW}| hard coal mine operation and hard coal preparation | Cut-off, U	kg oil e	10.04	0.10	0.12	0.06	8.80	0.43	0.53
Hard coal {RNA}| hard coal mine operation and hard coal preparation | Cut-off, U	kg oil e	9.96	0.16	0.39	0.31	7.33	1.22	0.57
Hard coal {AU}| hard coal mine operation and hard coal preparation | Cut-off, U	kg oil e	8.48	0.13	0.98	0.24	6.05	0.57	0.52
Acetone, liquid {RoW}| production | Cut-off, U	kg oil e	7.92	7.92	0.00	0.00	0.00	0.00	0.00
Petroleum {RoW}| petroleum and gas production, on-shore | Cut-off, U	kg oil e	7.07	0.18	1.98	0.66	1.08	0.70	2.47
Ethylene, average {RoW}| production | Cut-off, U	kg oil e	7.03	0.00	0.00	0.00	0.00	0.00	7.02
Petroleum {RME}| production, onshore | Cut-off, U	kg oil e	6.62	0.16	1.86	0.62	1.01	0.65	2.32
Hard coal {ID}| hard coal mine operation and hard coal preparation | Cut-off, U	kg oil e	6.48	0.10	0.72	0.18	4.68	0.43	0.37
Natural gas, unprocessed, at extraction {GLO}| production | Cut-off, U	kg oil e	5.97	0.15	0.35	0.03	1.30	0.75	3.39
Natural gas, high pressure {RoW}| natural gas production | Cut-off, U	kg oil e	5.75	0.16	0.39	0.04	1.47	0.84	2.84
Lignite {RoW}| mine operation | Cut-off, U	kg oil e	4.94	0.17	0.43	0.18	1.84	1.71	0.62
Natural gas, high pressure {US}| natural gas production | Cut-off, U	kg oil e	4.91	0.14	0.14	0.04	1.20	0.94	2.45
Hard coal {RU}| hard coal mine operation and hard coal preparation | Cut-off, U	kg oil e	4.88	0.07	0.65	0.16	3.35	0.27	0.37
Natural gas, high pressure {DZ}| natural gas production | Cut-off, U	kg oil e	4.40	0.16	0.17	0.06	1.62	1.05	1.34
Propylene {RoW}| production | Cut-off, U	kg oil e	4.01	3.87	0.00	0.00	0.00	0.00	0.13
Petroleum {RoW}| petroleum and gas production, off-shore | Cut-off, U	kg oil e	3.51	0.09	0.99	0.33	0.54	0.35	1.23
Ethylene, average {RER}| production | Cut-off, U	kg oil e	3.51	0.00	0.00	0.00	0.00	0.00	3.51
Natural gas, high pressure {RoW}| petroleum and gas production, on-shore | Cut-off, U	kg oil e	3.07	0.07	0.26	0.02	0.57	0.44	1.71
Petroleum {RU}| production, onshore | Cut-off, U	kg oil e	2.89	0.07	0.81	0.27	0.44	0.29	1.01
Hydrogen, liquid {RoW}| hydrogen cracking, APME | Cut-off, U	kg oil e	2.60	0.24	0.00	0.00	0.01	2.23	0.12
Natural gas, high pressure {US}| petroleum and gas production, on-shore | Cut-off, U	kg oil e	2.01	0.06	0.06	0.02	0.49	0.38	1.00
Natural gas, high pressure {NO}| petroleum and gas production, off-shore | Cut-off, U	kg oil e	1.94	0.06	0.06	0.01	0.13	0.03	1.65

In Table S10.12 it is evident that the Z and NN processes are predominant for this category. Similarly, the processes with the greatest contribution to the NN process are “Hard coal {CN}| hard coal mine operation and hard coal preparation | 22 Cut-off, U” and “Hard coal {RoW}| hard coal mine operation and hard coal preparation | Cut-off, U”, seconded by others linked to coal mining, close in magnitude to the second process. The processes with the greatest contribution in stage Z are “Ethylene, average {RoW}| production | Cut-off, U” and “Natural gas, high pressure {RU}| natural gas production | Cut-off, U.”

Annex S10.13. Results of contribution of processes to the ozone deterioration category in the stratosphere of BRF H-M-E-Z-S-NN

The results of contributions to processes and stages of the BRF to the category of fine particles 2.5 µm or less are shown in Fig. S10.13 and table S10.13.

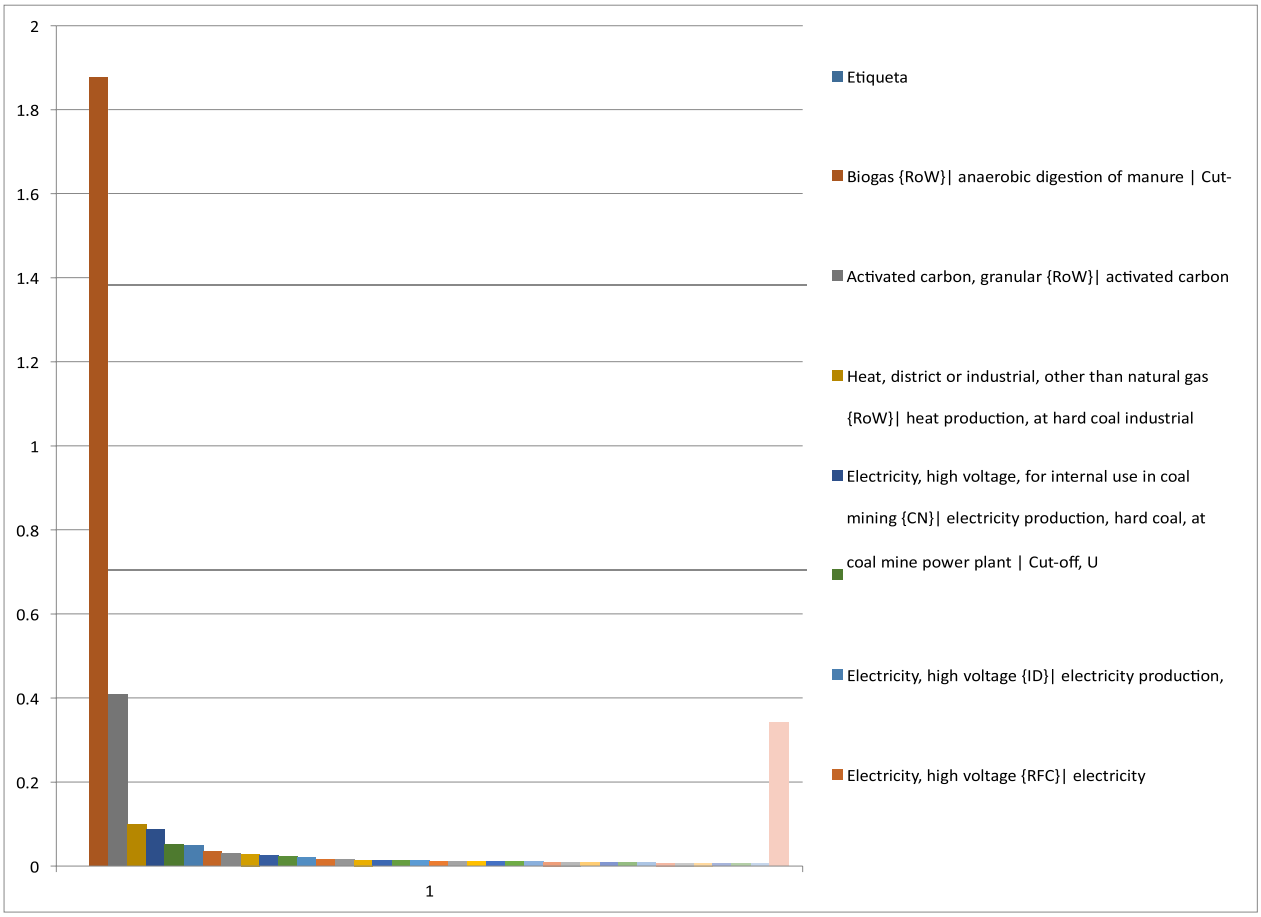


Figure S10.13. Overall contributions of BRF H-M-E-Z-S-NN processes to the Fine Particles 2.5 µm or less category

Fig. S10.13 and Table S10.13 show that the main process contributing to this category is the one related to the biogas process.

Table S10.13. Overall contributions of BRF stages H-M-E-Z-S-NN to the category Fine particles 2.5 μm or less: tabulated values in kg of 2.5 μm particles

Proceso	_BRF-ETAPA EXTRACCION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICACION	_BRF-ETAPA Z
El total de todos los procesos	4.51E-02	7.65E-01	1.22E+00	8.01E-01	2.06E-01	2.76E-01
Procesos remanentes	1.45E-02	3.18E-02	1.09E-02	9.24E-02	7.79E-02	1.15E-01
Biogas {RoW}| anaerobic digestion of manure | Cut-off, U	6.53E-05	5.92E-01	1.17E+00	1.16E-01	5.86E-04	6.95E-04
Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Cut-off, U	0.00E+00	0.00E+00	0.00E+00	4.08E-01	0.00E+00	0.00E+00
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	3.33E-03	6.75E-02	1.20E-04	2.23E-03	1.81E-03	2.33E-02
Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Cut-off, U	1.57E-03	8.90E-03	2.30E-03	5.95E-02	9.58E-03	5.34E-03
Sulfuric acid {RER}| production | Cut-off, U	9.29E-07	5.16E-06	8.63E-07	1.75E-06	7.34E-06	5.02E-02
Electricity, high voltage {ID}| electricity production, lignite | Cut-off, U	1.77E-03	2.61E-03	1.05E-03	2.09E-02	1.70E-02	5.26E-03
Electricity, high voltage {RFC}| electricity production, lignite | Cut-off, U	1.35E-03	1.59E-03	7.14E-04	1.36E-02	1.33E-02	4.86E-03
Electricity, high voltage {SERC}| electricity production, lignite | Cut-off, U	1.17E-03	1.38E-03	6.19E-04	1.18E-02	1.15E-02	4.20E-03
Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U	7.37E-04	1.20E-03	3.12E-04	1.41E-02	2.29E-03	9.83E-03
Sulfuric acid {RoW}| production | Cut-off, U	7.46E-04	6.76E-06	1.30E-06	2.10E-04	3.32E-04	2.33E-02
Sodium bicarbonate {RoW}| soda production, solvay process | Cut-off, U	0.00E+00	2.30E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW | Cut-off, U	2.12E-05	6.34E-03	1.24E-02	1.24E-03	1.12E-05	7.49E-05
Electricity mix, AC, consumption mix, at consumer, 1kV - 60kV EU-27 S System - Copied from ELCD	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.58E-02	0.00E+00
Acetone, liquid {RoW}| production | Cut-off, U	1.48E-02	1.82E-07	4.68E-08	9.13E-08	5.58E-08	8.83E-07
off, U	5.31E-04	7.52E-04	3.10E-04	5.85E-03	5.13E-03	1.62E-03

Annex S10.14. Process contribution results to BRF ionizing radiation category H-M-E-Z-S-NN

The results of contributions to processes and stages of the BRF to the ionizing radiation category are shown in Fig. S10.14 and Table S10.14.

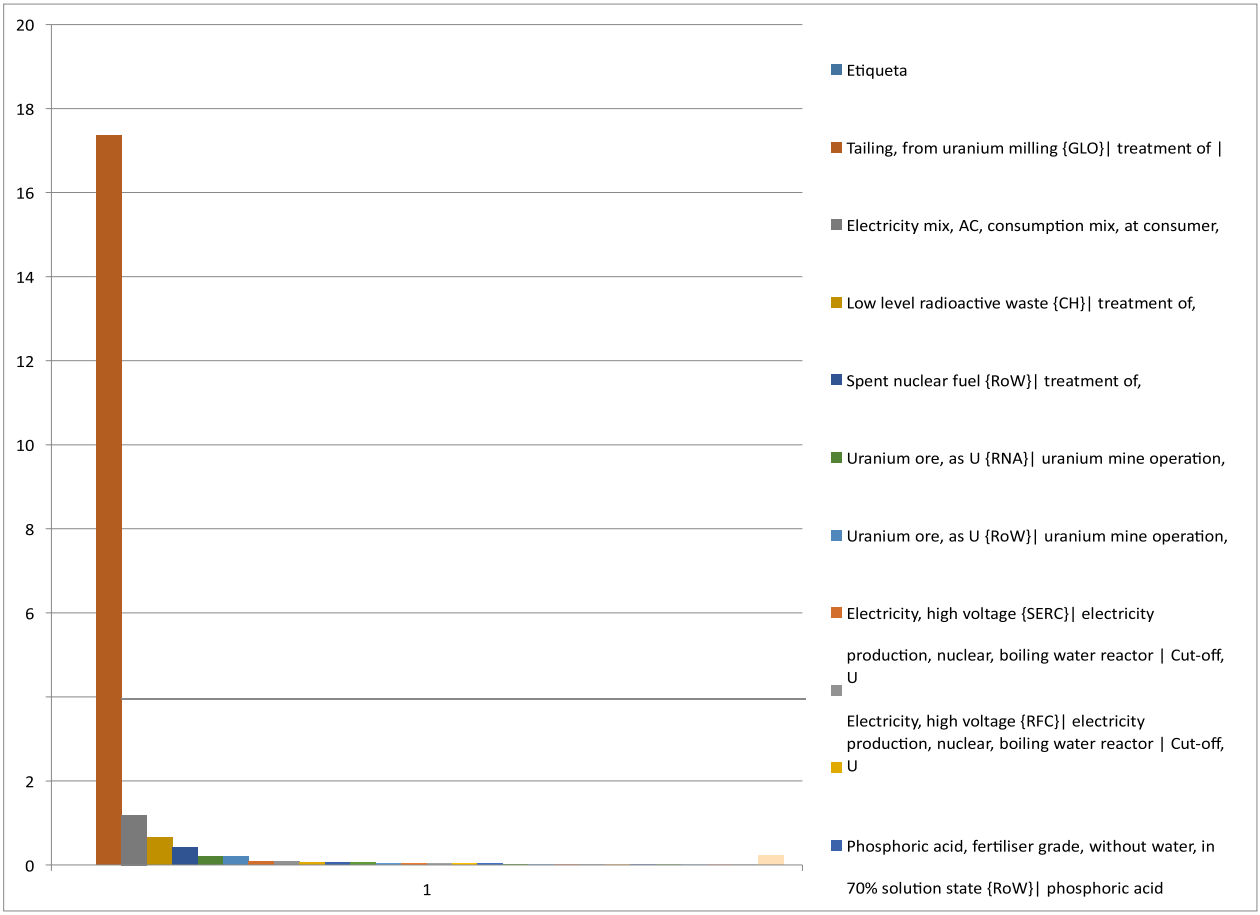


Figure S10.14. General contributions of H-M-E-Z-S-NN BRF processes to the ionizing radiation category

Table S10.14. Overall contributions of BRF stages H-M-E-Z-S-NN to the ionizing radiation category: tabulated values in kg Co-60 in air

PROCESO	_BRF-ETAPA EXTRACCION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICA-CIÓN	_BRF-ETAPA Z
El total de todos los procesos	0.651	1.753	0.591	6.506	7.302	4.078
Procesos remanentes	0.007	0.022	0.008	0.073	0.069	0.053
Tailing, from uranium milling {GLO}| treatment of | Cut-off, U	0.580	1.464	0.497	5.818	5.508	3.496
Electricity mix, AC, consumption mix, at consumer, 1kV - 60kV EU-27 S System - Copied from ELCD	0.000	0.000	0.000	0.000	1.190	0.000
Low level radioactive waste {CH}| treatment of, plasma torchincineration | Cut-off, U	0.017	0.155	0.051	0.123	0.093	0.211
Spent nuclear fuel {RoW}| treatment of, reprocessing | Cut-off, U	0.015	0.030	0.011	0.147	0.140	0.074
Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	0.007	0.017	0.006	0.068	0.064	0.041
Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	0.006	0.016	0.005	0.064	0.061	0.038
Electricity, high voltage {SERC}| electricity production, nuclear, boiling water reactor | Cut-off, U	0.003	0.003	0.002	0.029	0.029	0.010
Electricity, high voltage {RFC}| electricity production, nuclear, boiling water reactor | Cut-off, U	0.003	0.003	0.002	0.029	0.028	0.010

Annex S10.15. Process contribution results to BRF marine eutrophication category H-M-Z-S-NN

The results of contributions to processes and stages of the BRF to the marine eutrophication category are shown in Fig.S10.15 and Table S10.15.

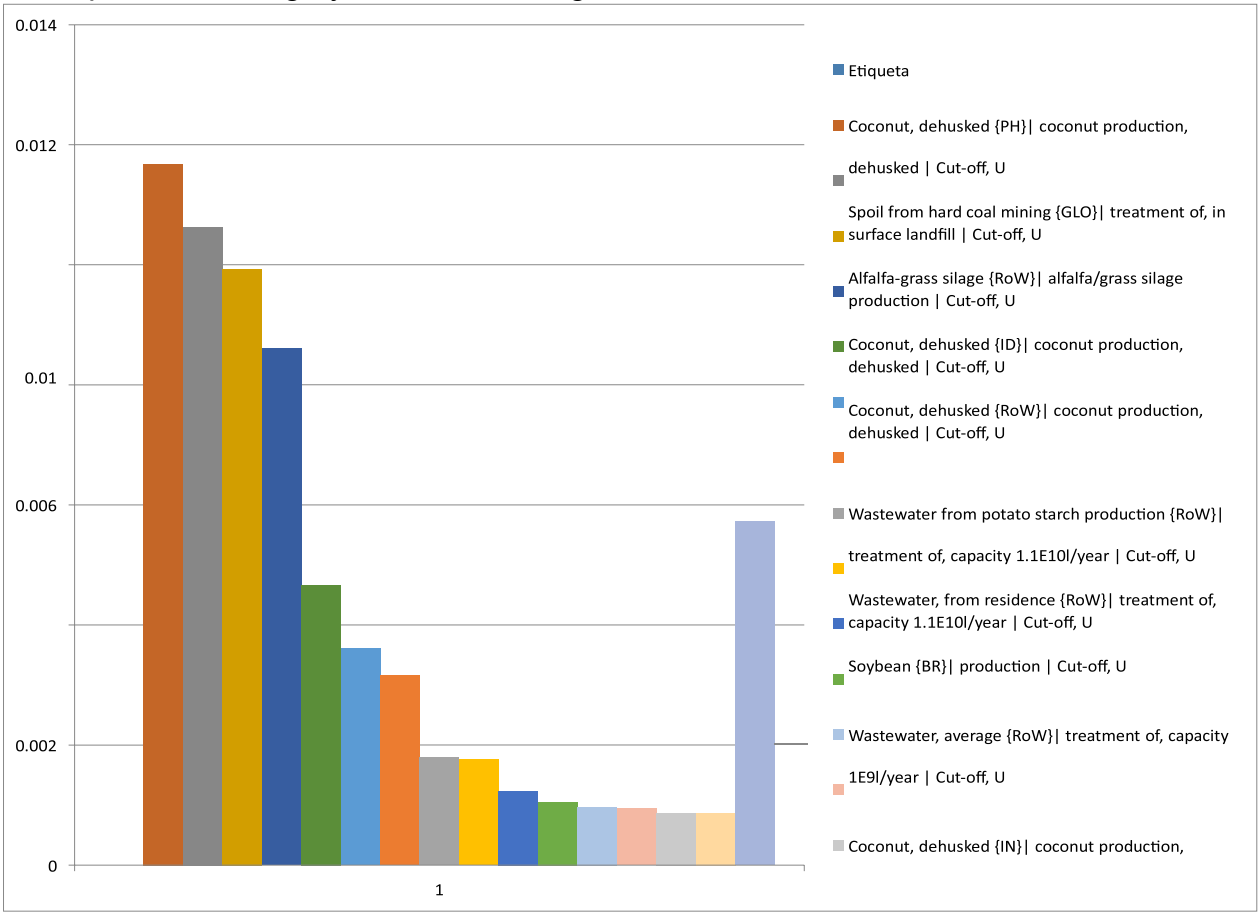


Fig. S10.15. Overall contributions of the BRF H-M-E-Z-S-NN processes to the marine eutrophication category

Table S10.15. Overall contributions of the BRF H-M-E-Z-S-NN stages to the marine eutrophication category: tabulated values in kg N e

Proceso	Total	ETAPA EXTRACCION	ETAPA H	ETAPA M	ETAPA NN	ETAPA SACARIFICA-CION	ETAPA Z
El total de todos los procesos	6.75E-02	3.28E-04	2.04E-03	6.26E-04	1.11E-02	3.30E-03	5.01E-02
Procesos remanentes	5.72E-03	3.55E-05	5.80E-04	1.60E-04	3.42E-04	5.71E-04	4.03E-03
Coconut, dehusked {PH}| coconut production, dehusked | Cut-off, U	1.17E-02	6.95E-10	2.06E-07	2.10E-09	5.40E-09	4.47E-09	1.17E-02
Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	1.06E-02	1.70E-04	9.89E-04	2.83E-04	7.57E-03	9.46E-04	6.71E-04
Alfalfa-grass silage {RoW}| alfalfa/grass silage production | Cut-off, U	9.94E-03	4.37E-21	7.36E-21	1.86E-21	6.74E-20	6.65E-21	9.94E-03
Coconut, dehusked {ID}| coconut production, dehusked | Cut-off, U	8.61E-03	5.12E-10	1.52E-07	1.55E-09	3.98E-09	3.30E-09	8.61E-03
Coconut, dehusked {RoW}| coconut production, dehusked | Cut-off, U	4.66E-03	2.77E-10	8.22E-08	8.38E-10	2.16E-09	1.79E-09	4.66E-03
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	3.61E-03	1.21E-04	3.54E-04	1.42E-04	1.25E-03	1.16E-03	5.90E-04
Hay {RoW}| production | Cut-off, U	3.16E-03	1.39E-21	2.34E-21	5.91E-22	2.14E-20	2.11E-21	3.16E-03
Wastewater from potato starch production {RoW}| treatment of, capacity 1.1E10l/year | Cut-off, U	1.79E-03	1.18E-10	1.17E-08	1.75E-10	4.51E-09	7.78E-10	1.79E-03
Wastewater, from residence {RoW}| treatment of, capacity 1.1E10l/year | Cut-off, U	1.76E-03	3.96E-10	1.79E-08	1.95E-09	1.76E-03	1.81E-09	4.51E-06
Soybean {BR}| production | Cut-off, U	1.23E-03	1.35E-08	4.91E-07	4.54E-08	1.59E-07	3.39E-08	1.23E-03
Maize silage {RoW}| production | Cut-off, U	1.05E-03	4.63E-22	7.81E-22	1.97E-22	7.15E-21	7.05E-22	1.05E-03
Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Cut-off, U	9.67E-04	1.66E-06	1.16E-04	4.04E-05	1.67E-04	6.31E-04	1.19E-05
Oat grain {RoW}| oat production | Cut-off, U	9.45E-04	4.16E-22	7.01E-22	1.77E-22	6.41E-21	6.33E-22	9.45E-04
Coconut, dehusked {IN}| coconut production, dehusked | Cut-off, U	8.71E-04	5.18E-11	1.54E-08	1.56E-10	4.03E-10	3.33E-10	8.71E-04
Soybean {AR}| soybean production | Cut-off, U	8.69E-04	9.49E-09	3.46E-07	3.20E-08	1.12E-07	2.39E-08	8.69E-04

Annex S10.16. Process contribution results to BRF water consumption category H-M-E-Z-S-NN

The results of process contributions and BRF stages to the water consumption category are shown in Fig. S10.16. and Table S10.16.

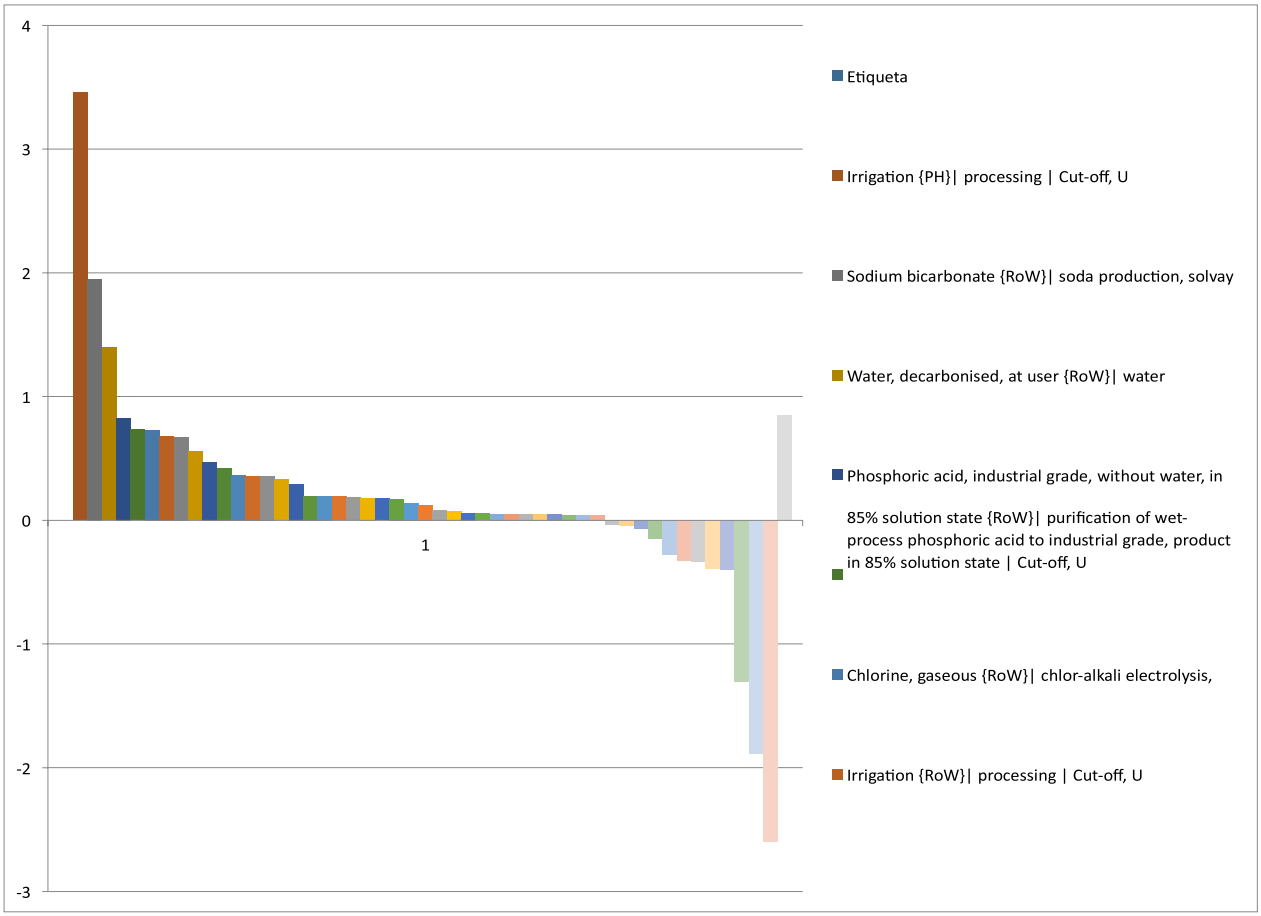


Fig. S10.16. Overall contributions of the BRF H-M-E-Z-S-NN processes to the water consumption category

Table S10.16. Overall contributions of the BRF H-M-E-Z-S-NN stages to the Marine Eutrophication category: tabulated values in m³

Proceso	Proyecto	Unidad	Total	BRF Sintético	_BRF-ETAPA EXTRACCION	_BRF-ETAPA H	_BRF-ETAPA M	_BRF-ETAPA NN	_BRF-ETAPA SACARIFICACION	_BRF-ETAPA Z
El total de todos los procesos		m3	8.8203	0	0.9667	2.0513	0.4414	0.0091	1.5242	3.8276
Procesos remanentes		m3	0.8465	0	0.0896	0.0486	-0.0005	0.1278	0.1625	0.4185
Irrigation {PH}| processing | Cut-off, U	Ecoinvent 3 - allocation, cut-off by classification - unit	m3	3.4584	0	0.0000	0.0001	0.0000	0.0000	0.0000	3.4583
Sodium bicarbonate {RoW}| soda production, solvay process | Cut-off, U	"	m3	1.9476	0	0.0000	1.9476	0.0000	0.0000	0.0000	0.0000
Water, decarbonised, at user {RoW}| water production and supply, decarbonised | Cut-off, U	"	m3	1.3974	0	0.0154	0.0308	0.5822	0.5771	0.1199	0.0719
Phosphoric acid, industrial grade, without water, in 85% solution state {RoW}| purification of wet-process phosphoric acid to industrial grade, product in 85% solution state | Cut-off, U	"	m3	0.8280	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.8280
Sulfuric acid {RER}| production | Cut-off, U	"	m3	0.7307	0	0.0000	0.0001	0.0000	0.0000	0.0001	0.7305
Chlorine, gaseous {RoW}| chlor-alkali electrolysis, membrane cell | Cut-off,	"	m3	0.7291	0	0.0000	0.0000	0.0000	0.1877	0.5411	0.0002
Irrigation {RoW}| processing | Cut-off, U	"	m3	0.6829	0	0.0000	0.0001	0.0000	0.0000	0.0000	0.6828
Phosphoric acid, fertiliser grade, without water, in 70% solution state {RoW}| phosphoric acid production, dihydrate process | Cut-off, U	"	m3	0.6725	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.6724
Water, decarbonised, at user {RER}| water production and supply, decarbonised | Cut-off, U	"	m3	0.5555	0	0.0061	0.0123	0.2314	0.2294	0.0476	0.0286
_Acetic acid modif2 HP, without water, in 98% solution state {RoW}| acetic acid production, product in 98% solution state | Cut-off, U	HMSZNN	m3	0.4679	0	0.4679	0.0000	0.0000	0.0000	0.0000	0.0000
Irrigation {CN}| processing | Cut-off, U	Ecoinvent 3 - allocation, cut-off by classification - unit	m3	0.4204	0	0.0000	0.0001	0.0000	0.0000	0.0000	0.4203
Chlorine, gaseous {RoW}| chlor-alkali electrolysis, diaphragm cell | Cut-off, U	"	m3	0.3661	0	0.0000	0.0000	0.0000	0.0021	0.3638	0.0001
Sulfuric acid {RoW}| production | Cut-off, U	"	m3	0.3572	0	0.0108	0.0001	0.0000	0.0030	0.0048	0.3384
Urea, as N {RoW}| production | Cut-off, U	"	m3	0.3563	0	0.0001	0.0015	0.0000	0.0001	0.0000	0.3546
Phosphoric acid, fertiliser grade, without water, in 70% solution state {US}| phosphoric acid production, dihydrate process | Cut-off, U	"	m3	0.3284	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.3284
Irrigation {US}| processing | Cut-off, U	"	m3	0.2919	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.2919
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	"	m3	0.1955	0	0.0035	0.0200	0.0052	0.1335	0.0215	0.0120
Ammonia, liquid {RoW}| ammonia production, steam reforming, liquid | Cut-off, U	"	m3	0.1930	0	0.0001	0.0055	0.0001	0.0012	0.0008	0.1853
Sodium chloride, powder {RoW}| production | Cut-off, U	"	m3	0.1896	0	0.0003	0.0000	0.0000	0.0407	0.1458	0.0027
Soda ash, light, crystalline, heptahydrate {RoW}| soda production, solvay process | Cut-off, U	"	m3	0.1843	0	0.0000	0.0000	0.0000	0.0019	0.0068	0.1756
4-methyl-2-pentanone {RoW}| production | Cut-off, U	"	m3	0.1781	0	0.1781	0.0000	0.0000	0.0000	0.0000	0.0000
Phosphoric acid, industrial grade, without water, in 85% solution state {RER}| purification of wet-process phosphoric acid to industrial grade, product in 85% solution state | Cut-off, U	"	m3	0.1744	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.1744
Acetone, liquid {RoW}| production | Cut-off, U	"	m3	0.1725	0	0.1725	0.0000	0.0000	0.0000	0.0000	0.0000
Electricity, high voltage {BR}| electricity production, hydro, reservoir, tropical region | Cut-off, U	"	m3	0.1429	0	0.0056	0.0068	0.0030	0.0560	0.0550	0.0165
Irrigation {IN}| processing | Cut-off, U	"	m3	0.1265	0	0.0000	0.0001	0.0000	0.0000	0.0000	0.1264
Electricity, high voltage {RU}| heat and power co-generation, hard coal | Cut-off, U	"	m3	0.0840	0	0.0031	0.0044	0.0018	0.0346	0.0304	0.0096
Calcium chloride {RoW}| soda production, solvay process | Cut-off, U	"	m3	0.0786	0	0.0000	0.0000	0.0000	0.0019	0.0069	0.0697
Ethylene, average {RoW}| production | Cut-off, U	"	m3	0.0569	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0569
Electricity, high voltage {CA-ON}| electricity production, nuclear, pressure water reactor, heavy water moderated | Cut-off, U	"	m3	0.0550	0	0.0021	0.0025	0.0011	0.0217	0.0210	0.0064
Soda ash, light, crystalline, heptahydrate {RER}| soda production, solvay process | Cut-off, U	"	m3	0.0531	0	0.0000	0.0000	0.0000	0.0005	0.0020	0.0506
Lime {RoW}| production, milled, loose | Cut-off, U	"	m3	0.0512	0	0.0000	0.0433	0.0000	0.0003	0.0005	0.0071
Oxygen, liquid {RoW}| air separation, cryogenic| Cut-off, U	"	m3	0.0501	0	0.0033	0.0000	0.0000	-0.0004	0.0000	0.0472
Electricity, high voltage {RoW}| heat and power co-generation, hard coal | Cut-off, U	"	m3	0.0477	0	0.0019	0.0022	0.0010	0.0190	0.0183	0.0054
Hydrogen, liquid {RoW}| hydrogen cracking, APME | Cut-off, U	"	m3	0.0469	0	0.0043	0.0000	0.0000	0.0002	0.0403	0.0021
Phosphate rock, as P2O5, beneficiated, wet {RoW}| phosphate rock beneficiation, wet | Cut-off, U	"	m3	0.0434	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0434
Irrigation {BR}| processing | Cut-off, U	"	m3	0.0432	0	0.0000	0.0001	0.0000	0.0000	0.0000	0.0431
Sodium chloride, powder {RER}| production | Cut-off, U	"	m3	0.0399	0	0.0001	0.0000	0.0000	0.0086	0.0307	0.0006
_Heat, district or industrial, natural gas modif1 HP {RoW}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	_HMSZNN	m3	-0.0386	0	0.0000	0.0000	-0.0355	-0.0031	0.0000	0.0000
Maize grain {RoW}| production | Cut-off, U	Ecoinvent 3 - allocation, cut-off by classification - unit	m3	-0.0452	0	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0452
Sodium chloride, brine solution {RoW}| production | Cut-off, U	"	m3	-0.0700	0	0.0000	-0.0602	0.0000	-0.0001	-0.0005	-0.0092

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Annex S10.17. Process Contribution Results to BRF Natural Resource Scarcity Category H-M-E-Z-S-NN

The results of process contributions and BRF stages to the natural resource scarcity category are shown in Fig. S10.17. and table S10.17.

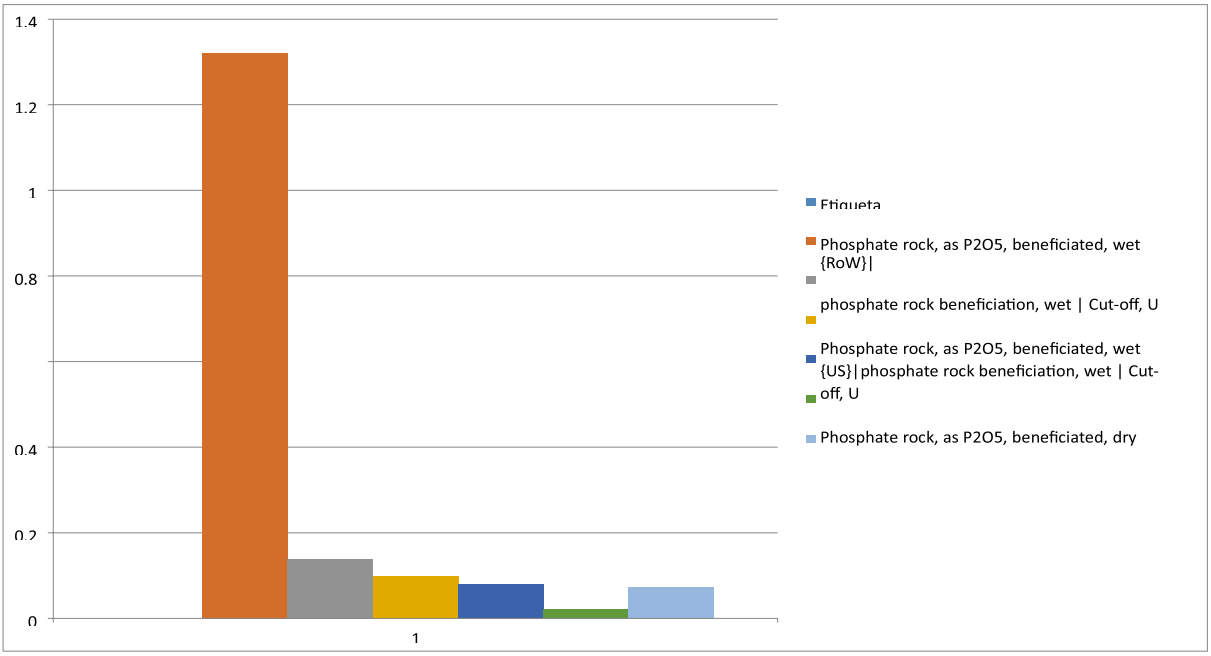


Fig. S10.17. Overall contributions of BRF H-M-E-Z-S-NN processes to the natural resource scarcity category

Table S10.17. General contributions of the BRF stages H-M-E-Z-S-NN to the natural resource scarcity category: tabulated values in kg of Cu e

Proceso	Unidad	Total	ETAPA EXTRACCION	ETAPA H	ETAPA M	ETAPA NN	ETAPA SACARIFICA-CION	-
El total de todos los procesos	kg Cu e	1.7837	0.0039	0.0165	0.0009	0.0171	0.0112	
Procesos remanentes	kg Cu e	0.1221	0.0032	0.0164	0.0009	0.0169	0.0109	
Phosphate rock, as P2O5, beneficiated, wet {RoW}| phosphate rock beneficiation, wet | Cut-off, U	kg Cu e	1.3208	0.0000	0.0000	0.0000	0.0000	0.0000	
Phosphate rock, as P2O5, beneficiated, wet {US}| phosphate rock beneficiation, wet | Cut-off, U	kg Cu e	0.1386	0.0000	0.0000	0.0000	0.0000	0.0000	
Phosphate rock, as P2O5, beneficiated, dry {RoW}| phosphate rock beneficiation, dry | Cut-off, U	kg Cu e	0.0995	0.0000	0.0000	0.0000	0.0000	0.0000	
Ammonium sulfate, as N {GLO}| nickel mine operation, sulfidic ore | Cut-off, U	kg Cu e	0.0799	0.0000	0.0000	0.0000	0.0000	0.0000	
Zinc concentrate {GLO}| zinc-lead mine operation | Cut-off, U	kg Cu e	0.0228	0.0007	0.0000	0.0000	0.0002	0.0003	

Annex S10.18. Process contribution results to BRF land use category H-M-E-Z-S-NN

The results of contributions to processes and stages of the BRF to the land use category are shown in Fig. S10.18 and Table S10.18.

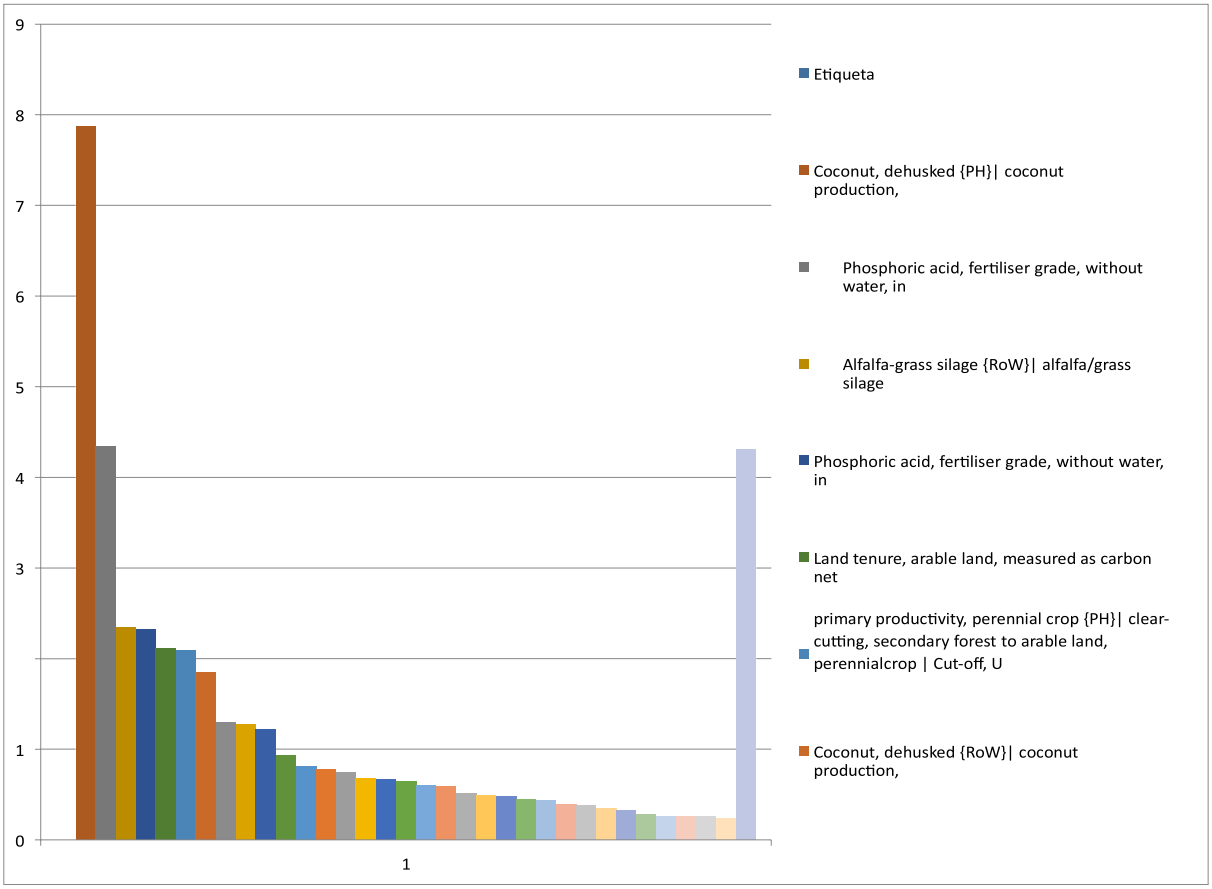


Fig. S10.18. Overall contributions of BRF H-M-E-Z-S-NN processes to the land use category

Table S10.18. Overall contributions of BRF stages H-M-E-Z-S-NN to land or land use category. Tabulated values: m2×yr annual crop land

Proceso	Unidad	ETAPA EXTRACCION	ETAPA H	ETAPA M	ETAPA NN	ETAPA SACARIFICA-CION
El total de todos los procesos	m2a crop e	0.113	2.454	0.316	2.092	0.455
Procesos remanentes	m2a crop e	0.033	1.037	0.143	0.643	0.150
Coconut, dehusked {PH}| coconut production, dehusked | Cut-off, U	m2a crop e	0.000	0.000	0.000	0.000	0.000
Phosphoric acid, fertiliser grade, without water, in 70% solution state {RoW}| phosphoric acid production, dihydrate process | Cut-off, U	m2a crop e	0.000	0.000	0.000	0.000	0.000
Alfalfa-grass silage {RoW}| alfalfa/grass silage production | Cut-off, U	m2a crop e	0.000	0.000	0.000	0.000	0.000
Phosphoric acid, fertiliser grade, without water, in 70% solution state {US}| phosphoric acid production, dihydrate process | Cut-off, U	m2a crop e	0.000	0.000	0.000	0.000	0.000
Land tenure, arable land, measured as carbon net primary productivity, perennial crop {PH}| clear-cutting, secondary forest to arable land, perennial crop | Cut-off, U	m2a crop e	0.000	0.000	0.000	0.000	0.000
Coconut, dehusked {ID}| coconut production, dehusked | Cut-off, U	m2a crop e	0.000	0.000	0.000	0.000	0.000
Coconut, dehusked {RoW}| coconut production, dehusked | Cut-off, U	m2a crop e	0.000	0.000	0.000	0.000	0.000
Land tenure, arable land, measured as carbon net primary productivity, annual crop {AR}| clear-cutting, secondary forest to arable land, annual crop | Cut-off, U	m2a crop e	0.000	0.001	0.000	0.000	0.000
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	m2a crop e	0.023	0.130	0.033	0.867	0.140
Soybean {US}| production | Cut-off, U	m2a	0.000	0.001	0.000	0.000	0.000

Annex S11. IER characterization impacts

This section shows the results of the contribution of IER processes to the environmental impact categories.

