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SUPPLEMENTARY INFORMATION TO MAXIMIZING ENVIRONMENTAL IMPACT SAVINGS POTENTIALS THROUGH INNOVATIVE BIOREFINERY ALTERNATIVES: AN APPLICATION OF THE TM-LCA FRAMEWORK FOR REGIONAL SCALE IMPACT ASSESSMENT.

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1. Methodology

1.1. Feedstock and Digestate before and after treatment

Table S1. Physiochemical charachteristics of mixture of liquid and solid cow manure and wine marc, before and after treatment.

		Post-processing		
	Feedstock Mix	**Sludge PHA**	**Sludge Biogas**	
Organic Matter	209.8	125.6	140.1	kg OM
TAN-N	2.7	4.0	3.7	kg TAN
Organic-N	3.1	1.9	2.1	kg ON
Total Nitrogen	5.8	5.8	5.8	kg N
H2O	756.6	767.6	767.6	kg H2O
Ash	22.6	22.6	22.6	kg Ash

1.2. Individual Feedstock Characterization

Values for wine marc, based on [1].

Table S2. Physiochemical charachteristics of each feedstock as well as mixture of feedstock used in the study.

	Mixture	Liquid Cow Manure		Solid Cow Manure		Wine Marc	
Raw protein %TS	10.8605	16.95	% TS	15.92	%TS		%TS
Fats	4.84475	5.31	% TS	2.47	%TS	5.2	%TS
Cellulose	17.9765	18.49	% TS	25.56	%TS	14	%TS
Hemicellulose	17.688	20.23	% TS	20.55	%TS	12.83	%TS
Lignin	15.08825	5.12	% TS	5.99	%TS	33.23	%TS
Ash	13.78375	20.72	% TS	16.78	%TS	2.6	%TS
Other Volatile (assume carb)	19.75825	13.20		12.75		32.14	
Total nitrogen	2.12375	2.70	% TS	2.55	%TS	1.12	%TS
P	0.1376525	0.07332	% TS	0.43995	%TS	0.1	%TS

1.3. Biogas and PHA Operating Parameters

Table S3. Operational parameters for biogas and PHA production.

Yield of PHA (biomass growth& PHA accumulation)	**0.11**	**kgCOD/kgCOD-VFA**	**[2]**
PHA as 100% PHB	1.67	kgCOD/kgPHB	[2]
Yield as PHB	0.07	kgPHB/kgCOD-VFA	[2]

CH_4 in Biogas	60	%	Primary data
Heat Value CH_4	9.94	kWh/Nm3	[3]
Biogas Yield	0.70	m3 biogas / kg VS	[3]
Electricity output cogeneration unit	40.8	%	Primary data

1.4. Field Emissions and Assumptions

1.4.1. Emission factor for reference cases

Table S4. Emission factors for based on [4] with the exception of N_2O emissions based on the IPCC values for national emission's inventories [5].

	PHA Digestate	**Biogas Digestate**	**Mineral fertilizer**	Unit
High Response FRANCE				
N2O emission rate	1.00% [a]	1.00% [a]	1.00% [a]	% tot N
NH3 emission rate	1.60%	1.60%		% TAN
NH3 emission rate	1.09%	1.03%	2.00% [b]	% tot N
NO3 ground	23.40%	23.40%	10.70%	% tot N
NO3 surface	25.40%	25.40%	11.20%	% tot N
Crop N uptake rate	27.10%	27.10%	62.70%	% tot N
LOW Response FRANCE				
N2O emission rate	1.00% [a]	1.00% [a]	1.00% [a]	% tot N
NH3 emission rate	1.60%	1.60%		% TAN
NH3 emission rate	1.09%	1.03%	2.00%[b]	% tot N
NO3 ground	31.40%	31.40%	31.60%	% tot N
NO3 surface	34.30%	34.30%	31.80%	% tot N
Crop N uptake rate	14.50%	14.50%	5.10%	% tot N

	PHA Digestate	**Biogas Digestate**	**Mineral fertilizer**	Unit
High Response OREGON				
N2O emission rate	1.00% [a]	1.00% [a]	1.00% [a]	% tot N
NH3 emission rate	1.60%	1.60%		% TAN
NH3 emission rate	1.09%	1.03%	2.00%	% tot N
NO3 ground	17.20%	17.20%	6.00%	% tot N
NO3 surface	39.20%	39.20%	13.70%	% tot N
Crop N uptake rate	18.20%	18.20%	62.00%	% tot N
LOW Response OREGON				
N2O emission rate	1.00% [a]	1.00%[a]	1.00% [a]	% tot N
NH3 emission rate	1.60%	1.60%		% TAN
NH3 emission rate	1.09%	1.03%	2.00%	% tot N
NO3 ground	20.10%	20.10%	26.80%	% tot N
NO3 surface	46.00%	46.00%	60.10%	% tot N
Crop N uptake rate	13.10%	13.10%	5.80%	% tot N

[a] IPCC [5]; [b] [6].