Annex S11.1. Process contribution results to the Human Carcinogenic Toxicity category

The results regarding human carcinogenic toxicity are shown below (Fig S11.1. and Table S11.1.).

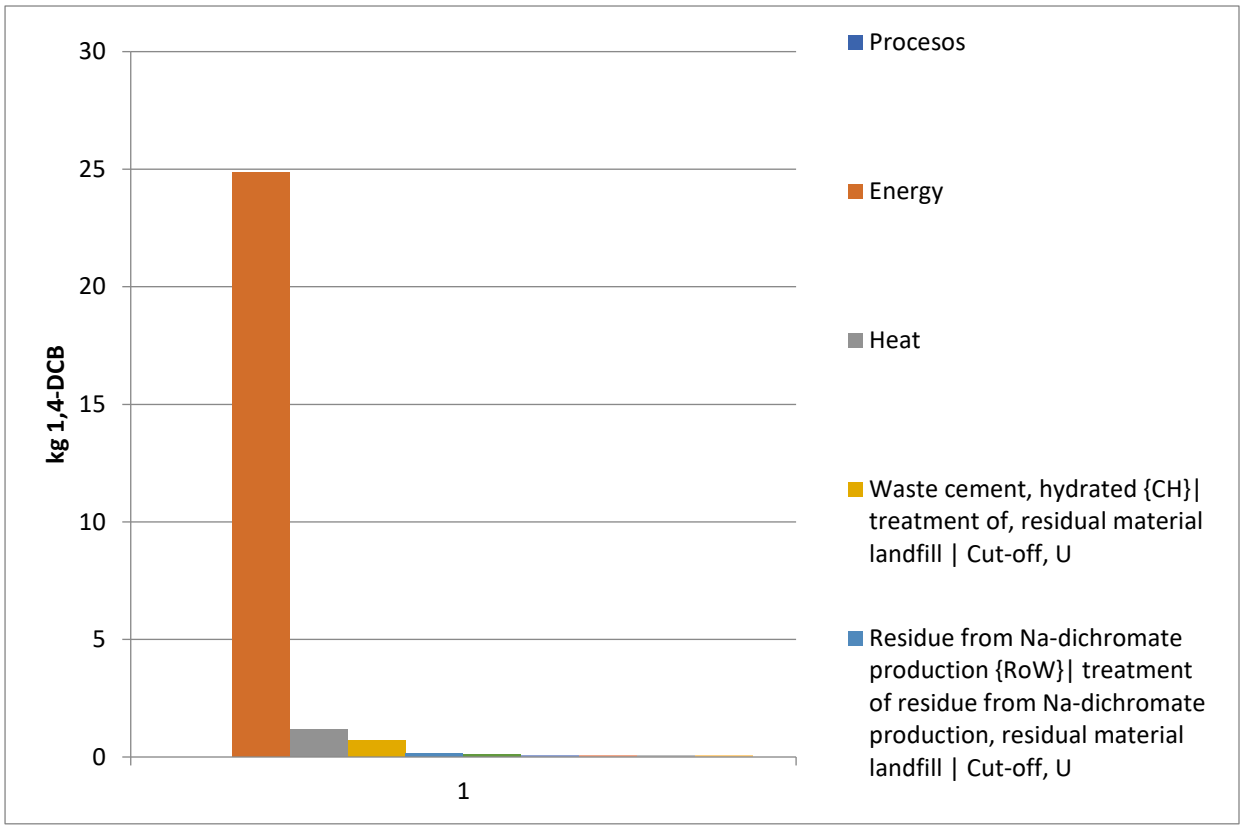


Fig. S11.1 General contributions of IER technology processes to the human carcinogenic toxicity category (ISO 14044, 2006)

Fig. S11.1. shows that the process with the greatest contribution to human carcinogenic toxicity is due to the generation of electrical energy. The rest of the observed processes do not indicate a relevant contribution to human carcinogenic toxicity.

The main concern in this category is Cr (VI) emissions, which is considered the main driver of carcinogenic toxicity (Hauschild et al., 2018). Also, the incomplete combustion of waste leads to the generation of dioxins, polychlorinated dibenzopdioxins, polychlorinated dibenzofurans and polychlorinated biphenyls, which are highly carcinogenic (Kumar, 2017).

Table S11.1. General contributions of IER technology processes to the human carcinogenic toxicity category

No.	Processes	Units	Total
1	Energy	kg 1,4-DCB e	24.859
2	Heat	kg 1,4-DCB e	1.168
3	Waste cement, hydrated {CH}| treatment of, residual material landfill | Cut-off, U	kg 1,4-DCB e	0.697
4	Residue from Na-dichromate production {RoW}| treatment of residue from Na-dichromate production, residual material landfill | Cut-off, U	kg 1,4-DCB e	0.122
5	Anthraquinone {RoW}| production | Cut-off, U	kg 1,4-DCB e	0.100
6	Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB e	0.059
7	Anthraquinone {RER}| production | Cut-off, U	kg 1,4-DCB e	0.049
8	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB e	0.045
9	Remanent processes	kg 1,4-DCB e	0.071

Referencia: Elaboración propia (ISO 14044, 2006).

In table S11.1. It is observed that energy generation contributes to an emission of 24.86 kg 1,4-DBCe (kg of 1,4-dichlorobenzene equivalent). To a lesser extent, the heat processes and treatment of some waste are observed. The TGC process and the leachates from this process are also related, which may contain emissions of: benzene, toluene, As, Pb, Ni, Hg, Zn, NH3 (Cole-Hunter et al., 2020).

Consequently, contact with these emissions, whether through inhalation, ingestion or exposure, can cause health damage (Kumar, 2017; Hauschild et al., 2018; Cole-Hunter et al., 2020).

Annex S11.2. Process Contribution Results to the Non-Carcinogenic Human Health Toxicity Category

The main processes that contribute to the generation of toxic emissions to non-carcinogenic human health are shown in Fig. S11.2. and in Table S11.2. below

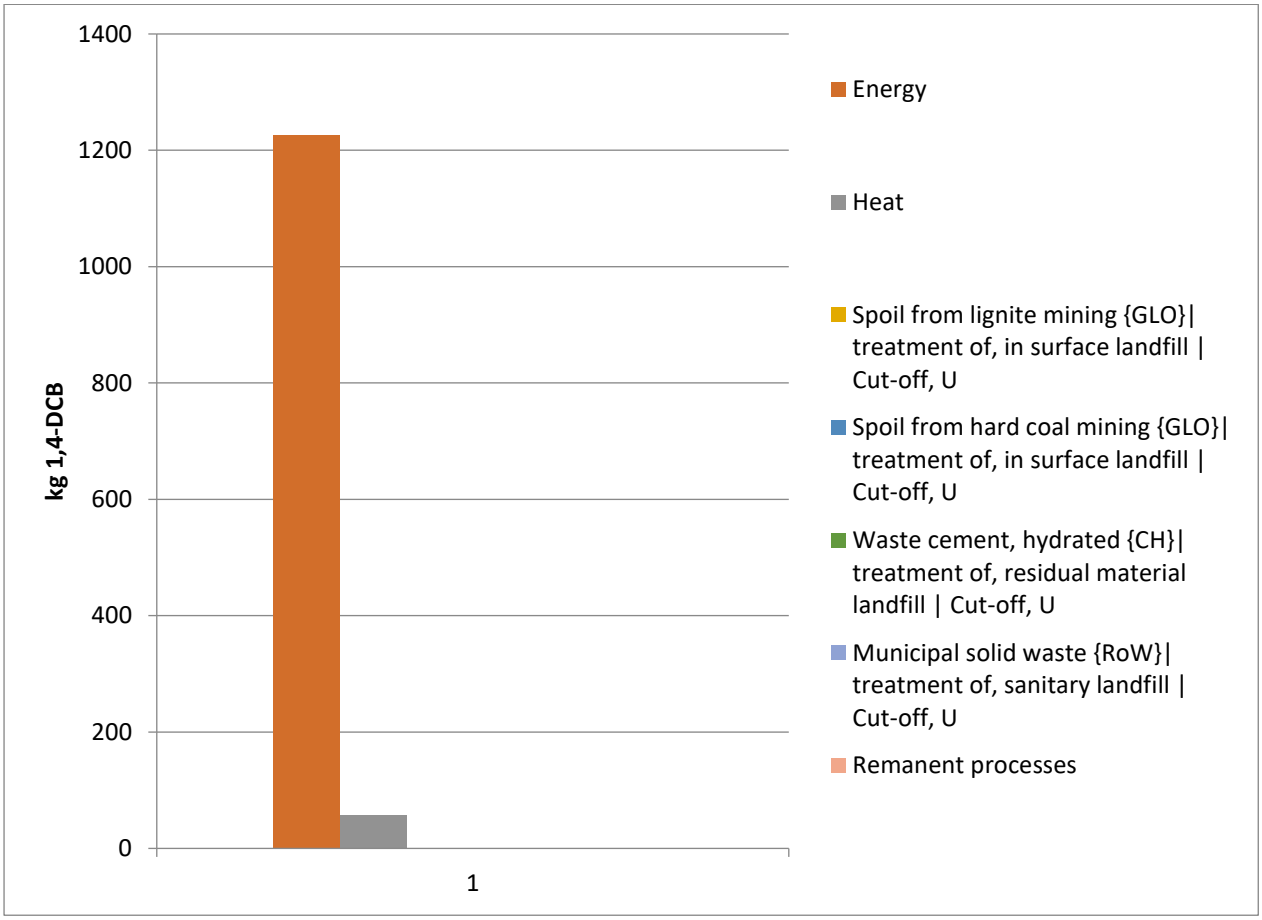


Fig. S11.2. General contributions of IER processes to the non-carcinogenic human toxicity category (ISO 14044, 2006)

Fig. S11.2. shows again that the predominant process contribution in the IER corresponds to the generation of electrical energy. The rest of the processes are not relevant to this category.

Table S11.2. General contributions of incineration technology processes with energy recovery, to the non-carcinogenic human toxicity category

No.	Processes	Units	Total
1	Energy	kg 1,4-DCB e	1226.6134
2	Heat	kg 1,4-DCB e	57.6612
3	Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB e	0.905
4	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB e	0.701
5	Waste cement, hydrated {CH}| treatment of, residual material landfill | Cut-off, U	kg 1,4-DCB e	0.3456
6	Municipal solid waste {RoW}| treatment of, sanitary landfill | Cut-off, U	kg 1,4-DCB e	0.2922
7	Remanent processes	kg 1,4-DCB e	1.4518

Table S11.2. shows that the main process that contributes to non-carcinogenic toxic emissions to human health is the product of energy generation with 1226 kg 1,4-DCB e.

Along these lines, As, Cu and Zn were identified as the most critical emissions for this category (Maresca et al., 2022). To a lesser extent, there is the generation of heat and processes related to the treatment of waste from the combustion process (landfill). To a lesser extent, coal mining waste and cement waste processes are observed. These processes are used for landfilling ashes.

Annex S11.3. Process contribution results to the Marine Ecotoxicity category
The results referring to the category of marine ecotoxicity to IER technology are shown below (Fig. S11.3. and Table S11.3.).

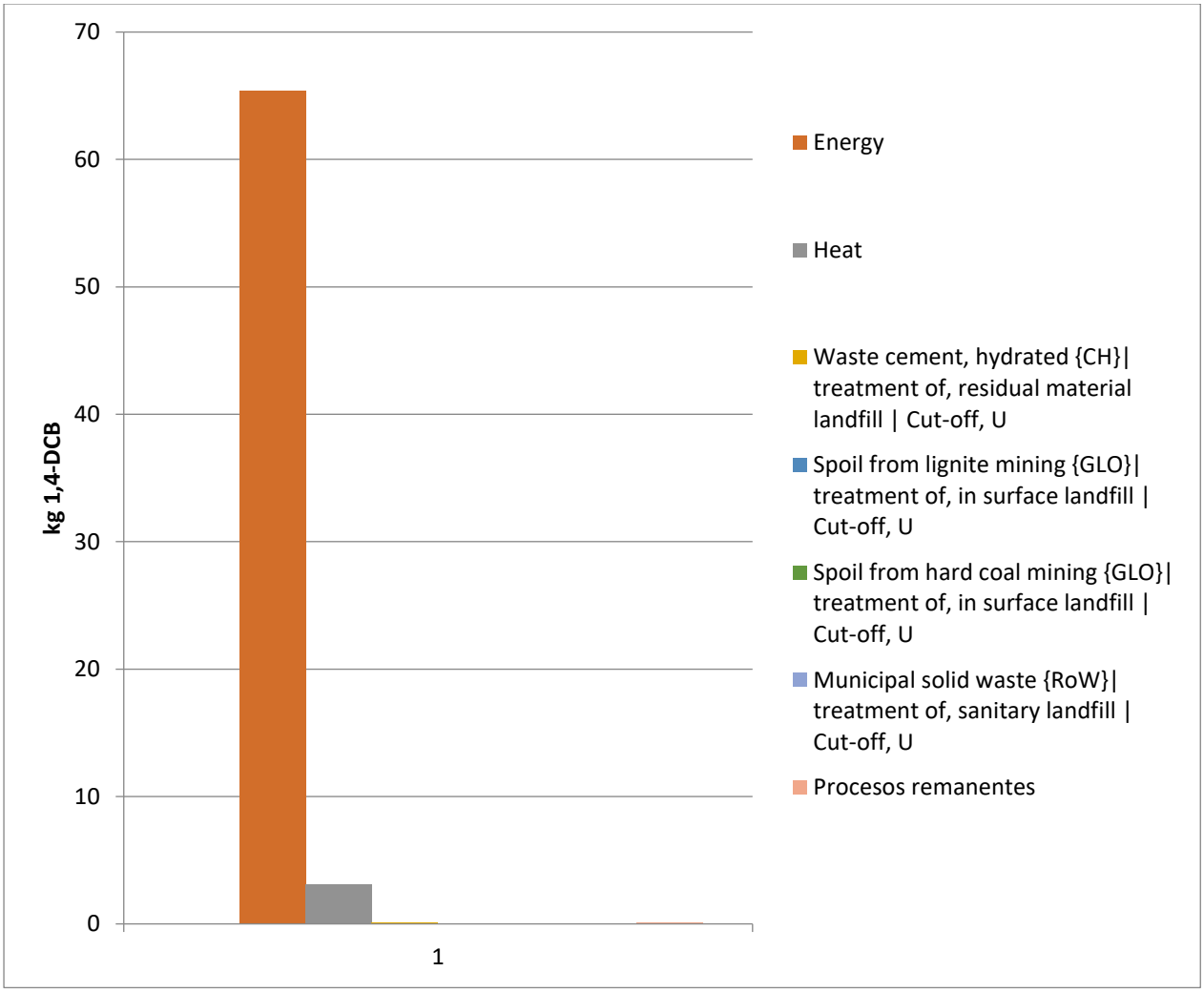


Fig. S11.3. General contributions of incineration technology processes with energy recovery, to the marine ecotoxicity category (ISO 14044, 2006)

In Fig. S11.3. it is observed that the predominant process in the category of marine ecotoxicity is the generation of electrical energy. In contrast to the rest of the processes, which are not observed with important contributions.

Table S11.3. General contributions of incineration technology processes with energy recovery, to the marine ecotoxicity category

No.	Processes	Units	Total
1	Energy	kg 1,4-DCB e	65.3779
2	Heat	kg 1,4-DCB e	3.0733
3	Waste cement, hydrated {CH}| treatment of, residual material landfill | Cut-off, U	kg 1,4-DCB e	0.1024
4	Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB e	0.0428
5	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4-DCB e	0.0321
6	Municipal solid waste {RoW}| treatment of, sanitary landfill | Cut-off, U	kg 1,4-DCB e	0.0179
7	Remanent processes	kg 1,4-DCB e	0.094

Table S11.3. shows that the process with the greatest contribution to the marine ecotoxicity category is the generation of electrical energy with 65.37 kg 1,4-DCB e which is mainly related to water emissions of heavy metals such as Cr, Ni, Zn, and Co (Hauschild et al., 2018). In lesser contribution are waste treatment processes, such as fly and fine ash, as well as reagents and reaction products formed because of the compounds used in TGC equipment (cyclones, precipitators, filters, etc.) (Tchoubanouglous & Kreith, 2002).

Annex S11.4. Process contribution results to the Freshwater Ecotoxicity category

Below are the results of the freshwater ecotoxicity category for the IER technology (Fig. S11.4 and Table S11.4.).

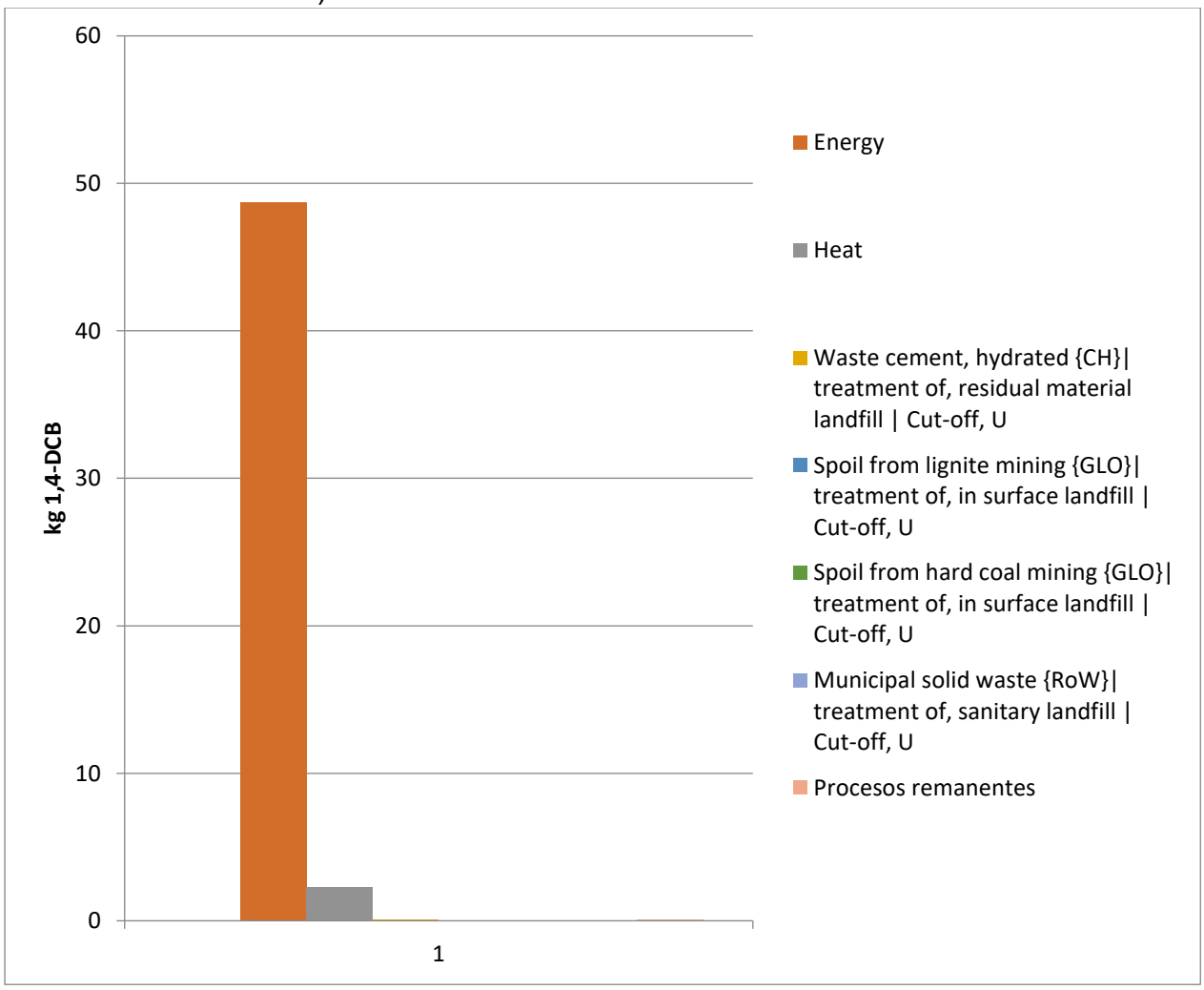


Fig. S11.4. General contributions of incineration technology processes with energy recovery, to the freshwater ecotoxicity category (ISO 14044, 2006)

In Fig.S11.4 t is observed that the process with the greatest contribution to the category of ecotoxicity to freshwater is the generation of electrical energy.

In a lesser contribution to this category are waste treatment processes such as fine ashes.

Table S11.4. General contributions of incineration technology processes with energy recovery, to the freshwater ecotoxicity category

No.	Processes	Units	Total
1	Energy	kg 1,4 DCB e	48.7041
2	Heat	kg 1,4 DCB e	2.2895
3	Waste cement, hydrated {CH}| treatment of, residual material landfill | Cut-off, U	kg 1,4 DCB e	0.0725
4	Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4 DCB e	0.0312
5	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg 1,4 DCB e	0.0233
6	Municipal solid waste {RoW}| treatment of, sanitary landfill | Cut-off, U	kg 1,4 DCB e	0.0137
7	Remanent processes	kg 1,4 DCB e	0.0588

Table S11.4. indicates that the processes with the greatest contributions in the category of ecotoxicity to fresh water are the generation of electrical energy with 48.7 kg 1.4 DCB e and to a lesser extent the heat process with 2.28 kg 1.4 DCB e.

The main water emissions that contribute in this category are Cu, As, Zn (II), Cr, Ni and Br in water (Hauschild et al., 2018). In lesser contribution in this category are waste treatment processes (fly and fine ash), as well as reagents and reaction products formed as a consequence of the compounds used in TGC equipment (Tchoubanouglous & Kreith, 2002).

Annex S11.5. Process contribution results to Global Warming category

Below are the results from the global warming category to the IER technology (Fig.S11.5. and Table S11.5).

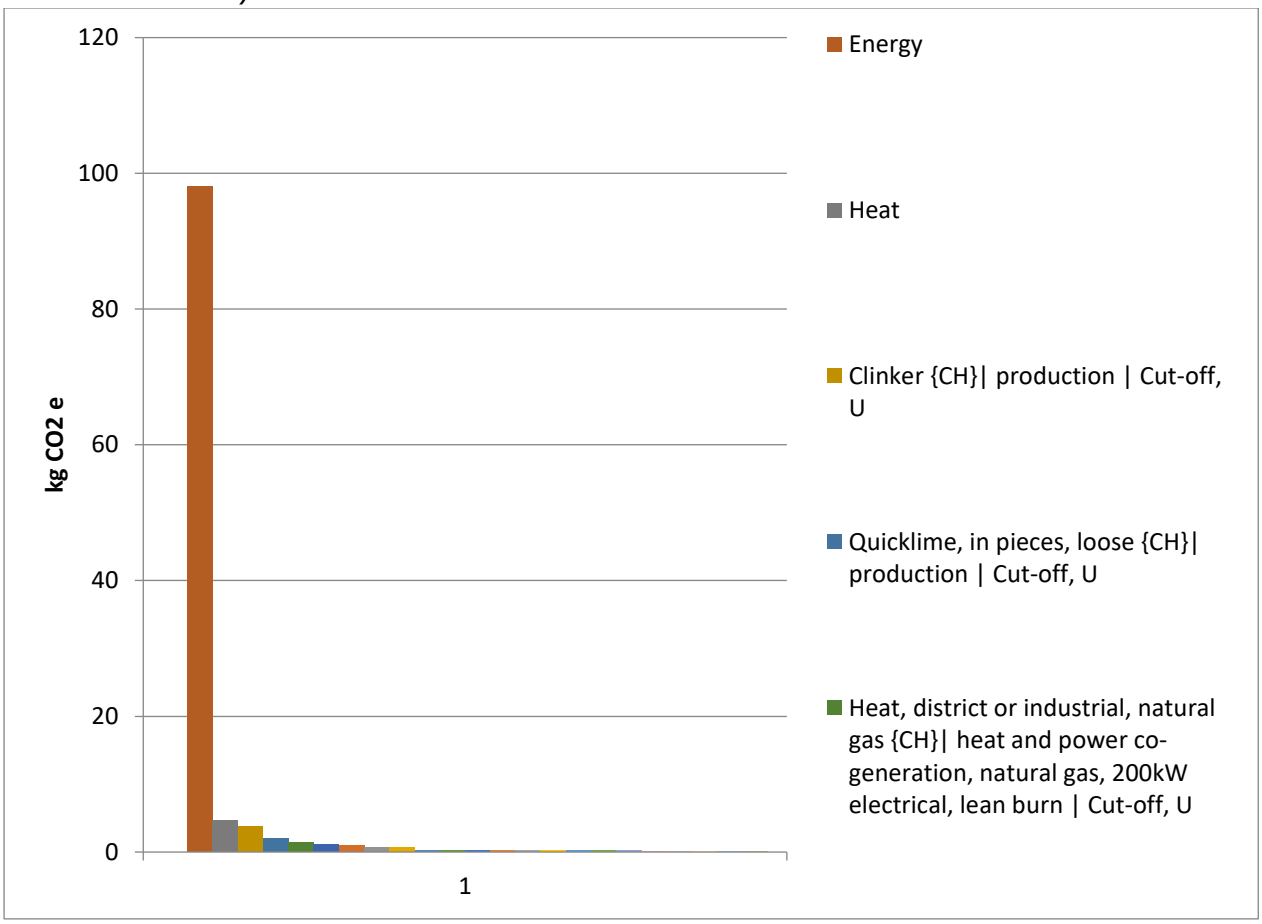


Fig. S11.5. Contribuciones generales de los procesos a la categoría calentamiento global de Incineración con recuperación de energía (ISO 14044, 2006)

It is seen in Fig. S11.4 and Table S11.5. that the process that contributes the most to global warming is the generation of electrical energy, since it occupies 98 Kg CO_2 e of emissions and is related to the combustion of waste.

The main emissions emanating from this process are CO_2, hydrocarbons and CO (Lou et al., 2015). To a lesser extent, heat processes (waste heat), slag, heat due to the use of natural gas as an auxiliary source and calcium oxide (lime) used in cleaning combustion gases (product of the heat emitted) contribute to global warming due to the reaction of lime with water).

Table S11.5. Contributions of Incineration with Energy Recovery to the Global Warming Category

No.	Processes	Units	Total
1	Energy	Kg CO_2 e	98.0404
2	Heat	Kg CO_2 e	4.6087
3	Clinker {CH}| production | Cut-off, U	Kg CO_2 e	3.6956
4	Quicklime, in pieces, loose {CH}| production | Cut-off, U	Kg CO_2 e	1.983
5	Heat, district or industrial, natural gas {CH}| heat and power co generation, natural gas, 200kW electrical, lean burn | Cut-off, U	Kg CO_2 e	1.3391
6	Heat, district or industrial, natural gas {CH}| heat and power co-generation, natural gas, 1MW electrical, lean burn | Cut-off, U	Kg CO_2 e	1.0735
7	Ammonia, liquid {RER}| ammonia production, steam reforming, liquid | Cut-off, U	Kg CO_2 e	0.9011
8	Heat, district or industrial, natural gas {CH}| heat and power co-generation, natural gas, 500kW electrical, lean burn | Cut-off, U	Kg CO_2 e	0.7068
9	Clinker {Europe without Switzerland}| production | Cut-off, U	Kg CO_2 e	0.682
10	Ammonia, liquid {RER}| ammonia production, partial oxidation, liquid | Cut-off, U	Kg CO_2 e	0.2559
11	Natural gas, low pressure {CH}| market for | Cut-off, U	Kg CO_2 e	0.2519
12	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	Kg CO_2 e	0.2121
13	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	Kg CO_2 e	0.1882
14	Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, U	Kg CO_2 e	0.1858
15	Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	Kg CO_2 e	0.1712
16	Hydrogen, liquid {RER}| hydrogen cracking, APME | Cut-off, U	Kg CO_2 e	0.1595
17	Transport, freight, lorry >32 metric ton, EURO4 {RER}| transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	Kg CO_2 e	0.1553
18	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	Kg CO_2 e	0.1518
19	Transport, pipeline, long distance, natural gas {RU}| processing | Cut-off, U	Kg CO_2 e	0.1384
20	Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	Kg CO_2 e	0.137
21	Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	Kg CO_2 e	0.1363
22	Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	Kg CO_2 e	0.132
23	Electricity, medium voltage {RU}| natural gas, burned in gas turbine, for compressor station | Cut-off, U	Kg CO_2 e	0.1283
24	Remanent processes	Kg CO_2 e	4.1428

Annex S11.6. Process contribution results to terrestrial ecotoxicity category

Below are the results referring to for IER technology (Fig.S11.6 and Table S11.6.).

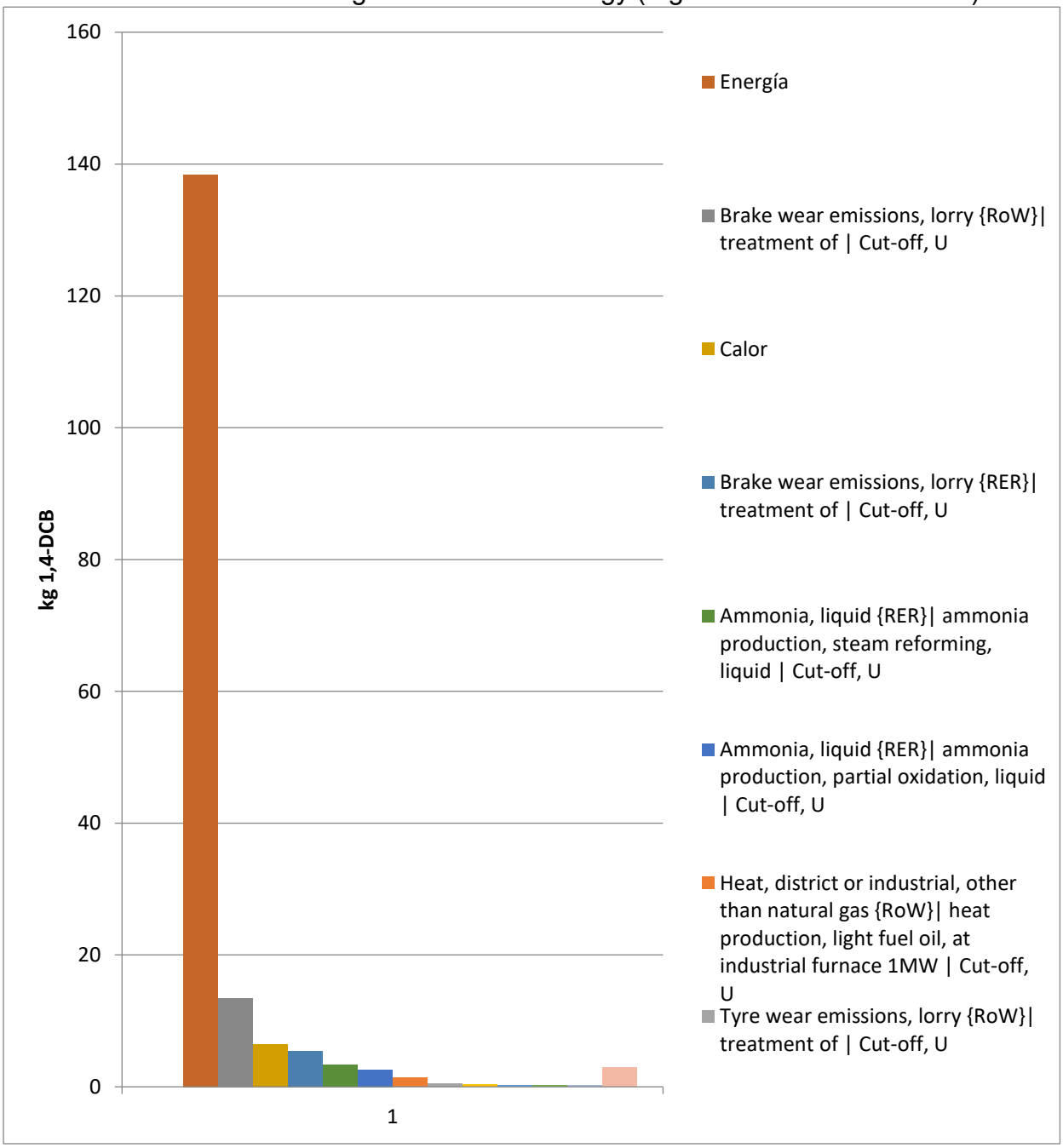


Fig. S11.6 General contributions of incineration technology processes with energy recovery, to the terrestrial ecotoxicity category (ISO 14044, 2006)

Table S11.6. General contributions of IER technology processes to the terrestrial ecotoxicity category

No.	Processes	Units	Total
1	Energía	kg 1,4 DCB e	138.3785
2	Brake wear emissions, lorry {RoW}| treatment of | Cut-off, U	kg 1,4 DCB e	13.4554
3	Calor	kg 1,4 DCB e	6.505
4	Brake wear emissions, lorry {RER}| treatment of | Cut-off, U	kg 1,4 DCB e	5.468
5	Ammonia, liquid {RER}| ammonia production, steam reforming, liquid | Cut-off, U	kg 1,4 DCB e	3.4124
6	Ammonia, liquid {RER}| ammonia production, partial oxidation, liquid | Cut-off, U	kg 1,4 DCB e	2.6214
7	Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U	kg 1,4 DCB e	1.3811
8	Tyre wear emissions, lorry {RoW}| treatment of | Cut-off, U	kg 1,4 DCB e	0.4875
9	Clinker {CH}| production | Cut-off, U	kg 1,4 DCB e	0.3873
10	Zinc monosulfate {RER}| production | Cut-off, U	kg 1,4 DCB e	0.2321
11	Uranium tailing, non-radioactive emission {GLO}| treatment of | Cut-off, U	kg 1,4 DCB e	0.2018
12	Tyre wear emissions, lorry {RER}| treatment of | Cut-off, U	kg 1,4 DCB e	0.1981
13	Remanent processes	kg 1,4 DCB e	2.9452

It is shown in table S11.6 and Fig. S11.6 that the processes with the greatest contributions in the terrestrial ecotoxicity category are the energy generation process with 138.4 kg 1.4 DCB and to a lesser extent the heat process with 2.28 kg 1.4 DCB e.

Mainly due to the waste and products derived from the gas purification process (salts) and the ashes that are sent to landfills.

Annex S11.7. Process contribution results to ozone formation and human health category

Below are the results of the ozone formation and human health category for IER technology (Fig. S11.7 and Table S11.7).

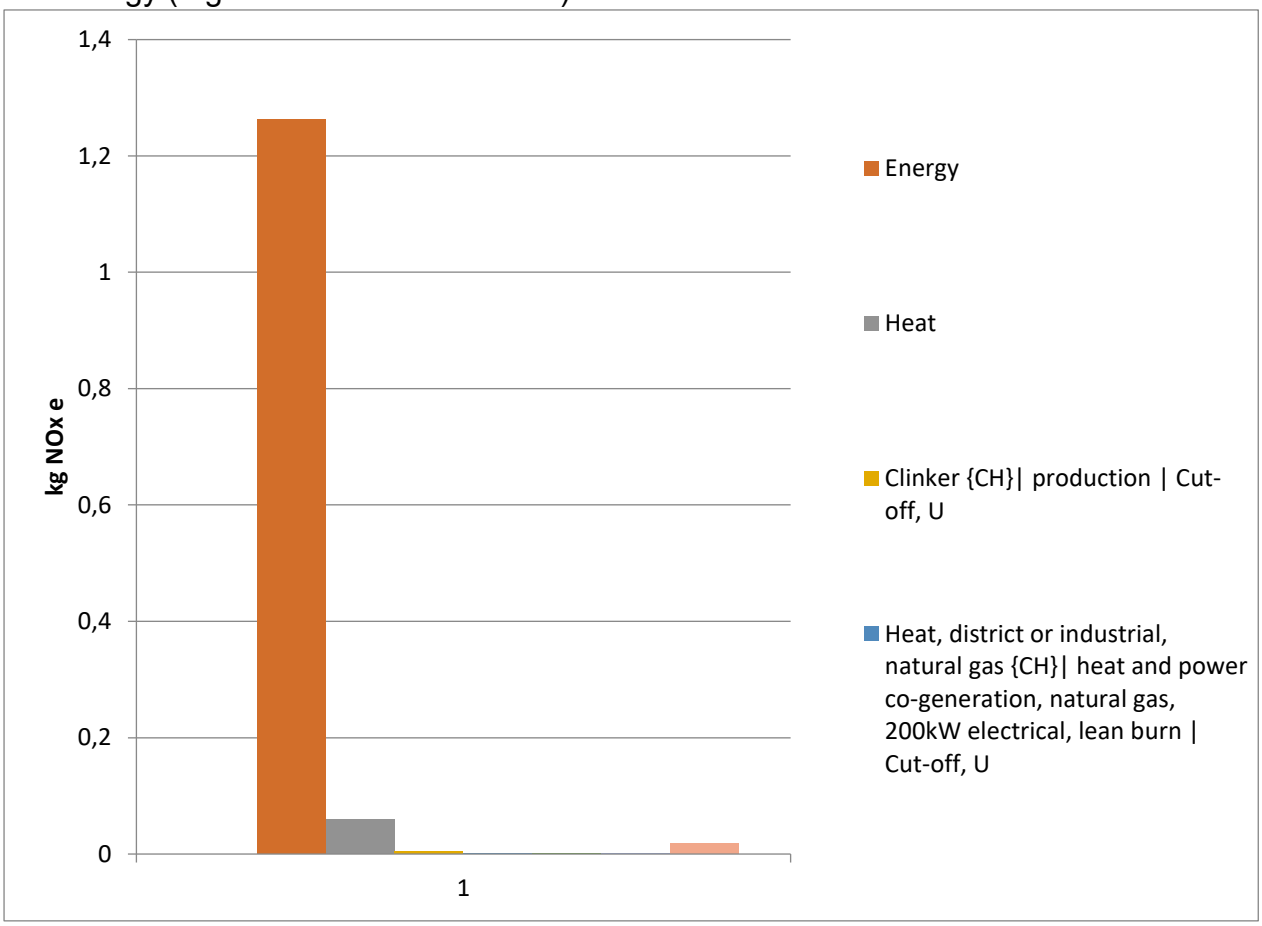


Fig. S11.7. General contributions of incineration technology processes with energy recovery, to the category of ozone and human health (ISO 14044, 2006).

Table S11.7. General contributions of incineration technology processes with energy recovery, to the ozone and human health category

No.	Processes	Units	Total
1	Energy	kg NOx e	1.2634
2	Heat	kg NOx e	0.0594
3	Clinker {CH}| production | Cut-off, U	kg NOx e	0.0043
4	Heat, district or industrial, natural gas {CH}| heat and power co-generation, natural gas, 200kW electrical, lean burn | Cut-off, U	kg NOx e	0.0016
5	Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, U	kg NOx e	0.0015
6	Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	kg NOx e	0.0014
7	Remanent processes	kg NOx e	0.0187

It is seen in Fig. S11.7 and in table S11.7. that the main contribution of IER technology to the O_3 human health impact is due to the generation of electrical energy. Electrical energy generation contributes 1.26 kg NOx e, followed by the heat production process. In a lesser contribution, processes related to the production of slag, infrastructure and transportation necessary for the ash landfill are observed.

Annex S11.8. Process contribution results to the terrestrial ecosystem ozone formation category

Below are the results for the terrestrial ecosystem ozone formation category using IER technology (Fig. S11.8 and Table S11.8).

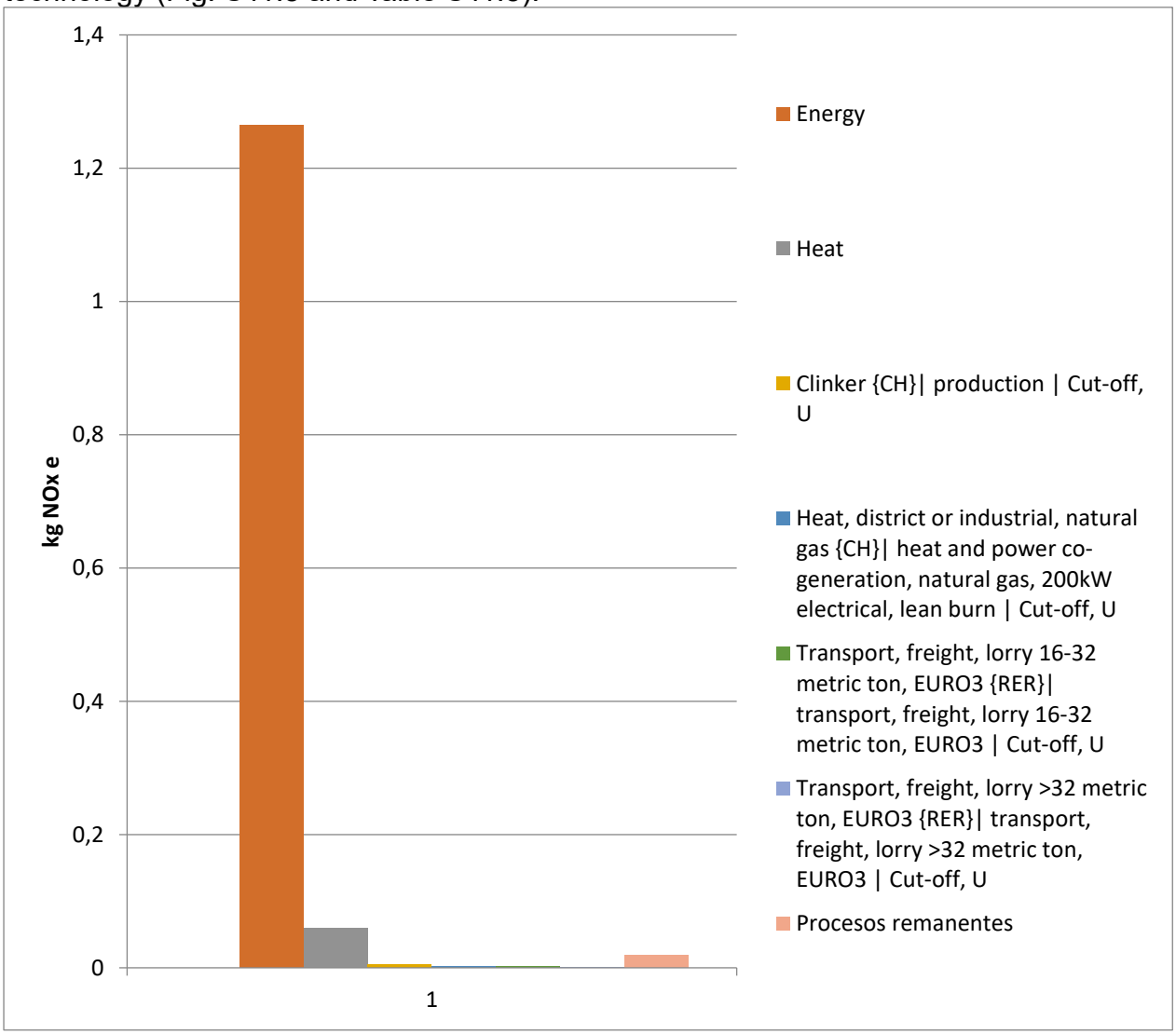


Fig. S11.8 General contributions of incineration technology processes with energy recovery, to the category ozone formation in terrestrial ecosystems (ISO 14044, 2006).

Table S11.8 General contributions of processes to IER category ozone formation in terrestrial ecosystems

No.	Processes	Units	Total
1	Energy	kg NOx e	1.2648
2	Heat	kg NOx e	0.0595
3	Clinker {CH}| production | Cut-off, U	kg NOx e	0.0044
4	Heat, district or industrial, natural gas {CH}| heat and power co-generation, natural gas, 200kW electrical, lean burn | Cut-off, U	kg NOx e	0.0016
5	Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, U	kg NOx e	0.0015
6	Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	kg NOx e	0.0014
7	Remanent processes	kg NOx e	0.0191

It is observed in Fig. S11.8 and in table Fig. S11.8 that the process with the greatest contribution to the category of ozone formation in terrestrial ecosystems is due to energy generation. Power generation contributes 1.26 kg NOx e /ton of incinerated OFMSW, while contributions from the rest of the processes are minimal. In this area, CO emissions are responsible for the formation of photochemical ozone, which may be due to the incomplete combustion of SOR.

Annex S11.9. Process contribution results to ozone deterioration in the stratosphere

Below are the results referring to the category of ozone deterioration in the stratosphere using IER technology (Fig.S11.9 and Table S11.9.).

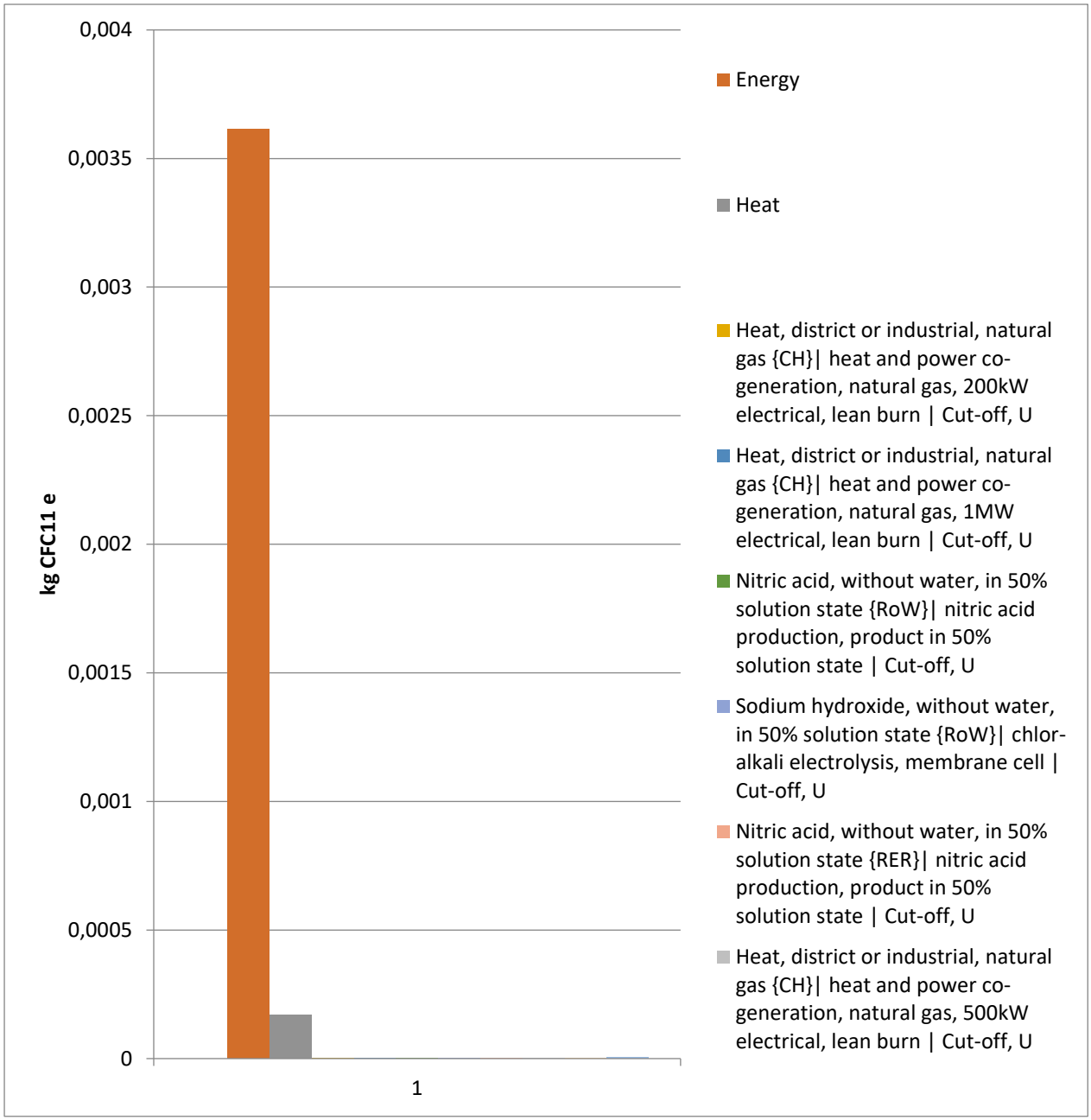


Fig. S11.9 General contributions of incineration with energy recovery technology processes to the stratospheric ozone depletion category (ISO 14044, 2006).

Table S11.9. General contributions of incineration technology processes with energy recovery, to the category on ozone deterioration in the stratosphere

No.	Processes	Units	Total
1	Energy	kg CFC11 e	0.0036
2	Heat	kg CFC11 e	0.0002
3	Heat, district or industrial, natural gas {CH}| heat and power co-generation, natural gas, 200kW electrical, lean burn | Cut-off, U	kg CFC11 e	1.22E-06
4	Heat, district or industrial, natural gas {CH}| heat and power co-generation, natural gas, 1MW electrical, lean burn | Cut-off, U	kg CFC11 e	9.78E-07
5	Nitric acid, without water, in 50% solution state {RoW}| nitric acid production, product in 50% solution state | Cut-off, U	kg CFC11 e	8.87E-07
6	Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, membrane cell | Cut-off, U	kg CFC11 e	8.73E-07
7	Nitric acid, without water, in 50% solution state {RER}| nitric acid production, product in 50% solution state | Cut-off, U	kg CFC11 e	6.95E-07
8	Heat, district or industrial, natural gas {CH}| heat and power co-generation, natural gas, 500kW electrical, lean burn | Cut-off, U	kg CFC11 e	6.44E-07
9	Transport, pipeline, long distance, natural gas {RU}| processing | Cut-off, U	kg CFC11 e	3.9E-07
10	Remanent processes	kg CFC11 e	3.78E-06

It is seen in Fig.S11.9 and Table S11.9. that the process with the greatest contribution to this category is the generation of energy with 0.0036 kg CFC11 e followed by the heat production process with 0.002 kg CFC11 e. Energy generation, as previously mentioned, is related to the combustion process and the emission of gases from this process. Ozone deterioration in the stratosphere is mainly affected by emissions such as NOx, Br, chlorofluorocrabons (CFCs) and other non-methane volatile organic compounds (Koppmann R., 2007).

Annex S11.10. Process contribution results to the category of ionizing radiation.

Fig. S11.10 and Table S11.9 show the results regarding the contribution of processes to the category of ionizing radiation**.**

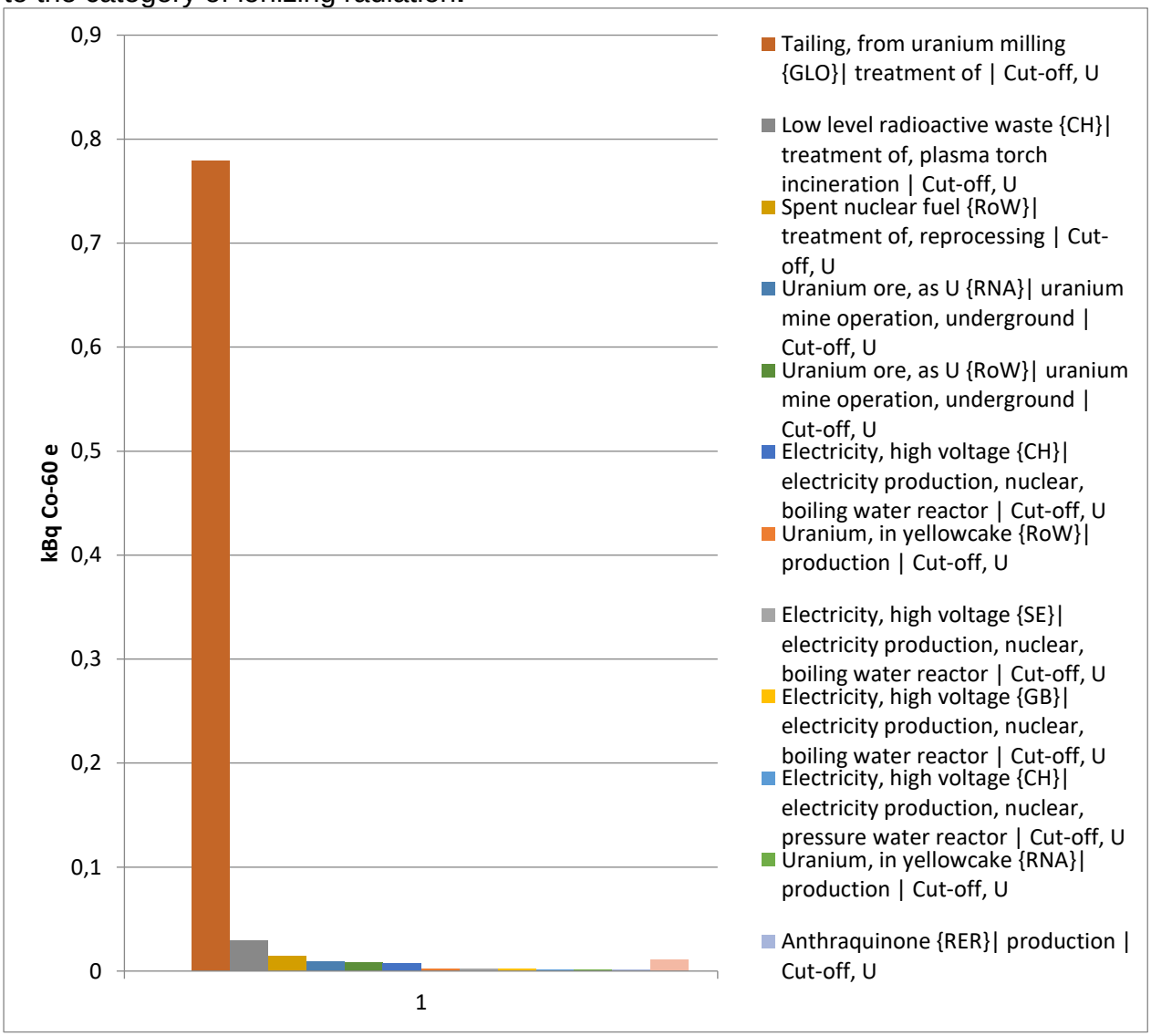


Fig. S11.10. General contributions of incineration technology processes with energy recovery, to the category of Ionizing Radiation

Table S11.10 General contributions of incineration technology processes with energy recovery, to the category of Ionizing Radiation

No.	Processes	Units	Total
1	Tailing, from uranium milling {GLO}| treatment of | Cut-off, U	kg Co-60 e	0.7794
2	Low level radioactive waste {CH}| treatment of, plasma torch incineration | Cut-off, U	kg Co-60 e	0.0291
3	Spent nuclear fuel {RoW}| treatment of, reprocessing | Cut-off, U	kg Co-60 e	0.0142
4	Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	kg Co-60	0.009
5	Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	kg Co-60 e	0.0086
6	Electricity, high voltage {CH}| electricity production, nuclear, boiling water reactor | Cut-off, U	kg Co-60 e	0.0074
7	Uranium, in yellowcake {RoW}| production | Cut-off, U	kg Co-60 e	0.0023
8	Electricity, high voltage {SE}| electricity production, nuclear, boiling water reactor | Cut-off, U	kg Co-60 e	0.0018
9	Electricity, high voltage {GB}| electricity production, nuclear, boiling water reactor | Cut-off, U	kg Co-60 e	0.0018
10	Electricity, high voltage {CH}| electricity production, nuclear, pressure water reactor | Cut-off, U	kg Co-60 e	0.0015
11	Uranium, in yellowcake {RNA}| production | Cut-off, U	kg Co-60 e	0.001
12	Anthraquinone {RER}| production | Cut-off, U	kg Co-60 e	0.001
13	Remanent processes	kg Co-60 e	0.0106

It is observed in Figure S11.10 and Table S11.10 that the process with the greatest contribution to this impact category is the generation of waste that may contain uranium with 0.7794 kg Co-60 in the air, followed by waste derived from the treatment of radioactive reagents.

Annex S11.11. Process contribution results to the category of fine particles 2.5 µm or less referring to IER technology

Figure S11.11 and Table S11.11 show the results regarding the contribution of processes to the category of fine particles 2.5 µm or less.

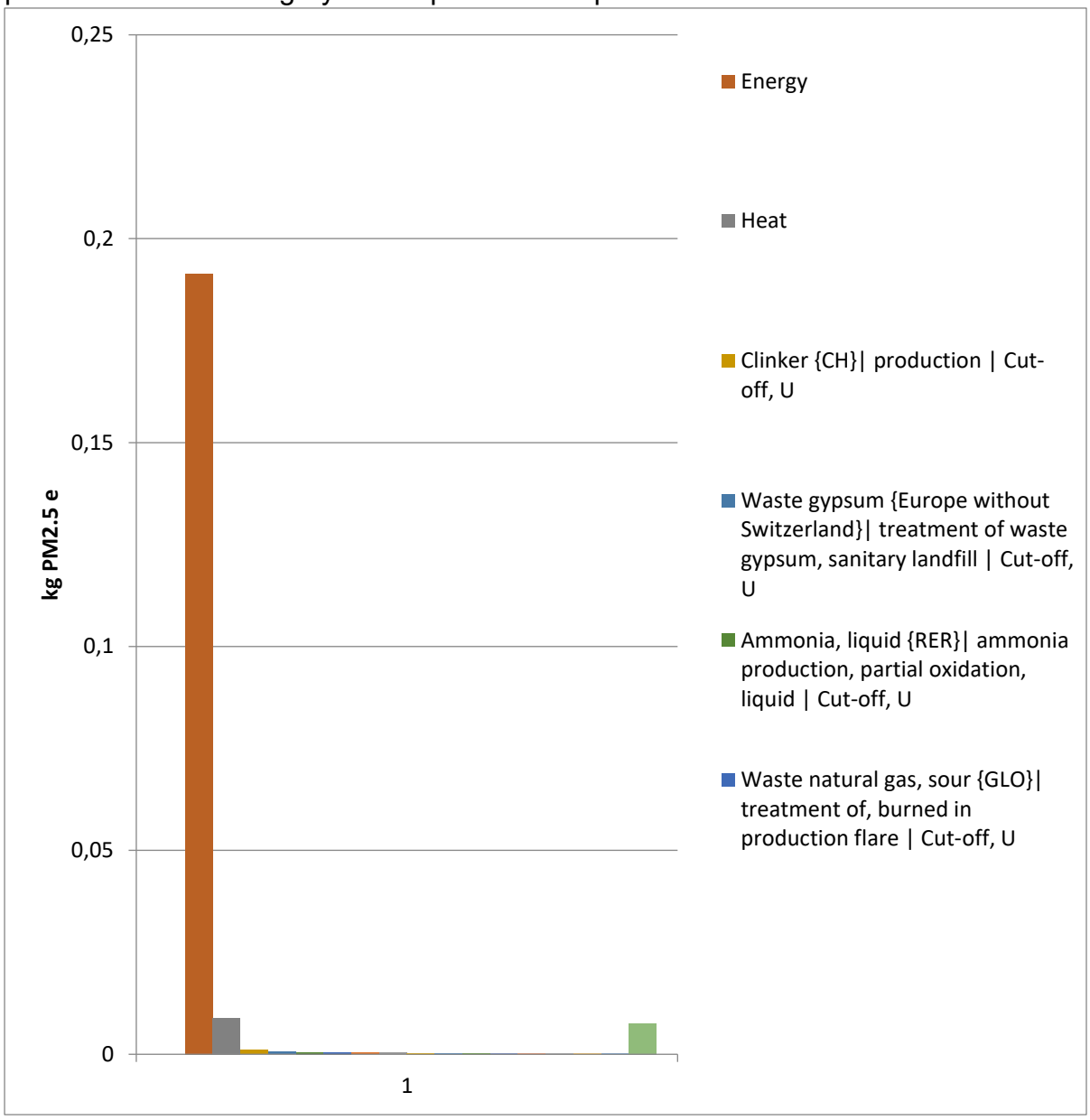


Fig.S11.11. Overall contributions of incineration technology processes with energy recovery, to the category of fine particles 2.5 µm or less

It is shown in Fig.S11.11 and Table S11.11 that the process with the greatest contribution to this impact category is due to the generation of energy with 0.1914 kg of 2.5 µm particles, the contribution of the rest of the processes to this category is minimal.

Table S11.11. General contributions of incineration technology processes with energy recovery, to the category of Fine particles 2.5 µm or less

No.	Processes	Units	Total
1	Energy	kg de partículas 2.5 µm	0.1914
2	Heat	kg de partículas 2.5 µm	0.009
3	Clinker {CH}| production | Cut-off, U	kg de partículas 2.5 µm	0.001
4	Waste gypsum {Europe without Switzerland}| treatment of waste gypsum, sanitary landfill | Cut-off, U	kg de partículas 2.5 µm	0.0006
5	Ammonia, liquid {RER}| ammonia production, partial oxidation, liquid | Cut-off, U	kg de partículas 2.5 µm	0.0005
6	Waste natural gas, sour {GLO}| treatment of, burned in production flare | Cut-off, U	kg de partículas 2.5 µm	0.0005
7	Electricity, high voltage {ID}| electricity production, lignite | Cut-off, U	kg de partículas 2.5 µm	0.0004
8	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	kg de partículas 2.5 µm	0.0004
9	Sour gas, burned in gas turbine {RoW}| processing | Cut-off, U	kg de partículas 2.5 µm	0.0003
10	Electricity, high voltage {RFC}| electricity production, lignite | Cut-off, U	kg de partículas 2.5 µm	0.0003
11	Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U	kg de partículas 2.5 µm	0.0003
12	Sulfuric acid {RER}| production | Cut-off, U	kg de partículas 2.5 µm	0.0003
13	Electricity, high voltage {SERC}| electricity production, lignite | Cut-off, U	kg de partículas 2.5 µm	0.0003
14	Quicklime, in pieces, loose {CH}| production | Cut-off, U	kg de partículas 2.5 µm	0.0003
15	Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Cut-off, U	kg de partículas 2.5 µm	0.0003
16	Ammonia, liquid {RER}| ammonia production, steam reforming, liquid | Cut-off, U	kg de partículas 2.5 µm	0.0002
17	Remanent processes	kg de partículas 2.5 µm	0.0076

Annex S11.12. Process contribution results to the category of freshwater eutrophication referring to IER technology

Fig. S11.12 and Table S11.12 show the results regarding the contribution of processes to the category of marine eutrophication.

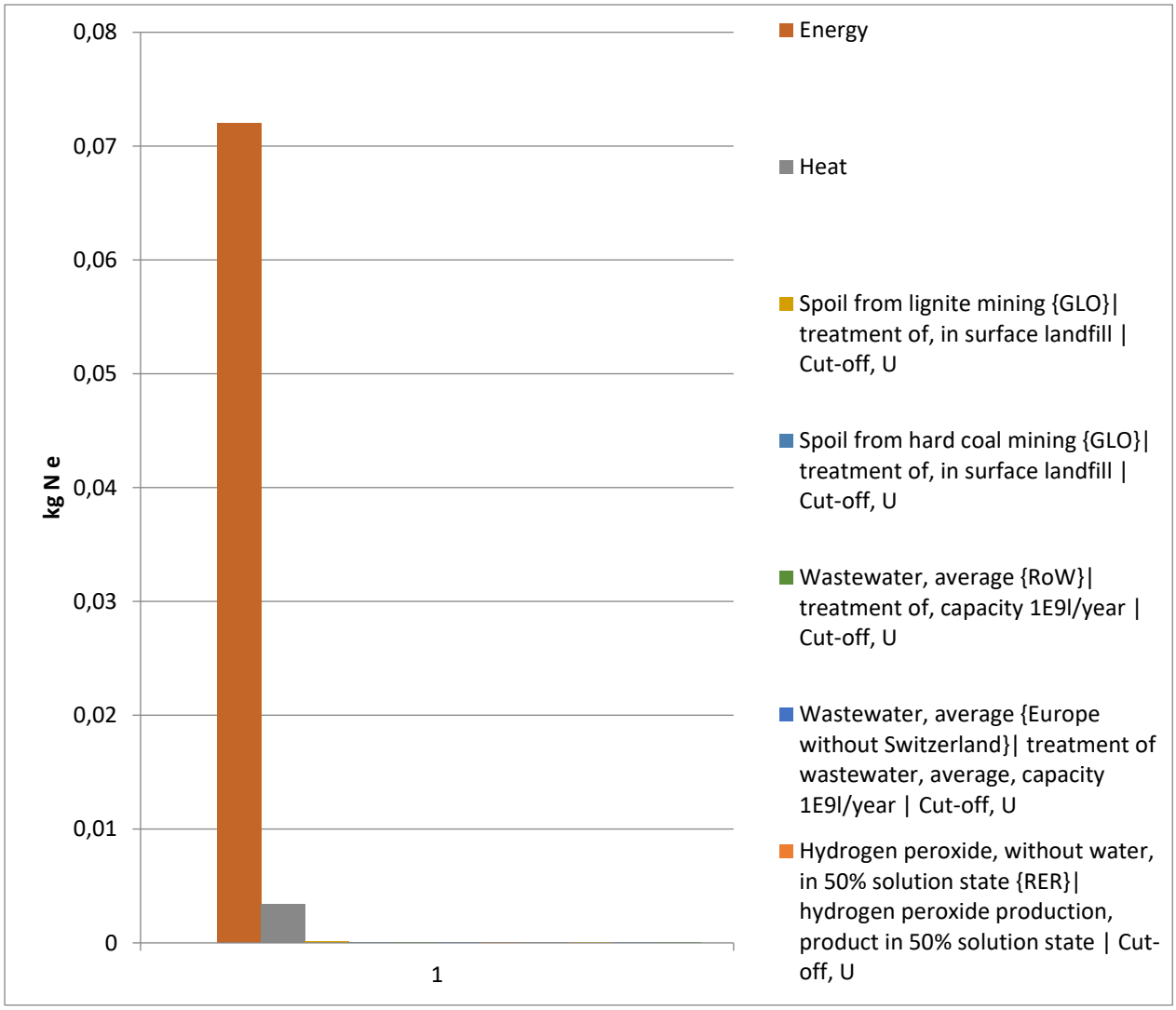


Fig.S11.12 General contributions of incineration with energy recovery technology processes to the marine eutrophication category

Table S11.12 General contributions of incineration with energy recovery technology processes to the marine eutrophication category

No.	Processes	Units	Total
1	Energy	kg N e	0.072
2	Heat	kg N e	0.0034
3	Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg N e	8.52E-05
4	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	kg N e	5.52E-05
5	Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Cut-off, U	kg N e	2.69E-05
6	Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Cut-off, U	kg N e	1.71E-05
7	Hydrogen peroxide, without water, in 50% solution state {RER}| hydrogen peroxide production, product in 50% solution state | Cut-off, U	kg N e	1.68E-05
8	Municipal solid waste {RoW}| treatment of, sanitary landfill | Cut-off, U	kg N e	1.62E-05
9	Uranium, in yellowcake {GLO}| uranium production, in yellowcake, in-situ leaching | Cut-off, U	kg N e	1.34E-05
10	Decarbonising waste {RoW}| treatment of, residual material landfill | Cut-off, U	kg N e	8.19E-06
11	Remanent processes	kg N e	2.0E-05

It can be seen in Fig. S11.12. and in Table S11.12. that the processes that contribute the most to the category of marine eutrophication is energy with 0.072 kg N e and heat with 0.0034 kg N e, the rest of the processes are minor.

Annex S11.13. Process contribution results to the category of land use category referring to IER technology

Fig.S11.13 and Table S11.13 show the results regarding the contribution of processes to the land use category.

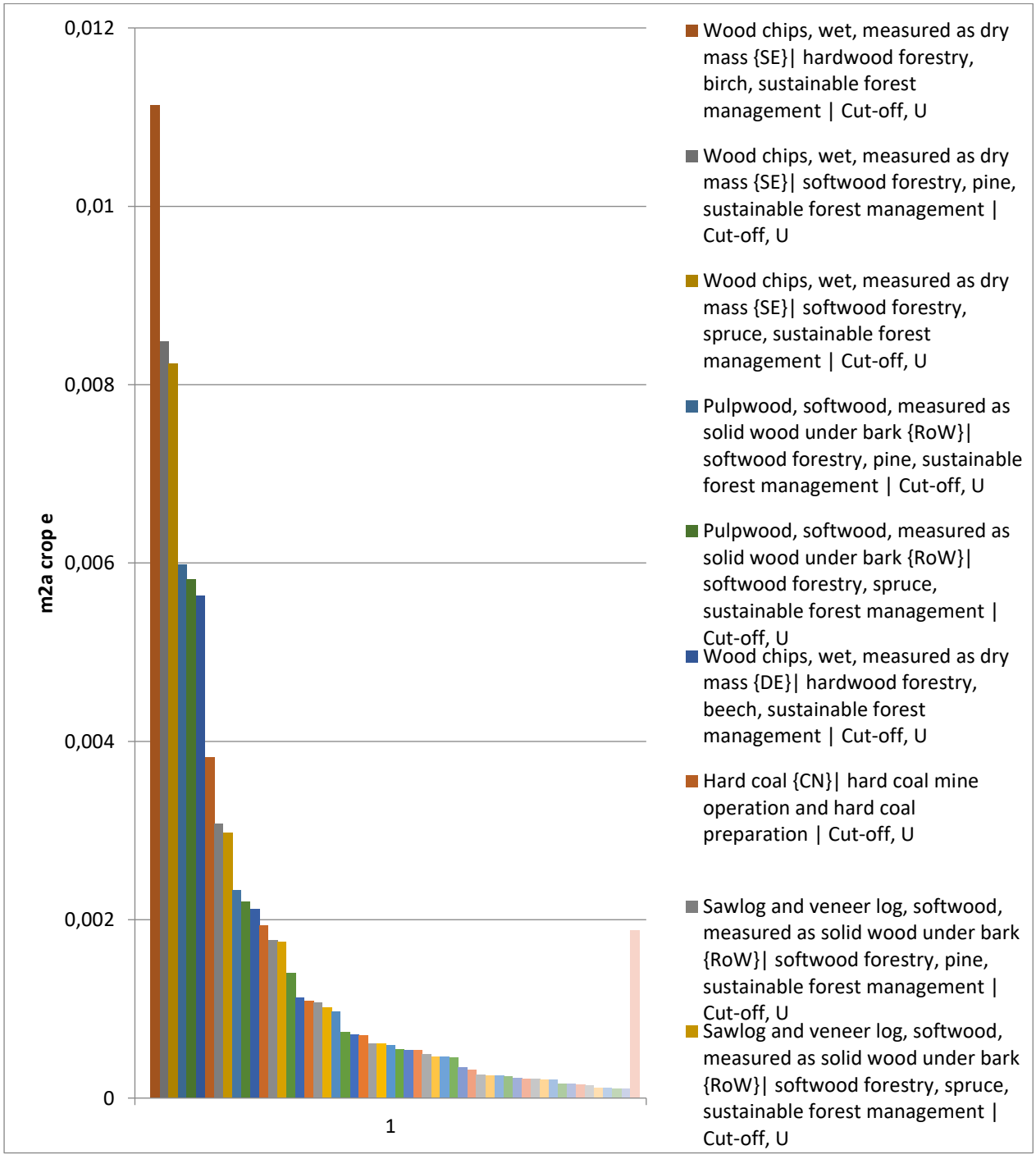


Fig. S11.13. General contributions of incineration technology processes with energy recovery, to the land use category

Table S11.13. General contributions of incineration technology processes with energy recovery, to the land use category

No.	Processes	Units	Total
1	Wood chips, wet, measured as dry mass {SE}| hardwood forestry, birch, sustainable forest management | Cut-off, U	m2×yr crop e	0.0111
2	Wood chips, wet, measured as dry mass {SE}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2×yr crop e	0.0085
3	Wood chips, wet, measured as dry mass {SE}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2×yr crop e	0.0082
4	Pulpwood, softwood, measured as solid wood under bark {RoW}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2×yr crop e	0.006
5	Pulpwood, softwood, measured as solid wood under bark {RoW}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2×yr crop e	0.0058
6	Wood chips, wet, measured as dry mass {DE}| hardwood forestry, beech, sustainable forest management | Cut-off, U	m2×yr crop e	0.0056
7	Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	m2×yr crop e	0.0038
8	Sawlog and veneer log, softwood, measured as solid wood under bark {RoW}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2×yr crop e	0.003
9	Sawlog and veneer log, softwood, measured as solid wood under bark {RoW}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2×yr crop e	0.003
10	Wood chips, wet, measured as dry mass {DE}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2×yr crop e	0.0023
11	Pulpwood, softwood, measured as solid wood under bark {SE}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2×yr crop e	0.0022
12	Pulpwood, softwood, measured as solid wood under bark {SE}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2×yr crop e	0.0021
13	Wood chips, wet, measured as dry mass {DE}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2×yr crop e	0.0019
14	Wood chips, wet, measured as dry mass {CH}| hardwood forestry, mixed species, sustainable forest management | Cut-off, U	m2×yr crop e	0.0018
15	Sawlog and veneer log, softwood, measured as solid wood under bark {CA-QC}| softwood forestry, mixed species, boreal forest | Cut-off, U	m2×yr crop e	0.0018
16	Wood chips, wet, measured as dry mass {RoW}| hardwood forestry, birch, sustainable forest management | Cut-off, U	m2×yr crop e	0.0015
17	Hard coal {RNA}| hard coal mine operation and hard coal preparation | Cut-off, U	m2×yr crop e	0.0014
18	Wood chips, wet, measured as dry mass {RoW}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2×yr crop e	0.0011
19	Wood chips, wet, measured as dry mass {RoW}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2×yr crop e	0.001
20	Wood chips, wet, measured as dry mass {DE}| hardwood forestry, oak, sustainable forest management | Cut-off, U	m2×yr crop e	0.001

It is shown in fig S11.13 and table S11.13 that the main contribution in this category is due to deforestation with 0.0111 m2×yr crop and may cause the installation of an incinerator.

Annex S11.14. Process contribution results processes to the mineral resource scarcity category referring to IER technology

Fig. S11.14 and table S11.14 show the results regarding the contribution of processes to the mineral resource scarcity category.

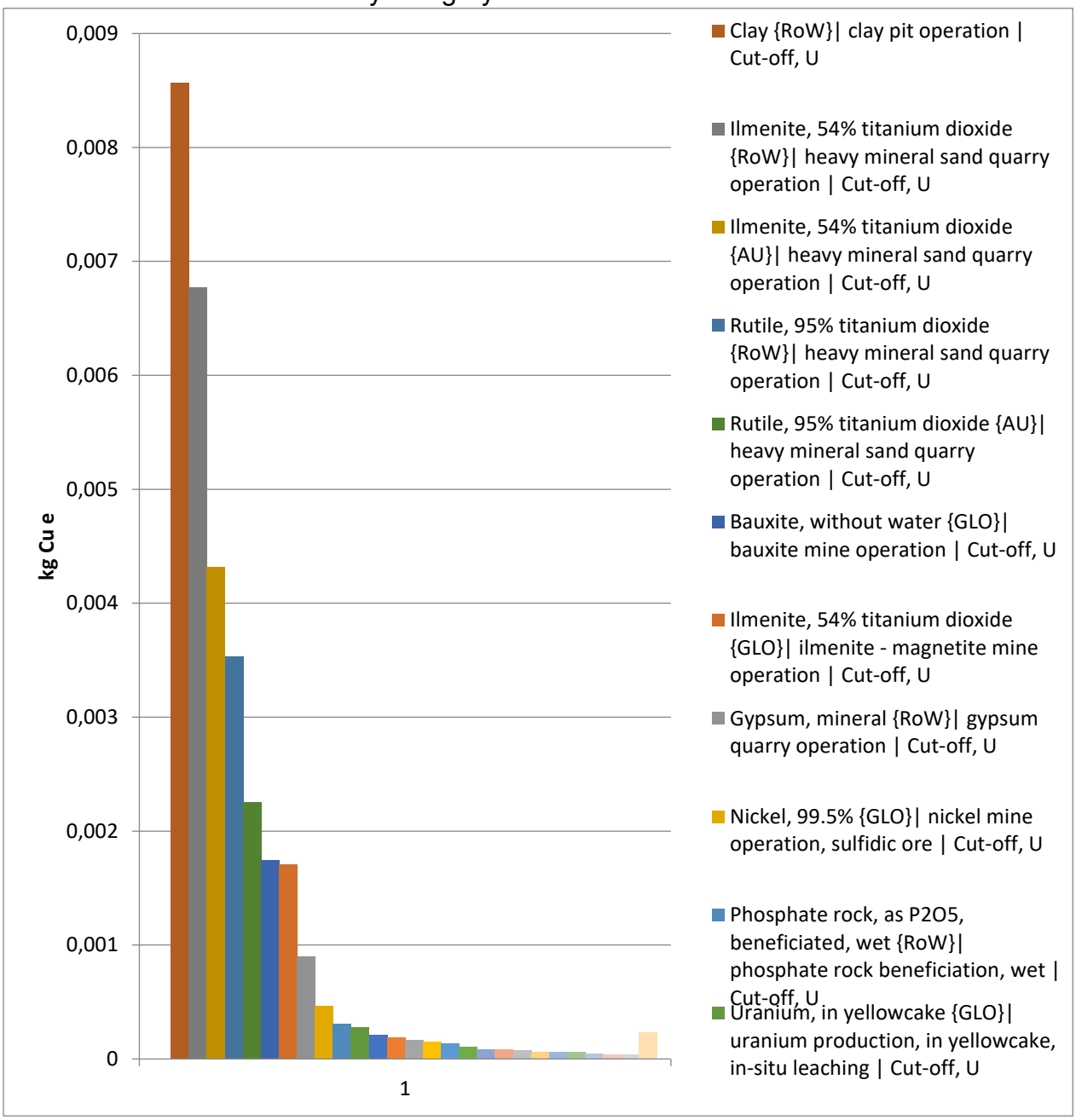


Fig S11.14. General contributions of incineration technology processes with energy recovery, to the category Scarcity of mineral resources

Table S11.14. General contributions of incineration technology processes with energy recovery, to the mineral resource scarcity category

No.	Processes	Units	Total
1	Clay {RoW}| clay pit operation | Cut-off, U	kg Cu e	0.0086
2	Ilmenite, 54% titanium dioxide {RoW}| heavy mineral sand quarry operation | Cut-off, U	kg Cu e	0.0068
3	Ilmenite, 54% titanium dioxide {AU}| heavy mineral sand quarry operation | Cut-off, U	kg Cu e	0.0043
4	Rutile, 95% titanium dioxide {RoW}| heavy mineral sand quarry operation | Cut-off, U	kg Cu e	0.0035
5	Rutile, 95% titanium dioxide {AU}| heavy mineral sand quarry operation | Cut-off, U	kg Cu e	0.0023
6	Bauxite, without water {GLO}| bauxite mine operation | Cut-off, U	kg Cu e	0.0017
7	Ilmenite, 54% titanium dioxide {GLO}| ilmenite - magnetite mine operation | Cut-off, U	kg Cu e	0.0017
8	Gypsum, mineral {RoW}| gypsum quarry operation | Cut-off, U	kg Cu e	0.0009
9	Nickel, 99.5% {GLO}| nickel mine operation, sulfidic ore | Cut-off, U	kg Cu e	0.0005
10	Phosphate rock, as P2O5, beneficiated, wet {RoW}| phosphate rock beneficiation, wet | Cut-off, U	kg Cu e	0.0003
11	Uranium, in yellowcake {GLO}| uranium production, in yellowcake, in-situ leaching | Cut-off, U	kg Cu e	0.0003
12	Nickel, 99.5% {RU}| platinum group metal mine operation, ore with high palladium content | Cut-off, U	kg Cu e	0.0002
13	Ferronickel, 25% Ni {GLO}| production | Cut-off, U	kg Cu e	0.0002
14	Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	kg Cu e	0.0002
15	Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	kg Cu e	0.0002
16	Platinum {ZA}| group metal mine operation, ore with high rhodium content | Cut-off, U	kg Cu e	0.0001
17	Anthraquinone {RoW}| production | Cut-off, U	kg Cu e	0.0001
18	Chromite ore concentrate {GLO}| production | Cut-off, U	kg Cu e	8.61E-05
19	Clay {CH}| clay pit operation | Cut-off, U	kg Cu e	8.33E-05
20	Barite {RoW}| production | Cut-off, U	kg Cu e	7.91E-05
21	Uranium ore, as U {RoW}| uranium mine operation, open cast | Cut-off, U	kg Cu e	6.17E-05
22	Zinc concentrate {GLO}| zinc-lead mine operation | Cut-off, U	kg Cu e	6.05E-05
23	Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe | Cut-off, U	kg Cu e	5.9E-05
24	Anthraquinone {RER}| production | Cut-off, U	kg Cu e	4.67E-05
25	Uranium ore, as U {RNA}| uranium mine operation, open cast | Cut-off, U	kg Cu e	4.31E-05
26	Nickel, 99.5% {ZA}| platinum group metal mine operation, ore with high rhodium content | Cut-off, U	kg Cu e	3.97E-05
27	Remanent processes	kg Cu e	0.0002

The main contributions observed in the Table S11.14. and in Fig. S11.14 correspond to the use and extraction of minerals used in the combustion gas cleaning and waste treatment process.

Results of process contribution to the land use category referring to IER technology

Annex S11.15. Process contribution results to the scarcity of fossil resources category

Fig. S11.15 and Table S11.15 show the results of contribution of processes to the land use category.

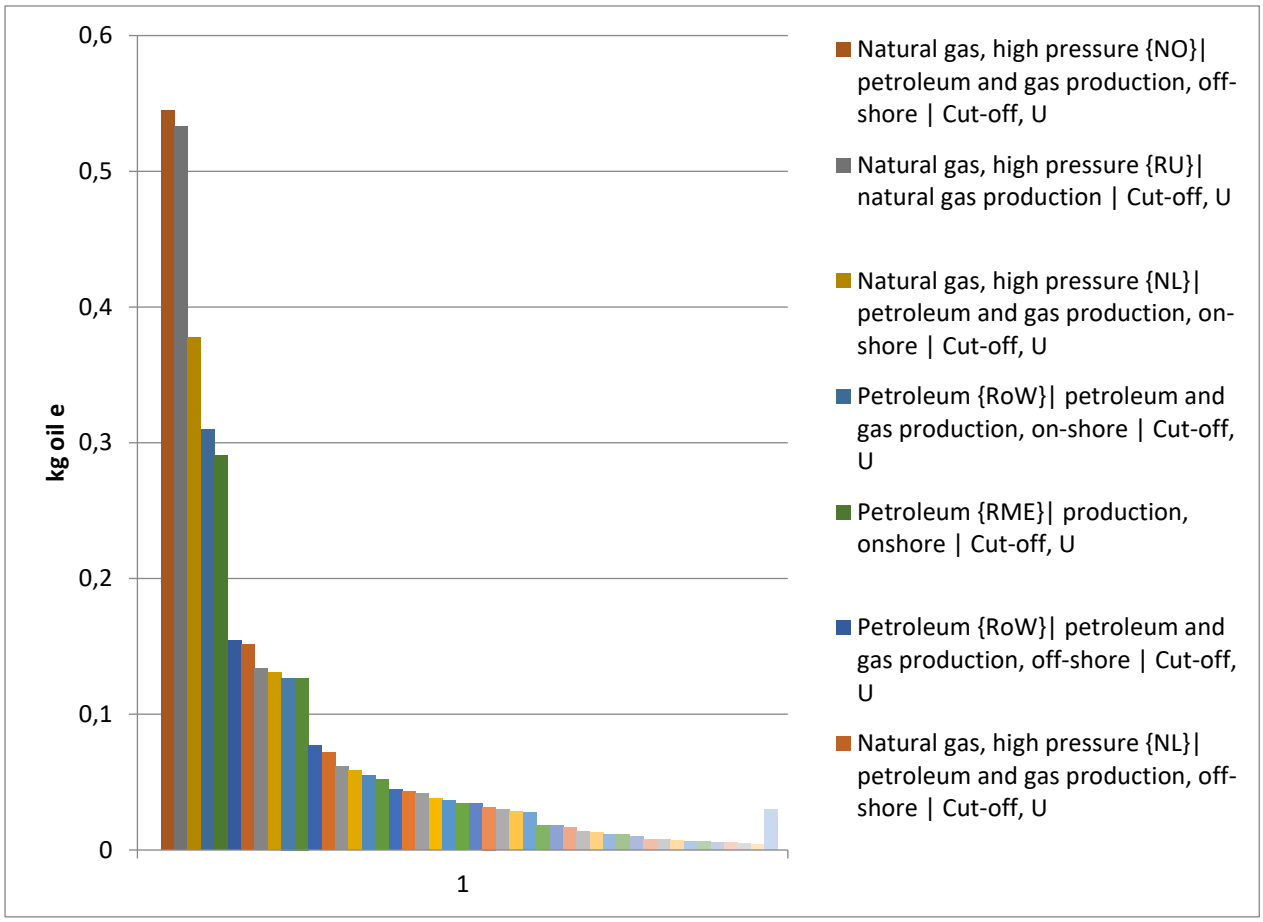


Fig. S11.15 General contributions of incineration technology processes with energy recovery, to the scarcity of fossil resources category

It is shown in Fig. S11.15 and Table S11.15 that the process with the greatest contribution to this impact category is due to the exploitation of fossil resources, in particular due to natural gas and oil.

Table S11.15. General contributions of incineration technology processes with energy recovery, to the category of scarcity of fossil resources

No.	Processes	Units	Total
1	Natural gas, high pressure {NO}| petroleum and gas production, off-shore | Cut-off, U	kg de petróleo bruto e	0.5449
2	Natural gas, high pressure {RU}| natural gas production | Cut-off, U	kg de petróleo bruto e	0.533
3	Natural gas, high pressure {NL}| petroleum and gas production, on-shore | Cut-off, U	kg de petróleo bruto e	0.3779
4	Petroleum {RoW}| petroleum and gas production, on-shore | Cut-off, U	kg de petróleo bruto e	0.3098
5	Petroleum {RME}| production, onshore | Cut-off, U	kg de petróleo bruto e	0.2903
6	Petroleum {RoW}| petroleum and gas production, off-shore | Cut-off, U	kg de petróleo bruto e	0.154
7	Natural gas, high pressure {NL}| petroleum and gas production, off-shore | Cut-off, U	kg de petróleo bruto e	0.1516
8	Natural gas, high pressure {DZ}| natural gas production | Cut-off, U	kg de petróleo bruto e	0.1338
9	Hydrogen, liquid {RER}| hydrogen cracking, APME | Cut-off, U	kg de petróleo bruto e	0.1308
10	Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	kg de petróleo bruto e	0.1268
11	Petroleum {RU}| production, onshore | Cut-off, U	kg de petróleo bruto e	0.1267
12	Natural gas, high pressure {DE}| natural gas production | Cut-off, U	kg de petróleo bruto e	0.0772
13	Lignite {RER}| mine operation | Cut-off, U	kg de petróleo bruto e	0.0716
14	Hard coal {Europe, without Russia and Turkey}| hard coal mine operation and hard coal preparation | Cut-off, U	kg de petróleo bruto e	0.0614
15	Lignite {RoW}| mine operation | Cut-off, U	kg de petróleo bruto e	0.0588
16	Hard coal {RNA}| hard coal mine operation and hard coal preparation | Cut-off, U	kg de petróleo bruto e	0.0547
17	Hard coal {RU}| hard coal mine operation and hard coal preparation | Cut-off, U	kg de petróleo bruto e	0.0516
18	Natural gas, high pressure {GB}| petroleum and gas production, off-shore | Cut-off, U	kg de petróleo bruto e	0.0445
19	Hard coal, run-of-mine {IN}| hard coal mine operation | Cut-off, U	kg de petróleo bruto e	0.0431
20	Hard coal {RoW}| hard coal mine operation and hard coal preparation | Cut-off, U	kg de petróleo bruto e	0.0416
21	Petroleum {RoW}| production, onshore | Cut-off, U	kg de petróleo bruto e	0.0383
22	Hard coal {AU}| hard coal mine operation and hard coal preparation | Cut-off, U	kg de petróleo bruto e	0.0366
23	Natural gas, unprocessed, at extraction {GLO}| production | Cut-off, U	kg de petróleo bruto e	0.0342
24	Natural gas, high pressure {RoW}| natural gas production | Cut-off, U	kg de petróleo bruto e	0.034
25	Natural gas, high pressure {US}| natural gas production | Cut-off, U	kg de petróleo bruto e	0.0317

Annex S11.16. Process contribution results to water consumption category

Fig. S11.16 and Table S11.16 show the results regarding the contribution of processes to the water consumption category.