1.4.2. Emission factor for N_2O sensitivity analysis

N_2O emissions sensitivity. High and low response France. Based on [4].

30 **Table S4.** N_2O emission factors used for sensitivity analysis.

	PHA Digestate	Biogas Digestate	Mineral fertilizer	Unit
High N2O emission rate	2.60%	2.60%	1.70%	% tot N
Low N2O emission rate	2.30%	2.30%	0.20%	% tot N

31

N2O sensitivity, Response OREGON				
	PHA Digestate	Biogas Digestate	Mineral fertilizer	Unit
High N2O emission rate	2.50%	2.50%	2.10%	% tot N
Low N2O emission rate	2.40%	2.40%	1.20%	% tot N

32 N application rate was assumed to be 139.3 kg N/ha [7]. Digestates were assumed to be
33 incorporated within 12 hours of application, with trailing hose. Soil is clay loam.

34 **2. Results**

35 *2.1. Midpoint results, PET as RP, 1% improvement process energy consumption PHA production, RR 93%*

Table S5. LCA results for midpoint impact categories ReCiPE 2016 (H). PET is replacement polymer at a 93% replacement ratio, while efficiency of PHA production improves by 1% per year.

	Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
FR- High demand future_Biogas	-3.54E-02	-3.85E+00	-5.33E-01	-6.11E-03	-2.35E+00	-3.95E-01	-1.67E+01	-3.98E+00	-6.69E-01	-7.66E-01	4.91E-01	-7.36E-01	-7.13E-02	-7.18E-02	3.25E-04	-1.07E-01	-6.11E+01	-1.60E-01
FR- High demand future_PHA	-3.94E-02	-6.10E+00	-5.99E-01	-7.18E-03	-6.58E+00	-5.46E-01	-1.94E+01	-3.05E+00	-6.34E-01	-8.73E-01	4.90E-01	-7.44E-01	-7.81E-02	-7.89E-02	3.25E-04	-1.10E-01	-7.21E+01	-2.07E-01
FR-Diversification future_Biogas	-3.57E-02	-3.95E+00	-5.37E-01	-6.12E-03	-2.61E+00	-3.97E-01	-1.67E+01	-3.52E+00	-6.83E-01	-7.72E-01	4.91E-01	-7.36E-01	-7.20E-02	-7.24E-02	3.25E-04	-1.08E-01	-6.17E+01	-1.58E-01
FR-Diversification future_PHA	-3.96E-02	-6.17E+00	-6.02E-01	-7.18E-03	-6.76E+00	-5.47E-01	-1.95E+01	-2.73E+00	-6.43E-01	-8.77E-01	4.90E-01	-7.44E-01	-7.85E-02	-7.94E-02	3.25E-04	-1.11E-01	-7.25E+01	-2.06E-01
FR-Low growth future_Biogas	-3.49E-02	-3.79E+00	-5.22E-01	-6.10E-03	-2.15E+00	-3.92E-01	-1.66E+01	-4.18E+00	-7.02E-01	-7.52E-01	4.91E-01	-7.36E-01	-7.04E-02	-7.08E-02	3.25E-04	-1.06E-01	-5.99E+01	-1.60E-01
FR-Low growth future_PHA	-3.90E-02	-6.06E+00	-5.91E-01	-7.17E-03	-6.45E+00	-5.44E-01	-1.94E+01	-3.18E+00	-6.57E-01	-8.63E-01	4.90E-01	-7.44E-01	-7.74E-02	-7.83E-02	3.25E-04	-1.09E-01	-7.13E+01	-2.07E-01
FR-New mix future_Biogas	-3.57E-02	-3.93E+00	-5.53E-01	-6.14E-03	-2.59E+00	-4.01E-01	-1.69E+01	-3.05E+00	-6.83E-01	-7.92E-01	4.91E-01	-7.36E-01	-7.19E-02	-7.23E-02	3.25E-04	-1.08E-01	-6.23E+01	-1.57E-01