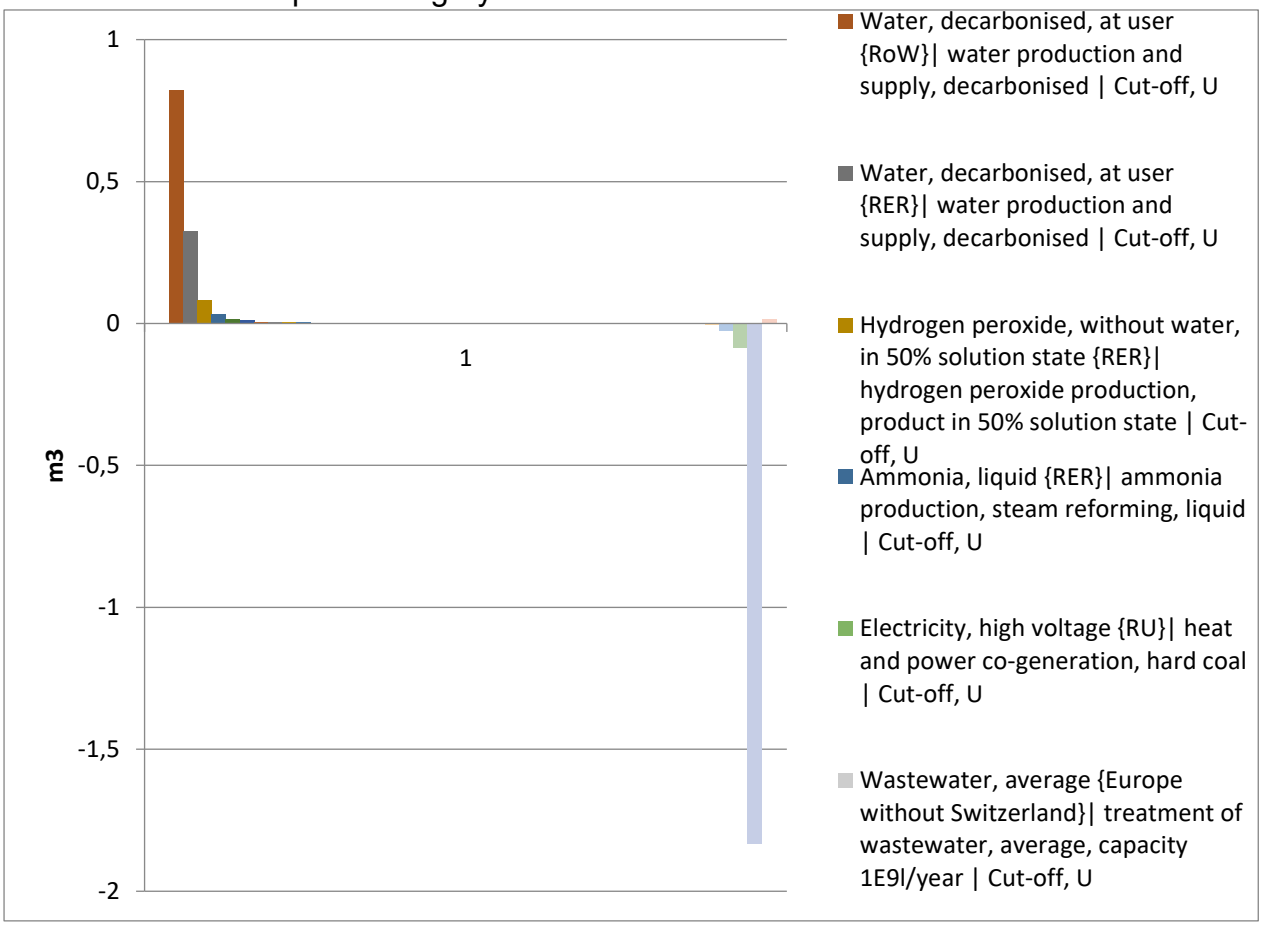


Fig. S11.16 General contributions of incineration technology processes with energy recovery, to the water consumption category

Table S11.16. General contributions of incineration technology processes with energy recovery, to the water consumption category

No.	Processes	Units	Total
1	Water, decarbonised, at user {RoW}| water production and supply, decarbonised | Cut-off, U	m^3 water	0.8228
2	Water, decarbonised, at user {RER}| water production and supply, decarbonised | Cut-off, U	m^3 water	0.327
3	Hydrogen peroxide, without water, in 50% solution state {RER}| hydrogen peroxide production, product in 50% solution state | Cut-off, U	m^3 water	0.0816
4	Ammonia, liquid {RER}| ammonia production, steam reforming, liquid | Cut-off, U	m^3 water	0.0335
5	Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, membrane cell | Cut-off, U	m^3 water	0.017
6	Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, diaphragm cell | Cut-off, U	m^3 water	0.0114
7	Sodium chloride, powder {RoW}| production | Cut-off, U	m^3 water	0.0067
8	Electricity, high voltage {CH}| electricity production, hydro, reservoir, alpine region | Cut-off, U	m^3 water	0.0063
9	Ammonia, liquid {RER}| ammonia production, partial oxidation, liquid | Cut-off, U	m^3 water	0.0059
10	Sulfuric acid {RER}| production | Cut-off, U	m^3 water	0.0044
11	Titanium dioxide {RER}| production, sulfate process | Cut-off, U	m^3 water	0.003
12	Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, membrane cell | Cut-off, U	m^3 water	0.0028
13	Electricity, high voltage {NO}| electricity production, hydro, reservoir, alpine region | Cut-off, U	m^3 water	0.0025
14	Hydrogen, liquid {RER}| hydrogen cracking, APME | Cut-off, U	m^3 water	0.0024
15	Electricity, high voltage {PL}| heat and power co-generation, hard coal | Cut-off, U	m^3 water	0.0021
16	Chlorine, gaseous {RER}| chlor-alkali electrolysis, membrane cell | Cut-off, U	m^3 water	0.0020
17	Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, diaphragm cell | Cut-off, U	m^3 water	0.0017
18	Diesel {Europe without Switzerland}| petroleum refinery operation | Cut-off, U	m^3 water	0.0016
19	Tap water {Europe without Switzerland}| tap water production, direct filtration treatment | Cut-off, U	m^3 water	0.0014
20	Sodium chloride, powder {RER}| production | Cut-off, U	m^3 water	0.0014
21	Heavy fuel oil {Europe without Switzerland}| petroleum refinery operation | Cut-off, U	m^3 water	0.0013
22	Electricity, high voltage {BR}| electricity production, hydro, reservoir, tropical region | Cut-off, U	m^3 water	0.0013
23	Chlorine, gaseous {RER}| chlor-alkali electrolysis, diaphragm cell | Cut-off, U	m^3 water	0.0012
No.	**Processes**	m^3 water	**Total**
25	Tap water {Europe without Switzerland}| tap water production, conventional treatment | Cut-off, U	m^3 water	0.0012
26	Oxygen, liquid {RER}| air separation, cryogenic | Cut-off, U	m^3 water	0.0009
27	Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, mercury cell | Cut-off, U	m^3 water	0.0009
28	Heavy fuel oil {CH}| petroleum refinery operation | Cut-off, U	m^3 water	0.0008
29	Electricity, high voltage {RU}| heat and power co-generation, hard coal | Cut-off, U	m^3 water	0.0008
30	Tap water {CH}| tap water production, underground water without treatment | Cut-off, U	m^3 water	0.0007

31	Sulfuric acid {RoW}| production | Cut-off, U	m^3 water	0.0007
32	Electricity, high voltage {IT}| electricity production, hydro, reservoir, alpine region | Cut-off, U	m^3 water	0.0006
33	Tap water {CH}| tap water production, direct filtration treatment | Cut-off, U	m^3 water	0.0006
34	Chlorine, gaseous {RER}| chlor-alkali electrolysis, mercury cell | Cut-off, U	m^3 water	0.0006
35	Lime {Europe without Switzerland}| lime production, milled, loose | Cut-off, U	m^3 water	0.0006
36	Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	m^3 water	0.0006
37	Transport, freight, sea, liquefied natural gas {GLO}| processing | Cut-off, U	m^3 water	
38	Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Cut-off, U	m^3 water	
39	Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Cut-off, U	m^3 water	
40	Wastewater, unpolluted {RoW}| treatment of, capacity 5E9l/year | Cut-off, U	m^3 water	
41	Heat	m^3 water	
42	Energy	m^3 water	-2
43	Other processes	m^3 water	0.017

It is observed in table S11.16 and Fig. S11.16 that there is a saving in water consumption in the energy process, this is because the incineration of MSW uses water in boilers and for other processes, such as cleaning. of combustion gases, which may come from treated water from some other source that does not involve drinking water.

Annex S12. The issue "How to evaluate the environmental sustainability of IER and BRF on a fair basis, focused on the OFMSW with the same or harmonized functional unit, using quantitative indicators based on LCA and ISO standards?" and evidence of the novelty of our current research/article

The purpose of this Annex is to answer the question **"How to evaluate the environmental sustainability of IER and BRF on a fair basis, focused on the OFMSW with the same or harmonized functional unit, using quantitative indicators based on LCA and ISO standards?"** and to provide evidence that the side-by-side comparison of the ES of IER and BRF is scarce in general, while the side-by-side comparison of ES of IER and the Mexican model BRF in our research is original and necessary (novel and necessary.

Also, as a reminder, we show in another sub-section of the 'Introduction' of the article that experts in Mexico have forecasted a replacement of landfilling of MSW by more intensive waste treatment and reclaiming technologies, such as IER and BRF (sub-section "*Shift from landfilling to intensive technologies IER and BRF for MSW treatment and management in developing (DingC) and underdeveloped countries (UC*)". Therefore, more knowledge on the ES of the target technologies is required for adequate selection and decision-making.

We conducted literature reviews in Web of Science-Clarivate Analysis in 2024 and Web of Science and Google Scholar in 2025. We selected and examined articles of interest, looking for the following issues related to the intended novelty and original contributions of our research as in Table S12.1

Table S12.1 Key issues of features and criteria to determine close to no relationship of articles in the open literature and our article

- Comparison between the two technologies biorefinery and incineration with energy recovery
- Focus on urban wastes (organic)
- Use of quantitative indices for determining the sustainability of each technology
- Indices defined in terms of normalized environmental impacts from LCA results and aligned with ISO standards
- Use of normalized indices that can be summed, subtracted, and divided in such a way that their combination gives significant and useful overall/global measurement of the environmental sustainability of each technology and their comparison.

The key subjects and issues of the articles were arranged in a comparative table (Table S12.2), where the column headings were related to the features and criteria exhibited in Table S12.1. A Rating for determining the intensity of the relationship was defined, see Table S12.1. The five features/criteria were given a score of 0 for No, and 1 for Yes. In case of mixed results, a prorated, intermediate score value was assigned. Therefore, the rating varied from 0 to 5 for each article. *A rating of 5 meant that the article has a very close similarity (thematic similarity) to our article. The lower the rating of a "related" article, the higher the novelty of our research results.*

We conducted four literature searches:

(i) "Comparison AND (biorefin* AND inciner*) AND (organic AND waste*)." Publication years: 2010-2025 in Web of Science (Fig, S12.1.) (repetition of the search made on 24/07/24)

(ii) “Comparison AND (biorefin* AND inciner*) AND (organic AND waste*) AND sustainab* AND (measurement* OR determination OR quantification)” Publication years: 2010-2025 in Web of Science (Fig.S12.2) (repetition of the search made on 24/07/24)

(iii) “Comparison AND (biorefin* AND inciner*) AND (organic AND waste*)AND(sustainability)” Publication years: 2010-2025 in Google Scholar (Fig. E. 3.3.) (04/02/25)

(iv) “(biorefin* AND inciner*) AND (organic AND waste*)AND(sustainability)” in Web of Science (Fig. S 13.4.) (04/02/25)

Below, four figures show typical screen captures from the searches. Based on the last search, we could only find four works that deserved a deeper analysis. Table S10.2 Summary of references dealing with environmental sustainability comparison of IER and BRF was updated with information from (iii) and (iv) searches. Table S10.2 as well as the updated discussion on results, are exhibited below.

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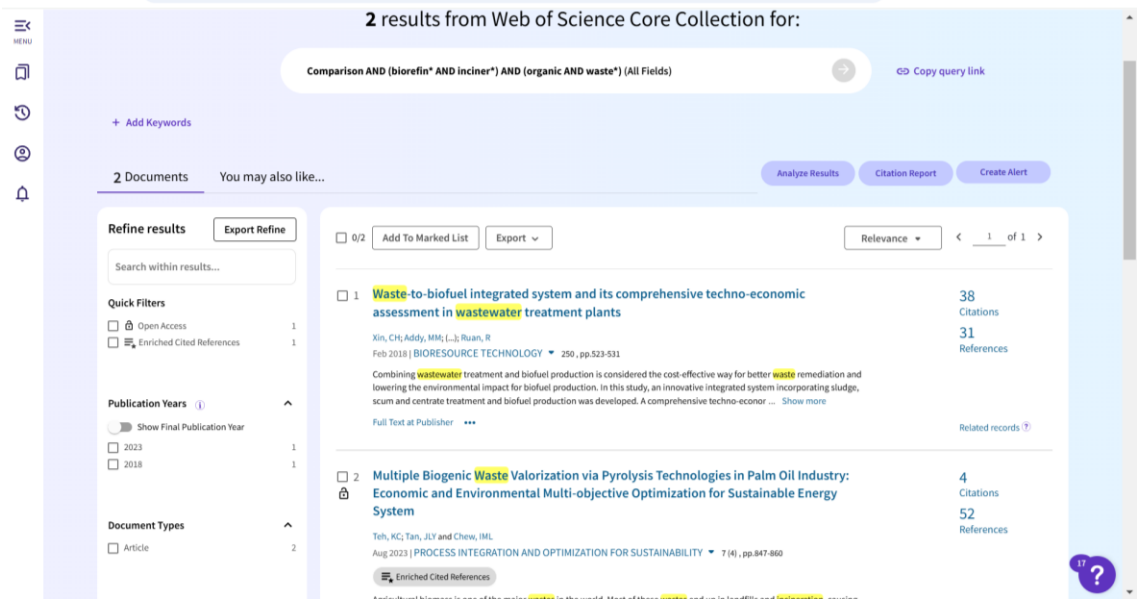


Fig. S12.1. Search (i). Screen capture of the search in Web of Science of the keywords “Comparison AND (biorefin* AND inciner*) AND (organic AND waste*). Publication years: 2010-2025. From these search 5 articles in the Search (i) were identified as “interest papers”.

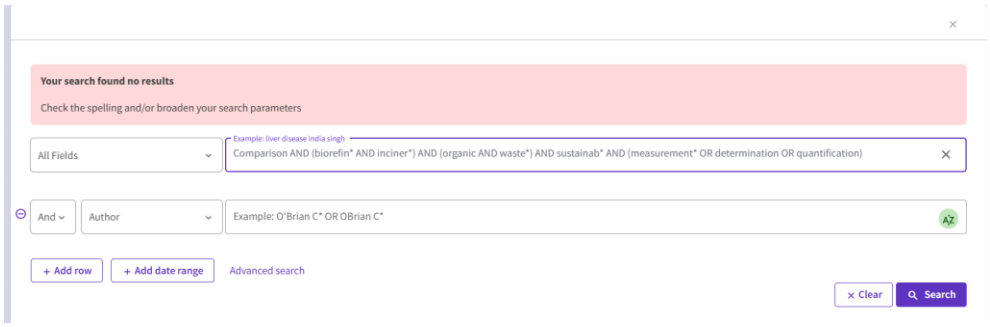


Fig. S12.2. Screen capture of the search in Web of Science of the keywords "Comparison AND (biorefin* AND inciner*) AND (organic AND waste*) AND sustainab* AND (measurement* OR determination OR quantification)" Publication years: 2010-2025. From this search: 0 article in Search (ii) were identified as "interest papers".

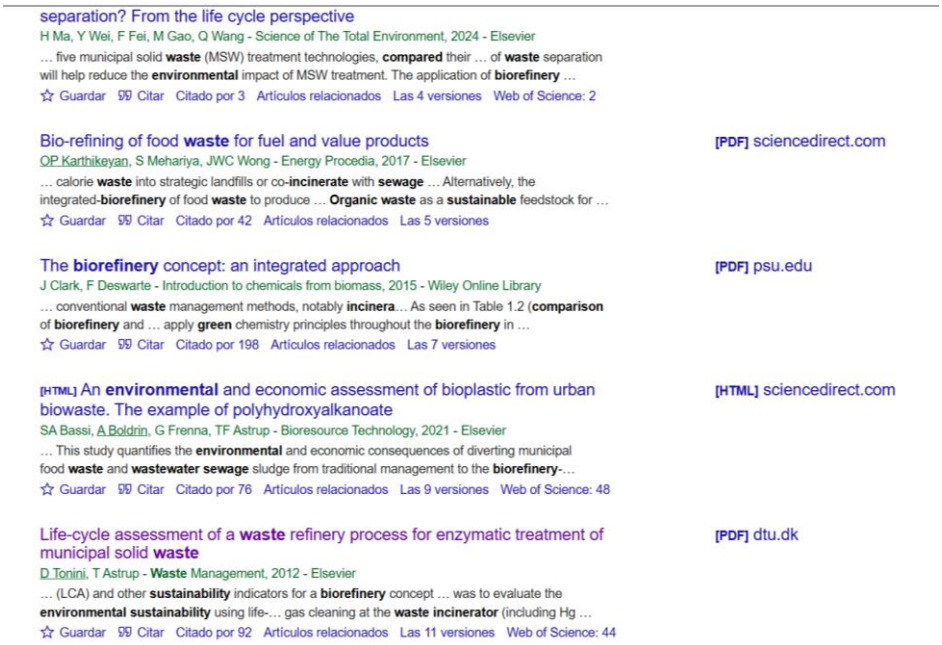


Fig. S12.3. Screen capture of the Google Scholar. Keywords "Comparison AND (biorefin* AND inciner*) AND (organic AND waste*)AND(sustainability)" Publication years: 2010-2025. From this search: 2 articles in Search (iii) were identified as "interest papers",

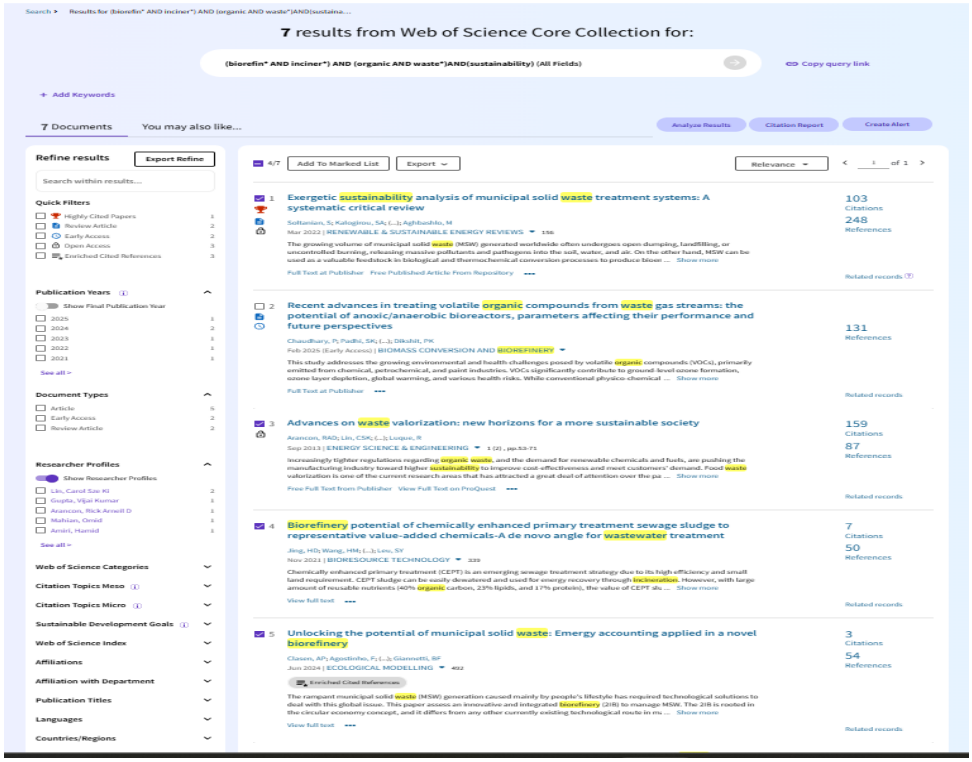


Fig. S12.4. Screen capture of the search in Web of Science of Keywords: (biorefin* AND inciner*) AND (organic AND waste*) AND (sustainability). From this search: 2 articles in Search (iv) were identified as “interest papers”. No limits in years.

General analysis of scores that determined the similarity of objectives on collected articles

The results of the literature searches were compiled in Table S10.2 The summarized trends are:
- a ranking from 0 to 5 points with a profile of five criteria (0 to 1 point each) was established; the criteria were consistent with the objectives and main features of our article (Table S12.1):
-Ten articles of interest in four literature searches were identified
-Up to seven articles can be considered false positives because either there was no true BRF-IER environmental sustainability comparison, or the the OFMSW was not the focus of the treatments or the process compared to the IER did not meet the definition of biorefinery (Fava et al., 2015). Despite this, a subset of these articles still achieved a non-zero score, although marginally low.
-Three articles exhibited a score equal to 0
-Five articles ranked in the interval $0 < \text{score} \leq 1$
-Two articles scored $1 < \text{score} \leq 2.5$
- No articles with score > 2.5

In summary, our article covers some unique objectives and exhibits original features that are not present in other possibly relevant or related articles of the open literature. The maximum similarity achieved by the closest articles is in the range 20 to 50%.

Discussion
A panoramic diagnostics of the literature search results is presented first. Second, a more detailed examination of the articles with the four highest scores is included. The

development of waste-based biorefineries would not only help to shift the linear economies toward circular economies but also contribute to improving public health and environment (Clasen et al., 2024; Nizami et al., 2017), reduction of waste generation as well as production of bioenergy and bioproducts that are incorporated to the productive cycles of modern societies, and decrease the society's reliance on raw material imports. Sadeleer et al. (2020) observed that boosting the circular economy through BRF reduces waste sent to landfills by promoting the continual circulation of waste-based products through redesign, reuse, recycling, and energy recovery.

Therefore, assessment and scientific validation of the environmental sustainability of a BRF and ES of alternative intensive MSW treatment and management technologies is paramount to avoid misleading results and poor decision-making. Side-by-side comparisons of the environmental sustainability of IER and BRF using indicators aligned with ISO standards and LCA are scarce in the open literature. The most frequent reasons are described now:

(i) According to the developed literature review, none of the identified related studies has applied the methodology used in our work to an innovative and integrated MSW biorefinery such as the GBAER BRF and to compare it to a non-biologically-driven intensive technology such as IER, to the best of our knowledge. On the one hand, most of the BRFs of the few that appeared in comparative studies are simple setups such as "waste refinery" (Tonini and Astrup, 2012, an enzymatic hydrolysis followed by either anaerobic digestion or incineration) or just ethanol production followed by incineration (Ma et al., 2024), or just a larvae-stabilizing process followed by composting (Ma et al., 2024), or only a sorting plant followed by anaerobic digestion and composting (Clasen et al., 2024), that hardly can be called biorefineries because only exhibit one or two co-bioproducts at most (Fava et al., 2015). On the other hand, our BRF includes two bioenergies and three co-bioproducts based on a relatively complex network of biological, physical, and phys-chem processes.

(ii) in some cases, there is no evidence that the comparison relies on using the same FU or at least a harmonized FU for both technologies (Clasen et al., 2024). Thus, these could lead to debatable results and an unfair comparison.

(iii) in other cases, the comparison is made by the use of other indicators (such as Eco-Indicator 99, now superseded, Toninin and Astrup, 2012) or emergy indicators (Clasen et al., 2024) whose results are not compared or translated to equivalent results of ISO-LCA based indicators.

(iv) in other words, results of the comparison of the technologies partially used PEI or NPEIs for comparison, but they only used a reduced number of PEIs or NPEIs, from one to seven (this represents only 0.06 to 38% of the eighteen contributing PEIs or NPEIs of the ReCiPe and LCA methodology).

(v) Furthermore, there is no evidence of using an adequate single score based on those impacts that could summarize the overall ES trends (Ma et al., 2024; Jing et al., 2021; Teh et al., 2023; Mu et al., 2016). Exceptions are the work by Tonini and Astrup (2012), who used the Eco-Indicator 99 milliPoints, and Clasen et al. (2024), who reported results with the ERI (emergy) indicator. Unfortunately, they did not use other indicators (mid-point or End-Point ones based on ISO-LCA) for internal comparison with the reported milliPoints or emjoules.

(vi) as a consequence of points (iii), (iv), and (v), in most articles, even those with higher ranking, a deep discussion of either the PEIs or NPEIs, as well as their critical contributions and recommended improvements to the examined technologies is missing.

Jing et al. (2021) (0.55 score) compared three treatments for sludges from the chemically enhanced primary wastewater treatment: IER, landfill, and one BRF that produces ethanol, lactic acid, and cellulase. Unfortunately, the OFMSW was not the focus of this comparison. The comparison criterion relied only on the GHG emissions of the selected processes. The authors found that the BRF emissions were lower than those of landfill and IER. Despite this encouraging result for the ES of the BRF, this article is not useful to our discussion because, in addition to focusing on a different waste (not OFMSW), the work did not follow the ISO-LCA methodology since the evaluation was based on only one type of impact out of eighteen contributing impacts. Obviously, an assessment of the overall ES of the processes and comparison was not achieved. This reference was included in the Table S12.2 as a sample of false positives of the search engine.

Tonini and Astrup (2012) (score 1) conducted a study of a pilot-scale waste refinery for the enzymatic treatment of municipal solid waste on a BRF. The refinery produced a liquid (liquefied organic materials and paper) and a solid fraction (non-degradable materials) from the initial waste. Four waste management scenarios involving enzymatic hydrolysis of residual MSW were evaluated and compared with incineration. They found that refining enzymatic waste using the products for energy recovery can represent a valuable alternative to incineration from both an energy and environmental point of view. However, this study

-used the Eco-Indicator methodology (Eurocentric method) that was superseded in 2023, results are expressed as normalized impact potentials in the unit milliPerson Equivalent (mPE) per t MSW ww;

-lacked a thorough application of ISO methodology for impact assessment (only seven environmental impacts out of 18 were included in their analysis);

-no comparison of results expressed in Points with other type of indicators (such as exergetic or emergetic) was performed.

-very significant, the waste refinery was not a waste *biorefinery* (it did not meet the classical BRF concept by Fava et al. (2015).

> *"Biorefineries could be described as integrated bio-based industries that use a variety of technologies to produce products such as chemicals, biofuels, food and feed ingredients, biomaterials, fibers, and heat and power, with the aim of maximizing added value along the three pillars of sustainability (environment, economy, and society)."*

Consequently, it cannot be stated that it was a side-by-side comparison of IER-BRF.

Clasen et al. (2024) (2.3 score) compared one Chinese and one Iranian IER with a Brazilian, so-called innovative, and integrated biorefinery (2IB). The 2IB consisted of an MSW sorting plant followed by anaerobic digestion and composting of the waste organic fraction. The evaluation was carried out using emergy indicators developed by Wang et al. (2018). Based on the emergy ERI indicator (emergy return indicator), they concluded the their 2IB performed better (environmentally) than IER: the values were 20.33; 2.84; 0.90 for 2IB, the Iranian IER, and the Chinese IER, respectively. However,

-the so-called BRF (2IB) is just a waste sorting plant followed by anaerobic digestion and composting of the organic fraction;

-the last two processes and their combination have been applied for decades to MSW management and sludge treatment. Thus, the claimed innovation of 2IB seems to be debatable;

-no detailed discussion of environmental impacts or damages is included (just emergy accounting).

-Furthermore, this is not a side by side comparison between BRF and IER, because it compares a so-called BRF that was fed an MSW generated by a group of rur-urban Brazilian municipalities to foreign IER fed MSW from Chinese and Iranian cities; no evidence of using the same FU or harmonizing the FU could be found.

Ma et al. (2024) (2.5 score) compared five scenarios for treating food waste and residual waste from MSW: TC1: incineration of MSW; TC2: AD (anaerobic digestion) of FW (fermented wastes) + incineration of residual waste (RW); TC3: AC (anaerobic composting) of FW + incineration of RW; TC4: ethanol production of FW + incineration of RW; TC5: Fly larva (BSF) treatment of FW + incineration of RW. Seven ReCiPe PEIs were used as criteria to determine environmental performance. The authors found that the environmental performance of Ethanol plus incineration and fly-larvae plus composting setups exhibited better environmental performance than IER. Yet, anaerobic digestion-incineration was the best in therms of ES. Several limitations of this work should be highlighted:

-only partial alignment to ISO and LCA standards and results, they did not use the remaining eleven PEIs and NPEIs in the environmental performance evaluation;
-there is no evidence of using a unifying score indicator such as the normalized End-Point one or another own unifying indicator;
-it is very debatable that the technological setups can be classified as biorefineries since, at most, they exhibit two co-bioproducts, and at most, the alleged BRF has two processes. In principle, it is debatable whether these setups meet the experts' definition (Fava et al., 2015);
-most set-ups include incineration as a significant, embedded process of the alleged BRFs;
-There is no evidence of studying the influence of weighting by applying a second set of indicators and running the corresponding comparison among indicators, nor is there any evidence of sensitivity analysis.

To the best of our knowledge, the articles of interest in the open literature registered by the literature searches did not meet the target five features/criteria. In fact, at most, a couple of articles reach approximately a 50% or lower similarity to our research. A significant issue is that the Mexican model of BRF (GBAER type BRF) of our work is very different of the BRF or so-called BRF reported in the other publications. Our current research is novel and relevant; it fills a current void of information.

Table S12.2. Summary of environmental sustainability issues of references dealing with the comparison of BRF and IER

Column

1	2	3	4	5	6	7	8	9	10
No.	**Comparison of technologies BRF and IER**	**Summary description of technol (type of process, products)**	**Type of waste**	**Use of LCA for environ impact eval.**	**Use of quantitative indices for determination of global ES**	**Indices defined/based on NPEIs of LCA**	**Remarks**	**Ranking (similarity to our intended research)**	**Ref**
	No=0, Yes=1		**Other=0, Urban organic waste=1**	**No=0, Yes=1**	**No=0, Yes=1**	**No=0, Yes=1**			
1	0	It is An Review dedicated to the exergetic analysis of environmental analysis of the MSW management	MSW 1	0	0	0	-it is not an experimental, original article. It was a review -No evidence of comparison of ES of IER and BRF, even from the exergetic analysis point of view. It was clearly a false positive of the search engine -no evidence of references dealing with the comparison of environmental sutainability of IER and BRF for OFMSW treatment	1	(Soltanian et al. 2022)
2	0.5	MSW: 56 % of FW and 44 % of RW are included in 1 ton of MSW. The purpose is to determine whether biorefinery technologies such as fermentation for ethanol production and BSF treatment can be applied to the treatment of source-separated FW. Comparison of 5 scenarios TC1: incineration of MSW; TC2: AD of FW + incineration of RW; TC3: AC of FW + incineration of RW; TC4: ethanol production of FW + incineration of RW; TC5: BSF treatment of FW + incineration of RW. BSF (black soldier fly): BSF treatment is a common bioconversion method. BSF pre-pupae's nutrients can be readily absorbed because their amino acid makeup is relatively similar to that of fish meal.	MSW 1	1	0	0	-Only partial alignment to ISO and LCA standards and results, they did not use the remaining eleven PEIs and NPEIs in the environmental performance evaluation; -there is no evidence of using unifying score indicator such as the normalized End-Point one; -it is very debatable that the technological setups can be classified as biorefineries since at most, they exhibit two co-bioproducts and do not meet the experts definition (Fava etal., 2015); -most set-ups include incineration as a significant, embedded process; -There is neither evidence of studying the influence of weighting nor applying a second set of indicators and running the corresponding comparison among indicators, nor sensitvity analysis	2.5	(Ma et al. 2024)
3	0.5	Incineration with energy recovery. BRF - enzymatic hydrolysis of CEPT sludge for the production of ethanol, lactic acid, and cellulase	0 Chemically enhanced primary treatment (CEPT) is an emerging sewage treatment strategy due to its high efficiency and small land requirement	0	0	0.05	-It does no treat OFMWS; it treats sludge from waste water treatment -Not aligned with LCA methodology and ISO standards, It only compares GHG emission/sequestration of current CEPT sludge treatment method and biorefinery method in this study. It does not follow ISO methodology. -No evidence of use of quantitative indices for determination of global sustainability -No evidence of using NPEIs from LCA -There is neither evidence of studying the influence of weighting nor applying a second set	0.55	(Jing et al. 2021)

							of indicators and running the corresponding comparison among indicators, nor sensitvity analysis - It was clearly a false positive of the search engine		
4	0.3	Comparison of an incinerator with heat recovery and a BRF that process MSW. The BRF consisted of MSW diverted to a mechanical separation process that includes a manually pre-screening to remove bulky waste, a crusher, and at the end a separator/dehydrator that will remove the inorganics from organics. Inorganic waste undergoes a thermoplastic transformation system. The organic/biodegradable fraction is treat with anaerobic disgestion, producing biogas that are burned to generate heat and electricity.	1 Municipal solid waste	0	1 Emergy indicators	0	-2IB, the so-called BRF is just a sorting plant followed by anaerobic digestion and composting of the organic fraction; the last two processes and their combination has been applied for decades to MSW management and sludge treatment; 2IB des not meet the BRF definition of WFava et al. (2015) -no detailed discussion of environmental impacts or damages is included (just emergy accounting). -It is not a side by side comparison, because it compares a BRF from Brazil with incinerators from China and Iran. -No evidence of the same FU or harmonized FU in the comparisons between IER and the 2IB, the so-called BRF -There is neither evidence of studying the influence of weighting nor applying a second set of indicators and running the corresponding comparison among indicators, nor sensitvity analysis -Only emergy indicators used, no other indicators employed and consequently no comparison of results from different indicators was performed.	2.3	(Clasen et al. 2024)
5	0	Five different scenarios for the treatment of MSW: (1) INC: all waste was incinerated (2) CC-CC: co-combustion of the liquid and solid fractions (3) CC-INC: co-combustion of the liquid fraction and incineration of the solid fraction (4) BG-CC: anaerobic digestion of the liquid fraction, co-combustion of the solid fraction (5) BG-INC: anaerobic digestion of the liquid fraction, incineration of the solid fraction	1 Residual municipal solid waste	Only 7 environmental impacts. The results of the LCIA are expressed as normalized impact potentials in the unit milliPerson Equivalent (mPE) per ton ww	0	0	- Eurocentric method, Eco-Indicator 99 methodology used which was superseded in 2023 -lacked a thorough application of ISO methodology for impact assessment (only 7 environmental impacts out of 18); -the waste refinery was not a waste *biorefinery* (it did not meet the BRF concept by Fava et al (2015). -There is neither evidence of studying the influence of weighting nor applying a second set of indicators and running the corresponding comparison among indicators	1	(Tonini and Astrup 2012)
6	0	The study aims to compare the biosynthesis technology with traditional technology (incineration and landfill) in aspects of resource utilization, cost and environmental impact	0	0	0	0	-The study does not present data nor a comparison of different treatment methods. -It was clearly a false positive of the search engine -Obviously, there is neither evidence of studying the influence of weighting nor applying a second set of indicators and running the corresponding comparison among indicators, nor sensitvity analysis	0	(Wang, 2025)

7	0	♦Incineration and biological degradation of cocaine by considering techno-economic and environmental aspects. ♦ BRF was not compared ♦Cocaine removal: 99.7% by biol degradation pure culture; 95% by incineration	0 Wastes: seized cocaine. Not organic urban waste	0.5 Only 8 characterization potential environ impacts , confusing functional unit and reference flow (debatable analysis)	0 WAR methodology, not aligned to ISO standars (missing 10 PEIs). Unknown and no references cited for used factors	0 See cell (3,6) Used characterization PEI, not the NPEIs	Very little relationship with our research, just 10% Obscure article regarding the defining issues of this research (the environmental indices definition and use, and type of waste). ♦Similar costs per kg cocaine removed ♦Biological degradation exhibited a specific energy consumption and potential environmental impact, 5 and 10 fold lower than the incineration, respectively -It was clearly a false positive of the search engine -Obviously there is neither evidence of studying the influence of weighting nor applying a second set of indicators and running the corresponding comparison among indicators, nor sensitvity analysis	0.5	(Díaz-Vargas et al., 2021)
8	0	♦Integrated biofuel production associated to wastes from a WWTP was assessed. ♦Only one technology was covered, that is not a BRF although has some relationship ♦Incineration was not evaluated as alternative technology ♦No environmental assessment of the target technology (of any kind), only techno-economic-analysis was performed. Cost results available.	0 Wastes from WWTP	0	0	0	-Only one technology was covered, that is not a BRF -Incineration was not evaluated as alternative technology -No environmental assessment of the target technology (of any kind), only techno-economic-analysis was performed. Cost results available -It was clearly a false positive of the search engine -Obviously, there is neither evidence of studying the influence of weighting nor applying a second set of indicators and running the corresponding comparison among indicators, nor sensitvity analysis	0	(Xin et al., 2018)
9	0	♦Palm oil biomass wastes (POW) tested to generate bio-oil by pyrolysis technologies such as conventional pyrolysis, microwave pyrolysis, and thermo-catalytic pyrolysis. That is, it dealt with the comparison among three pyrolysis processes. ♦Incineration and biorefinery were not evaluated ♦The feedstock was not urban organic waste	0 POW, not organic urban waste	0 Only one PEI was evaluated (GW). This is not LCA	0 ES was not determined. No environmental indices were used	0 Since there was no assessment of ES, indices based on NPEI of LCA were not defined and used	Results available as annualized profit in US$/t POW, and GHG emissions kg CO2 equivalent/t POW. They were used for the evaluation of the pyrolysis variants -It was clearly a false positive of the search engine -Obviously, there is neither evidence of studying the influence of weighting nor applying a second set of indicators and running the corresponding comparison among indicators, nor sensitvity analysis	0	(Teh et al., 2023)
10	0	♦This study evaluated Scum-to-Biodiesel technology (StB) and compared the technology with scum anaerobic digestion and combustion processes ♦ The feedstock was not urban organic waste ♦The BRF from organic urban waste was not compared.	0 Scum was the target waste, not organic urban waste. Scum is a semisolid waste that is removed from the upper layer of sedimenters in WWTP. Typically consists of	0.5 Only four characterization PEIs were evaluated and used. The LCA consists of 18 characterization PEIs according to ISO standards	0 ES was not determined. No environmental indices were used	0 Since there was no assessment of ES, indices based on NPEI of LCA were not defined and used	♦StB had the lowest fossil fuel depletion, GHG emissions, and eutrophication impacts. ♦combustion had the lowest potential acidification impact ♦The StB also obtained made the highest revenue. ♦BRFwas not evaluated or compared. It was clearly a false positive of the search engine	0.5	(Mu et al., 2016a)

			greases and oil as well as collapsed foams						
11	1	♦Evaluation and comparison of the ES of two urban waste treatment technologies were performed, BRF HMEZS-NN and the IER. The feedstock was OFMSW. ♦The evaluation of ES was based on the results of the LCA ♦The novel GBAER environmental sustainability index α aligned with ISO (14040 & 14044) standards and the new methodology σ-τ was developed to compare the ES of two technologies. ♦Applying these indices, the BRF resulted more sustainable (with restrictions) than IER.	1	1	1	1		5	This work

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Annex S13. The first part of the issue "Why evaluate the ES of the technologies?" is afundamental part of the Rationale of the research

This discussion is to be placed in the Introduction of the RMS. It is consistent with recommendations on reinforcing the rationale of our research in the 'Introduction' of the article. To put this in the own words of an anonymous adviser,

> *"The introduction section of the manuscript is kind of weak and needs a careful revision with proper organization in terms of the key concept development/problem identification towards the comparative analysis of the biorefineries and incineration of biomass waste."*

A substantial part of the Introduction is devoted to answering the question "Why evaluate the ES of IER and BRF?". In the elaboration of this significant subject of our research, we will present in the article a succinct background of the selected subjects Here in the Annex we will present only the plan of this discussion (Fig. S13.1):
-outlook of municipal solid waste treatment and management in the world
-landfilling of MSW: importance, trends, advantages and disadvantages
-Incineration with energy recovery of MSW: importance, trends, advantages and disadvantages
-biorefinery of organic wastes: importance, trends, advantages and disadvantages
- shift from landfilling to intensive technologies IER and BRF for MSW treatment and management in developing (DingC) and underdeveloped countries (UC).
-usefulness of and needs for comparative ES evaluation of the above mentioned technologies.

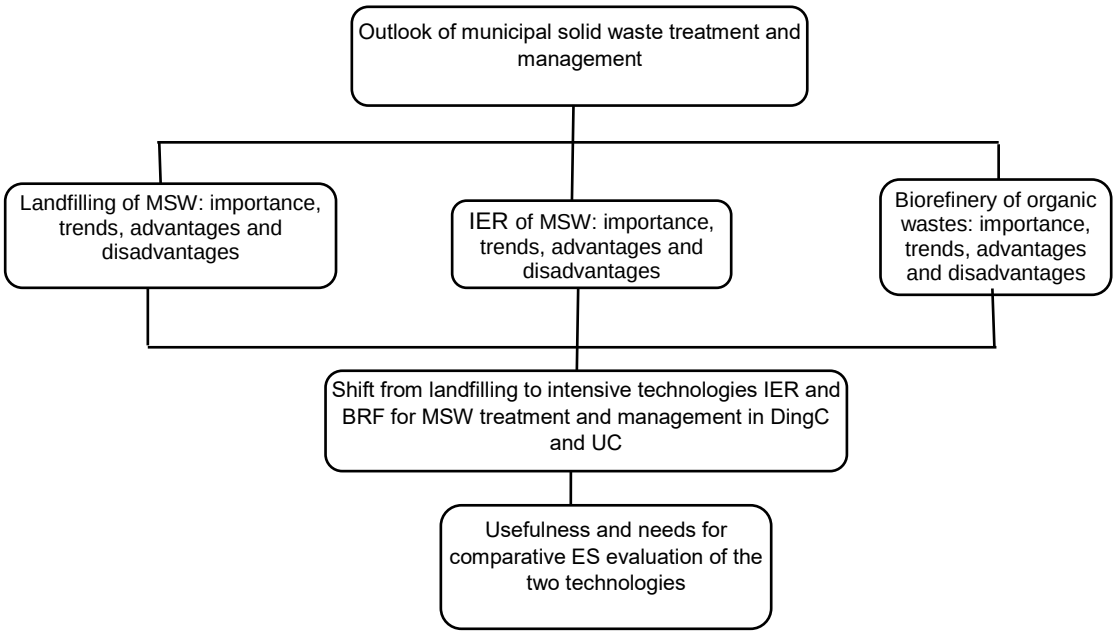


Fig. S13.1. Plan of the reorganized background (Introduction) in the RMS

The reorganized background will present technology trends that identify that BRF and IER are candidates for replacing landfilling in MSW treatment and management in DingC and UC. This is referred to as “shift” in MSW management in those countries.

It will also identify the need for side-by-side comparative ES evaluation of BRF and IER as well as the development and application of new LCA-based quantitative indices to measure ES, in order to assist policymakers, decision-makers, manufacturers and suppliers of technology and equipment, communities interested in MSW management, etc., in selecting the most sustainable option.

Introduction

A substantial part of the background in the ‘Introduction’ is devoted to answering the question, "Why evaluate the environmental sustainability (ES) of IER and BRF?". In the elaboration of this significant subject of our research, we will present here a succinct background of the following subjects, among others (Fig. S13.1).

-outlook of municipal solid waste treatment and management in the world
-landfilling of MSW: importance, trends, advantages and disadvantages
-Incineration with energy recovery of MSW: importance, trends, advantages and disadvantages
-biorefinery of organic wastes: importance, trends, advantages and disadvantages
- shift from landfilling to intensive technologies IER and BRF for MSW treatment and management in developing and underdeveloped countries
-the usefulness and need for comparative ES evaluation of the abovementioned technologies.

Therefore, the background will present trends that identify that waste-based biorefinery (BRF) and incineration with energy recovery (IER) are candidates for replacing landfilling in MSW treatment and management in developing (DingC) and underdeveloped countries (UC.) This is also referred to as a "shift" in MSW management in those countries. It will also identify the need for a side-by-side comparative ES evaluation of BRF and IER, as well as the development and application of new LCA-based quantitative indices to measure ES, to assist

governmental policymakers, decision-makers, manufacturers and suppliers of technology and equipment, communities interested in MSW management, among others, in selecting the most sustainable option.

13.1.Outlook of municipal solid waste treatment and management in the world

The treatment and disposal of waste continue to be one of the most significant challenges globally. Waste generation is a consequence of population growth, urbanization, and economic development of countries. In 2018, it was estimated that an annual generation of 2.01 E12 metric tons of waste globally is made up of approximately 44% garden and food waste (44 %) followed by dry recyclables (cardboard and paper, 17%), plastics (12%), and glass and metals (5 and 4%, respectively.) This waste generates *ca.* 1.6 E12 tons of greenhouse gas emissions (GHG) to the atmosphere (Kaza et al., 2018).

In addition to the severe problem of GHG emissions such as methane (CH_4), dinitrogen oxide (N_2O), and carbon dioxide (CO_2), the inadequate management and disposal of municipal solid waste (MSW) adversely affects the environment and human health. These effects are most intense in low—and middle-income countries (Botello-Álvarez et al., 2018; Kaza et al., 2018; Mor & Ravindra, 2023) . Worldwide, about 37% of MSW is disposed of in some landfill, 33 % in open dumps, 11 % is incinerated, and 19 % is recycled and composted, and (Kaza et al., 2018). Middle-income countries (or developing countries, DingC) practice the highest percentage of landfilling, with 54 %, and high-income countries, 39 %. In high-income countries, 22 % is incinerated, and 35 % of MWS is either composted or recycled (Kaza et al., 2018).

13.2. Landfill

Importance

Landfilling is a relatively low-cost and extensively used technology for MSW disposal (Nath & Debnath, 2022). Despite the solid waste treatment methods that have emerged, such as anaerobic digestion, composting, pyrolysis, gasification, and incineratio (Kumar & Eswari Jujjavarappu, 2023; Kundariya et al., 2021; Naveenkumar et al., 2023)the vast majority of underdeveloped (UC) and developing (DingC) countries still dispose of waste in open dumps and landfills.

Trends

MSW disposal or treatment using engineered LF or more stringently operated technologies occurs almost exclusively in high and upper-middle-income countries. In contrast, open dumping predominates in lower-income countries, with 93 %, and only 2 % in high-income countries (Kaza et al., 2018). For example, the treatment and disposal methods used in Latin America are landfills (52%) and open landfills (27%), and to a lesser extent, in garbage dumps (15%) and recycling (4.5%) (Kaza et al., 2018).

A few years ago, more stringent environmental regulations related to waste landfilling were issued in India. This change has drawn the attention of decision-makers and officials to potentially more sustainable and cost-effective Energ-from Waste (EfW) technologies. This approach has become well-received in countries such as Brazil, Russia, Indonesia, Pakistan, Nigeria, and Bangladesh, which produce massive quantities of solid waste and demand high amounts of energy (Lino & Ismail, 2018; Mia et al., 2018; Starostina et al., 2018).

According to data from the report "Basic Diagnosis for the Comprehensive Management of Waste" (SEMARNAT, 2020)., it was estimated that *ca.*120,000 tons of MSW were generated daily in Mexico in 2019. SEMARNAT (SEMARNAT, 2020) has reported that 46% of the waste is organic from food, crops, and wood. This waste is disposed of in landfills and open dumps, while the INECC (INECC, 2018) estimates emissions of 21,920.6 Gg of CO_2 e from the final disposal of MSW.

Advantages and disadvantages

Along with its relatively low cost, LF can represent a source of informal employment in DingC and UC (Nath & Debnath, 2022). However, LF may cause groundwater contamination (leachate). Leachate is a potentially aggressive and toxic liquid produced due to chemical and biological reactions of water in the fill (moisture from waste and rain-infiltrated water) with the waste and soil present in the landfill. Leachate can severely pollute the subsurface soil, soil, and groundwater. The second type of contamination is related to biogas, a mixture of CH_4 and CO_2 (and a minority of other gases) produced by the anaerobic fermentations in the LF. Biogas typically contributes to air pollution (Luo et al., 2020; Nath & Debnath, 2022; Renou et al., 2008).

In 2016, it was estimated that 1.6 E12 billion tons of CO_2 were emitted from MSW treatment and disposal. Harmful practices such as disposal in LF lacking biogas collection and combustion systems, or worse, in open dumps, are thought to be the primary causes. Those emissions were nearly 5 % of the overall emissions (Kaza et al., 2018).

According to Mexican regulations (NOM-083, 2003), the final disposal site must be at least 500 m from surface water bodies with continuous flow, such as lakes and lagoons. Further regulations mandate that LF should not be placed close to water bodies, estuarine areas, mangroves, marshes, wetlands, swamps, alluvial plains, aquifer recharge zones, and archaeological areas. In localities with more than 2,500 inhabitants, the limit of the final disposal site must be at a minimum distance of 500 m.

13.3.Incineration

Importance

Incineration is reported to process 18 % of MSW across Europe and Central Asia, North America 12 %, and Latin America and Caribbean 4.5% (Kaza et al., 2018). Incineration is currently considered a competitive technology for simultaneously reducing waste volume and allowing energy recovery, which can reduce GHG emissions(Istrate et al., 2023; Rajaeifar et al., 2017; Yaman et al., 2020). In developed countries (DC), IER plays a crucial role in solid waste management, thus avoiding CH4 emissions from buried waste (Coelho & Diaz-Chavez, 2020; Khan et al., 2022; Sisani et al., 2022).

More than 255 E06 metric tons of MSW have been incinerated annually since 2015 (Reddy, 2016). In China, the incineration of MSW has increased from ca. 5% to 51% from 2003 to 2019. Nearly 80% of MSW was incinerated in Japan; Japan was the world's leading country in IER by 2017 (Michaels Ted & Krishnan Karunya, 2018). Over 1700 energy-from-waste plants (WfE) were operating worldwide by 2019; 589 were in Europe (United Nations Environment Programme, 2019).

Trends

An energy evaluation of the feasibility of IER of waste in Mexico (Escamilla-García et al., 2020) indicates that incineration can provide a greater generation capacity than the current capacity of other renewable sources such as hydroelectric and wind power. The potential total energy generation is ca. 11,681 GWh, contributing to 4.3% of the national demand. However, the economic feasibility of incineration was not verified. Escamilla-García et al. (Escamilla-García et al., 2020) results are aligned with the SEMARNAT-GIZ German Society for International Cooperation (GIZ) study (GIZ MÉXICO et al., 2016), which showed that incineration of waste can be an efficient option for electricity generation in Mexico.

In 2017 SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales, 2017) supported waste management through thermovalorization plants as an environmentally appropriate option for the MSW problem in Mexico. The thermal waste recovery plant was required to process 4,500 tons of waste per day of the daily 13,000 tons of MSW generated in

the city. However, the implementation was postponed; no alternative was proposed except landfills.

Advantages and disadvantages

However, incineration technology has several concerns, mainly related to its adverse potential environmental impacts. It is necessary to assess and compare its environmental performance since pollutants' emissions into the air and waste discharges/disposal are still significant challenges of incineration impact (Faragó et al., 2023; Lou et al., 2015; Monni, 2012; Van Caneghem et al., 2012; Vermeulen et al., 2012; Zhu et al., 2022) .

Two primary wastes produced during incineration are bottom ash, the residue remaining after combustion on the grate, and fly ash, which is extracted from the exhaust gases. Fly ash typically contains high concentrations of trace metals/metals and inorganic salts that can be sources of contamination of the soil, groundwater bodies, and biota or sources of contamination of the atmosphere such as NOx, acid gases, heavy metals, and particulate matter (Faragó et al., 2023; Van Caneghem et al., 2012; Vermeulen et al., 2012).

In the work by Yaman et al. (Yaman et al., 2020), three waste management options were evaluated regarding GHG emissions and global warming potential (GWP) for a scenario of 1480 Gg/yr MSW as a representative waste amount in 2020. The options were (1) a landfill (LF), (2) IER, and (3) a material recovery facility (MRF) with composting. The IER was second place in both criteria, as follows:

GHG (tCO2e/t MSW): 3 MRF -2,142,618 < 2 IER -287,873 < 1 LF -1.1;

GWP (tCO2e/t MSW): 3 MRF -1.091 < 2 IER- -0.147 < 1 LF +0.265.

Thus, IER had lower GHG emissions and GWP than LF, a waste management option widely used in developing countries in Latin America. The Authors also highlighted that IER could produce up to 1.91*E09 kWh/yr electricity, which could avoid using 1.12*E06 bbl/yr fossil fuel. In contrast, the option MRF, which had better GHG and GWP performance than IER, did not generate electrical energy. Unfortunately, this work did not include a biorefinery of MSW in the comparison.

13.4.Biorefinery

Importance

An alternative that is currently attracting attention for treating MSW is the BRF approach (Duan et al., 2022; Khoshnevisan et al., 2021; Ladakis et al., 2022; Shah et al., 2022). BRF technology uses core biotechnological processes (other processes can be involved as well) and biomass as feedstock, which complies with the principle of environmental sustainability by not compromising inputs for human consumption, among other features (Escamilla-Alvarado et al., 2017; Fava et al., 2015; Kirtay, 2011; Poggi-Varaldo et al., 2014).

The BRFs are facilities with an integrated, efficient and flexible conversion of renewable biomass to various products. Depending on the integration and type of BRF, it has been proposed to obtain biogas and VAPs such as microbial protein, bio-succinic acid and lactic acid (Gottardo et al., 2023; Hernández-Correa et al., n.d.; Vermeulen et al., 2012); the extraction of oils and fats, the extraction of proteins, the production of enzymes and the production of succinic acid (Gottardo et al., 2023).

Escamilla-Alvarado et al. (Escamilla-Alvarado et al., 2017) designed and analyzed a model BRF coined HMZS that produces hydrogen (H), methane (M), enzymes (Z) and saccharified liquors (S) from the organic fraction of the MSW (OFMSW.) It was shown that the BRF HMZS exhibited lower environmental impacts than LF. Sotelo Navarro et al. (Sierra-Gachuz et al., 2022) proposed a model biorefinery coined "HMEZS-NN" configuration that also incorporates the production of bionanobioparticles (NN) for wastewater and groundwater remediation.

Sierra-Gachuz et al. (Sierra-Gachuz et al., 2022) evaluated the ES of a family of Mexican models of BRF and compared their environmental performance to that of LF. All the biorefinery cases were environmentally more sustainable (α ranging from 16.41 to 18. 21 person*year/ 1000 kg OFMSW) than landfills (α of 118.62 person*year/ 1000 kg OFMSW).

Trends

In 2022, the International Energy Agency (IEA) reported 1,312 operational biorefineries worldwide (International Energy Agency, 2022; U.S. Energy Information Administration., 2023). According to U.S. Energy Information Administration more than 40 biorefineries were found in the USA, Finland, Germany, France, Holland, Sweden, and China. Between 10 to 40 biorefineries were located in Austria, Belgium, Denmark, Spain, Italy, Brazil, Canada, India, Japan, the U.K., and Australia, and 1 BRF in Mexico(U.S. Energy Information Administration., 2023). Furthermore, a search performed on the Web of Science showed that the publication of articles related to BRF technology has grown exponentially from 2019 to 2023, with 697, 1229, 1499, and 1963 articles published correspondingly per year, which is a significant sign of relevance and interest in this technology.

Advantages and disadvantages

BRF technology experts have proposed the significant potential of BRF systems that incorporate VAPs and bioenergy (Venkata Mohan et al., 2016) to support the overall commercial transformation towards sustainable BRF implementation and facilitate the conversion to more sustainable industrial systems (Makepa & Chihobo, 2024) .

Regarding disadvantages, according to experts, the BRF could imply high (production) costs. However, it depends on BRF configuration and marketing issues, such as the proportion of consumers willing to pay more for bio-based products. Also, the quantitative evidence of BRF's environmental sustainability still needs to be determined. Sometimes, doubts arise about perceived competition with food (International Energy Agency, 2022). Very often, the environmental sustainability of BRF is taken for granted, mainly when the feedstock is organic waste, which is perceived as a substantial environmental benefit. Comments often accompany these considerations on (non-determined) the high circularity feature without providing quantitative measurements of either the ES or the circularity (Venkata Mohan et al., 2016).

13.5. Shift from landfilling to intensive technologies IER and BRF for MSW treatment and management in developing (DingC) and underdeveloped countries (UC).

Due to several factors, several DingC and UC countries are under pressure to change the management of UOW in landfills and implement intensive and potentially sustainable technologies that allow the recovery of valuable resources for the economies of said countries. In the open and gray literature, IER and BRF are mainly considered.

Among other driving factors of this shift are the lack of space for LF near large cities, the relatively high potential environmental impacts of LF, the existence of comparative studies that indicate the lower environmental sustainability of LF compared to BRF, for example (Escamilla-Alvarado et al., 2017; Sierra-Gachuz et al., 2022) [41,47], and the increase of energy demand in DingC and UC. Regarding the latter, for Mexico, it is estimated that energy demand will increase by approximately 70% by 2030 (Renewable Energy Agency, 2015). Therefore, a solution to this problem may be using more intensive technologies such as IER and BRF that use the OFMSW and provide energy/bioenergy and VAPs.

Several researchers and institutions advocate a change of paradigm that supports the use of BRF for solid waste management (Alto Nivel, 2024; Escamilla-Alvarado et al., 2017; Sacramento-Rivero & Navarro-Pineda, 2019; Sierra-Gachuz et al., 2022) (Venkata Mohan et al., 2016). Findings of the two last references in the preceding list have been discussed above under the Biorefinery heading.

Policy reforms are recommended to attract investments; a bioeconomy policy is proposed as a significant step towards aligning Mexico with the UN's Sustainable Development Goals. Yáñez Vergara et al., 2022 concluded in 2022 the need to design, approve, and enforce a regulatory framework for waste-based BRF in Mexico. It was advocated that such regulations would foster new technologies and contribute to sustainable development in Mexico.

Other researchers and references in turn (Escamilla-García et al., 2020; GIZ MÉXICO et al., 2016; Secretaría de Medio Ambiente y Recursos Naturales, 2017) advocate and present preliminary evidence for the implementation of IER in Mexico. The first reference in the preceding list was discussed above under the heading of Incineration. In 2017, SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales, 2017) supported waste management through IER plants as an environmentally appropriate option for the MSW problem in Mexico. A thermal waste recovery plant was proposed to process 4,500 tons of waste per day of the daily 13,000 tons of MSW generated in the city. SEMARNAT-GIZ (GIZ MÉXICO et al., 2016) showed that waste incineration efficiently generates electricity in Mexico. As mentioned above, more stringent environmental regulations related to waste landfilling were issued in India. This change has drawn the attention of authorities and experts to potentially more sustainable and cost-effective Energy-from Waste (EfW) technologies (Gupta et al., 2015; Khan et al., 2022).

According to experts, IER and BRF can be intensive alternatives to replace LF in Mexico and other DingC, seeking a higher stage of OFMSW management, with the recovery of valuable energy and resources and possible reduction of the environmental impacts produced by LF.

13.6. Needs for evaluation and comparison of global ES of environmental technologies.

The shift mentioned above creates the need to select one of the two intensive technologies for Mexico and other countries. One crucial characteristic of the technologies considered is their environmental sustainability (ES). The ES is considered a condition of interconnection, resilience, and equilibrium that satisfies modern societies' needs while simultaneously avoiding harm to the regeneration capacity of the ecosystems and fostering the conservation of diversity(Teh et al., 2023).

Therefore, comparative studies of the environmental sustainability of IER and BRF for the same application, that is, the UOW management of a large city, are needed. The results of this comparison can help those responsible for planning MSW management, government decision-makers at different levels of government, technology manufacturers and suppliers, potential users of the products obtained in IER and BRF, and communities interested in MSW management.

In turn, evaluating the global ES of a technology or process requires quantitative techniques and the development of measurement indices based on the influence of all potential environmental impacts that arise from the LCA (18). Ideally, those indices should be aligned with ISO standards. The LCA is a very attractive tool because it is one of a comprehensive methodology for the environmental analysis of complex systems, which systematically takes into account the inputs and outputs of materials, energy, and emissions to the environment, both explicit in the life cycle inventory analyzed as well as implicit (or embedded) in the declared process currents and energy flows and embedded processes (proxies).

Another critical aspect is that new indices involving a global expression of the PEI (which generally have heterogeneous units among themselves) must be sought to lead to magnitudes with homogeneous common simple units or dimensionless. Thus, the comparison of ES of the two technologies would be mathematically consistent and easy to perform. Normalization of the PEIs according to ISO standards is a candidate for this. Thus, the normalized environmental impacts could be combined and algebraically operated into expressions representing each technology's overall environmental sustainability.

Unfortunately, studies on a systematic side-by-side comparison of the ES of BRF and IER are unavailable in the open literature, or at least are very scarce, according to the literature

review in Web of Science-Clarivate Analysis 2014-2024. More detailed information on this part of the background can be found in Annex 12, Supplementary Material. The search results were analyzed in light of the following issues/criteria, as in Table 1 below.

Table S13.1 Key issues of features and criteria to determine the characteristics of articles in the open literature that potentially compare the ES of biorefinery and incineration

- Comparison of the two technologies, BRF and IER
- Focus on urban wastes (organic)
- Use of full LCA results for the first environmental assessment of both technologies
- Use of quantitative indices for determining the sustainability of each technology
- Indices defined in terms of normalized environmental impacts from LCA results and aligned with ISO standards
- Use of normalized indices that can be summed, subtracted, and divided in such a way that their combination gives significant and valuable measurements for the comparison of the global environmental sustainability of each technology

The results in Table S12. 2 strongly indicate that the intended objectives of our research have yet to be covered in articles published in the open literature; *i.e*., *side-by-side comparison of IER and BRF of urban organic waste and development/application of new ES indices are needed.*

13.7. Life cycle assessment

A key tool for further determination of ES is the LCA methodology which is an iterative technique used to evaluate a wide and comprehensive variety of environmental impacts through a set of protocols and methodologies (ISO 14040, 2006; ISO 14044, 2006), and also evaluates the consumption of resources during each stage of manufacture, use, and final disposal (Anshassi et al., 2019; Guo & Murphy, 2012). LCA often used to compare waste management technologies (Cherubini et al., 2009; Dastjerdi et al., 2021; Evangelisti et al., 2015; Rigamonti et al., 2016) and understand which is the most effective technologies and minimize the environmental impacts (Tagliaferri et al., 2016). The LCA consists of four steps and in principle can be considered an iterative technique for improving the environmental performance of products, processes, technologies, and services.

Other researchers proposed and applied a more specific sustainability index to energy projects (Commission on Environment, 1987). Regarding process and industrial technologies, the use of indices associated with an absolute sustainability scale called “Greenscope methodology” was proposed by Ruiz-Mercado et al. (Ruiz-Mercado et al., 2012). Manzini et al. (Manzini et al., 2011) developed an environmental sustainability index that allows evaluation of the ES of energy projects. Such an index integrates environmental sustainability indicators throughout the life of the project. They did not use environmental impacts determined by LCA for the construction of such an index; only four *ad hoc* indices were considered for the analysis of a hydroelectric energy project (dissolved oxygen, GHG emissions, loss of vegetal coverage, threatened species.) Only one of the four indicators was normalized. The overall index was obtained as a sum of the weighed four indicators.

13.8. Sustainability and qualitative main and auxiliary principles for biorefineries

Environmental as well as industrial technologies (BRF among the first ones) seek to comply with the general concept of sustainability, which is defined as (World Commission on Environment and Develpoment, 1987):

"the development that meets the needs of the current generation without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987)".

It is known that general sustainability is related to three axes: Environmental, Social, and Economic sustainabilities. So far, we have focused on the environmental sustainability. Social sustainability is defined as a measure of human well-being at an intergenerational level (Mohamed & Paleologos, 2021). Economic sustainability includes aspects related to society's economic progress and well-being in the present and future (Douglas Brodie et al., 2016; Mohamed & Paleologos, 2021). Economic sustainability should be distinct from Economic feasibility. The latter can be calculated using methods already published and available in several engineering and process engineering textbooks (Peters et al., 2003). In contrast, there are no general or consensed methods for calculating economic sustainability because, so far, a synthesis that links the economic consequences of economic activities with the economic issues of environmental impacts is still behind(Pérez-Morales et al., 2024). In particular, BRF should comply with the fundamental principle of sustainability and four auxiliary principles that contribute to achieving sustainability: 1) the cascading principle (it refers to using organic waste as processed raw materials to maximize product per-formance), 2) the principle of non-competition between food and energy(Demirbas Ayhan, 2008; Poggi-Varaldo et al., 2014) , 3) the principle of carbon footprint neutrality (Balat & Kirtay, 2010; Escamilla-Alvarado et al., 2014; Muthu, 2021), 4) principle of value-added products (that seeks to influence economic sustainability) (Escamilla-Alvarado et al., 2014; Pérez-Morales et al., 2024).

1) Cascade principle. It refers to using organic waste as processed raw materials to maximize product performance. There are two models: direct and indirect cascade. The indirect model is used in the GBAER-BRF and is distinguished by organic waste processing in three large stages: bioenergy, bioproduct, and bioenergy generation arrangement. In contrast, in the direct cascade or traditional approach, organic waste is first used to produce value-added bioproducts. Subsequently, the waste from previous processes is subjected to bioenergy production. The indirect cascading is well suited for attaining the energy self-sufficiency of the BRF, which is particularly convenient for countries that import fossil energy.

2) Principle of non-competition between food and bioenergy. It refers to avoiding using food crops as feedstock of the BRFs and using organic wastes, such as food waste, municipal organic waste, and agro-industrial waste among others, as feedstocks for BRF. Therefore, waste biomass is considered one of the most valuable feedstocks among renewable energy sources due to its low cost and wide availability at the global level (Demirbas Ayhan, 2008; Poggi-Varaldo et al., 2014). The GBAER-BRF complies with this principle since OFMSW is the raw material.

3) Principle of carbon footprint neutrality. The carbon footprint refers to the total amount of GHG produced directly or indirectly by an activity or accumulated during the life cycle of a product (Muthu, 2021). Using the above-mentioned wastes to produce biohydrogen decreases the net mass of CO_2 released into the biosphere. Indeed, the released CO_2 was previously captured and fixed through plant and algae photosynthesis (Balat & Kirtay, 2010). Thus, the neutrality of the carbon footprint is favored by the BRF HMEZS-NN since carbon is uptaken from the atmosphere and converted to residual biomass so that the BRF can be integrated into the biogeochemical carbon cycle and is not a net producer of CO_2 (Escamilla-Alvarado et al., 2017) .

4) Principle of compliance with VAPs. Value-added compliance suggests that a process's economic sustainability can be increased by including the production of VAPs in a BRF. The

BRF HMEZS-NN seeks to consolidate the BRF's sustainability as much as possible by processing residual biomass through multiple processes, converting it into marketable products, such as bioenergy and bioproducts (VAPs).

These four principles help to achieve the ES of BRF and other technologies and constitute a useful qualitative guide for developing quantitative indices of ES as well as the economic and social sustainability. It is necessary ES quantitative evaluation studies for comparing the ES of different technologies that allow us to compare and select the best technology for a given application.

The GBAER (acronym for the Environmental Biotechnology and Renewable Energy of the Center for Research and Advance Studies, Mx, Cinvestav) developed a biorefinery called “HMEZS-NN” that integrates additional processes to the BRF HMEZS (Escamilla-Alvarado et al., 2017; Pérez-Morales et al., 2024; Sotelo-Navarro et al., 2022) . It incorporates a stage of extraction of organic acids from the fermented solids before the production of industrial enzymes and a stage of production of bionanobioparticles (NN) using saccharified liquors. The bionanobioparticles constitute a granular medium with biological and abiotic activities designed to purify wastewater and groundwater polluted with toxic organochlorine compounds. Although the integration of the HMEZS-NN BRF was developed within an environmental framework, modifications to the proposed processes may increase environmental impacts, so the final environmental sustainability must be evaluated and verified.

According to the probable shift to replace landfills with more intensive and sustainable technologies (such as IER and BRF) in Mexico and the lack of information on side-by-side comparison of such technologies that we have documented above, we aimed to evaluate and compare the ES of these two intensive urban waste treatment technologies, the BRF HMEZS-NN and the IER, to select the most environmentally sustainable option for treating MSW in a large city such as Mexico City. The evaluation of environmental sustainability was based on the results of the LCA methodology. As a subsidiary objective, a new environmental sustainability index α aligned with LCA and ISO-related standards (14040 & 14044) (ISO 14040, 2006; ISO 14044, 2006) and a novel methodology σ-τ were developed to determine and compare the overall ES of such technologies.

Cited references can be found in the general list of complete references at the end of this document

Annex 14. Economic assessment of specific investment costs of the biorefinery and the incineration plant

In this Annex we give more details on the methods and equations used for performing a preliminary evaluation of the specific investment costs of our biorefinery and the incineration plan. First, we start with the Notation table. The specific references that support Annex 14 can be found at the end of this Annex as well as the final List of References of the Supporting Material document.

Nomenclautre

A	outside area of an equipment with an L/D ratio of 3 and a factor of free head space in the bioreactor
A_{bottom}	bottom area
A_{side}	side area
A_{top}	top area
BBL	barrels
BRF	biorefinery
CCCPP	combined cycle cogeneration power plant
	characterization impact/(person*yr)
c_p	specific heat capacity
D	tank diameter
DC	developed country
DCBe	dichlorobenzene equivalent
DingC	developing country
E	enzymes
ES	environmental sustainability
ESP	electrostatic fly ash precipitator
$f_{conditioning}$	is a factor that reflects any increase of the m_{FU} by dilution, pH and alkalinity adjustment
Fn	factor of normalization, used to calculate the NPEI from PEI
FP	fine particle
FU	functional unit
FW	fermented wastes
FWEc	freshwater ecotoxicity
FWEu	freshwater eutrophication
GBAER	Environmental Biotechnology and Renewable Energies Group
GHG	greenhouse gas effect
GW	global warming
H	hydrogen
HCT	human carcinogenic toxicity
HNCT	human non-carcinogenic toxicity
IER	incineration with energy recovery
j	top, bottom, side wet, side dry
L	tank height
Let N	number of FU/d
L/D	height per diameter
LCA	life cycle assessment

LCI	life cycle inventory
LU	land use
M	methane
m'_a	actual mass flowrate in the equipment or process, based on Γ_{FU} and variations due to conditioning, material additions, and removals/degradation
m_a	actual mass after the m_{FU} has been modified by conditioning, other
ME	marine ecotoxicity
MEu	Marine eutrophication
m_{FU}	mass associated to the Functional Unit
MSW	municipal solid waste
N	number of functional units per day
N_{EVT}	N° of NPEI in REFT higher than EVT, or equivalently, No of NPEI in EVT that are lower than the corresponding NPEI in REFT
NN	bionanobioparticles
NPEI	normalized potential environmental impact
N_{REFT}	N° of NPEI in EVT higher than REFT, or equivalently, No of NPEI in REFT that are lower than the corresponding NPEI in EVT
NSCR	non-selective catalytic reduction
NSCR	non-selective catalytic reduction
OFH	ozone formation, human health
OFMSW	organic fraction of municipal solid waste
OFTE	ozone formation terrestrial ecosystems
PEI	potential environmental impact
PET	terephthalate - polyethylene
PHA	polyhydroxyalkanoate
P_{mixing}	power consumed by the recirculation pump, in W,
POI	photochemical ozone impact
Q	heat load in actual (scaled) conditions
q_{FU}	heat load per functional unit
S	saccharified liquors
SCR	selective catalytic reduction
SM	supplementary material
SMR	scarcity of mineral resources
SOD	Stratospheric ozone depletion
StB	Scum-to-Biodiesel technology
t	1 day time of operation, in seconds, i.e., 86400 sec/d
TA	terrestrial acidification
T_{amb}	is the ambient (or environment) temperature, K or ^oC,
T_H	is the operation temperature in the bioreactor, K or ^oC,
T_i	is an intermediate temperature of the feedstock
TIC	total investment cost
TS	total solids
U	unit load of environmental impact per person and per year (in unit of the characterization environmental impact times yr per person)
U	in heat transfer issues, U represents the overall heat transfer coefficient, typically in W/(m*K)
UOW	urban organic waste
VAPs	value added products

VOA	volatile organic acids
WC	water consumption
WWTP	wastewater treatment plant
Y	generic yield, in mass of a product or amount energy per entering unit
$Y_{H2/FU}$	example of Y, in mass of hydrogen harvested per functional unit
$\forall_{geometric}$	geometric volume of a bioreactor or tank
$\forall_{w}$	working volume of a bioreactor or tank
$\forall'$	volumetric flowrate, typically in m^3/s or m^3/d

Greek characters

α	sum of the normalized environmental impacts of a given technology, in (person*yr/FU)
α_R	recirculation ratio, $\alpha_R = \forall'_{recirculation}/\forall'_{feed}$
β	Power intensity of mixing, $P_{mixing}/\forall$
Γ	Capacity
Γ_a	Actual capacity of a process or stage in a biorefinery, in terms of actual mass fed, t/d or kg/h
Γ_{FU}	Capacity of a process or stage in a biorefinery, in terms of functional unit mass fed, t/d or kg/h
γ	Specific investment cost, in USD/t waste or biomass fed
Δ	increase or decrease of the magnitude
ΔH^o	standard enthalpy change (of evaporation, combustion, or reaction, etc.)
ΔP	total head of a pump expressed in pressure units, Nt/m^2
δ	correction for the different dry matter contents
ε_{FU}	Electricity flow per FU, in kWh/FU
η	efficiency
η_{pump}	efficiency of the pump (hydraulic efficienty, decimal number between 0 and 1)
η_{motor}	efficiency of the electrical motor (decimal number between 0 and 1)
θ	mass retention time of a continuous process in steady state, typically in day
θ_{batch}	incubation time in a batch process
ρ	is the density of m_a, in kg/m^3 or t/m^3
σ	GBAER sustainability index aligned with ISO standards, that compares the α values of two technologies; the index is used in the σ-τ plane
ξ	Complexity of the biorefinery, low 1 to 2 bioenergy or products, degree 2.5; medium or moderate 3 to 5 bioenergies or products, degree 5.5; high, 6 or higher bioenergies or products, degree 9; degrees normalized in a scale 1 to 10
τ	GBAER sustainability index related to the restrictions used in the plane σ-τ
ϕ	correction for different reference flows

The importance of a discussion on the relative economic accessibility of the BFR vs IER cannot be underestimated. However, on the one hand, economic analysis and evaluation are complex and long pieces of work (Peters et al. 2016, Tsagkari et al. 2016). On the other hand, a full economic analysis of the BRF and the IER is out of the scope of this article.

In this annex, preliminary analysis that could provide a first insight into the economic performance of the technologies, using literature information on total investment costs (TICs) was performed. The latter is one of the significant variables in economic evaluations. The analysis is made for both technologies using information from the literature and focused on the specific investment costs, although it should be taken with caution. As for the scope of this analysis, operating costs and revenues were not reviewed or presented (Peters et al., 2004). This analysis will be useful in locating the orders of magnitude for these specific investment costs. It will allow a first and useful comparison of these values for the technology discussed in this article, since investment costs are significant in themselves and are often the first criterion considered by decision-makers when continuing or abandoning the adoption of environmental technology.

As shown below, we define the specific investment costs (γ) by equation S14.1 (Gergel, 2024). Then, if Γ is the plant capacity in t/yr in terms of the waste or biomass fed and the total investment costs (TIC), γ will be equal to

$$\gamma = \frac{total\ investmet\ costs}{\Gamma} * F_{correction}\ (\frac{USD}{(t/yr)}) \qquad \text{(S14.1)}$$

where

$F_{correction}$ is the correction factor expressed in USD in January 2025, given that the data were typically calculated in different years.

In Tables S14.1 and S14.2, information was compiled from the literature regarding specific investment costs for BRF and IER, respectively. From the information in tables S14.1 and S14.2, equations S14.2 and S14.3 were calculated.

Table S14.1. Biorefinery cases investment costs

Specific investment costs γ (USD[a] /(t/yr))	**Complexity (ξ)**	**References**
795 Sorbitol case 770 Glucaric acid case	1000 t Sugarcane bagasse /d, Very complexity	Kapanji et al. (2019) Solarte-Toro et al. (2021)
468-500 Operational costs (average) 8.7-10	6500 t sugarcane/d at 35 % humidity, Moderate complexity	Gnansounou et al. (2015)
327	Corn, actually it is an alcohol factory, Low complexity degree	Tsagkari et al. (2016)
Average: 531 USD/t		

[a] Specific investment costs were calculated using the correction factor expressed in USD in January 2025.

Table S14.2. Incineration cases investment costs

Specific investment costs γ (USD[a] /(t/yr))	**Capacity Γ (t/yr)**	**Reference**

1500 Small-scale plants: Around $4.12 million to $9.62 million. 1,026 Medium-sized plants: Approximately $41 million 680 Larger plants: Around $169 million	5000 t/yr 40,000 t/yr 250000 t/yr	Gergel, (2024)
1527 Cost Basis in the EU (advanced technical set-up, 2 furnace lines) Initial investment: 135 – 185 million EUR	150000 t/yr	GIZ, (2017)
Average: 1183 USD/t		

[a] Specific investment costs were calculated using the correction factor expressed in USD in January 2025.

Equation S14.2 allows for the specific investment cost of a BRF to be determined from its complexity.

$$\gamma = 75.821\xi + 101.68; \quad R^2 = 0.9999 \qquad \text{(S14.2)}$$

where
γ =specific investment cost
ξ= complexity of the BRF

For its part, Eq S14.3 allows for the estimation of the specific cost of incineration based on its annual capacity for feeding processed waste.

$$\gamma = -210.02 \ln\Gamma + 3276.9; \quad R^2 = 0.9971 \qquad \text{(S14.3)}$$

where
γ =specific investment cost
Γ= capacity of the incineration plant

The γ of BRF increases significantly with increasing complexity, as might be expected. The trend is approximately proportional (Fig. S14.1 A). This trend is also expressed as Eq S14.2, with a good fit despite the limitations of the analysis (R^2 = 0.9999). Our BRF can be considered of moderate complexity, with 3 to 6 products (bioenergy and bioproducts, either commodities or VAPs), corresponding to a γ of 484 USD/(t/yr) (Table S14.1)

On the other hand, γ of incineration decreases significantly with increasing Γ; this relationship becomes linear downward if the natural logarithm of this last variable is considered (Fig. S14.1 B, Eq S14.3). The fit of the Eq. S14.2 is very satisfactory as linear regression (R^2 = 0.9971). Regarding the incineration plant and considering a metropolis of the size of Mexico City, the IER would be of great capacity, so it would correspond to γ of 680 USD/(t/yr) (Table S14.2).

The comparison indicates that the specific investment cost of the incineration plant seems to be higher than that of the BRF, that is, 484 and 680 USD/(t/yr), respectively. In relative terms is 40.49% higher. These preliminary results are encouraging and confirm that

the economic analysis of these technologies should be continued and expanded in the near future.

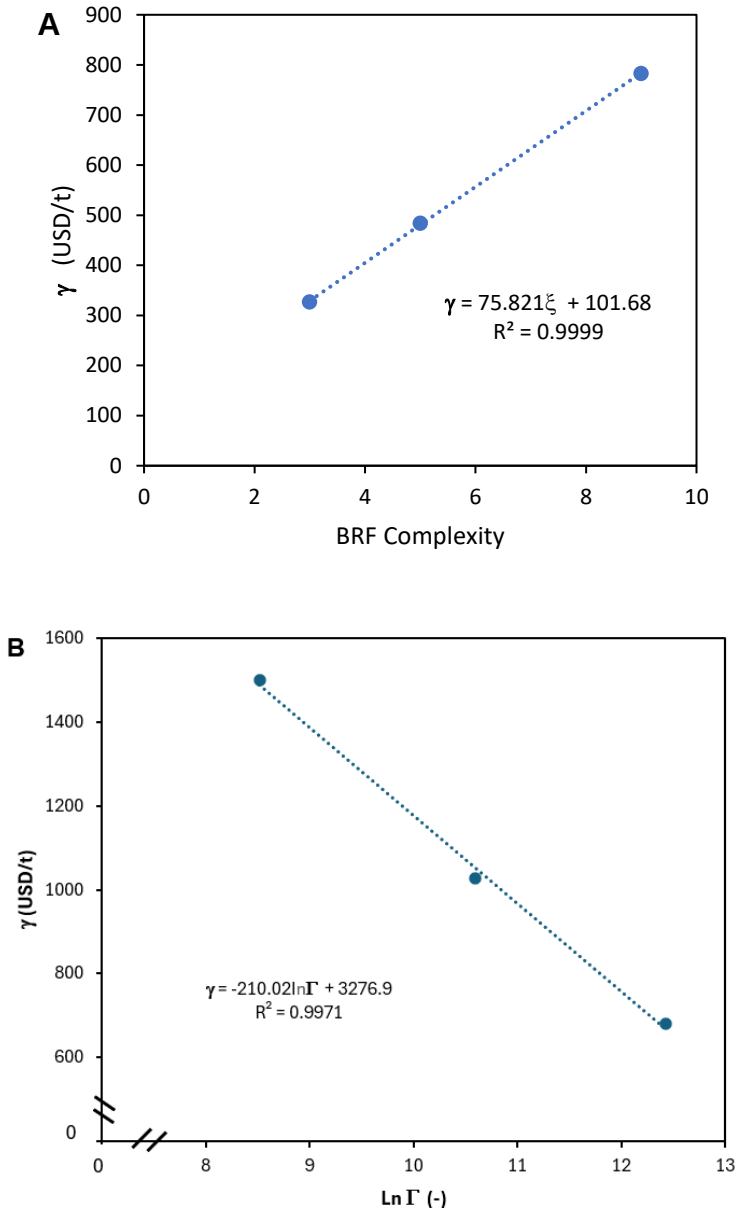


Fig.S14.1. Specific investment costs for (A) biorefinery, and (B) incineration plant

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Annex 15. Calculations of energy flows of the biorefinery and incineration plant

In this Annex we give more details on the methods and equations used for estimating the energy flows of our biorefinery and the incineration plant, for readership benefit.

First, we start with the Nomenclature table for easy consultation by the readership. The specific references that support the Annex 15 can be found both at the end of this Annex and the final List of References of this document.

Nomenclature

A	outside area of the equipment with an L/D ratio of 3 and a factor of free head space in the bioreactor
A_{bottom}	bottom area
A_{side}	side area
A_{top}	top area
BBL	barrels
BRF	biorefinery
CCCPP	combined cycle cogeneration power plant
	characterization impact/(person*yr)
c_p	specific heat capacity
D	tank diameter
DC	developed country
DCBe	dichlorobenzene equivalent
DingC	developing country
E	enzymes
ES	environmental sustainability
ESP	electrostatic fly ash precipitator
$f_{conditioning}$	is a factor that reflects any increase of the m_{FU} by dilution, pH and alkalinity adjustment
Fn	factor of normalization, used to calculate the NPEI from PEI
FP	fine particle
FU	functional unit
FW	fermented wastes
FWEc	freshwater ecotoxicity
FWEu	freshwater eutrophication
GBAER	Environmental Biotechnology and Renewable Energies Group
GHG	greenhouse gas effect
GW	global warming
H	hydrogen
HCT	human carcinogenic toxicity
HNCT	human non-carcinogenic toxicity
IER	incineration with energy recovery
j	top, bottom, side wet, side dry
L	tank height
Let N	number of FU/d
L/D	height per diameter
LCA	life cycle assessment
LCI	life cycle inventory

LU	land use
M	methane
m'_a	actual mass flowrate in the equipment or process, based on Γ_{FU} and variations due to conditioning, material additions, and removals/degradation
m_a	actual mass after the m_{FU} has been modified by conditioning, other
ME	marine ecotoxicity
MEu	Marine eutrophication
m_{FU}	mass associated to the Functional Unit
MSW	municipal solid waste
N	number of functional units per day
N_{EVT}	N° of NPEI in REFT higher than EVT, or equivalently, No of NPEI in EVT that are lower than the corresponding NPEI in REFT
NN	bionanobioparticles
NPEI	normalized potential environmental impact
N_{REFT}	N° of NPEI in EVT higher than REFT, or equivalently, No of NPEI in REFT that are lower than the corresponding NPEI in EVT
NSCR	non-selective catalytic reduction
NSCR	non-selective catalytic reduction
OFH	ozone formation, human health
OFMSW	organic fraction of municipal solid waste
OFTE	ozone formation terrestrial ecosystems
PEI	potential environmental impact
PET	terephthalate - polyethylene
PHA	polyhydroxyalkanoate
P_{mixing}	power consumed by the recirculation pump, in W,
POI	photochemical ozone impact
Q	heat load in actual (scaled) conditions
q_{FU}	heat load per functional unit
S	saccharified liquors
SCR	selective catalytic reduction
SM	supplementary material
SMR	scarcity of mineral resources
SOD	Stratospheric ozone depletion
StB	Scum-to-Biodiesel technology
t	1 day time of operation, in seconds, i.e., 86400 sec/d
TA	terrestrial acidification
T_{amb}	is the ambient (or environment) temperature, K or ^oC,
T_H	is the operation temperature in the bioreactor, K or ^oC,
T_i	is an intermediate temperature of the feedstock
TIC	total investment cost
TS	total solids
U	unit load of environmental impact per person and per year (in unit of the characterization environmental impact times yr per person)
U	in heat transfer issues, U represents the overall heat transfer coefficient, typically in W/(m*K)
UOW	urban organic waste
VAPs	value added products
VOA	volatile organic acids

WC	water consumption
WWTP	wastewater treatment plant
Y	generic yield, in mass of a product or amount energy per entering unit
$Y_{H2/FU}$	example of Y, in mass of hydrogen harvested per functional unit
$\forall_{geometric}$	geometric volume of a bioreactor or tank
$\forall_{w}$	working volume of a bioreactor or tank
$\forall'$	volumetric flowrate, typically in m^3/s or m^3/d

Greek characters

α	sum of the normalized environmental impacts of a given technology, in (person*yr/FU)
α_R	recirculation ratio, $\alpha_R = \forall'_{recirculation}/\forall'_{feed}$
β	Power intensity of mixing, $P_{mixing}/\forall$
Γ	Capacity
Γ_a	Actual capacity of a process or stage in a biorefinery, in terms of actual mass fed, t/d or kg/h
Γ_{FU}	Capacity of a process or stage in a biorefinery, in terms of functional unit mass fed, t/d or kg/h
γ	Specific investment cost, in USD/t waste or biomass fed
Δ	increase or decrease of the magnitude
ΔH^o	standard enthalpy change (of evaporation, combustion, or reaction, etc.)
ΔP	total head of a pump expressed in pressure units, Nt/m^2
δ	correction for the different dry matter contents
ε_{FU}	Electricity flow per FU, in kWh/FU
η	efficiency
η_{pump}	efficiency of the pump (hydraulic efficienty, decimal number between 0 and 1)
η_{motor}	efficiency of the electrical motor (decimal number between 0 and 1)
θ	mass retention time of a continuous process in steady state, typically in d
θ_{batch}	incubation time in a batch process
ρ	is the density of m_a, in kg/m^3 or t/m^3
σ	GBAER sustainability index aligned with ISO standards, that compares the α values of two technologies; the index is used in the σ-τ plane
ξ	Complexity of the biorefinery, low 1 to 2 bioenergy or products, degree 2.5, medium or moderate 3 to 5 bioenergies or products, degree 5.5, high 6 or higher bioenergies or products, degree 9; degrees normalized in a scale 1 to 10
τ	GBAER sustainability index related to the restrictions used in the plane σ-τ
ϕ	correction for different reference flows

15.1 Energy calculations for the biorefinery

15.1.1. General approach

The energy flows in the HMZES-NN BRF were estimated by a combination of
(i) our experimental data published in articles in the open literature (journals indexed in JCR,

Clarivate Analytics) and Master and Doctoral theses of the Environmental Biotechnology and Renewable Energies Group (GBAER) of Cinvestav (Escamilla-Alvarado 2017, 2015, 2014, 2013a, 2013b, 2012; Bretón-Deval and Poggi-Varaldo, 2017; Bretón Deval et al., 2015, 2016; Hernández-Correa et al. 2017; Romero-Cedillo et al., 2020; Sotelo-Navarro et al., 2022),
(ii) accepted procedures of sizing and design in Chemical (Perry and Green, 2008; Aerstin and Street 1978; McCabe et al., 2005); and Biochemical Engineering (van't Riet and Tramper, 199.; Doran, 2012, Lee, 1991),
(iii) use of proxies (life cycle inventories in Ecoinvent database) close to the BRF process in question, particularly when the process or stage is complex (Guinée et al. 2002), which is an accepted practice in LCA. The energy flows in the proxy were summed up (in each category, heat and electricity inputs and outputs; and the results were harmonized according to the FU of the proxy and our FU, similarly to what was done in Subsection 2.1.4. using factors ϕ and δ, Eq. 3 and 4 of the article), and
(iv) a calculation technique that we call the "ping-pong strategy" that is used when the energy flow per FU is sensitive to the size of the equipment, such as the heat loss of an equipment to the ambient through its external area surface.