FR-New mix future_PHA	-3.96E-02	-6.16E+00	-6.13E-01	-7.20E-03	-6.74E+00	-5.49E-01	-1.95E+01	-2.41E+00	-6.43E-01	-8.90E-01	4.90E-01	-7.44E-01	-7.85E-02	-7.93E-02	3.25E-04	-1.11E-01	-7.29E+01	-2.05E-01
FR-Static Scenario	-3.60E-02	-3.95E+00	-4.95E-01	-6.09E-03	-2.68E+00	-3.91E-01	-1.65E+01	-4.32E+00	-7.23E-01	-7.20E-01	4.91E-01	-7.36E-01	-7.23E-02	-7.27E-02	3.25E-04	-1.09E-01	-6.05E+01	-1.61E-01
FR-Static Scenario_PHA	-3.98E-02	-6.17E+00	-5.73E-01	-7.16E-03	-6.81E+00	-5.43E-01	-1.93E+01	-3.29E+00	-6.71E-01	-8.41E-01	4.90E-01	-7.44E-01	-7.87E-02	-7.96E-02	3.25E-04	-1.12E-01	-7.17E+01	-2.07E-01
OR-Biomass scenario_Biogas	-3.50E-02	-4.27E+00	-5.33E-01	-7.07E-03	-3.77E+00	-4.54E-01	-1.76E+01	-6.61E-01	-9.57E-01	-7.68E-01	4.38E-01	-7.33E-01	-7.17E-02	-7.21E-02	3.24E-04	-1.08E-01	-5.61E+01	-1.52E-01
OR-Biomass scenario_PHA	-3.91E-02	-6.39E+00	-5.99E-01	-7.83E-03	-7.56E+00	-5.85E-01	-2.01E+01	-7.66E-01	-8.32E-01	-8.74E-01	4.37E-01	-7.42E-01	-7.83E-02	-7.92E-02	3.24E-04	-1.11E-01	-6.86E+01	-2.02E-01
OR-Even growth scenario_Biogas	-3.47E-02	-4.26E+00	-5.36E-01	-7.02E-03	-3.73E+00	-4.52E-01	-1.75E+01	-6.57E-01	-7.78E-01	-7.71E-01	4.38E-01	-7.33E-01	-7.12E-02	-7.17E-02	3.24E-04	-1.07E-01	-5.62E+01	-1.52E-01
OR-Even growth scenario_PHA	-3.89E-02	-6.38E+00	-6.01E-01	-7.80E-03	-7.53E+00	-5.84E-01	-2.00E+01	-7.63E-01	-7.09E-01	-8.76E-01	4.37E-01	-7.42E-01	-7.80E-02	-7.89E-02	3.24E-04	-1.10E-01	-6.87E+01	-2.01E-01
OR-Wind and solar scenario_Biogas	-3.46E-02	-4.26E+00	-5.38E-01	-6.99E-03	-3.71E+00	-4.51E-01	-1.74E+01	-6.55E-01	-6.78E-01	-7.74E-01	4.38E-01	-7.33E-01	-7.10E-02	-7.14E-02	3.25E-04	-1.06E-01	-5.63E+01	-1.51E-01
OR-Wind and solar scenario_PHA	-3.88E-02	-6.38E+00	-6.03E-01	-7.78E-03	-7.51E+00	-5.84E-01	-1.99E+01	-7.61E-01	-6.40E-01	-8.78E-01	4.37E-01	-7.42E-01	-7.78E-02	-7.87E-02	3.24E-04	-1.09E-01	-6.87E+01	-2.01E-01
OR-Static Scenario_Biogas	-3.55E-02	-4.84E+00	-5.44E-01	-8.24E-03	-5.85E+00	-5.38E-01	-1.82E+01	-6.49E-01	-4.03E-01	-7.87E-01	4.38E-01	-7.32E-01	-7.47E-02	-7.51E-02	3.25E-04	-1.08E-01	-5.48E+01	-1.51E-01
OR-Static Scenario_PHA	-3.94E-02	-6.78E+00	-6.07E-01	-8.64E-03	-8.99E+00	-6.44E-01	-2.05E+01	-7.57E-01	-4.50E-01	-8.87E-01	4.37E-01	-7.42E-01	-8.04E-02	-8.13E-02	3.24E-04	-1.11E-01	-6.77E+01	-2.01E-01

Cumulative midpoint results, PET as RP, 1% improvement process energy consumption PHA production, RR 93%

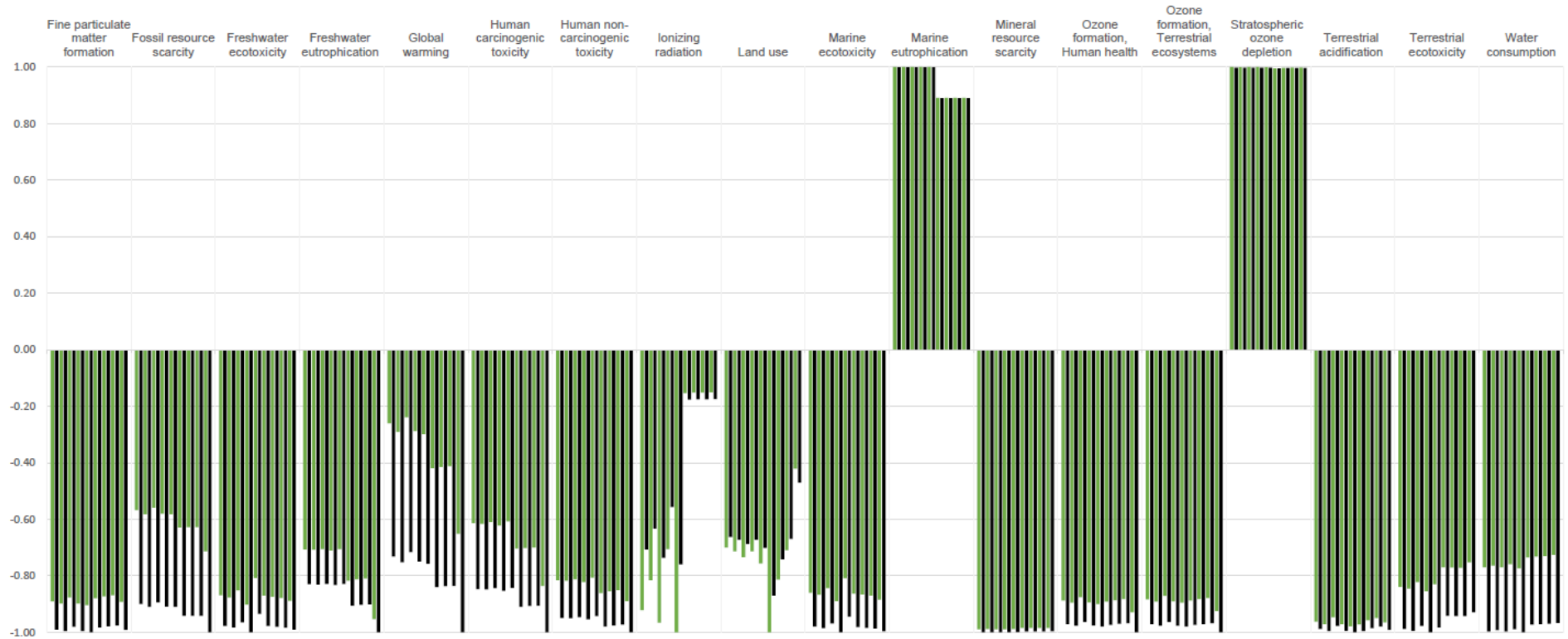

Figure S1. Cumulative midpoint level impacts for all 18 impact categories, ReCiPe 2016 (H). Green bars show Biogas-only production, while black bars show combined PHA-biogas. To the left, the first 10 bars correspond to Languedoc energy mixes, while the 8 from the right correspond to Oregon scenarios. Scenarios were internally normalized to the worse or best performing scenario per impact category.

2.2. Midpoint results, PLA as RP, 1% improvement process energy consumption PHA production, RR 64%

Table S6. LCA results for midpoint impact categories ReCiPE 2016 (H). PLA is replacement polymer at a 64% replacement ratio, while efficiency of PHA production improves by 1% per year.

	Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
FR- High demand future_Biogas	-3.54E-02	-3.85E+00	-5.33E-01	-6.11E-03	-2.35E+00	-3.95E-01	-1.67E+01	-3.98E+00	-6.69E-01	-7.66E-01	4.91E-01	-7.36E-01	-7.13E-02	-7.18E-02	3.25E-04	-1.07E-01	-6.11E+01	-1.60E-01
FR- High demand future_PHA	-3.76E-02	-5.37E+00	-5.70E-01	-6.82E-03	-5.13E+00	-4.93E-01	-1.85E+01	-3.05E+00	-6.18E-01	-8.28E-01	4.90E-01	-7.41E-01	-7.56E-02	-7.63E-02	3.25E-04	-1.06E-01	-6.80E+01	-1.89E-01
FR-Diversification future_Biogas	-3.57E-02	-3.95E+00	-5.37E-01	-6.12E-03	-2.61E+00	-3.97E-01	-1.67E+01	-3.52E+00	-6.83E-01	-7.72E-01	4.91E-01	-7.36E-01	-7.20E-02	-7.24E-02	3.25E-04	-1.08E-01	-6.17E+01	-1.58E-01
FR-Diversification future_PHA	-3.78E-02	-5.43E+00	-5.73E-01	-6.83E-03	-5.32E+00	-4.94E-01	-1.85E+01	-2.73E+00	-6.27E-01	-8.33E-01	4.90E-01	-7.41E-01	-7.60E-02	-7.67E-02	3.25E-04	-1.07E-01	-6.84E+01	-1.88E-01
FR-Low growth future_Biogas	-3.49E-02	-3.79E+00	-5.22E-01	-6.10E-03	-2.15E+00	-3.92E-01	-1.66E+01	-4.18E+00	-7.02E-01	-7.52E-01	4.91E-01	-7.36E-01	-7.04E-02	-7.08E-02	3.25E-04	-1.06E-01	-5.99E+01	-1.60E-01
FR-Low growth future_PHA	-3.72E-02	-5.32E+00	-5.62E-01	-6.81E-03	-5.00E+00	-4.91E-01	-1.84E+01	-3.19E+00	-6.41E-01	-8.18E-01	4.90E-01	-7.41E-01	-7.49E-02	-7.56E-02	3.25E-04	-1.05E-01	-6.71E+01	-1.89E-01
FR-New mix future_Biogas	-3.57E-02	-3.93E+00	-5.53E-01	-6.14E-03	-2.59E+00	-4.01E-01	-1.69E+01	-3.05E+00	-6.83E-01	-7.92E-01	4.91E-01	-7.36E-01	-7.19E-02	-7.23E-02	3.25E-04	-1.08E-01	-6.23E+01	-1.57E-01
FR-New mix future_PHA	-3.78E-02	-5.42E+00	-5.84E-01	-6.84E-03	-5.30E+00	-4.97E-01	-1.86E+01	-2.39E+00	-6.27E-01	-8.47E-01	4.90E-01	-7.41E-01	-7.59E-02	-7.67E-02	3.25E-04	-1.07E-01	-6.88E+01	-1.88E-01
FR-Static Scenario	-3.60E-02	-3.95E+00	-4.95E-01	-6.09E-03	-2.68E+00	-3.91E-01	-1.65E+01	-4.32E+00	-7.23E-01	-7.20E-01	4.91E-01	-7.36E-01	-7.23E-02	-7.27E-02	3.25E-04	-1.09E-01	-6.05E+01	-1.61E-01
FR-Static Scenario_PHA	-3.80E-02	-5.44E+00	-5.43E-01	-6.81E-03	-5.37E+00	-4.90E-01	-1.84E+01	-3.29E+00	-6.56E-01	-7.96E-01	4.90E-01	-7.41E-01	-7.62E-02	-7.70E-02	3.25E-04	-1.07E-01	-6.76E+01	-1.90E-01
OR-Biomass scenario_Biogas	-3.50E-02	-4.27E+00	-5.33E-01	-7.07E-03	-3.77E+00	-4.54E-01	-1.76E+01	-6.61E-01	-9.57E-01	-7.68E-01	4.38E-01	-7.33E-01	-7.17E-02	-7.21E-02	3.24E-04	-1.08E-01	-5.61E+01	-1.52E-01
OR-Biomass scenario_PHA	-3.73E-02	-5.66E+00	-5.70E-01	-7.50E-03	-6.14E+00	-5.34E-01	-1.91E+01	-7.07E-01	-8.22E-01	-8.30E-01	4.37E-01	-7.39E-01	-7.58E-02	-7.65E-02	3.24E-04	-1.07E-01	-6.44E+01	-1.84E-01
OR-Even growth scenario_Biogas	-3.47E-02	-4.26E+00	-5.36E-01	-7.02E-03	-3.73E+00	-4.52E-01	-1.75E+01	-6.57E-01	-7.78E-01	-7.71E-01	4.38E-01	-7.33E-01	-7.12E-02	-7.17E-02	3.24E-04	-1.07E-01	-5.62E+01	-1.52E-01
OR-Even growth scenario_PHA	-3.71E-02	-5.65E+00	-5.72E-01	-7.46E-03	-6.11E+00	-5.33E-01	-1.90E+01	-7.04E-01	-6.95E-01	-8.32E-01	4.37E-01	-7.39E-01	-7.55E-02	-7.62E-02	3.24E-04	-1.06E-01	-6.45E+01	-1.84E-01
OR-Wind and solar scenario_Biogas	-3.46E-02	-4.26E+00	-5.38E-01	-6.99E-03	-3.71E+00	-4.51E-01	-1.74E+01	-6.55E-01	-6.78E-01	-7.74E-01	4.38E-01	-7.33E-01	-7.10E-02	-7.14E-02	3.25E-04	-1.06E-01	-5.63E+01	-1.51E-01
OR-Wind and solar scenario_PHA	-3.70E-02	-5.65E+00	-5.74E-01	-7.45E-03	-6.09E+00	-5.32E-01	-1.90E+01	-7.03E-01	-6.25E-01	-8.34E-01	4.37E-01	-7.39E-01	-7.53E-02	-7.60E-02	3.25E-04	-1.05E-01	-6.46E+01	-1.84E-01
OR-Static Scenario_Biogas	-3.55E-02	-4.84E+00	-5.44E-01	-8.24E-03	-5.85E+00	-5.38E-01	-1.82E+01	-6.49E-01	-4.03E-01	-7.87E-01	4.38E-01	-7.32E-01	-7.47E-02	-7.51E-02	3.25E-04	-1.08E-01	-5.48E+01	-1.51E-01
OR-Static Scenario_PHA	-3.76E-02	-6.06E+00	-5.78E-01	-8.33E-03	-7.61E+00	-5.94E-01	-1.96E+01	-6.98E-01	-4.30E-01	-8.43E-01	4.37E-01	-7.39E-01	-7.79E-02	-7.87E-02	3.25E-04	-1.06E-01	-6.35E+01	-1.83E-01