Such a strategy was used for selected processes in several stages of the biorefinery that require the estimation of heat losses of equipment to the environment, the electricity of pumping per FU, and electricity per FU associated with mixing. Calculations performed for continuously operated process units were assumed to be at a steady state. All equipment was assumed to be fitted with appropriate thermal insulation, 1 to 2 inches thick, and with correct maintenance. First, we conducted the mass balances, mostly based on our experimental data.

15.1.2. Ping-pong strategy description and justification

The need for this approach becomes evident in the calculations of heat losses to the environment from a piece of equipment, among others. Heat losses to ambient are sensitive to the specific area of the equipment and thus sensitive to the degree of scaling. The ping-pong strategy for a continuous process consists of at least five steps, as follows:
(i) set a large-scale capacity (t/d or t/h),
(ii) estimate the actual mass flowrate of feedstock corresponding to this capacity,
(iii) size the piece of equipment (usually a tank, bioreactor, etc.) and determine the outside areas and working volume. Afterward,
(iv) estimate the energy flows (heat, electricity) for these conditions, and last
(v) standardize the energy flows in terms of the FU (J/FU for heat loads, kWh/FU for electricity.)

First, the justification for the strategy will be demonstrated. For instance, heat losses to the environment are typically a function of the outside area A of a piece of equipment. Usually, we have in mind cylindrical or spherical bioreactors/tanks. For example, if we calculate the heat loss for a tank containing only 1 FU mass, the tank will be small (approximately 3.5 m^3 considering the conditioning of the mass of one FU). *The smaller the tank, the higher the specific outside area* $A/\forall_{geometric}$, where $\forall_{geometric}$ is the geometric volume of the tank.

Consequently, the heat loss in small recipients will be overestimated. That is, for a small bioreactor of 3.5 m^3, the heat loss per FU will be much higher than the heat loss per FU calculated for a bioreactor of 350 m^3
For a tank with an L/D ratio of 3, diameter D, height L, and a factor of free headspace in the bioreactor

$$\forall_{geometric}/\forall_{w} = 1.3 \qquad \text{(S15.1)}$$

where
$\forall_w$ is the working or wet volume

$$\forall_{geometric} = (3/4)*\pi*D^3 \quad \text{(S15.2)}$$

$$D = ((4/(3*\pi))*\forall_{geometric})^{1/3} \quad \text{(S15.3)}$$

$$A_{bottom} = A_{top} = (\pi/4)*D^2 \quad \text{(S15.4)}$$

$$A_{side} = \pi*D*L = 3*\pi*D^2 \quad \text{(S15.5)}$$

The specific area per unit volume for a cylinder becomes

$$(A/\forall_{geometric}) = [2*(\pi/4)*D^2 + 3*\pi*D^2)]/[(3/4)*\pi*D^3] = (14/3)/D \propto 1/D \quad \text{(S15.6)}$$

Thus, Eq. S15.6 clearly states that $A/\forall_{geometric}$ is inversely proportional to the D for a cylindrical tank. This relationship also confirms our previous statement '*The smaller the tank (smaller D), the higher the specific outside area A/* $\forall_{geometric}$'. The proof for a spherical tank is similar and more straightforward. Following for the two cylindrical tanks of volume 3.5 and 350 m^3 volumes (1 and 100 FU, respectively), and assigning them the subscripts 1 and 2, respectively, it can be shown first that the heat loss loads q_1 and q_2 per FU are in the ratio.

From Eq (S15.2) above,

$$D_2/D_1 = (350/3.5)^{1/3} = (100)^{1/3} = 4.642 \quad \text{(S15.7)}$$

and

$$q_{FU,2}/q_{FU,1} = (D_2^2/100)/(D_1^2/1) = (D_2/D_1)^2/100 = 4.642^2/100 =$$

$$= 21.54/100 = 0.2154 \quad \text{(S15.8)}$$

where
$q_{FU,1}$ and $q_{FU,2}$ are the heat losses per FU in the small and the large bioreactor, respectively, 1 and 100 are the N of FU for the small and the large bioreactor, respectively.

This clearly shows that the unit heat loss load per FU of the small bioreactor is nearly five times higher than that of the larger bioreactor and justifies the implementation of the ping-pong strategy (a gross overestimation of 400%.) *Therefore, to calculate realistic heat losses (and not unfeasible high values) the engineer should consider a realistic (large-scale) tank for the calculations.* On the other hand, the values of electricity loads per FU for mixing calculated in terms of the power intensity β ($\beta = P_{mixing}/\forall_w$, in W/m^3, Benítez, 2022; Brown et al., 1951) are also sensitive to the size of the equipment. Finally, the ping-pong strategy can be easily adapted to the calculation of energy flows in batch processes.

15.1.3. Application of ping-pong strategy to continuous hydrogenogenic bioreactor in H stage

Now we continue with the example of energy flow calculations for the hydrogenogenic bioreactor. The bioreactor operates in the thermophilic regime, at temperature T_H. It is a well-mixed bioreactor, although mechanical mixers are not recommended because the paper in the feedstock favors the clogging of mixer impellers by the paper fibers thus leading to inefficient mixing in addition to excessive power consumption that burned the electrical motors (Pompano Beach project anaerobic digestion of municipal solid wastes using complete-mix reactors, in Florida 50 years ago.) Instead, mixing by recirculation using concrete pumps was chosen (De Baere, private communication, 2001). Karassik et al. (1986; Section 9.17. Solids pumping. Pp. 9.261 to 9.276) also consider screw pums for slurry transfer.

The bioreactor sector is fitted with two heat exchangers for preheating the feedstock fed to the bioreactor. Heat exchanger 1 preheats the feedstock against a stream of hot fermented solids (temperature T_H , typically 55ºC) from the bioreactor. The feedstock then reaches an intermediate temperature T_i, Tamb < T_i < T_H. On the other hand, the hot fermented solids stream is cooled down to a temperature in the mesophilic range (for instance, 37-40ºC) because it is fed to the methanogenic bioreactor downstream. Afterward, the feedstock at T_i is fed to Heat exchanger 2 where it is heated to the temperature T_H against a stream of hot water or low-pressure steam.

Also, the sector has one feed concrete pump, one concrete unit for recirculation, one concrete pump for the discharge of the hot fermented solids from the bioreactor. Optionally, there could be a fourth pump between the two heat exchangers to boost the pressure of the feedstock stream in-between.

Let N = number of FU/d,
m_{FU} = mass of a functional unit of the process, t or kg
Γ_{FU} = nominal capacity in terms of FU fed to process, also

$$\Gamma_{FU} = N*m_{FU}, \text{ in t/d or kg/d} \qquad \text{(S15.9)}$$

Let m_a = actual mass fed to the process, t or kg. The latter can be estimated as follows

$$m_a = (m_{FU}*f_{conditioning} + \text{additions} + \text{removals})*f_{splitting} \qquad \text{(S15.10)}$$

where
$f_{conditioning}$ is a factor that reflects any increase of the m_{FU} by dilution, pH and alkalinity adjustment, etc.,
$f_{splitting}$ reflects the fraction of the mass that is fed to the process given a bifurcation event, removals may include biodegradation.
For instance, for the hydrogenogenic bioreactor, the conditioning rises the 1 t of OFMSW to nearly 3.2 t. Thus, a $f_{conditioning}$ of 3.2 should be used. No further additions or removals occurred so both terms are zero. The conditioned feed will be fed 100% to the bioreactor, therefore $f_{splitting}$ is 1.0. Both factors used, *ad hoc* additions and removals come from experimental data and mass balances previously performed by our Group.
Very important, there is a correspondence between m_{FU} and m_a.

Γ_a = actual capacity, t/d or kg/d. Γ_a can be estimated as follows

$$\Gamma_a = N*m_a \text{ , in t/d or kg/d} \qquad \text{(S15.11)}$$

The working volume of the bioreactor can be found as

$$\forall_w = \Gamma_a * \theta / \rho \qquad \text{(S15.12)}$$

where
θ is the mass retention time in the hydrogenogenic bioreactor, in d
ρ is the density of m_a, in kg/m^3 or t/m^3

For heat loss to ambient, it is convenient to divide the outside area of a bioreactor in four parts: top, bottom, side wet, and side dry, that is, A_{top}, A_{bottom}, $A_{side\ wet}$, and $A_{side\ dry}$ (Kumana and Kothari, 1982). The determination of the corresponding four overall heat transfer coefficients followed the methods reported in Kumana and Kothari (1982) and Green and Perry (2008). Usually, $U_{bottom} \cong U_{side\ wet}$

The overall heat loss load Q_{loss} for the large bioreactor is calculated with this equation

$$Q_{loss} = \Sigma(U_j * A_{j)} * (T_H - T_{amb}) * t * f_{time\ conversion}, \text{ in J/d} \qquad \text{(S15.13)}$$

where
j = top, bottom, side wet, side dry
t = 1 day time of operation, in seconds, i.e., 86400 sec/d
T_H is the operation temperature in the bioreactor, K or ^oC,
T_{amb} is the ambient (or environment) temperature, K or ^oC,

The heat load Q_{sens} for pre-heating the feedstock stream is calculated with Eq. Bz (Kern et al., 2019) (actually it is a change of enthalpy from the application of the 1st law of Thermodynamics to a heat exchanger, Cengel, 2002.)

$$Q_{sens} = \Gamma_a * c_p * (T_H - T_{amb}), \text{ in J/d} \qquad \text{(S15.14)}$$

wich consists of two terms, i.e.,

$$Q_{sens,1} = \Gamma_a * c_p * (T_i - T_{amb}), \text{ in J/d} \qquad \text{(S15.15)}$$

This occurs in the Heat Exchanger 1. The T_i is an intermediate temperature of the feedstock, determined by the low temperature of the counter-current stream of hot fermented solids exiting the bioreactor (typically in the mesophilic range).
The latter needs to be fed to the mesophilic methanogenic bioreactor. Thus, its cooling is from T_H =55 ^oC to 37-40 ^oC. Heat exchanger 1 allows for a moderate heat recovery.
Regarding the feedstock, in the Heat Exchanger 2 the stream is heated from T_i to T_H, using low pressure steam or hot water at 80 ^oC.

$$Q_{sens,2} = \Gamma_a * c_p * (T_H - T_i), \text{ in J/d} \qquad \text{(S15.16)}$$

The overall overall heat load (input) is the sum of Eq. S12.13 and S12.14 and affected by a factor of $f_{appurtenances}$ to account for the heat losses of pipes, fittings, and auxiliary equipment. A reasonable value of this factor is 1.3,

$$Q_{heating} = [\Sigma U_j * A_j * (T_H - T_{amb}) * t * f_{time\ conversion} +$$

$$+ \Gamma_a * c_p * (T_H - T_{amb})] * f_{appurtenances}, \text{ in J/d} \qquad \text{(S15.17)}$$

The contribution of the heat of biochemical reaction that is an output and could subtract from the $Q_{heating}$ was neglected. The enthalpy of anaerobic reactions is relatively low (Doran, 2012, van´t Riet and Tramper, 1991). Therefore, we save calculation complications and we are on the safe side of any underestimation of $Q_{heating}$.

Regarding the electricity flows (input) in the bioreactor sector, we distinguish the electricity flow for mixing (by recirculation of bioreactor contents) and the corresponding flows of the transfer pumps (feedstock pump, hot fermented solids flow). Concerning the first energy flow, Levenspiel (1972) has shown that a plug flow can be converted to a well-mixed reactor by increased recirculation rates. It is an asymptotic result since the bioreactor becomes a complete-mix one when the recirculation ratio tends to infinity. The mechanical mixing is replaced by a convenient pump. Problems with clogging the impellers with the abundant paper fibers of the OFMSW (inefficient mixing and excessive power consumption of the electrical motors conducive to motor burning) are avoided.

$$P_{mixing} = \Delta P * \forall'_{recirculation} / (\eta_{pump} * \eta_{motor}) \qquad \text{(S15.18)}$$

where
P_{mixing} = power consumed by the recirculation pump, in W,
$\forall'_{recirculation}$ = volumetric flowrate of the recirculation of fermented hot solids, in m^3/s,
η_{pump} = efficiency of the pump (hydraulic efficienty, decimal number between 0 and 1),
η_{motor} = efficiency of the electrical motor (decimal number between 0 and 1),
ΔP = increment of pressure between the circuit discharge and pump suction, N/m^2,
with

$$\Delta P = \Delta P_{friction\ loss} + \Delta P_{static\ pressure} + \Delta P_{height\ change} + \Delta P_{kinetic\ change} \qquad \text{(S15.19)}$$

Karassik et al. (1986; Section 8.1., pp. 8.3 to 8.77)
Usually, the fourth term in the right member of the equation can be neglected.
The $\forall'_{recirculation}$ is estimated as a multiple of the feedstock rate to bioreactor. If α_R is the recirculation ratio defined as

$$\alpha_R = \forall'_{recirculation} / \forall'_{feed} \qquad \text{(S15.20)}$$

then

$$\forall'_{recirculation} = \alpha_R * \forall'_{feed} \qquad \text{(S15.21)}$$

with a reasonably high value of α_R

$$Electricity_{mixing} = [\Delta P * \forall'_{recirculation} / (\eta_{pump} * \eta_{motor})] * t * f_{kWh/J}, \text{ in kWh/d} \qquad \text{(S15.22)}$$

Designing the symbol $\varepsilon_{FU,\ mixing}$ for the $Electricity_{mixing}$ per FU, we have

$\varepsilon_{FU,\ mixing}$ = $Electricity_{mixing}$/N ((kWh/d)/(number of FU/d) = kWh/FU) (S15.23)

Similarly, the energy flow for pumping feedstock and exit fermented solids are

$Electricity_{pumping\ feedstock}$ = $[\Delta P^{*}\forall'_{feedstock}/(\eta_{pump}{}^{*}\eta_{motor})]^{*}t^{*}f_{kWh/J}$, in kWh/d (S15.24)

$\varepsilon_{FU,\ pumping\ feedstock}$ = $Electricity_{pumping\ feedstock}$/N, in kWh/FU (S15.25)

$Electricity_{pumping\ fermented\ solids}$ = $[\Delta P^{*}\forall'_{fermented\ solids}/(\eta_{pump}{}^{*}\eta_{motor})]^{*}t^{*}f_{kWh/J}$, in kWh/d (S15.26)

$\varepsilon_{FU,\ pumping\ feedstock}$ = $Electricity_{pumping\ fermented\ solids}$/N, in kWh/FU (S15.27)

Safety factors are recommended in the calculation of these electricity flows. Blodgett (2015) suggests estimating the pump power for water and apply factors of 4 and higher for thickened sludges. Our feedstock and fermented solids streams contain approx. 20% and 18% total solids, respectively.

15.1.4. Other energy flows

Electricity input of mixing by mechanical impellers

Alternatively, the $Electricity_{mixing}$ can be estimated on the basis of the power density β from literature (Benítez, 2022; Brown et al., 1951), as follows

$Electricity_{mixing}$ = β $(W/m^3)^{*}$ $\forall_w(m^3)^{*}t$ (seconds/d)$^{*}f_{kWh/J}$, in kWh/d (S15.28)

$\varepsilon_{FU,mixing}$ = $Electricity_{mixing}$/N, in kWh/FU (S15.29)

The β should be chosen at the high side of the recommended intervals Also, some safety factors similar to those used for paper stocks in the pulp and paper industry or slurry processing can be used, since most of our streams are between 15 to 20% total solids.

Electricity output of the fuel cell in stage H, $\varepsilon_{fuel\ cell/FU}$

$\varepsilon_{fuel\ cell/FU}$ = $Y_{H2/FU}{}^{*}\Delta H^{o}_{Combustion,H2}{}^{*}\eta_{fuel\ cell}{}^{*}f_{kWh/J}$ in kWh/FU (S15.30)

where

$Y_{H2/FU}$ is the amount of H_2 produced, in kg per functional unit of OFMSW, according to our experiments,

$\Delta H^{o}_{Combustion,H2}$ is the standard enthalpy of combustion of H_2 gas, in J/kg, from literature,

$\eta_{fuel\ cell}$ is the efficiency of the fuel cell, dimensionless and decimal, from the literature

$f_{kWh/J}$ is the conversion factor from J to kWh

The $\eta_{fuel\ cell}$ is relatively high, between 0.40 to 0.60, from the literature (Dick and Rand,

2018; Tsakiris, 2019) although some fuel cells can exceed 60% (US-DOE, 2016.) The fuel cell efficiency is much higher than the thermal efficiency of a combustion engine (typically 0.20 to 0.25) and an actual steam thermoelectric plant (0.30 to 0.35) because the fuel cell is a chemical device, not a thermal engine. Unlike a thermal engine, the fuel cell does not operate between two heat reservoirs and does not transfer a huge amount of heat to the sinking deposit of a typical thermal engine setup. Therefore, the flow of energy to electricity is higher in the fuel cell. Incidentally, this is a crucial advantage of fuel cells over thermal engines, a (0.55-0.30)/0.30)*100 = 83% average superiority concerning electrical energy efficiency.

Heat output by cogeneration of methane from the methanogenic bioreactor
We have determined in our experiments the yield of methane per FU, $Y_{CH4/FU}$.
Cogeneration is an interesting approach that maximizes the use of the fuel heat value since both products, electricity and heat, are effectively used reaching an overall use efficiency of fuel heat that can reach 80% (Boyen, 1980; Boyce, 2010).
The heat per FU generated in the combined cycle cogeneration power plant (CCCPP) is estimated by Eq S15.31 below,

$$Heat_{cogeneration} = Y_{CH4/FU} * \Delta H^{o}_{Combustion,CH4}\ (J/kg) * 0.50, \text{ in } J/FU \qquad (S15.31)$$

where
$\Delta H^{o}_{Combustion,CH4}$ is the standard enthalpy of combustion of CH_4 gas, in J/kg, from literature.
The factor 0.50 is the proportion of the combustion energy converted to heat, that is, the complement of the thermal efficiency of the CCCPP, dimensionless and decimal, from literature. It is conservatively low according to modern trends (Boyce, 2010).

Electricity output in cogeneration of methane from the methanogenic bioreactor
We have determined in our experiments the yield of methane per FU, $Y_{CH4/FU}$.
The electricity generated by the combined cycle cogeneration plant process CCCPP per FU is estimated by Eq S15.32 below,

$$\varepsilon_{FU,cogeneration} = Y_{CH4/FU} * \Delta H^{o}_{Combustion,CH4}\ (J/kg) * 0.33 * f_{kWh/J}, \text{ in } kWh/FU \qquad (S15.32)$$

The factor 0.33 is the proportion of the combustion energy that is converted to electricity, that is, the thermal efficiency, dimensionless and decimal, from literature. The reader is referred to Table S15.1 below for a summary of energy flow calculations of the biorefinery.

Table S15.1. Compilation with more detailed information on energy flow calculations of the biorefinery in this work.

Stage/Process/ Type of energy flow/ Input or output	Methods and remarks	References
Conditioning/Conditioning/ Electricity (Mixing power)/ Input	Eq. S12.28 and S12.29 Ping-pong strategy used. Sizing the volume of conditionng tank according to experimental formulation and additives and ping-pong strategy. The mass flowrate of fermented-extracted solids determined from mass balances using our experimental data. Mixing energy estimated from mixing intensities method (Benitez, 2022; Brown et al., 1951). Information from rheology of suspensions in Biotechnology (Clark and Blanch, 1997) and thickened sludges from Sludge treatment	Benitez (2022) Blodgett (2015) proxy _Plaster mixing modif2 HP {RoW}|processing|cut-off,U Brown et al. (1951) Tchobanoglous et al. (2014) Clark and Blanch (1997)

	and conditioning (Blodgett, 2015; Tchobanoglous et al., 2014) to check for safety factors	Escamilla-Alvarado et al. (2017)
H/Biological hydrogen production. Heat transfer/Heating Pre-heating feedstock to bioreactor/ Input	Eq S12.11, S12.14, S12.14, S12.16 Ping-pong strategy used. Calculation m'a feedstock flowrate using nominal capacity and mass balances. Sensible heat calculations in conventional heat exchanges1st law Q = m'*cp*delta T between Tbioreactor and T cold feedstock or between Tsteam and Twarm feedstock. Two heat exchangers were included to provide sensible heat to the feedstock: one exchanger between the cold feedstock and the hot fermented solids exiting the bioreactor (some heat recovery), and a second heat exchanger of warm feedstock-low pressure steam to reach the bioreactor operation temperature of 55 C. All the heated equipment has adequate thermal insulation.	Aerstin and Street (1978); Cengel (2002) Escamilla-Alvarado et al. (2017) Green and Perry (2008) Kern et al. (2019)
H/Biological hydrogen production Heat transfer/Heating load Heat loss bioreactor to ambient Input	Eqs. S12.11 and S12.13 Ping-pong strategy used. Calculation m'a feedstock flowrate using nominal capacity and mass balancesU*A*delta T, overall U from literature data Sizing bioreactor was required to define working volume and transfer areas (side area of the working volume, side area of the bioreactor headspace, bottom area, cover area).Mass retention time and operation temperature of bioreactor for sizing were taken from own experimental work U coefficients were selected from literature. All heated equipment has adequate thermal insulation.	Aerstin and Street (1978); Cengel (2002) Escamilla-Alvarado et al. (2017) Green and Perry (2008) Kern et al. (2019) Kumana and Kothari (1989);
H/ Biological hydrogen production Heat transfer/Heating load Heat loss of piping and appurtenances to ambient Input	Eq S12.17 A Ping-pong strategy used. A factor 0.3 of the sum of previous heat loss load of the bioreactor (30%); it was incorporated to the equation as 1.3. Since the detailed piping, fittings, etc., are not defined yet, we chose to estimate this heat load as a fraction of the heat loss of the bioreactor plus the sensible heat invested in feedstock pre-heating. All heated equipment has adequate thermal insulation.	--------
H/Biological hydrogen production Electricity (power) Pumping feedstock to bioreactor Input	Eq. S12. 24, S12. 25 Ping-pong strategy used. Pump sizing. Density from own experimental data. Feedstock flowrate estimated by our previous mass balance. Total head of the pump constituted by Height head equal the height of the bioreactor, kinetic head neglected, friction head estimated as the sum of pipe friction head loss,plus and typical heat exchanger headloss, and difrernetial static pressure head (Karassik, 1986). Concrete pump type selected. Conservatively low pump and motor efficienies selected. Unit operations/Fluid mechanics internal flows. Information from pumping high solids suspensons (thickened sludges, Blodgett, 2015 and Tchobanoglous et al., 2014, paper stocks, Karassik, 1986, thick mycelia broths, Clark and Blanch, 1997) pastes in Food Technology and thickened sludges from Sludge treatment and conditioning	Blodgett (2015) Clark and Blanch (1997) DeBaere (2001) Escamilla-Alvarado et al. (2017) Karassik et al. (1986) Levenspiel (1972) OWS Private communication, Dranco process Tchobanoglous et al. (2014)
H/Biological hydrogen production Pumping fermented solids Input	Eqs. S12.26, S12. 27; Ping-pong strategy used. Pump sizing. Density from own experimental data. Feedstock flowrate estimated by our previous mass balance. Total head of the pump constituted by Height head equal the height of the bioreactor, kinetic head neglected, friction head estimated as the sum of pipe friction head loss,plus and typical heat exchanger headloss, and diferential static pressure head (Karassik, 1986). Concrete pump type selected. Conservatively low pump and motor efficienies selected. Unit operations/Fluid mechanics internal flows. Information from pumping high solids suspensons (thickened sludges, Blodgett, 2015 and Tchobanoglous et al., 2014, paper stocks, Karassik, 1986, thick mycelia broths, Clark and Blanch, 1997) pastes in Food Technology and thickened sludges from Sludge treatment and conditioning	Blodgett (2015) Clark and Blanch (1997) DeBaere (2001) Escamilla-Alvarado et al. (2017) Karassik et al. (1986) Levenspiel (1972) OWS Private communication, Dranco process Tchobanoglous et al. (2014)
H/Biological hydrogen production Electricity (power) Mixing bioreactor content by recirculation (pumping) Input	Eq. S12.18 to S12.23 Ping-pong strategy applied. Density from own experimental data. Sludge recirculation flowrate estimated as 150% or higher thant that of the feedstock flowrate. Total head of the pump constituted by Height head equal the height of the bioreactor, kinetic head neglected, friction head estimated as the sum of recirculation pipe friction head loss, and static differential pressure head. Concrete pump type selected. Conservatively low pump and motor efficiencies selected. Unit operations/Fluid mechanics internal flows. Information from pumping paper stocks (Karassik et al., 1986), thickened sludges from Sludge treatment and conditioning (Tchobanoglous et al., 2014; Blodgett, 2015), and thick mycelial broths (Clark and Blanch, 1997)	Blodgett (2015) Clark and Blanch (1997) DeBaere (2001) Escamilla-Alvarado et al. (2017) Karassik et al. (1986) Levenspiel (1972) OWS Private communication, Dranco process Tchobanoglous et al. (2014)
H/Biological hydrogen production Heat generation in the bioreactor Heat of exothermic reaction	Enthalpy of reaction in anaerobic processes (fermentation and methanization) is low (Doran, 2012; van't Riet and Tramper, 1991). This heat output was neglected. This decision is in the safe side because will increase the amount of heat input required.	Doran (2012) van't Riet and Tramper (2012)

Output		
H/Biogas hydrogen purificationElectricity spent in the purification process of biogas H Input	The electricity flow was calculated using the specific indicator method applied to the production of m3 H2 per FU (experimental, we have the mass of H2 per FU, this mass was converted to standard m3 using ideal gas law) Wantz et al. (2023) gave an overall indicator of 0.3 kWh/m3 biogas using a water high pressure scrubber with water recovery along with the mass or cubic meter of biogas H generated per FU which is an experimental result. . This method does not require the ping-pong approach	Escamilla-Alvarado et al. (2017) Wantz et al. (2023)
H/ Biogas hydrogen purification Heat load. Cooling of compressed biogas H. Negligible Output	H2 mass flowrate estimated from our experimental data of biological hydrogen production, after purification (Escamilla-Alvarado et al., 2012; Escamilla-Alvarado et al., 2013b; Valdez-Vazquez and Poggi-Varaldo, 2009) . Heat transfer for Isothermic operation of compressors from literature	----------
H/ Energy production by Hydrogen fuel cell /Electricity (power) Production of electricity by H2 fuel cell Output	Eqs. S12.30A and S12.30B H2 mass flowrate estimated from our experimental data of biological hydrogen production, after purification. Electricity production of H2 fuel cells indicators form literature. Electrical effiencies of fuel cell f9rom the literature (Tsakiris, 2019; US-DOE, 2016)	Escamilla-Alvarado et al. (2012) Escamilla-Alvarado et al. (2013b) Valdez-Vazquez and Poggi-Varaldo (2009) Tsakiris (2019) US-DOE (2016).
M/Biological methane production Heat transfer/Heating Pre-cooling feed to the methanogenic bioreactor, Output This is the opposite of the pre-heating of feedstock in the H stage in the heat exchanger 1 slurry-slurry	It is not considered because it would represent double accontability. The heat was recovered from the stream of hot fermented solids, as described above	----------
M/Biological methane production Electricity (power) Pumping fermented solids to bioreactor Input	Eqs. S12.11 and S12.13 Ping-pong strategy used. A factor 0.3 of the sum of previous heat loss load of the bioreactor (30%); it was incorporated to the equation as 1.3 for estimating heat losses of appurtenances, see below.. Since the detailed piping, fittings, etc., are not defined yet, we chose to estimate this heat load as a fraction of the heat loss of the bioreactor. All heated equipment has adequate thermal insulation.U*A*delta T, overall U from literature data .Mass retention time and operation temperature of bioreactor for sizing were taken from own experimental work U coefficients were selected from literature. All heated equipment has adequate thermal insulation.	Aerstin and Street (1978); Cengel (2002) Escamilla-Alvarado et al. (2017) Green and Perry (2008) Kern et al. (2019) Kumana and Kothari (1989);
M/Biological methane production Electricity (power) Pumping fermented solids to bioreactor Input	Eq. S12. 24, S12. 25 Ping-pong strategy used. Pump sizing. Density from own experimental data. Feedstock flowrate estimated by our previous mass balance. Total head of the pump constituted by Height head equal the height of the bioreactor, kinetic head neglected, friction head estimated as the sum of pipe friction head loss,plus and typical heat exchanger headloss, and difrernetial static pressure head (Karassik, 1986). Concrete pump type selected. Conservatively low pump and motor efficienies selected. Unit operations/Fluid mechanics internal flows. Information from pumping high solids suspensons (thickened sludges, Blodgett, 2015 and Tchobanoglous et al., 2014, paper stocks, Karassik, 1986, thick mycelia broths, Clark and Blanch, 1997) pastes in Food Technology and thickened sludges from Sludge treatment and conditioning	Blodgett (2015) Clark and Blanch (1997) DeBaere (2001) Escamilla-Alvarado et al. (2017) Karassik et al. (1986) Levenspiel (1972) OWS Private communication, Dranco process Tchobanoglous et al. (2014)
Biological methane production Electricity (power) Mixing bioreactor content by recirculation (pumping) Input	Eq. S12.18 to S12.23 Ping-pong strategy applied. Density from own experimental data. Sludge recirculation flowrate estimated as 150% or higher thant that of the feedstock flowrate. Total head of the pump constituted by Height head equal the height of the bioreactor, kinetic head neglected, friction head estimated as the sum of recirculation pipe friction head loss, and static differential pressure head. Concrete pump type selected. Conservatively low pump and motor efficiencies selected. Unit operations/Fluid mechanics internal flows. Information from pumping paper stocks (Karassik et al., 1986), thickened sludges from Sludge treatment and conditioning (Tchobanoglous et al., 2014;	Blodgett (2015) Clark and Blanch (1997) DeBaere (2001) Escamilla-Alvarado et al. (2017) Karassik et al. (1986) Levenspiel (1972) OWS Private communication, Dranco process Tchobanoglous et al. (2014)

	Blodgett, 2015), and thick mycelial broths (Clark and Blanch, 1997)	
M/Biological methane production Heat generation in the bioreactor Heat of exothermic reaction Output	The enthalpy of reaction in anaerobic processes (fermentation and methanization) is low (Doran, 2012; van't Riet and Tramper, 1991). This heat output was neglected. From the engineering point of view, this decision is on the safe side because will increase the amount of heat input actually required.	Doran (2012) van't Riet and Tramper (1991)
M/Biogas methane purification Electricity spent in the purification process of biogas H Input	The electricity flow was calculated using the specific indicator method applied to the production of m3 CH4 per FU (experimental, we have the mass of CH4 per FU, this mass was converted to standard m3 using ideal gas law) Wantz et al. (2023) gave an overall indicator of 0.3 kWh/m3 biogas using a water high pressure scrubber with water recovery along with the mass or cubic meter of biogas H generated per FU which is an experimental result. . This method does not require the ping-pong approach	Wantz et al. (2023)
M/ Biogas methane purification Heat load. Cooling of compressed biogas M. Negligible Output	Methane mass flowrate estimated from our experimental data of methanization of fermented solids, after purification. Heat transfer for Isothermic operation of compressors from literature (McCabe et al., 2005).	Escamilla-Alvarado et al. (2012) Escamilla-Alvarado et al. (2014)
M/ Energy production Electricity (power) Production of electricity by co-generation Output	Eq S12.32 For this output, the methane mass flowrate was estimated from our experimental data of methanization of 40% of the fermented solids exiting the H bioreactor, after purification.	Boyce (2010) Boyen (1980) Proxi Ecoinvent modified from "Electricity, high voltage CCCPP {RoW}|Heat and Power Co-generation, natural gas, combined cycle power plant, 400 MW electrical | cut-off, U" Escamilla-Alvarado et al (2017)
M/Energy production Heat load Production of heat by co-generation Output	Eq.S12.31 For this output, the methane mass flowrate was estimated from our experimental data of methanization of 40% of the fermented solids exiting the H bioreactor, after purification.	Boyce (2010) Boyen (1980) Proxi Ecoinvent modified from "Electricity, high voltage CCCPP {RoW}|Heat and Power Co-generation, natural gas, combined cycle power plant, 400 MW electrical | cut-off, U" Escamilla-Alvarado et al (2017)
M/Methanogenic solids (digestates) dewatering in thickeners Electricity (power), pumping Input	It was not considered because the proxy "_M-bioreactor" file already includes the proxy "Anaerobic digestion plant, for biowaste {RoW}|construction| Cut-off, U" contains composting of solids and accounts for energy flows.	Guinée (2002)
M/Centrifugation of methanogenic dewatered solid Electricity (power), centrifugation Input	It was not considered because the proxy "_M-bioreactor" file already includes the proxy "Anaerobic digestion plant, for biowaste {RoW}|construction| Cut-off, U" contains composting of solids	Guinée (2002)
E/Extraction of organic acids and low molecular weight solvents/ Electricity (power), mixing and pumping/ Input	Eqs S12.24 b, S12.28, S12.29 No heating was required in this process Flowrate of fermented solids and the yield of volatile organic acids and low molecular weight solvents from own experimental work (Valdez-Vazquez et al., 2009; Escamilla-Alvarado et al.,2012. 2013b). Equipment sized according to the corresponding volume and solids contents of the actual flow rate of fermented solids (ping-pong strategy). Retention time in mixers in the order of 2 to 5 min .and hydraulic loading ($V'/A_{horizontal}$) of 2gpm/ft^2 = 1.354E-3 m3/(m2*s)) (911the metallurgist, 2017). The first indicator allowed for sizing the volume of the mixer, while the second indicator is the basis for estimating the area of the settler. A high mixing intensity given by β (Benítez, 2022; Brown, 1951) was used to finish the power calculation per mixer. The second parameter helped calculating the area of the settlers. Two stage coutercurrent mixer-settler system assumed. Pumping electricity was calculated as a factor of the electricity flow for	Valdez-Vazquez et al. (2009) Escamilla-Alvarado et al. (2012, 2013b) Benitez (2022) Brown (1951) 911the metallurgist (2017) Rashid et al. (2013).

	mixing (50%) because of the absence of piping layout. Alternatively, a rapid sizing based on a secific power consumption of 1.8 kWh/m³ of treated feed (range 0.5 to 2 kWh/m³ (Rashid et al., 2013) can be used along with Eq S12.24 b and Eq S12.28 and 20 to determine the electricity flow due to agitation in the mixers.	
E/Solvent separation/ Heat load for distillation/ Electricity (power), pumping/ Inputs	"The pentanone flow rate was estimated from the ratio of solvent-to-fermented solids from literature and the flow rate of fermented solids according to our experimental work. The heat required for solvent separation is estimated from the standard enthalpies of evaporation and flowrates of pentanone and the components of the mixture of organic acids and solvents of low molecular weight present in the fermented solids. The yields of the organic acids and solvents in the mixtures are known from our experimental work. No heat recovery was considered in the distillation process as a safety net. Pumping electricity equal to the pumping electricity of the previous process. The heat of distillation was calculated using the yields of each low molecular weight (LMW) acids and solvents, Y_j in kg of organic acid or solvent j/FU (from experiments), as follows: $q_{FUdistillation} = [\Sigma Yj*\Delta H^o_{evap,j}$ + ratio solvent-to-compounds*$\Sigma Yj*\Delta H^o_{evap,solvent}]*f_{SF}$, in J/FU where $\Delta H^o_{evap,j}$ is the enthalpy of evaporation of the acid or solvent j to be extracted, in J/kg $\Delta H^o_{evap,solvent}$ is the enthalpy of evaporation of the solvent Y_j is the yield of each LMW organic acid and solvent j, kg/FU ratiosolvent-to-compounds is the ratio of extraction solvent mass to the $_{extracts}$, from literature (Green and Perry, 2008; Benítez, 2022), f_{SF} is a safety factor to account for heat losses to the ambient of the equipment and appurtenances, and sensible heats of the feed to the distillation sector of the E stage	911the metallurgist (2017) Benitez (2022) Brown (1951) Escamilla-Alvarado et al. (2012, 2013b) Green and Perry (2008) Rashid et al. (2013) Valdez-Vazquez et al. (2009)
Z/Feed conditioning and sterilization/ Heat load for sterilization/ Input	Ping-pong strategy applied, batch variation. The mass of fermented-extracted solids determined from mass balances using our experimental data. Water addition is needed to lower the fermented-extracted solid concentration in the broth down to 2% TS, according to experiments. Addition of P and N nutrients. Heating loads for sterilization of the broth according to procedure by Lee (1999); heat loadings of the bioreactor during the sterilizaton estimated with Eqns. modified for batch operation (sensible heat for increasing the temperature form ambient to 93oC and heat losses to ambient in transient state based on Kern et al. (2019)	Escamilla-Alvarado et al. (2013 a) Escamilla-Alvarado et al. (2017) Lee (1999) Kern et al. (2019)
Z/Enzyme production/Electricity flow/ Input	0.2 kWh per kg of concentrated enzymes, indicators from Escamilla-Alvarado et al. (2017). The enzyme yield was 0.342 kg enzyme concentrate/FU, after ultrafiltration, from our experiments. Heating just from 25 to 30 ^oC since the stream of fermented-extracted solids came out at 37^oC from the M bioreactor and as a safety factor it was assumed that there was some cooling during the extraction stage.	Escamilla-Alvarado et al. (2013 a) Escamilla-Alvarado et al. (2017)
Z/ Enzyme production/ heat load for the bioreactor/ (heat losses to the ambient)/Heat load/ Input	0.2183 MJ per kg of concentrated enzymes, indicators from Escamilla-Alvarado et al. (2017). The enzyme yield was 0.342 kg enzyme concentrate/FU, after ultrafiltration, from our experiments. Heating just from 25 to 30 ^oC since the stream of fermented-extracted solids came out at 37oC from the M bioreactor and as a safety factor it was assumed that there was some cooling during the extraction stage."	Escamilla-Alvarado et al. (2013 a) Escamilla-Alvarado et al. (2017)

S15.2 Energy calculations for the incineration plant

Energy flows for IER were estimated following the typical composition of organic waste in Mexico. The calculations were performed according to Buekens, 2013; Tchobanoglous & Kreith, 2002; Niessen, 2002) and can be reviewed in Annex S3 in this same document. Below the steps for the calculation of energy flows performed according to the references mentioned above are described:

(i) The elementary composition of our OFMSW was determined by a weighted combination of the elementary composition of feed waste and paper and cardboard waste (Tchobanouglous and Kreith, 2002)
(ii)The heat of combustion was calculated following Dulong´s equation $\Delta H_{combustion}$ dry OFMSW according to Eq S12.33 (Tchobanouglous and Kreith, 2002)

$$\Delta H_{combustion\ OFMSW} = 327.81\ (C) + 1504.1(H-O/8) + 92.59(S) + $$

$$+49.690(O) + 24.36(N)\ kJ/kg \qquad (S15.33)$$

where (C), (H). etc., are the percentages of each element (decimal numbers) in the dry OFMSW
(iii) The total available heat was calculated by subtracting the value of the latent heat contained in the combustion gases from the total heat of combustion.
(iv) Heat losses within the combustion chamber were estimated at 5% (heat loss in piping fittings, cracked insulation, steam leaks, heating makeup water, etc.)
(v) Net available heat was determined by subtracting heat losses and latent heat from the gross available heat.
(vi) An overall 20% electrical efficiency was assumed, based on open literature reports and given the 35% humidity content of the whole OFMSW. A significant part of the combustion heat is spent in drying and evaporating the humidity of the OFMSW.
More detailed information and calculations can be found in Annex 3 of the Supplementary Materials document.

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Annex S16. Sensitivity of weighting approaches and error analysis of indicators

Nomenclature

a	the number of impacts in subset B, see Lemma S16.1
b	the number of impacts in subset A, see Lemma S16.1
A	subset of the remaining impacts, see Lemma S16.1. A is also used to represent the sum of NPEIs in subset A, baseline case.
AE	academic editor
B	subset of NPEIs whose importance and effect on the value of the indicator wants to be examined, see Lemma S16.1. B is also used to represent the sum of the NPEIs in B, baseline case.
BRF	biorefinery
CI	confidence interval for α and α_w
CVar	coefficient of variation, typically in decimals
ES	environmental sustainability
EW	equal weighting
FU	functional unit
GW	global warming
IER	incineration with energy recovery
LL	lower limit of the confidence interval
M	the ratio of the baseline sums of impacts A/B = m
NPEI	normalized potential environmental impacts, mid-point values from ReCiPe methodology
SD	standard deviation, used to represent the absolute error of a magnitude, either for NPEIj or indicators α and α_w
$S_{\alpha,wk}$	local, absolute sensitivity of α or α_w with respect to w_k
$S_{\alpha,NPEIh}$	local, absolute sensitivity of α or α_w with respect to $NPEI_h$
UL	upper limit of the confidence interval
w	weight,
WC	water consumption
w_p	high value weight used in the weighting procedure
w_r	low value weight used in the weighting procedure

Greek characters

α	indicator based on the sum of the eighteen NPEIs of a given process, technology, or product
α_w	indicator based on the sum of the weighted eighteen NPEIs of a given process, technology, or product
σ	GBAER indicator based on the α of two processes or technologies that which one is more environmentally sustainable
τ	GBAER indicator that determines whether one technology is more environmentally sustainable than the other, with ***dominance*** or ***restrictions***.

S16.1. General considerations

This section deals with the sensitivity analysis using different weighting profiles and an error analysis of the indicator proposed and used in our work.

There are several methods for performing weighting in sustainability assessments, such as (it is not an exhaustive list) (Luan et al., 2017; Gan et al., 2017; Mikulić et al., 2015; Nardo et al., 2005; OECD, 2008):

- Equal Weighting: Assigning equal importance to all impact categories.
- Expert Judgment**:** Consulting experts to assign weights based on their knowledge and experience.
- Stakeholder Preferences: Gathering input from stakeholders to determine the relative importance of different impact categories.
- Analytic Hierarchy Process (AHP): A structured technique that uses pairwise comparisons to derive weights.
- Economic Valuation: Assigning weights based on the economic value of the impacts.
- Entropy Method: Weights are determined based on the amount of information each indicator provides, with less informative indicators receiving lower weights.
- Global Sensitivity Analysis: Methods like the Extended Fourier Amplitude Sensitivity Test (EFAST) quantify the sensitivity of indicators to the overall sustainability assessment

Equal weighting (EW), and weighting by Expert Judgment (panels) or Public opinion (polls) are among the most recommended by some specialists (Gan et al., 2017). The two last methods are recommended for application to strong sustainability scenarios. Also, there is active research looking for weighting methods that determine the weight values without the *ad hoc* intervention of experts or people (Luan et al., 2017; Gan et al., 2017).

Usually, the sum of weights is typically 1 (or 100%) to ensure that the total importance is distributed among the impact categories, which represents a constraint. In our case, the 100% is represented for the eighteen NPEIs. So, in general,

$$\Sigma\, w_j = 1,\ j= 1, 2, \ldots,, N \qquad \text{(S16.1)}$$

In our case

$$\Sigma\, w_j = 18,\ \ j= 1, 2, \ldots,,18 \qquad \text{(S16.2)}$$

which is equivalent to Eq S16.1. by a factor of 18.

However, there is also the possibility of "free" weighting, where the weights do not necessarily sum to 1 or N, but this approach is less common and the interpretation of results could be more difficult to perform.

The sensitivity of the indicator α to weighting was examined for a variety of scenarios. First, high weights coefficients were chosen for global warming and water consumption NPEIs, since these impacts are of concern to professionals, experts, communities and plain citizens in Mexico. In a second test, the influence of high weights assigned to a subset of NPEIs associated to ecosystem toxicity and damage was determined. The third scenario determined the influence of assigning high weights to a subset of NPEIs associated to human health effects. Each scenario, in turn, included two sub-scenarios at two levels of high weights. We also determined the local sensitivities of the indicators with respect to the weight coefficients, both the absolute and relative sensitivities.

According to Saltelli et al. (2007, 2000) the so-called local sensitivity of a response variable (usually a real dependent variable which is a function of several real variables) with respect to an independent variable of interest is defined by the partial derivative of the first with respect to the second. Adapting this definition to our case, we have the

-the absolute sensitivity S_k of a response function F (any alpha index, for instance) with respect to the weighting factor w_k

$S_{F,wk} = \partial F/\partial w_k$ (S16.3)

-the relative sensitivity s_k of a response function F (F can be any alpha index, for instance) with respect to the weighting factor w_k is

$s_{F,wk} = (1/F)*\partial F/\partial w_k$ (S16.4)

and
-the normalized sensitivity is

$S_{n,F,wk} = (w_k/F)*\partial F/\partial w_k$ (S16.5)

The first two magnitudes have units, the third one is dimensionless.