Midpoint impacts PLA as RP, 1% improvement process energy consumption PHA production, RR 64%

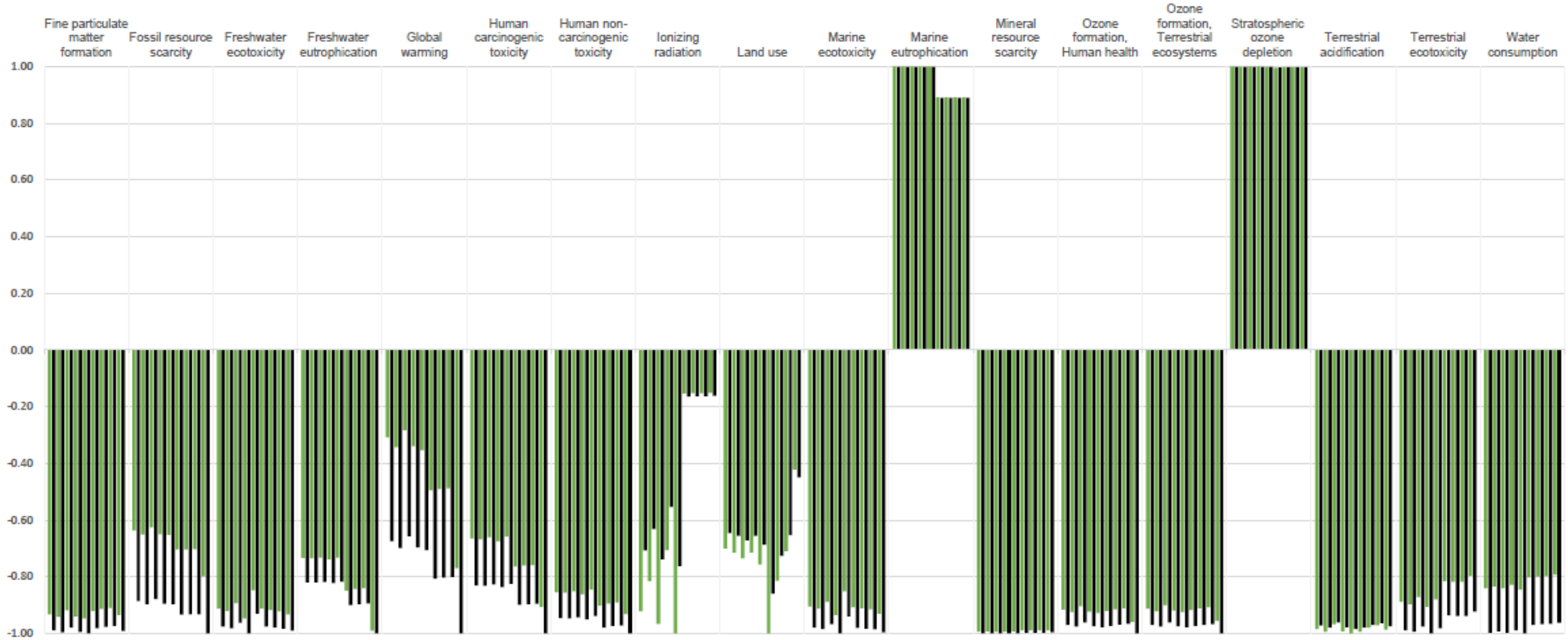

Figure S2. Cumulative midpoint level impacts for all 18 impact categories, ReCiPe 2016 (H). Green bars show Biogas-only production, while black bars show combined PHA-biogas. To the left, the first 10 bars correspond to Languedoc energy mixes, while the 8 from the right correspond to Oregon scenarios. Scenarios were internally normalized to the worse or best performing scenario per impact category.

2.3. Sensitivity analysis improvement in process consumption, tested values are 0% and 5% yearly improvement in energy efficiency, with PLA as replacement polymer