Similarly, the sensitivities of the response function F with respect to a $NPEI_h$ of interest, $S_{F,NPEIh}$, can be defined (absolute, relative, and normalized, Eq. S16.6 to S16.8 below):

$S_{F,NPEIh} = \partial F/\partial NPEI_h$ (S16.6)

$s_{F,NPEIh} = (1/F)*\partial F/\partial NPEI_h$ (S16.7)

$s_{n,F,,NPEIh} = (1/F)*\partial F/\partial NPEI_h$ (S16.8)

They are easy to define and determine, especially for indicators that are linear combinations of NPEIs. The method is immediate and transparent. Local sensitivities helped the discussion on indicators' trends in weighting scenarios. Yet, the partial derivative involved in the definition equation of sensitivity provides only a punctual sensitivity measure. It may not capture nonlinear or global behavior. Sensitivity can vary depending on the values of other variables, especially in systems with interactions or dependencies between variables. This is in part our case; when one w_j or more weight coefficients are increased, another or other w_k ($j \neq k$) should decrease because of the constraint $\Sigma w_j = 18$ mentioned above. It is like a seesaw effect. In our discussion the absolute sensitivity
$S_{F,wk} = \partial F/\partial w_k$ Eq (S16.3) or the adapted version Eq (S16.11) will be used, as well as results of Lemma S16.1 downstream.

it can be demonstrated that the punctual or local $S_{\alpha,wk}$ of α with respect to a weight of interest w_k is the corresponding $NPEI_k$ because of the aggregation form of the indicator (Eq. S16.11 below). Therefore, the α_w is doomed to be more sensitive to the large-value impacts (either for increase or decrease of α_w) than the low-value impacts such as GW and WC. On the other hand, it can be shown that the local punctual sensitivity of α_w with respect to a $NPEI_h$ ($S_{\alpha,NPEIh}$) is the weight w_h. This type of sensitivity is not used in our discussion.

We recall that the indicators α and α_w (the first is the simple or equal-weight EW version, the second stands for the weighted indicator) are defined by the equations below:

$\alpha = \Sigma NPEI_j \quad j=1, 2, 3,\ldots,18$ (S16.9)

$\alpha_w = \Sigma w_j*NPEI_j \quad j=1, 2, 3,\ldots,18$ (S16.10)

Applying the definition of absolute sensitivity with respect to w_k (Eq. S16.3) the result is immediate:

$$S_{\alpha w,wk} = \partial\alpha_w/\partial w_k = NPEI_k \quad \text{(S16.11)}$$

because the derivatives of all the terms w_j*$NPEI_j$, $j \neq k$, vanish (they are constants with respect to w_k). The only term whose derivative should be considered is w_k*$NPEI_k$, whose derivaties with respect to w_k is just $NPEI_k$.
The relative and normalized sensitivities can be written by replacing F by α_w in Eqs S16.4 and S16.5.
It is interesting to highlight that
-the highest the $NPEI_k$, the highest sensitivity of α_w with respect to w_k,
-the sensitivity does not depend on the value of the weight or other weights,
-thus, these absolute sensitivities are constant for all the weighting scenarios (Table S16.2)

In contrast, the absolute sensitivity with respect to $NPEI_h$ is the weight w_h. These sensitivities will be different with each weighting scenario (Table S16.2). Weighting results for several scenarios are compiled in Table S16.1. Local sensitivities of indicators with respect to weight factors are displayed in Table S16.2.

The sensitivity of the indicator α to weighting was examined for a variety of scenarios. First, high weights coefficients were chosen for global warming and water consumption NPEIs, since these impacts are of concern to professionals, experts, communities and plain citizens in Mexico. In a second test, the influence of high weights assigned to a subset of NPEIs associated to ecosystem toxicity and damage was determined. The third scenario determined the influence of assigning high weights to a subset of NPEIs associated to human health effects. Each scenario, in turn, included two sub-scenarios at two levels of high weights. We also determined the local sensitivities of the indicators with respect to the weight coefficients, both the absolute and relative sensitivities.Weighting results for several scenarios are compiled in Table E.8.1. Local sensitivities of indicators to weight factors are displayed in Table E.8.2.

S16.2. Trends of the weighting sensitivity tests.

S16.2.1. Weighting and global warming and water consumption

S16.2.1.1. First weighting

The first weighting attempted to examine the influence of water consumption and global warming impacts on the value of the indicator α (α_w), since they are issues of wide concern of Mexican and international experts as well as the public opinion of Mexico City. Weighting factors of $w_p = 4$ for GW and WC, and $w_r = 0.625$ for the other sixteen impacts, were chosen (Table S16.1.)

The selection of the above-mentioned impacts was based on actual and rising concerns of academicians, expert professionals of the Environment sector, and public opinion in Mexico. Water consumption was considered a significant potential environmental impact for Mexico City conditions, where a considerable part of the inhabitants (nearly 600 neighborhoods or “colonias” are subjected to water rationing. Up to 70% of the City's water

Table S16.1. Tests of weighting sensitivity in the determination of α_w and influence of the errors of the NPEIs on the overall error of α and α_w

		Equal weighting indicator, baseline case				Global warming and water consumption emphasis				Ecotoxicity emphasis				Human health emphasis			
		NPEI[a]		w[b]		w		w		w		w		w		w	
No.	Category	IER[c]	BRF[d]	IER	BRF	IER	BRF	IER	BRF	IER	BRF	IER	BRF	IER	BRF	IER	BRF
1	Global warming	0,021	0,118	1	1	4,000	4,000	6,000	6,000	0,36354	0,36354	0,04545	0,04545	0,5	0,5	0,25	0,25
2	Stratospheric O_3 de pletion	0,089	0,039	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	2	2	2,5	2,5
3	Ionizing radiation	0,003	0,043	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	2	2	2,5	2,5
4	O_3 formation, human health	0,092	0,133	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	2	2	2,5	2,5
5	Fine particulate matter formation	0,012	0,13	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	2	2	2,5	2,5
6	O_3 formation, terrestrial ecosystems	0,107	0,196	1	1	0,625	0,625	0,375	0,375	2	2	2,5	2,5	0,5	0,5	0,25	0,25
7	Terrestrial acidification	0,020	0,465	1	1	0,625	0,625	0,375	0,375	2	2	2,5	2,5	0,5	0,5	0,25	0,25
8	Fresh water eutrophication	0,432	0,422	1	1	0,625	0,625	0,375	0,375	2	2	2,5	2,5	0,5	0,5	0,25	0,25
9	Marine eutrophication	0,023	0,015	1	1	0,625	0,625	0,375	0,375	2	2	2,5	2,5	0,5	0,5	0,25	0,25
10	Terrestrial ecotoxicity	0,238	0,803	1	1	0,625	0,625	0,375	0,375	2	2	2,5	2,5	0,5	0,5	0,25	0,25
11	Fresh water ecotoxicity	58,601	8,756	1	1	0,625	0,625	0,375	0,375	2	2	2,5	2,5	0,5	0,5	0,25	0,25
12	Marine ecotoxicity	93,557	13,604	1	1	0,625	0,625	0,375	0,375	2	2	2,5	2,5	0,5	0,5	0,25	0,25
13	Human CT[e]	13,777	13,933	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	2	2	2,5	2,5
14	Human NCT[f]	12,139	1,819	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	2	2	2,5	2,5
15	Land use	2,02E-05	0,007	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	0,5	0,5	0,25	0,25

16	Mineral resource scarcity	3,82E-07	1,49E-05	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	0,5	0,5	0,25	0,25
17	Fossil resource scarcity	0,006	0,207	1	1	0,625	0,625	0,375	0,375	0,36354	0,36354	0,04545	0,04545	0,5	0,5	0,25	0,25
18	Water consumption	0,001	0,034	1	1	4,000	4,000	6,000	6,000	0,36354	0,36354	0,04545	0,04545	0,5	0,5	0,25	0,25
α^g or $\alpha_w{}^h$		179,12	40,724			112,02	25,966	67,293	16,127	315,459	54,507	383,633	61,401	128,73	44,508	103,53	46,399
$\alpha_{IER}/\alpha_{BRF}{}^i$		4,398				4,314		4,173		5,787		6,248		2,892		2,231	
σ		0,6433				0,6349		0,6204		0,7625		0,7957		0,4612		0,3486	
$w_p/w_r{}^j$		1	1			6,40	6,40	16,00	16,00	5,50	5,50	55,01	55,01	4,00	4,00	10,00	10,00
Absolute error of α or α_w (person*yr/FU)																	
	Cvar ^{k} 0.05	5,596	1,073			3,497	0,671	--	--	11,045	1,641	--	--	3,315	1,463	--	--
	Cvar 0.10	11,191	2,146			6,995	1,342	--	--	22,089	3,282	--	--	6,630	2,925	--	--
	Cvar 0.15	16,787	3,218			10,492	2,013	--	--	33,134	4,923	--	--	9,945	4,388	--	--
Relative error of α or α_w, in decimals																	
	Cvar 0.05	0,0312	0,0263			0,0312	0,0258	--	--	0,0350	0,0301	--	--	0,0258	0,0329	--	--
	Cvar 0.10	0,0625	0,0527			0,0624	0,0517	--	--	0,0700	0,0602	--	--	0,0515	0,0657	--	--
	Cvar 0.15	0,0937	0,0790			0,0937	0,0775	--	--	0,1050	0,0903	--	--	0,0773	0,0986	--	--

[a] normalized potential environmental impact
[b] weight
[c] incineration with energy recovery
[d] biorefinery
[e] human carcinogenic toxicity
[f] human non-carcinogenic toxicity
[g] indicator α, calculated as the sum of the eighteen NPEIs
[h] indicator α_w, calculated as the sum of the eighteen weighted NPEIs.

[l] ratio of the indicator α or α_w of the IER to the corresponding indicator of the BR
[j] ratio of the highest weight w_p and lowest weight w_r in a given combination of eighteen weights used for estimating a_w
[k] coefficient of variation of the normalized potential environmental impacts

Table S16.2. Sensitivities of α_w to the weight w_k, $S_{\alpha,wk}$, and to the $NPEI_h$, $S_{\alpha,NPEIh}$, for the scenario 2.1.1. Similar tables can be built for other scenarios with only changes in the subsection **$S_{\alpha,NPEIh}$ Sensitivities of α_w with respect to a $NPEI_h$**; these sensitivities are equal to the corresponding weight factors of the particular scenario.

Cate-gory [a]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
$S_{\alpha,wk}$ Sensitivities of α_w to the weight w_k																		
IER [b]	0,021	0,089	0,003	0,092	0,012	0,107	0,020	0,432	0,023	0,238	58,601	93,557	13,777	12,139	2,02 E-05	3,82 E-07	0,006	0,001
BRF[c]	0,118	0,039	0,043	0,133	0,13	0,196	0,465	0,422	0,015	0,803	8,756	13,604	13,933	1,819	0,007	1,49 E-05	0,207	0,034
$S_{\alpha,NPEIh}$ Sensitivities of α_w with respect to a $NPEI_h$																		
IER	4	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	4
BRF	4	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	4

[a] Please refer to Table S16.1, columns 1 and 2, for the NPEI related to each number in the category row of this table
[b] incineration with energy recovery
[c] biorefinery

supply comes from an overexploited aquifer beneath the city; this aquifer is deficiently recharged. As a consequence, there is a pronounced subsidence of up to 30 cm/yr that has caused infrastructure damage in some subregions of the city (López-Quiroz et al., 2017; Cabral Cano et al. 2008; Osmanoglu et al., 2011.) A 18% of the water supply comes from treated water of the Cutzamala system, at 200 km average far from the City. Drinking water should rise approximately 2200 m average to reach its destination, and also overcome the friction in the pipes and fittings. This, in turn, translates into a huge electricity consumption of 2280 million of kWh per year (Shortell, 2024; Tortajada, 2006; Semarnat, 2021.) Global warming effects in Mexico City and the country are also of concern to wide sectors of professionals and public opinion (Climate Reality Project, 2024; MIT Climate Portal, 2024; Shortell, 2024; Wikipedia Climate Change in Mexico, 2024). Mexico City has experienced rising temperatures since the 1960s due to global warming. Climate change has exacerbated water scarcity in Mexico City. Rising temperatures and altered weather patterns have also contributed to increased air pollution in Mexico City (Climate Reality, 2018; Grillo, 2015). Climate change has led to more intense and frequent rainfall events, as well as alteration of the rain season patterns, increasing the risk of flooding and landslides in the city. Negative consequences are traffic disruption, damage to infrastructure, and risks to human health and safety. Climate change has affected agriculture in several rur-urban subregions of Mexico City, particularly for smallholder; altered precipitation patterns and warming temperatures have led to economic insecurity for these farmers.

The results of the weighting were “counter-intuitive” (Table 16.1), since an increase of weights on the GW and WC NPEIs by 300% led to a decrease of the indicator α_w from 179.12 to 112.02 person*yr/FU(37.46%) and 40.724 to 24.966 person*yr/FU (36.24%) for IER and BRF, respectively. Interestingly, the percentage decrease was very close for both technologies. Thus, the ratios $\alpha_{IER}/\alpha_{BRF}$ for equal weighting and the weighted indicators was very similar, 4.398 and 4.314, respectively. Therefore, the pattern of the ES for both technologies based on those ratios suggests that the BRF is nearly 4 times more environmentally sustainable than IER, irrespective of the weighting or not.

To some extent, the decrease of indicator α_w with increases in weights of GW and WC NPEIs could occur because the increase of their weights up to 4 would not achieve a noticeable net increase of the indicator because the corresponding NPEIs are very low, < or << 1 (0.021 and 0.118 GW for IER and BRF, respectively; 0.001 and 0.034 WC for IER and BRF, respectively.) On the other hand, given the restriction $\Sigma w_j = 18$, the w_j of the remaining sixteen impacts have decreased by 47.5% ($w_r = 0.625$) reflecting the seesaw effect on the weight factors. These lower w_rs significantly decreased the contributions of the high valued NPEIs such as those of ecotoxicity and human health to α_w, when compared to $w_j = 1$ in the equal-weighting α (for instance, marine ecotoxicity NPEI of 93.557 and 13.604 for IER and BRF, respectively.) These decrements were much larger than the very poor increases due to weighted GW and WC impacts. Thus, this feature could

explain the lack of direct influence of using high w_j for GW and WC on the estimation of α_w.

We have estimated the local sensitivity of the indicator with respect to the weight factors (Saltelli et al., 2007) Using values of absolute sensitivity of the α with respect to a w_k it can be demonstrated that the punctual or local $S_{\alpha,wk}$ is the corresponding $NPEI_k$ because of the aggregation form of the indicator. Therefore, the α_w is doomed to be more sensitive to the large-value impacts (for decrease of α_w) than the increases reached with high values w applied to the low-value impacts such as GW and WC.

S16.2.1.2. Second weighting

A second set of weights that emphasized the participation of GW and WC NPEIs was chosen. Their weights were 6 (500% higher than the baseline case EW indicator) whereas the sixteen impacts were multiplied by the weight 0.375. The result was a decrease of the indicator α_w, from 179.12 to 67.893 (-62.43%) and 40.724 to 16.127 (-60.40%) for IER and BRF, respectively. Again, the percentage decrease was very close for both technologies. Thus, the ratio $\alpha_{IER}/\alpha_{BRF}$ for equal weighting and the weighted indicators was very similar, 4.398 and 4.173, respectively. Therefore, the pattern of the ES for both technologies based on those ratios suggests that the BRF continues to be 4 times more environmentally sustainable than IER, irrespective of the current weighting. The explanation and discussion of this behavior of the α_w follow the lines of thought already mentioned in section S2.1.1.

It can be concluded that GW and WC do not contribute to the indicator, even for the reasonable highest weight factors. The influence of the latter is not enough to determine an increase of α_w, even if they are multiplied by high value w_p.

S16.2.2. Weighting impacts related to the ecosystem

S16.2.2.1. First weighting

A subset of seven NPEIs related to the ecosystem were chosen and assigned a weight of 2 (Table S16.1), while the other 11 NPEIs received a weight of 0.36354. For example, such a scenario could be recommended by a panel of experts that support the strong sustainability cultural approach. We refer to the Egalitarian stand of ReCiPe method. This perspective adopts a long-term view and is rooted in the precautionary principle. It assumes that environmental risks should be minimized as much as possible, even if the likelihood of certain impacts is uncertain. It reflects a more cautious and risk-averse stance.

The w_p/w_r was 5.5. The α_w of both technologies increased, a 76.12% for IER and 33.84% for BRF. As a result, the ratio $\alpha_{w,IER}/\alpha_{w,BRF}$ was 5.787, nearly 31.52% higher than the baseline ratio of 4.39 (EW baseline) (Table S16.1). In this regard, the new ratio suggests that the BRF is nearly six times more environmentally sustainable than the IER. The increases in α_w were commanded by the combined effects of the high w_p that multiplied the high values of key NPEIs related to ecotoxicity, such as Freshwater ecotoxicity and marine ecotoxicity, as well as

moderate values of Terrestrial ecotoxicity, Fresh water ecotoxicity, and Terrestrial acidification (Table S16.1). On the other hand, the other eleven impacts, most very low-to-moderate magnitudes, were multiplied by w_r = 0.36354, which is 63% lower than the baseline w = 1. As a consequence, their contribution to the α_w was almost eclipsed.

Similarly to what was discussed above in relation to Sensitivity $S_{\alpha w,wk}$, the highest sensitivities (Table S16.2) in this scenario correspond to the largest impacts, two of which are Fresh water ecotoxicity and Marine ecotoxicity, and in second place contributed by the four moderate impacts mentioned above. Therefore, the increases of $\alpha_{w,IER}$ and $\alpha_{w,BRF}$ are consistent with the $S_{\alpha,wk}$ exhibited in Table S16.2.

S16.2.2.2. Second weighting

The subset of seven NPEIs related to the ecosystem were assigned a weight of 2.5, while the other 11 NPEIs received a weight of 0.04545. The w_p/w_r was 55; it is near the limit case that would be w_p = 2.5714 and w_r = 0.00 (Table S16.1). The α_w values of IER and BRF increased by 114.18 and 50.77%, respectively. As a result, the ratio $\alpha_{w,IER}/\alpha_{w,BRF}$ was 6,248, approximately 42 % higher than the baseline ratio of 4.39 (EW baseline). In this regard, the new ratio suggests again that the BRF is more environmentally sustainable than the IER. The explanation and discussion of these results are similar to the lines of thought mentioned above in subsection S2.2.1.

In summary, the seven NPEIs related to ecosystem toxicity and damage contribute decisively to the indicators α and α_w. The use of high weighting factors for these impacts increases the environmental sustainability gap between IER and BRF, favoring the ES of the BRF.

S16.2.3. Weighting and impacts related to human health issues

S16.2.3.1. First weighting

A subset of six NPEIs related to human health issues were selected (Table S16.1) and assigned a weight of 2 (it represented an increase of 100% over the baseline w = 1), while the other 12 NPEIs received a weight of 0.5 (it represented a -50% change compared to the baseline w =1.)

The w_p/w_r ratio was 4. The changes on α_w were different for each technology. The IER α_w decreased by -28.13% whereas the value of BRF slightly increased by 9.29%. As a result, the ratio $\alpha_{w,IER}/\alpha_{w,BRF}$ was 2.892, nearly 34.27% lower than the baseline ratio of 4.39 (EW baseline). It seems that there is a “convergence” trend between $\alpha_{w,IER}$ and $\alpha_{w,BRF}$; however, this convergence was not enough to reverse the superiority of BRF over IER on environmental sustainability. In this regard, the new ratio suggests that the BRF is nearly three times more environmentally sustainable than the IER.

The decrease in $\alpha_{w,IER}$ was determined by the decrease of of high value impacts of key NPEIs related to ecotoxicity contributions (as affected by w = 0.5 instead of 1) such as Freshwater ecotoxicity and marine ecotoxicity, as well as

moderate values of Terrestrial ecotoxicity, Fresh water ecotoxicity, and Terrestrial acidification (Table S16.1). This decrease overcame the moderate increase due to health-related impacts, of low-to-moderate magnitudes, even with the help of weight factors 2. Thus, the overall effect of this trends led to a lower $\alpha_{w,IER}$. On the other hand, values of ecotoxicity high NPEIs are of the same order than those of human health in BRF (for example, Marine ecotoxicity of 13.064 and Human carcinogenic toxicity of 13.933). In this scenario, the role of different weights (high w=2 in human health impacts, low w=0.5 in ecotoxicity impacts) was enough to combine in an overall trend of $\alpha_{w,BRF}$ increase (although slight).

Similarly to what was discussed above in relation to Sensitivity $S_{\alpha w,wk}$, the highest sensitivities of IER (Table S16.2) in this scenario correspond to the largest impacts, two of which are Fresh water ecotoxicity and Marine ecotoxicity, and in second place contributed by the four moderate impacts mentioned above. Sensitivites of α to human health-related impacts are considerably lower. Therefore, the decrease of $\alpha_{w,IER}$ effected by impacts with $w_r = 0.5$ is superior to the increase contributed by moderate sensitivity human-health impacts; overall, the $\alpha_{w,IER}$ is consistent with the $S_{\alpha,wk}$ exhibited in Table S16.2. In contrast, for the BRF, the sensitivities profile for the ecotoxicity impact subset is similar to that of the human health subset. So, the effect of doubling the contribution of the human-health impacts overcame the decrease effect of halving the contributions of the ecosystem and other impacts.

Lemma S16.1 below could help predicting and understanding this trade-off and the expected trends of α_w for weighing procedures where a subset of indicators B is assigned a high weight value w_p each while the remainder indicators (subset A) are assigned a low value weight w_r,(and complementary to w_p) subject to the constraint $\Sigma w_j = 18$, j = 1, 2, …., 18

Lemma S16.1

Hypothesis

There is a set of eighteen NPEIs according to the characteristics of mid-point ReCiPe methodology.

Let B be the subset of NPEIs whose importance and effect on the value of the indicator wants to be examined; let b the number of such impacts, and w_p the chosen weight (typically > 1.) B is also used to represent the sum of the NPEIs in B, baseline case.

Let A be the subset of the remaining impacts; let ‘a’ be the number of such impacts, and w_r their weight (typically < 1.) A is also used to represent the sum of NPEIs in subset A, baseline case.

Thesis

If the left member of unequality Eq S16.12 below < right member, then $\alpha < \alpha_w$, and the weighted indicator increases (trivial) with respect to the baseline indicator

If the left member of the inequality Eq S16.12 > right member, then $\alpha > \alpha_w$, and the weighted indicator decreases (trivial) with respect to the baseline indicator (what we have called “counter-intuitive” result when discussing caseS 16. 2.1.1.)

$(a -18)*m + a > < (a – 18*b*m)*w_p$ (S16.12)

Proof
First, by definition, we have

$a + b = 18$ (S16.13a) $a = 18 - b$ (S16.13b)

$w_r*a + w_p*b = 18$ (S16.14)

$w_r = (18 - w_p*b)/a$ (S16.15)

By definition,
$\alpha = A + B$ S16.16)

$\alpha_w = w_r*A + w_p*B$ (S16.17)

$A/B = m$ (S16.18)

Then (substituting Eqs S16. 15and S16.18 in Eqs S16.16 and S16.17), it is obtained

$\alpha = (m + 1)*B$ (S16.19)

$\alpha_w = [(18-bw_p)/a]*m*B+ w_p*B = [(18-bw_p)/a)*m + w_p]*B$ (S16.20)

Let us write the unequality
$\alpha >$ or $< \alpha_w$ (S16.21)

Now replace Eqs E.8.19 and E.8.20 in the unequality Eq S16.21, and cancel B in both sides (B is positive, then, the direction of the inequality does not change). This gives

$(m + 1) > < [(18-bw_p)/a]*m + w_p$ (S16.22)

Rearranging Eq S16.22 for isolating w_p terms on the RM leads to

$(a -18)*m + a > < (a – 18*b*m)*w_p$ (S16.12)

Since we have only summed and subtracted terms, avoiding the multiplying or division by negative factors any of the two members of the Inequality, then the direction of the Inequalities Eq. S16.21 and S16.12 is preserved. The latter has the

same direction given by the inequality S16.21, that is (splitting Eq. 16.12 in two inequalities)

$(a -18)*m + a > (a – 18*b*m)*w_p$ is equivalent to $\alpha > \alpha_w$ (S16.23)

and

$(a -18)*m + a < (a – 18*b*m)*w_p$ is equivalent to $\alpha < \alpha_w$ (S16.24)

End of the proof

Remarks:
(i) the criterion for the trend of α_w in the Lemma is somewhat elegant and terse, because no complete calculations with NPEIs and their multiplication by w_j are involved. Only quantities such as the highest weight factor, the ratio m, and numbers a and b of NPEI in the two subsets are required.

(ii) the unequalities S16.23 and 24 can depict and explain the trade-off of interrelationships of the algebraic parameters of the linear, addition aggregation indicators α and α_w, as well as the seesaw or teeter-totter of the weighting factors (when w_p is increased, there is a mandatory and related decrease of w_r that could have contradicting effects, difficult to predict at first sight), (the play-ground device seesaw is also known as **tilting board** or **tilting plank**). The Lemma criterion can save long qualitative discussions when trying to explain “counter-intuitive” results.

(iii) Table S16.3 summarizes the results of applying Lemma 16.1 to the current case. Results of Lemma completely agreed with results obtained by independent calculations with the NPEIs and the full set of weighting factors, Table S16.1.

(iv) Lemma S16.1 can be applied to predict the trends of α and α_w in weigthing cases presented above in sections S2.1. and S2.2, as well as below in case S2.3.2. This task is left to the reader as an exercise.

Table S16.3. Summary of results from application of Lemma S16.1 to Case S2.3.1.

	IER[a]	**BRF**[b]
A[c]	153,006	24,627
B[d]	26,112	16,097
a[e]	12	12
b[f]	6	6
m[g]	5,8596	1,5299

w_p [h]	2	2	
w_r [i]	0,5	0,5	
LM [j]	-23,158	2,821	
factor in RM [k]	-23,158	2,821	
RM [l]	-46,315	5,641	
Comparison	***LM > RM***	***LM < RM***	
Predicted trend of α_w	decreases	increases	***Validated***
Actual trend α_w	decreases	increases	***Validated***

[a] incineration with energy recovery
[b] biorefinery
[c] sum of the remaining NPEIs, second subset, baseline case
[d] sum of the subset of NPEIs whose effect on the weighted indicator wants to be examined, baseline case
[e] number of NPEIs in the first subset
[f] number of NPEIs in the second subset, a + b = 18
[g] ratio (sum of the remaining NPEIs, second subset, baseline case)/(sum of the subset of NPEIs whose effect on the weighted indicator wants to be examined, baseline case)
[h] high weight factor
[i] low weight factor
[j] left member of the unequality (also known as left side)
[k] factor that multiplies the w_p in the RM of the unequality
[l] right member of the unequality (also known as left side)

S16.2.3.2. Second weighting

The same subset of six NPEIs related to human health issues were selected as in S16.2.3.1. section and assigned a weight of 2.5 (it represented an increase of 150% over the baseline w = 1), while the other 12 NPEIs received a weight of 0.25 (it represented a -70% change compared to the baseline w =1.)
The w_p/w_r ratio was 10. The changes on α_w showed similar trends (more exacerbated) to the trends described in section S2.3.1. above. Indicator changes were different for each technology. The IER α_w decreased by -42.20% whereas the value of BRF moderately increased by 13.94%. As a result, the ratio $\alpha_{w,IER}/\alpha_{w,BRF}$ decreased to 2.231, nearly 49.18% lower than the baseline ratio of 4.39 (EW baseline). The “convergence” trend between $\alpha_{w,IER}$ and $\alpha_{w,BRF}$ was confirmed; however, this convergence was not enough to reverse the superiority of BRF over IER regarding environmental sustainability. In this regard, the new indicator ratio suggests that the BRF is still twice more environmentally sustainable than the IER. The explanation and discussion of these results follow the arguments mentioned above in subsection S2.3.1. It can be concluded that the six NPEIs related to human health effects slightly contribute to the increase of BRF’s α_w, but not of that

of IER. There is a somewhat “convergence” of indicator values; in consequence, the indicator ratio $\alpha_{w,IER}/\alpha_{w,BRF}$ significantly decreased from 4.39 to values around 2 to 3, depending on the w_p/w_r ratio. This means that the environmental performance gap between IER and BRF was reduced; however, the superiority trend of BRF over IER concerning environmental sustainability was not reversed.

S16.2.4. Weighting and impacts related to resources
This analysis was not performed. Because of the low values of the three impacts related to resources (Table S16.1, all of them << 1), a pattern similar to the one reported in section S2.1. (analysis of GW and WC) is anticipated. That is, the influence of increasing the weight of these impacts is not decisive on the indicator values. Indicator values are expected to decrease with increasing weights w_p applied to those impacts, due to the significantly lower participation of the high value impacts that are assigned reduced weights w_r. Ratio between indicator values for IER and BRF is not expected to decrease significantly compared to the baseline value 4.39. Then, in spite of decreasing α_w, the ratio of environmental sustainabilities represented by the ratio $\alpha_{IER,w}/\alpha_{BRF,w}$ would be kept around 3.5 to 4.4. That is, the BRF would still be nearly four times more environmentally sustainable than IER when increasing the weighting factors of the resources-related impacts.

In summary, the ES of BRF was better than that of IER for the three weighing scenarios, pointing out to the consistency of the indicators α, α_w, and σ. For GW and WC high weighting, the relationship of ES was nearly uniform (ca. 4). For high weighting of ecotoxicity-related impacts, the relationship of ES of BRF to IER increased with respect to that of the baseline scenario, and for high weighting of human health-related impacts the relationship of ES of BRF to IER decreased but still the ES of BRF was superior.

S16.3. Error analysis applied to the α indicator

An analysis was conducted to determine the influence of errors on the NPEIs on the absolute and relative uncertainties of the indicators α and α_w,
Since we do not have information on the error structure of the NPEIs, we assumed that the NPEIs came from normal distribution, all of them had a similar coefficient of variation CVar leading to heteroscedastic NPEIs with increasing standard deviations (SD, each SD proportional to the average value of the NPEI). This approach is referred as the homogenous CVar/heteroscedastic model (non-homogeneous variance). Error propagation was based on accepted procedures reported in Kreyszig (1978, Chapter 19, section 19.2)

The equation used for error propagation (estimation of the error of an indirect magnitude F of unknown error; F is calculated by functional relationships of other independent variables, the errors of the latter are known as standard deviations SD) is

For F = α

$SD_{\alpha} = \{\Sigma[(\partial\alpha/\partial NPEI_j)^2*(SD_{NPEIj})^2]\}^0.5 = \{\Sigma[(SD_{NPEIj})^2]\}^0.5$ (S16.25)

because $\partial\alpha/\partial NPEI_j = 1$ for all j.

For F = α_w

$SD_{\alpha} = \{\Sigma[(\partial\alpha_w/\partial NPEI_j)^2*(SD_{NPEIj})^2]\}^0.5 = \{\Sigma[(w_j*SD_{NPEIj})^2]\}^0.5 =$

$= \{\Sigma[(w_j*CVar_{NPEIj}*NPEI_{j,ave})^2]\}^0.5$ (S16.26)

because $\partial\alpha_w/\partial NPEI_j = w_j$ for all j, and $SD_{NPEIj} = CVar_{NPEIj}*NPEI_j$ by definition of coefficient of variation.

This is a limited model and likely each NPEI could have a different CVar or a more complex relationship between its SD and the value of the NPEI. Yet, the homogeneous CVar/heteroscedastic model approximately holds for several environmental parameters, such as chemical oxygen demand of wastewaters (Sawyer et al., 2002; Baird et al., 2017), parameters of proximal analysis of solid wastes and feeds, etc. Also, it could give an approximate appraisal of the error propagation and its impact on the overall uncertainty of the indicator (the baseline and the weighted values of the indicator). It could answer whether we could expect a rampant error propagation with inflated confidence intervals for α and α_w (and poorly reliable values of such indicators) or, hopefully, to achieve relatively narrow confidence intervals that allow for establishing significant differences among results. Moreover, it is a statistical model easy to implement for linear, addition aggregation indicators such as our α and α_w. We have assumed three CVar levels for the NPEIS, 0.05, 0.10, and 0.15, in order to also find the pattern of increasing CVar on the final errors of the indicators.

Tables S16.1 (bottom part) and S16.4 below summarize the error estimation results. The main trends follow:

(i) As it was expected, the absolute and relative errors of both α and α_w increased with increasing values of CVar (Table S16.1). This increase was nearly proportional.

(ii) When the weighting led to $\alpha_w < \alpha$, the absolute error of α_w decreased accordingly

(iii) When the weighting led to $\alpha_w > \alpha$, the absolute error of α_w ncreased accordingly.

(iv) Similar trends to (ii) and (iii) were observed for the relative errors of the indicators. Relative errors were ≤ 0.10 for all cases, even for the high CVar and highest α_w.

(v) In no case was a rampant increase or decrease of errors of our indicators.

(vi) The confidence intervals for α_w and α were reasonably narrow, even for the largest CVar 0.15 of the NPEIs (Table S16.4). For all the chosen scenarios, there was no overlapping between the CI for IER with the CI for BRF. In fact, the $LL_{IER} >> UL_{BRF}$ for each examined scenario. Even for the most conservative case S2.3.1,

where a "convergence" of α_w of IER and BRF was found, the corresponding CI did not overlap and still $LL_{IER} >> UL_{BRF}$. Even for this conservative scenario, it could be said that the $\alpha_{w,IER}$ was significantly higher than that of $\alpha_{w,BRF}$. This assertion holds, with more reason, for the other examined scenarios.

Table S16.4. Analysis of errors on the indicators based on NPEIs with errors characterized by a coefficient of variation 0.15 (decimal) and heteroscedastic.

Scenarios		**Baseline S16.2.1.1.**		**S16.2.2.1. Weighting GW[a] and WC[b]**		**S16.2.3.1. Weighting Ecosystems impacts**		**S16.2.4.1. Weighting Human health impacts**	
		IER[c]	**BRF[d]**	**IER**	**BRF**	**IER**	**BRF**	**IER**	**BRF**
CI 95%[e] for α and α_w	UL[f]	195,905	43,942	122,515	27,978	348,593	59,430	138,672	48,895
	LL[h]	162,331	37,506	101,531	23,953	282,325	49,583	118,782	40,120
$z_{c,\ 0.025}$ [g] = 1.96		No CI overlapping $LL_{IER} >> UL_{BRF}$		No CI overlapping $LL_{IER} >> UL_{BRF}$		No CI overlapping $LL_{IER} >> UL_{BRF}$		No CI overlapping $LL_{IER} >> UL_{BRF}$	

[a] global warming NPEI
[b] water consumption NPEI
[c] incineration with energy recovery
[d] biorefinery
[e] confidence interval at 95%
[f] upper limit of the confidence interval
[g] critical value at probability 0.025 of the normalized gaussian statistic
[h] lower limit of the confidence interval

In summary, a useful, although simplified, error analysis revealed that the absolute error of the indicators α and α_w increased with the magnitude of the errors of the NPEIs, as expected. That increase is not rampant. It leads to relatively "controlled" (reasonably narrow) confidence intervals 95% for the indicators. Confidence intervals for indicators of IER and BRF in each examined scenario did not overlap. Moreover, even for the most conservative scenario, the $LL_{IER} >> UL_{BRF}$. This suggests that the indicator for IER is significantly higher than the value for BRF, either for baseline and weighted indicators examined in this work.

Finally, according to Gan et al. (2017), Table 4, the applications of equal weighting indicators as the one proposed in our work (α) are rated as follows:

Purposes	
Assessing State/Prediction	Recommended
Comparison	Applicable
Spatial scales (coarse and fine)	Recommended for both scales
Temporal scales (long and short)	Recommended for both scales

Weak sustainability	Recommended
Strong sustainability	Not recommended

Additive aggregation of sustainability indicators (SI), which is the aggregation used in our α, exhibited a similar positive rating than the equal weighting type indicators (EW, Gan et al., 2017; Table 4).

Therefore, we feel that the use of α and α_w in our work is meaningful. It does not mean that other types of indices were not suitable for this task. Yet, the advantages of α and α_w are
-calculations are easy to perform, and transparent,
-the bricks for building the α indicator are already available from software (the NPEIs from characterization mid-point impacts),
-the NPEIs typically give detailed information on contributions of flows of materials, energies, emissions, other processes, etc.; thus, discussion and detection of crucial contributions can be made for further improvement of a process or technology,
-the indicators are aligned with ISO standards and LCA technique and software, which is a powerful and recognized framework, and
-new indicators can be built using the α that are useful for comparing the environmental sustainability of two technologies, contingent that both technologies have the same FU or harmonized FU. An example is the σ and τ indicators presented and used in our work.
It should be stressed that the requisite of the same FU or harmonized FU when comparing the sustainability of technologies is common to ALL indicators. Unfortunately this issue is not clear in the units of the magnitudes of other sustainability indicators as we have shown in our Annex S17. For instance, in some applications of the environmental sustainability studies using exergetic analysis, emergy analysis, or Eco-Indicator 99 this requisite is not clearly enforced (Clasen et al., 2024) leading to unfair comparisons and possibly debatable comparative results.

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Annex 17. Discussion and comparison of selected environmental sustainability indicators

Nomenclature

AE	academic editor
BRF	biorefinery
CHP	combined heat and power
EEI	exergetic ecological index
EI99	Eco Indicator 99
ES	environmental sustainability
ESI	exergetic sustainability index
EW	equal weighting
ExA	exergy analysis
FU	functional unit
GBAER	Environmental Biotechnology and Renewable Energies Group, abbreviation for its Spanish name
GW	global warming
IER	incineration with energy recovery
LCA	life cycle assessment
LCIA	life cycle impact assessment
NPEI	normalized potential environmental impacts, mid-point values from ReCiPe methodology
Pt	point
SEI	Sustainability Efficiency Indicator
SM	supplementary material
WC	water consumption

Greek characters

α	indicator based on the sum of the eighteen NPEIs of a given process, technology, or product
α_w	indicator based on the sum of the weighted eighteen NPEIs of a given process, technology, or product
σ	GBAER indicator based on the α of two processes or technologies that determines which one is more environmentally sustainable
τ	GBAER indicator that determines whether one technology is more environmentally sustainable than the other, with ***dominance*** or ***restrictions***.

S17.1. Exergetic-based environmental sustainability indicators.

According to Tsatsaronis and Cziesla (2019) and Gutowsky (2020) the Exergy is the theoretical maximum of useful work (shaft work or electrical work) that can be obtained from a thermal system as this is brought into thermodynamic equilibrium

with the reference environment while heat transfer occurs with this environment only. Alternatively, exergy is the theoretical minimum of mechanical or electrical work required to raise a system from the reference state to the system-specified state. Exergy analysis (ExA) is used in engineering to optimize energy systems, reduce waste, and improve efficiency (Tsatsaronics and Cziesla, 2019; Aloui and Dincer, 2018) and has played a revolutionary-like role in classical Thermodynamics in the late XX century and current siècle XXI.

Celik and Aydemir (2025) listed four metrics as environmental exergetic indicators based on Exergy Analysis:

-Exergetic Efficiency: Measures the efficiency of energy conversion processes by comparing the useful work output to the exergy input.

-Exergetic Sustainability Index (ESI): Evaluates the sustainability of a system by considering the exergy destruction and the environmental impact.

-Exergetic Ecological Index (EEI): Assesses the ecological impact of a system by analyzing the exergy destruction and its effect on the environment.

-Exergy-based Sustainability Efficiency Indicator (SEI): Combines exergy analysis with sustainability indicators to provide a comprehensive assessment of environmental performance.

The first three indicators are focused on energy sustainability and optimization, whereas the fourth is an exergetic sustainability metric.

One key feature of ExA is undoubtedly rooted in its effectiveness for minimizing irreversibilities and maximizing the useful work obtained from or minimizing the required work by thermal processes in energy use optimization. Any improvement in energy flows and exergy management will positively impact the environment. For instance, minimizing the work required by a system will minimize energy entries from the technosphere; saving energy inputs will reduce environmental impacts associated to energy production. However, a strong and general link between ExA alone and environmental performance and sustainability remains to be demonstrated. For instance, Stougle and Kooi (2009, 2012) reported the application of ExA to two case studies (the production of polystyrene and aluminum). They hypothesized that exergy losses and environmental impact were related; however, they could not provide general and definitive proof. They concluded that the exergy loss could be a qualitative measure in these cases, and expressed optimism that exergy analysis would help in the environmental policy design of technological processes. Dewulf et al. (2008) reviewed the potential and limitations of exergy analysis in environmental science and technology. They stated that it might make sense to assess emissions' impacts in some cases by considering the exergy loss caused by abatement of the emissions. More recently, advances have been made in linking exergy losses to land use and resources' consumption (Stougie et al., 2018; Finnveden et al., 2016; Koroneos et al., 2012) that increased the application of exergetic environmental sustainability determination. Despite these advances, Finnveden et al. (2016) and Soltanian et al. (2022) recognize that the ExA should be significantly extended to tackle studies on ES of biotic and some abiotic systems and that the ExA does not give results consistent with those other methods. Indeed, Finnveden et al (2016) stated that

> "….The aim of this paper is to illustrate the use of the thermodynamic approach in case studies and to compare the results with other approaches, and thus contribute to the discussion of how to measure resource use. The two case studies are the recycling of ferrous waste and the production and use of a laptop. The results show that *the different methods produce strikingly different results when applied to case studies, which indicates the need to further discuss methods for assessing resource use*…….. The exergy approach captures most resources that are considered important by other methods. Furthermore, the composition of the ores is shown to influence the results. *The thermodynamic approach could also be further developed for assessing a broader range of biotic and abiotic resources, including land and water*."

Moreover, Soltanian et al. (2022) in a very comprehensive and updated review on exergetic methods concluded that

> " …..Exergy-based methods are promising tools for achieving the Un's sustainable development goals due to their ability to locate, quantify, and comprehend the thermodynamic inefficiencies, cost losses, and environmental impacts of waste treatment systems. Therefore, the present review paper aims to comprehensively summarize and critically discuss the use of exergetic indicators for the sustainability assessment of MSW treatment systems. …….. *The overall exergy efficiency values of integrated anaerobic digestion-based MSW processing systems (34–73%) were generally higher than those based on the thermochemical processes. In most published works, Exergy destruction and efficiency were the most popular exergetic indicators used for decision-making. However, exergoeconomic and exergoenvironmental indices have rarely been used in the published literature to make decisions on the sustainability of waste treatment pathways. Future studies need to focus on developing and realizing integrated waste biorefinery systems using advanced exergy, exergoeconomic, and exergoenvironmental methods."*

The integration of ExA with other methods holds promise (as examples, we mention the SEI reported above (Gungor Celik and Aydemir, 2025) and a combined framework by Cano-Londoño et al. (2022) for determining the sustainability of processes and systems. Cano-Londoño et al. (2022) stated that Exergy Analysis (ExA), Life Cycle Assessment (LCA), and Emergy Analysis (EmA) that account for sustainability indicators in environmental, economic, and/or social dimensions cannot provide an assessment under these three dimensions in a robust way by themselves. They proposed the Integrated Sustainability Index (ISI) as a sustainability unified performance metric that could assess the three axes of sustainability. The exergetic analysis, emergy indices, and indices from life cycle assessment were combined in an integrated approach, although not

interchangeable, thus giving more complete information for sustainability decision-making.

Exergetic sustainability studies have been performed in power generation, focused on combined heat and power (CHP) systems, and renewable energy systems (Aloui and Dincer, 2018; Gungor-Celik and Aydemir, 2025; Stougie et al. 2012; Stougie et al., 2018). CHP systems simultaneously produce electricity and useful heat from the same energy source. By utilizing the waste heat from electricity generation, CHP systems achieve higher exergy efficiency compared to separate heat and power generation. Regarding Renewable energy systems, solar, wind, and hydroelectric power systems are examples of renewable energy sources that have high exergy efficiency. These systems convert natural energy flows into electricity with minimal exergy losses, making them sustainable options for power generation. Concerning industrial applications, an ExA of chemical plants was performed to identify inefficiencies in their processes. These plants can improve their sustainability and reduce environmental impacts by optimizing energy use and reducing exergy losses. Industrial waste heat recovery from industrial processes (many industrial processes generate waste heat), such as steel plants, can generate electricity or provide heating for nearby buildings, improving overall exergy efficiency. Building and construction studies have been performed on the design of green buildings to maximize energy efficiency and minimize exergy losses. They often incorporate high-performance insulation, energy-efficient windows, and renewable energy systems to achieve high exergy efficiency.

S17.2. Eco-Indicator 99 and environmental sustainability

The Eco Indicator 99 (EI99) is a damage-oriented method for Life Cycle Impact Assessment (LCIA). It is used to evaluate the environmental impact of products and processes throughout their life cycle. The method focuses on three main damage categories: human health, ecosystem quality, and resource depletion.
The Eco Indicator 99 method involves several steps:

1. Inventory Analysis**:** Collecting data on the inputs and outputs of a product's life cycle.
2. Impact Assessment**:** Evaluating the potential environmental impacts based on the inventory data.
3. Damage Assessment: Translating the impacts into damage scores for human health, ecosystem quality, and resource depletion.

The method uses a single score to represent the overall environmental impact, making comparing different products and processes easier. The scores are expressed in points (Pt), where 1 Pt represents 1/1000th of the annual environmental load of an average European citizen (PRé Consulting, 2000; Chisco-Benavides, 2023).
One of the key strengths of the Eco Indicator 99 is its ability to provide a comprehensive assessment of environmental impacts across multiple categories.
Standard Eco-indicator 99 values are available for:
-Materials. The indicators for production processes are based on 1 kg of material.
-Energy generation processes. Units are given for electricity and heat.

-Transport processes. These are mostly expressed in the unit t-kilometer.
-Production processes. Treatment and processing of various materials. Expressed for each treatment in the unit appropriate to the particular process (square meters of rolled sheet or kilo of extruded plastic).
-Disposal scenarios. These are per kg of material, subdivided into types of material and waste processing methods. *Average European figures are used for this calculation.*

These features make the EI99 a valuable tool for decision-makers who need to balance different environmental concerns. However, using the method in conjunction with other tools and approaches is important to get a complete picture of a product's environmental performance. The Eco Indicator 99 has been widely used in various industries to assess the environmental performance of products and processes. It helps companies identify areas for improvement and make more sustainable choices. However, it also has some limitations:
-The base of reference is exclusively European; it is a Eurocentric method (PRé Consulting, 2000);
-For example, according to the Authors of the method, it relies on certain assumptions and simplifications, which may not always accurately reflect real-world conditions PRé Consulting (2000).
-The EI 99 method is based on a fixed set of assumptions and data, which may not reflect evolving scientific understanding or emerging environmental issues. For example, it does not adequately address newer concerns like microplastic pollution or climate change feedback loops (Sala et al., 2017). In contrast, mid-point PEIs used in GBAER indicators and the End-Point impacts of ReCiPe method are more flexible, and they are updated. It is known that the mid-point PEI part of the ReCiPe method is regularly revised for mechanisms and magnitudes (Huijbregts et al., 2016).
-Another limitation of EI-99 is the unclear definition and algebraic handling of the units of Point or milliPoint, the units of the standard indicators, the units of the total environmental load (annual, for Europe) as well as the units of the Effects calculated using the standard indicators and the flow of materials or energy per FU for a given category (materials, energy, etc.) in a given project.
As noted above, the definition of Point is the 1/1000 of the Annual total environmental load of a country or Europe divided by the number of inhabitants, according to the Report (2000) Dutch Ministery of Housing Eco-indicator 99 Manual for Designer PRé Consulting (2000). So, the units 'person' and 'year' are implicit and should be made explicit. 2. Then, the units of the Point should be (Units of Total Environmental Load)/(person*year), very different from being just dimensionless. To make things worse, the units of the Environmental Load are not disclosed/defined in the Report. It is also stated that the standard indicators based on Point and milliPoint are dimensionless PRé Consulting (2000).

> *"1.7 The unit of Eco-indicators "The standard Eco-indicator values can be can be considered as dimensionless figures. As a name we use the Eco-indicator point (Pt)…."*

This is misleading and confuses the readership.

On the one hand, the standard indicators clearly have the units milliPoint/kg for materials, milliPoint/kW-h or milliPoint/J for energy flows, etc. Please check the Tables at the end of the Report (PRé Consulting, 2000).
On the other hand, the units of the Point should be

Units of Point = (units of the annual environmental load Europe)/
/(person*year) (S17.1)

Consequently, as another example of inconsistencies, the units of the environmental effect of a given amount of material used per functional unit (FU) of a given project, should be

Effect = mass of material j (kg/FU)*
*[standard indicator for the material j (milliPoint/kg)] (S17.2)

Thus,
Units of effect = units of milliPoint/FU =
= (units of environmental Load)/(person*year*FU) (S17.3)

Note: It could be said that the Points are normalized, *but not dimensionless.*

-Another limitation is stated in PRé Consultants (2000; pp 8-9),

> *",,, It is a tool to be used in the search for more environmentally-friendly design alternatives and is intended for internal use.*
> • *The standard Eco-indicator values are not intended for use in environ-mental marketing, for environmental labeling or for publicly proving that product A is better than product B.*
> • *The standard Eco-indicator values are also not intended as an instrument for the Government to set standards and draw up guidelines."*

One might wonder what is the point to invest time in designing/applying a time-consuming tool when comparisons between/among products or processes, as well as obtaining official guidelines and standards are not allowed.

-Finally, the most drastic limitation, is that unfortunately the indicator was superseded around 2023, according to PRé Consulting (2023).
Despite its limitations, applications of Eco-Indicator 99 helped to advance the knowledge of the environmental sustainability of products and processes during a quarter of a century. Regretfully, it seems that Eco-Indicator 99 reached its end-of-life cycle.

S17.3. End-Point Method of ReCiPe, Hierarchical (Damage Method)
The ReCiPe (Resource Consumption and Environmental Impact) methodology is a widely used life cycle assessment (LCA) tool that evaluates the environmental

impacts of products and processes. It consists of two main approaches: Mid-Point and End-Point. The End-Point method aggregates environmental impacts into broader categories, such as damage to human health, ecosystems, and resources. While this approach simplifies interpretation and communication with decision-makers (both Government and private sector), it has several disadvantages and limitations.

The endpoint method of the ReCiPe, Hierarchical cultural approach, also known as the damage method, aggregates eighteen normalized impacts from LCA into three main categories https://www.rivm.nl/en/life-cycle-assessment-lca/recipe:

1. Human Health: Measures the impact on human health, often expressed in disability-adjusted life years (DALYs).
2. Ecosystem Quality: Assesses the impact on biodiversity, typically measured in species lost per year.
3. Resource Scarcity: Evaluates the depletion of resources, often quantified in terms of surplus energy required for future extraction or a monetary value referred to as USD 2013.

Among the advantages of the End-Point Method and Indicators we can cite:

-The ReCiPe endpoint method offers several advantages over other sustainability indicators, such as exergetic sustainability indicators and the Eco-Invent 99 method, https://www.rivm.nl/en/life-cycle-assessment-lca/recipe:

*It can provide a holistic view of environmental impacts with comprehensive coverage because ReCiPe includes a broad set of midpoint impact categories and aggregates them into the above-mentioned three endpoint indicators,

*The method uses impact mechanisms with a global scope, making it applicable to various regions and contexts.

-By converting midpoint indicators to endpoint indicators, ReCiPe simplifies the interpretation and communication of LCIA results, making it easier for decision-makers to understand the overall environmental impact.

-The method allows for a final step where the three end-point damage impacts are normalized and aggregated to report one dimensionless supra-indicator, using the additive aggregation and weighting factors recommended by experts (400-400-200 Ecosystem/Health/Resources, respectively).

-ReCiPe is regularly updated to incorporate new data and research, ensuring that it remains a state-of-the-art method.
https://www.rivm.nl/en/life-cycle-assessment-lca/recipe

However, according to the Authors of the End-Point system,
- with each aggregation step of the LCIA outcomes, uncertainty in the results increases (https://www.rivm.nl/en/life-cycle-assessment-lca/recipe.)

> *"…*Midpoint indicators focus on single environmental problems, for example climate change or acidification. Endpoint indicators show the environmental impact on three higher aggregation levels, being the 1) effect on human health, 2) biodiversity, and 3) resource scarcity.

> Converting midpoints to endpoints simplifies the interpretation of the LCIA results. *However, with each aggregation step, uncertainty in the results increases. The figure below provides an overview of the structure of ReCiPe…."*

The End-Point method involves modeling the cause-effect chain from emissions to final damage (e.g., from CO_2 emissions to human health impacts). This chain includes significant uncertainties, especially in the characterization of long-term or complex impacts (e.g., biodiversity loss.) Estimating the damage to ecosystems from a specific pollutant may involve assumptions about species sensitivity, recovery rates, and ecosystem resilience, which are often uncertain.

-the risk of subjectivity on results because of the incorporation of weighting.

The End-Point method relies on weighting factors to combine different impact categories into a single score in the last stage of the procedure. Despite the weighting is an accepted practice in LCA and has several supporters and methods, other experts are uncomfortable with weighing, irrespective of whether a panel of experts or polls sets the weights. A line of thought in academia feels that these weights are often based on value choices (e.g., societal preferences or expert judgments), which can introduce subjectivity and bias.

This negative thought about weighting can also be extended to other indicators that use or have used this procedure, such as Eco-Indicator 99. For example, different stakeholders may prioritize human health over ecosystem damage, leading to varying results depending on the weighting scheme used. It is very common to find the prioritization of global warming. here is an open literature of articles whose discussion of the environmental sustainability of processes or technologies rely on only global warming, or global warming plus energy balances, or global warming and a couple or more environmental impacts (Teh et al., 2023; Jing et al. 2021; Mu et al., 2016). Of course, these papers do not adhere to the End-Point methodology. Still, they are examples of the "reductionist" and debatable approach of some analysis when considering the environmental impacts for evaluating environmental sustainability.

-The End-Point method may not cover all relevant environmental impacts, particularly emerging or less-studied issues (e.g., microplastic pollution, emerging pollutants, land use change, impacts on biodiversity) (Bare, 2011). For instance, the ReCiPe method traditionally focuses on well-established impact categories, potentially overlooking newer or region-specific environmental concerns. To be fair, this feature is common to other indicators as well, it is not a specific disadvantage of the End-Point method. As a compensatory argument, it should be recalled that ReCiPe makes efforts to update magnitudes and mechanisms underlying potential environmental impacts. Perhaps the perceived drawback of End-Point mentioned before should be mitigated with words of caution referring to differences between the speed of environmental changes and the speed of updating the scientific tools.

S17.4. GBAER indicators

Our indicators are based on the normalized potential environmental impact of the LCA as building blocks (the mid-point impacts), which in turn are aligned to ISO

Standards. In this regard, one of our indicators is similar to the first step of the End-Point indicators. On the one hand, this provides a solid background to our indicators (a recognized, quantitative framework). Our indicators consider eighteen NPEIs and allow for the detailed analysis of contributions of key stages of the analyzed or considered technology (in terms of materials and processes) that help identify the factors that contribute the most to the unsustainability and serve as a trigger to conduct the virtuous iterative improvement of the examined technology, which is a positive characteristic of the LCA.

Our proposed metrics are based on ISO standards and LCA and, in their current status, are restricted to determining the environmental sustainability of environmental and possibly industrial technologies/processes. The measure of economic and social sustainabiliies are out of the scope of our metrics. Moreover, there are no applications for determining the sustainability of countries, regions, etc. Yet, our metrics could be useful and contribute to the development of integrated indicators of overall sustainability (with a focus on environmental and industrial process studies) in the current efforts made by Cano-Londoño et al. (2022) and others (Keller et al., 2015; Tsang and Sonnemann, 2019*).*

It is worth clarifying that NPEIs are determined based on the set of characterization PEIs determined by ReCiPe, and the LCA is based on that method. The characterization PEIs of the LCA (also called the mid-point impacts) are expressed in units of characterization impact per FU. The Normalized Potential environmental impacts are the ratio of the characterization PEIs and the unit loads of ReCiPe 2016 and ISO. The unit loads, in turn, are expressed in the physico-chemical-biological-toxicity units of impact /[person*year]. These unit loads are the inverse of the corresponding normalization factors F_n reported by Recipe 2016 (National Institute for Public Health and the Environment-Ministry of Health, Welfare, and Sports, 2024; Recipe Report, 2016-Normalization scores, Simapro database Manual Methods Report, 2022; see also our Annex S7). The normalization factors were also confirmed by dividing each NPEI reported by Simapro by the corresponding characterization PEI reported by Simapro. The normalization factors from both sources coincided.

The first level GBAER indicator α is the plain sum of the NPEIs (mid-point ReCiPe). The higher the α, the lower the environmental sustainability of the process or technology. In principle, another indicator (σ) is built on values of α and is defined in such a way that performs the comparison of two processes or technologies, *isto est*, where one is a reference technology and the other one is the target technology (or the technology to be evaluated), using a definition based on the two corresponding αs (Annex 8, Eq.A8.1, this document). The usefulness of σ can be generalized by proving some kind of transitive property, which is intuitive and perhaps trivial but should be demonstrated to keep the peace of mind regarding the consistency of this indicator, as follows:

Lemma S17.1: Transitive-like property of the indicator σ

Hypothesis: Given two technologies 1 and 2, and a reference technology ref. with known values of the indicator σ.
It is known that $\sigma_{1,ref} > \sigma_{2,ref}$ (that is, the ES of technology 1 with a reference technology is superior to that of technology 2 with respect to the same reference technology)

Thesis: Then, the direct comparison of ES of the technologies 1 and 2 given by $sigma_{1,2}$ complies with these relationships

(i) $\sigma_{1,2} = \sigma_{1,ref} - \sigma_{2,ref}$ (S17.4)

That is, the indicator of ES between technologies 1 and 2 can be found by subtraction of the σ calculated between each technology and the technology of reference.

(ii) $\sigma_{1,2} > 0$ (S17.5)

that is, it states that technology 1 is more ES than technology 2

Proof:
First, let us recall the definition of $\sigma_{j,ref} = \log(\alpha_{ref}/\alpha_j)$ $j = 1, 2$; and
$\sigma_{1,2} = \log(\alpha_2/\alpha_1)$ (S17.6)

Second, we start with the ratio

$\alpha_2/\alpha_1 = (\alpha_2/\alpha_1)^* (\alpha_{ref}/\alpha_{ref}) = (\alpha_{ref}/\alpha_1)/(\alpha_{ref}/\alpha_2)$ (S17.7)

Taking logarithms in both members of the equation:

$\log(\alpha_2/\alpha_1) = \log[(\alpha_{ref}/\alpha_1)/(\alpha_{ref}/\alpha_2)] = \log(\alpha_{ref}/\alpha_1) - \log(\alpha_{ref}/\alpha_2)$ (S17.8)

By definition, Eq S17.8 becomes

$\sigma_{1,2} = \sigma_{1,ref} - \sigma_{2,ref}$ (S17.4)

By hypothesis, $\sigma_{1,ref} > \sigma_{2,ref}$; then $\sigma_{1,ref} - \sigma_{2,ref} > 0$ (S17.9)

Combining Eqs S17.4 and S17.9, then it is obtained

$\sigma_{1,2} > 0$ (S17.5)

End of the proof

Finally, the GBAER indicators proposed and applied in our work have the following features:

- Unlike other approaches (Eco-Indicator 99, EPS Method, LIME, and Impact 2002+) and similarly to the End-Point method above, it does not include potential impacts from future extractions in the impact assessment but assumes such impacts have been included in the inventory analysis (https://pre-sustainability.com/articles/recipe/).

-They are aligned with ISO standards and LCA up to the calculation of the mid-point NPEIs, including In this regard, it shares several advantages of the End-Point method, which is also based on ReCiPe 2016 mid-point environmental impacts.

-The estimation of the indicator alpha is easy, either weighted or equal-weighting indicators, by a simple algebraic equation (application of equal weighting indicator and aggregation as a sum have good ratings or recommendations by Gan et al., 2017; Table 4.).

-Weight definition could be arranged to be performed by a panel of experts or public opinion (either wide or restricted poll) that will increase the range of application of the indicators (Gan et al., 2017).

-Our indicators provide the characterization of the environmental sustainability patterns in the comparison of two technologies (or two products). We refer to the concepts of ‘one technology is more ES with ***dominance*** than the second one’, or ‘one technology is more ES with ***restrictions*** than the second one’. Please see section 3.4 of the article and Annex S8 in this document. Other examined indicators do not include these concepts that help characterize the pattern of the ES.

-For a fair comparison, both technologies, processes, or products should have the same FU or at least harmonized FU (see our procedure in subsection 2.1.4. of the RRRRMS). This feature is also or ***should be*** a requirement ***common to all the other indicators*** examined in this discussion; however, the ambiguous handling of the units of involved magnitudes leads to the “fading” of the role of the FU in the mid-point NPEIs and other normalized impacts (especially in the milliPoint-based Eco-Indicator 99, the three End-Point ReCiPe normalized indicators also known as “damages”, as well as the final normalized one score).

The GBAER indicator α, as initially proposed in our work, belongs to the Class of indicators that are Equal Weighting class (Gan et al., 2017, Table 2; Beliakov et al., 2007; Pollesch and Dale, 2015) and Additive aggregation (Gan et al., 2017, Table 3). Regarding the Equal Weighting feature, α is ranked as simple, replicable, and straightforward with the drawback of little insight into elementary indicators’ relationships (the ones that intervene in the equation of the overall sustainability indicator SI). Concerning additive aggregation, α is ranked as

transparent and straightforward, and it is easy to execute the sensitivity analysis and uncertainty quantification. Last, in the concluding Table 4 of Gan et al. (2017), indicators like ours are ranked as Recommended for Purposes of Assessing the state and prediction of sustainability on the one hand, and Applicable for Comparison between sustainabilities on the other hand; Recommended for analysis at Coarse and Fine Spatial Scales, Recommended for analysis at both Long and Short temporal, and Recommended for analysis in scenarios of Weak Sustainability (Jeronen, 2020; Tapio, 2024.) It is not recommended for scenarios of Strong Sustainability (Neumayer, 2013; Dietz and Neumayer, 2007.) However, this drawback of our α is shared with Eco-Indicator 99 and End-Point methods. Incidentally, Budget Allocation (Eco-Indicator 99), Public Opinion, and Analytic Hierarchy Process methods had a slightly similar ranking profile to our α with the drawback of a 'Not recommended' in the application of those methods to Coarse Spatial scales (α achieved a Recommended in this category) and an Applicable (OK) for scenarios of Strong Sustainability for the first two methods (Gan et al., 2017, Table 4).

Therefore, we conclude that the GBAER indicators, based on mid-point NPEIs ReCiPe 2016 and posterior own definitions and calculations (indicators σ and τ, at this stage of our research, can be useful and easy to apply for the preliminary determination and characterization of the environmental sustainability of environmental technologies or processes, and likely of industrial technologies or processes as well. Our indicators will characterize the comparison of ES with the concepts of ***dominance*** and ***restrictions***, a feature not included in other indicators to our knowledge.

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Annex S18. Sensitivity of biorefinery environmental sustainability to changes of type of activated carbon used

Nomenclature

AC	activated carbon
BRF	biorefinery
BRF-FAC	biorefinery using fossil-origin activated carbon
BRF-VAC	biorefinery using vegetal-origin activated carbon
EVT	evaluated technology
FAC	fossil-origin activated carbon
FRS	fossil resource scarcity
FU	functional unit
FWEc	freshwater ecotoxicity
FWEu	freshwater eutrophication
GW	global waming
HCT	human carcinogenic toxicity
HNCT	human non-carcinogenic toxicity
IER	incineration with energy recovery
LCA	life cycle assessment
MEc	marine ecotoxicity
N_{EVT}	N° of NPEI in EVT (evaluated technology, that is BRF-VAC) that are lower than the corresponding impacts in REFT.
NN	stage of the biorefinery that produces bionanobioparticles to be used in bioremediation of waters and wastewaters.
NPEI	normalized potential environmental impacts
N_{REFT}	N° of NPEI in REFT (reference technology, that is, BRF-FAC) lower than the corresponding impacts in EVT
PEI	characterization potential environmental impacts
REFT	reference technology
RoW	rest of the world
RRRMS	version of the MS submitted on December 2024
RRRRMS	version of the MS written at present
SM	supplementary material document
VAC	vegetal-origin activated carbon

Greek characters:

α	sum of the normalized environmental impacts of Biorefinery, in (person*yr/FU)
σ	GBAER sustainability index related to the quantitative comparison the environmental sustainability between two technologies
τ	GBAER sustainability index related to the dominance/restrictions in the environmental sustainability in the comparison of two technologies

The analysis of environmental impacts, as well as the contributions of stages, processes, and materials on PEI and NPEIs of the BRF, identified that the use of activated carbon of fossil origin (FAC) in the NN stage of the BRF could be associated to high values of selected impacts of ecotoxicity and human health in that stage, as well as contributions to other NPEIs. The Authors discussed the following in the text of the article

> *"The NN stage was critical for HNCT, GW, FWEu, FWEc, and MEc. The NN stage contributed 49.5% to the HNCT category, probably related to the use of activated carbon of fossil origin. The latter is used to produce BNBPs and is associated with the treatment of mining waste and fossil coal. Therefore, the use of activated carbon of fossil origin again becomes a burden for the environmental impact of BRF, especially for the NN stage."*

Also, the Authors suggested in the body of the article and previous works (Yáñez et al. 2023) that it would be worth determining the effect of a change of material, that is, a replacement of FAC by another adsorbent such as activated carbon of vegetal origin (VAC), on the profile of environmental impacts of NN stage contribution of the material to the NN.

> *"Given the importance of the NN in the highest NPEI and GW, one can speculate that the use of activated carbon in the BRF merits further study. The LCA analysis strongly suggests that using activated carbon can become a negative burden in terms of the environmental impact of the BRF, especially for the NN stage. As the LCA is iterative, it is helpful to consider replacing activated carbon of fossil origin with activated carbon of plant origin. It would be worthwhile to conduct such a study- if a benefit is found, the impacts of key BRF stages, processes and products on key NPEIs could be reduced and a modified BRF would be more sustainable."*

Consequently, looking for an alternative to activated carbon of fossil origin (FAC), such as activated carbon of plant origin (VAC) or any other suitable adsorbent material with a lower environmental impact, is advisable.
Therefore, a sensitivity analysis was performed for BRF using either FAC or VAC. The LCI for the FAC was obtained from proxy "Activated carbon, granular {RoW}| activated carbon production |Cut-off, U; the LCI for the VAC was reported by Arena et al. 2016 Table 4, scenario 2 and is transcribed below (Table S18.1)

The characterization potential environmental impacts of both biorefineries, the one with fossil-origin activated carbon (BRF-FAC) and the second one with vegetal-origin activated carbon (BRF-VAC) are exhibited in Fig. S18.1 below. The main trends are the following:

-Seventeen PEIs of BRF-VAC were lower than those of BRF-FAC. The highest percentage decreases were found for the PEIs: FWEu 48.31%, HNCT 44.93%, MEc 40.50%, FRS 38.00%, and FWEc 37.91%. There was one tie: the stratospheric O_3 depletion.

-All the relative contributions (in percentage) of the stage NN to PEIs of BRF-VAC were lower than those of BRF-FAC.

-As a consequence, the absolute contributions (in units of PEI) of the stage NN to the BRF-VAC impacts were lower than those absolute contributions to impacts of BRF-FAC

Table S18.1. Burdens for the production of 1 t of Activated Carbon from coconut shells[a] for the base case scenario considered in the present sensitivity analysis (excerpted and adapted from Arena et al., 2016, Table 4).

Direct burdens for tonne of activated carbon	**Scenario 2**
Resource consumptions of the activated carbon process	
Electric energy (Mexican energy mix)[b] (MJ)	2160
Thermal energy (Mexican energy mix)[b](MJ)	1330
Water (kg)	1550
Air emissions of AC production process	
Carbon dioxide, biogenic (kg)	3760
Water (kg)	3860
Oxygen (kg)	690
Nitrogen (kg)	9900
Carbon monoxide (g)	1510
Nitrogen oxides, as NO_2 (g)	1130
Dust (g)	38
Tar (as naphthalene) (kg)[c]	783

[a] the input mass of coconut shells was 6.7 t
[b] it was replaced by a Mexican energy mix
[c] the Scenario 2 assumes that distillate products from carbonization unit (such as tar, for instance) are released into the atmosphere. It is a conservative assumption/scenario (the worst one).

The analysis of the NPEIs of both biorefineries confirmed the findings in Fig. S18.1. Fig. S18.2 depicts the eighteen NPEIs of both the BRF with fossil-origin activated carbon and vegetal-based activated carbon. Seventeen environmental impacts decreased their NPEIs for BRF VAC. The most outstanding decreases corresponded to high-value ecotoxicity-related NPEIs and human health-related impacts.

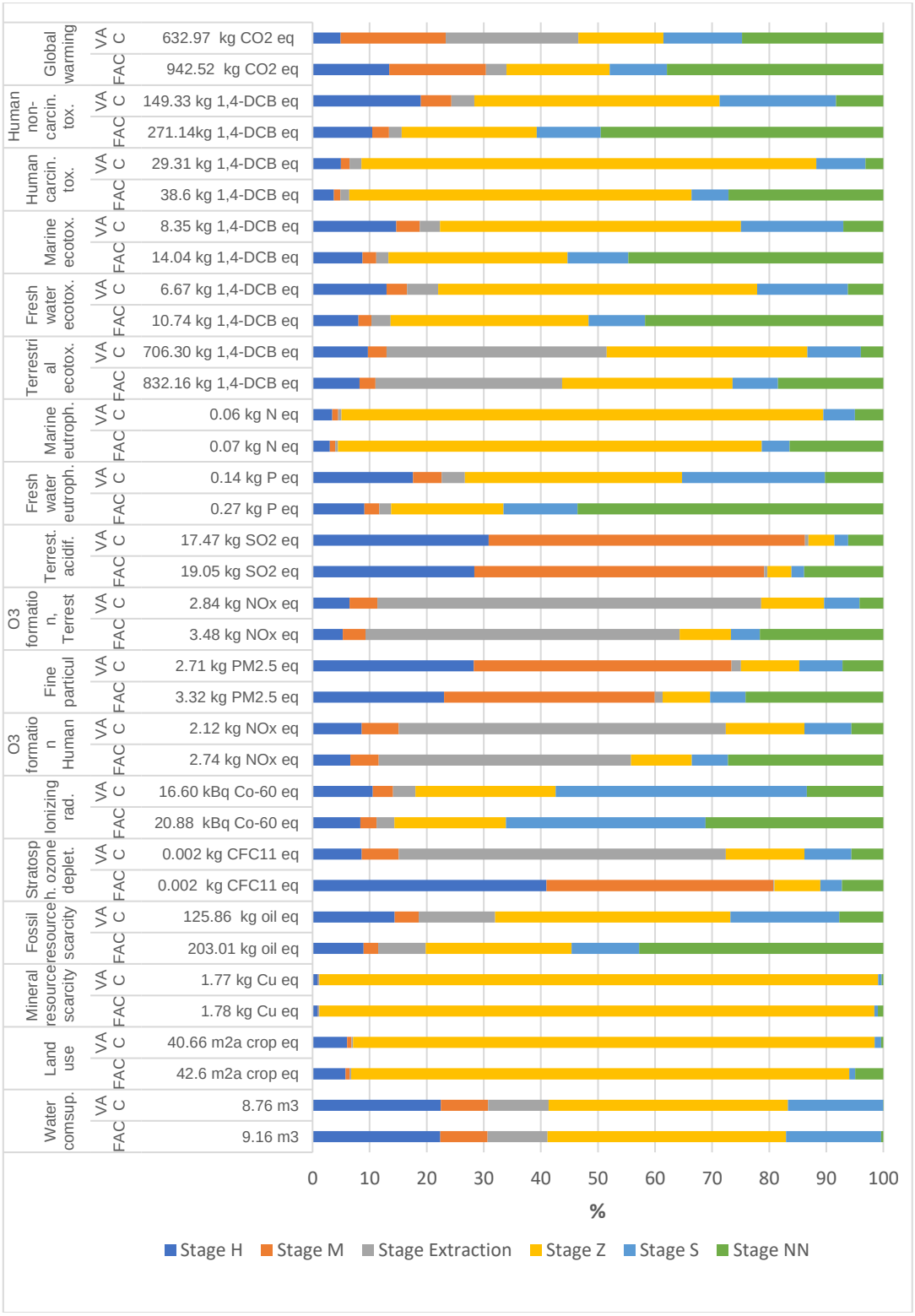


Fig. S18.1. Characterization potential environmental impacts for both biorefineries (the one using FAC and the other using VAC.)

Keys: BRF-FAC stands for biorefinery using fossil-origin activated carbon; BRF-VAC stands for biorefinery using vegetal-origin activated carbon.

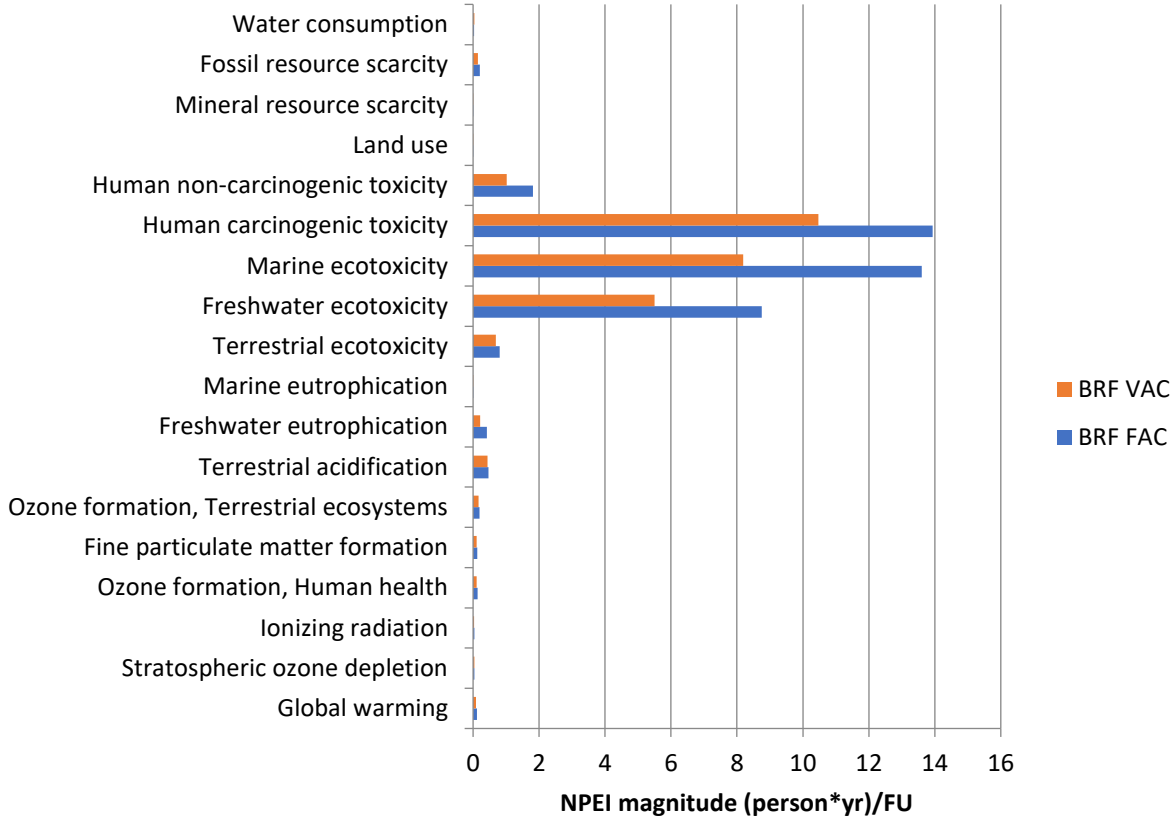


Fig S18.2. Normalized potential environmental impacts of the BRF with fossil-origin activated carbon and vegetal-based activated carbon.
Keys: BRF-FAC stands for biorefinery using fossil-origin activated carbon; BRF-VAC stands for biorefinery using vegetal-origin activated carbon.

Table S18.2 Indicators σ-τ for biorefineries using fossil-origin activated carbon and vegetal activated carbon

$\alpha_{BRF\ FAC}$ [a]	$\alpha_{BRF\ VAC}$ [b]	σ [c]	N_{EVT} [d]	N_{REFT} [e]	τ [f]
40.73	27.041	log(40.73/27.041)= 0.1779	18	0	Log[(17+0.5+1)/(0.5+1)] = 1.091[g]

[a] sum of the normalized environmental impacts of biorefinery with fossil-origin activated carbon, in (person*yr/FU)
[b] sum of the normalized environmental impacts of biorefinery with vegetal activated carbon, in (person*yr/FU)
[c] GBAER sustainability index related to the quantitative comparison of the environmental sustainability between two technologies
[d] N° of NPEI in EVT (evaluated technology, that is BRF-VAC) that are lower than the corresponding NPEI in REFT
[e] N° of NPEI in REFT (reference technology, that is, BRF-FAC) lower than EVT, or equivalently,
[f] GBAER sustainability index related to the dominance/restrictions in the environmental sustainability in the comparison of two technologies
[g] one PEI (stratospheric O_3 depletion) was a tie, so the impact influence od one is halved in the numerator and the denominator of the indicator τ

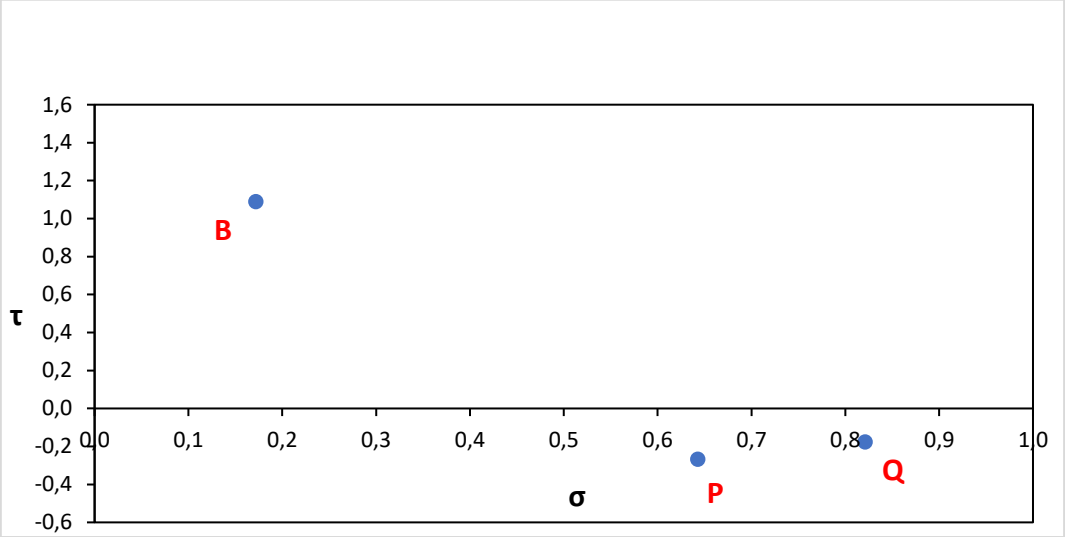


Fig. S18.3. Positions of the points B and Q that represent the environmental sustainability comparison of both biorefineries and the ES comparison of IER between IER and BRF-VAC, respectively, in the σ-τ plane. The point P that represents the ES comparison of IER and BRF-FAC is also included.

Table S18.3. Indicators σ-τ for a biorefinery using vegetal-origin activated carbon and incineration with energy recovery.

α_{IER} [a]	$\alpha_{BRF\ VAC}$ [b]	σ [c]	N_{EVT} [d]	N_{REFT} [e]	τ [f]
179.11	27.041	log(179.11/27.041)= 0.8211	7	11	Log[(7+1)/(11+1)]= -0.1761

[a] sum of the normalized environmental impacts of IER, in (person*yr/FU)
[b] sum of the normalized environmental impacts of biorefinery with vegetal activated carbon, in (person*yr/FU)
[c] GBAER sustainability index related to the quantitative comparison of the environmental sustainability between two technologies
[d] N° of NPEI in EVT (evaluated technology, that is BRF-VAC) that are lower than the corresponding NPEI in REFT
[e] N° of NPEI in REFT (reference technology, that is, IER) lower than EVT, or equivalently,
[f] GBAER sustainability index related to the dominance/restrictions in the environmental sustainability in the comparison of two technologies

The immediate consequence of this pattern was that the indicator α for the BRF-VAC was significantly lower than that of BRF-FAC. Their values are shown in Table S18.2. The α indicator decreased from 40.73 to 27.041 (person*yr/FU) (-40.13%) when replacing FAC with VAC in the BRF, which represented an absolute net decrease of 13.42 (person*yr/FU) (Table S18.2). The values of the other two indicators were σ = 0.178 and τ = 1.091. Point B, which compares both BRFs in the s-t plane, lies on Quadrant 1. According to the discussion in Annex 8 and section 3.4. of the RRRRMS, this means that the BRF that used VAC was more environmentally sustainable than the BRF that used FAC with ***dominance*** (Fig. S18.3). Please also see Annex 8 in SM for calculating the environmental sustainability indices α, σ, τ based on normalized environmental impacts.

The ES comparison between IER and the BRF-VAC is summarized in Table S18.3. and Fig. S18.4. The values of the indicator α were 179.11 and 27.041 (person*yr/FU) for the IER and the BRF-VAC, respectively (a difference of 73.77%), which represented an absolute, net decrease of 152.069 (person*yr/FU) (Table S18.3). The Point P, which holds for comparing IER and BRF-FAC, is included for comparison. The restrictions in comparing IER/BRF-VAC (point B) were lower than those in comparing IER/BRF-FAC because the τ value for the first case increased. This is favorable to the BRF-VAC from the ES evaluation/comparison standpoint with IER. *In conclusion, replacing fossil-origin-activated carbon with VAC in the BRF significantly improved the BRF's environmental sustainability and increased its environmental superiority concerning IER. The ES of the three technologies, in descending order, were BRF-VAC > BRF-FAC > IER*

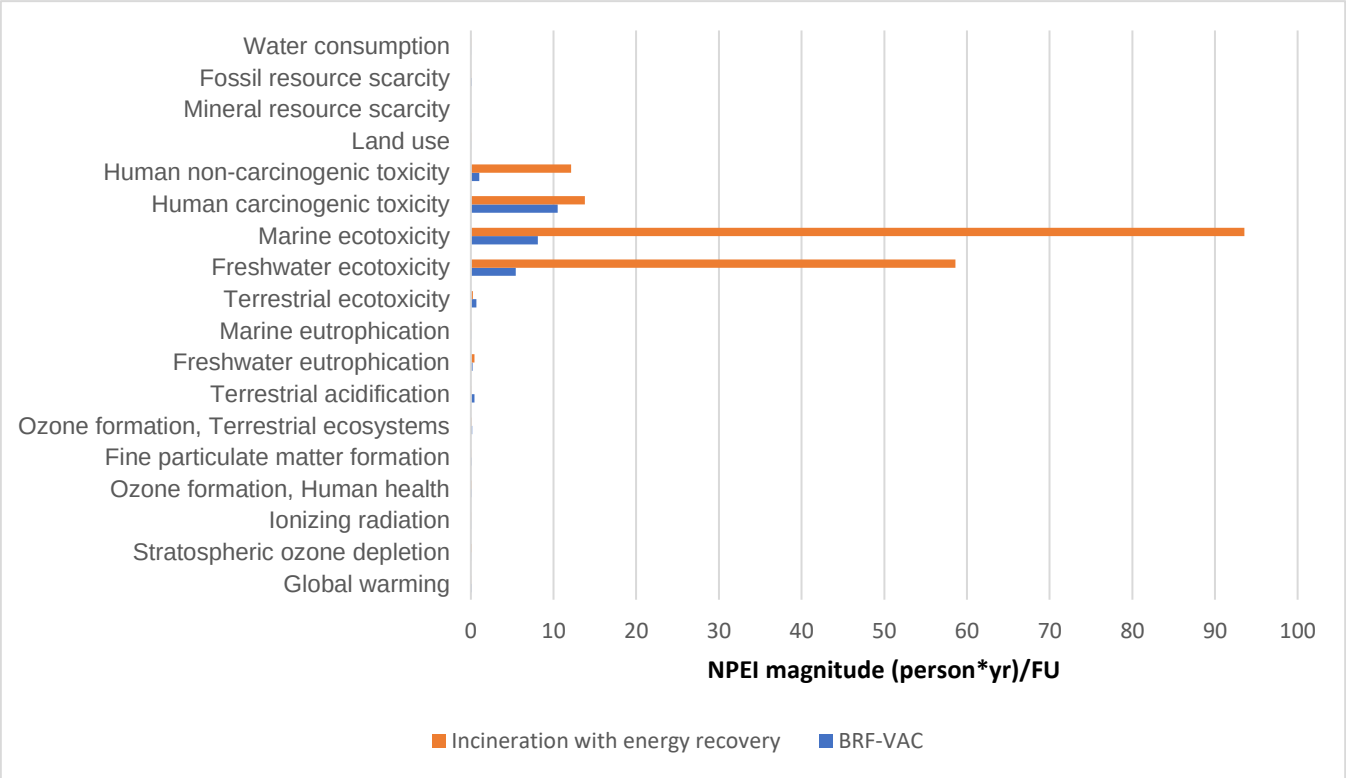


Fig. S18.4 Normalized potential environmental impacts of Incineration with energy recovery and the BRF vegetal-based activated carbon (Arena et al. 2016)**.**

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Annex S19. Emissions to the atmosphere of the incineration plant in this work.

For the incinerator emissions, the steps shown in Fig. S19.1 were followed. First, the proxy entitled "Biowaste {CH}| treatment of municipal incineration with fly ash extraction | Cut-off, U" was selected from the Ecoinvent 3.5 database. Next, the FU was harmonized by the total mass of the two functional units (the proxy and our BRF) and the two dry matter contents, using the factors δ and ϕ (sub-section 2.1.4. of the article). Emissions for the harmonized FU were estimated by multiplying the emissions in the proxy by both δ and ϕ. Subsequently, the harmonization of the proxy emissions for the harmonized FU was carried out taking into account the maximum permissible levels (MPV) of emissions in the regulations on emissions to the atmosphere by incinerators in Mexico and Switzerland (NOM-098-SEMARNAT-2002; European Energy Agency, 2022). To do this, the ratios of the MPV of each reported item were determined, with the Mexican MPV in the numerator and the MPV of the Swiss regulation in the denominator. With these ratios, an average quotient (factor) was obtained. Next, the corresponding emissions of the modified proxy were multiplied by this factor to account for Mexican regulations' permissibility, poorer maintenance, etc. The ratio average factor might change (decrease) in the future. However, the Mexican Government has not announced any intention to update the emissions regulations of incinerators to the atmosphere, that is, to replace the MPV with more stringent levels.

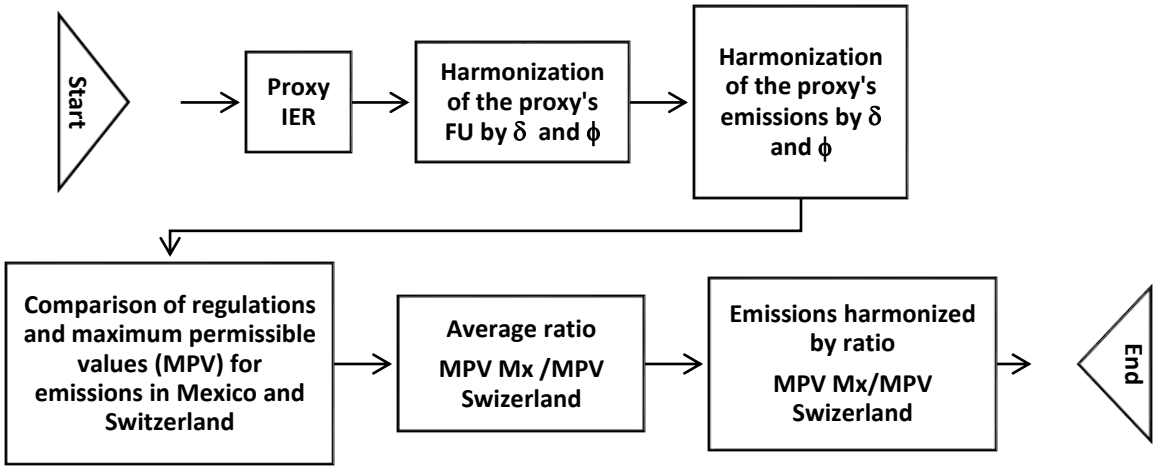


Fig. S19.1. Procedure for harmonization of incineration's emissions of the proxy selected from Eco-Invent database.

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