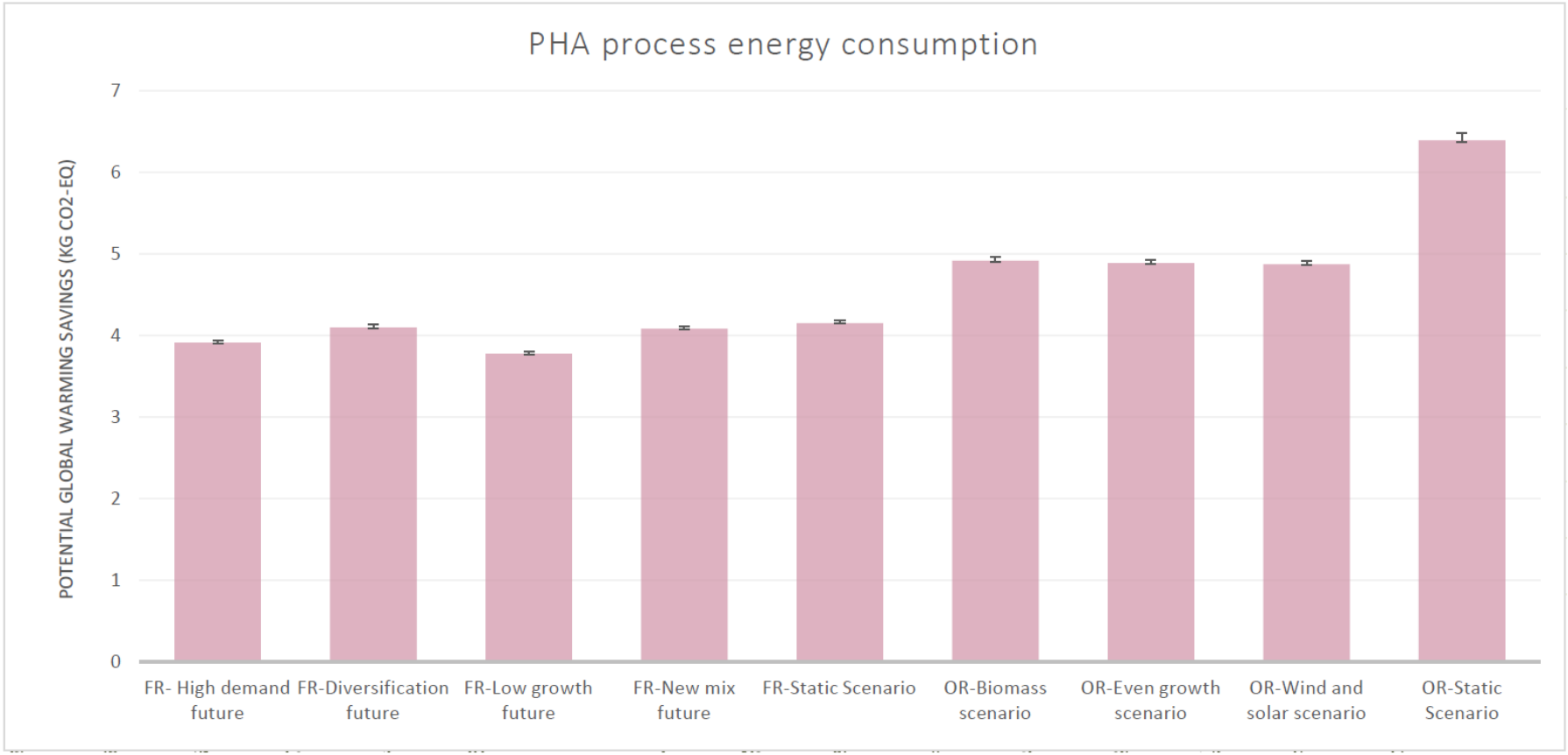

Figure S3. shows cumulative GWP savings in relation to Biogas-only scenario. Error bars show the small influence of the energy efficiency values for PHA process consumption tested

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2.4. Sensitivity analysis N_2O emission factors

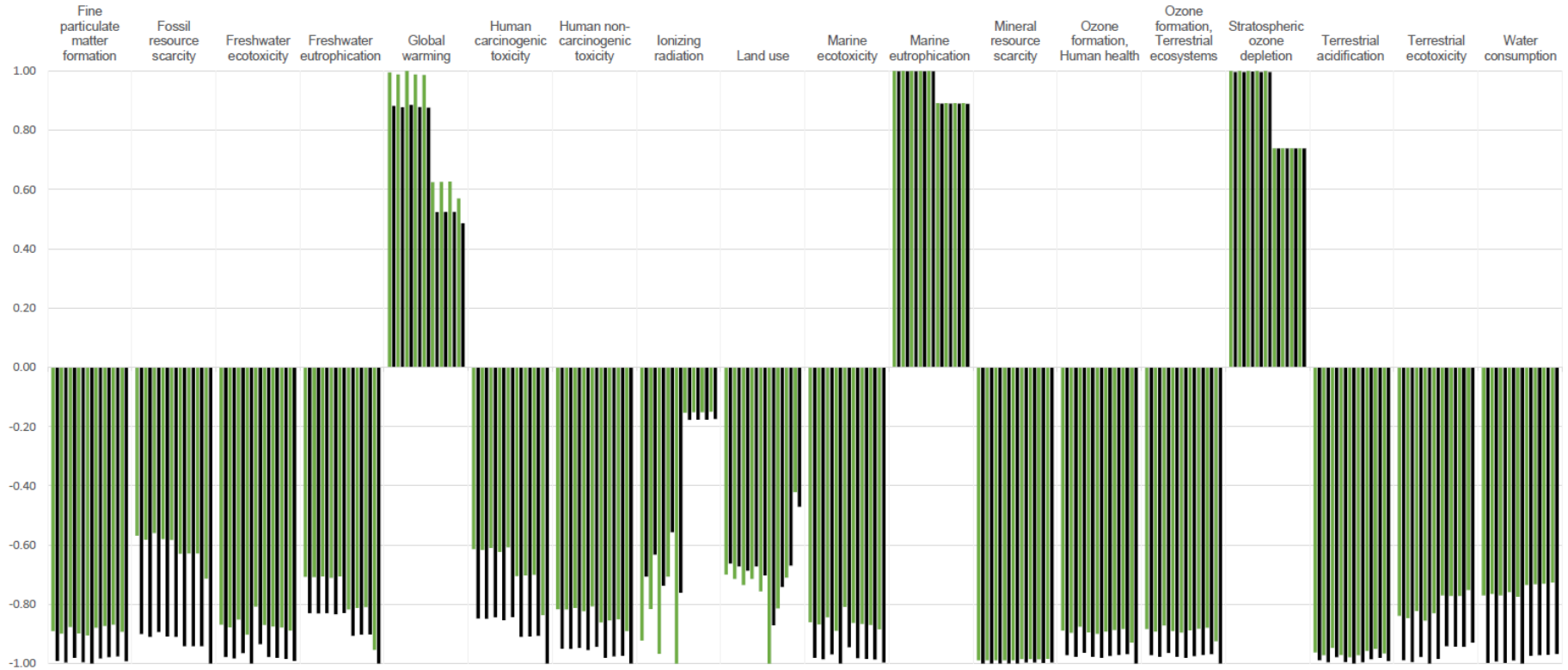

Figure S4. Cumulative midpoint level impacts for all 18 impact categories, ReCiPe 2016 (H). Green bars show Biogas-only production, while black bars show combined PHA-biogas. To the left, the first 10 bars correspond to Languedoc energy mixes, while the 8 from the right correspond to Oregon scenarios. Scenarios were internally normalized to the worse or best performing scenario per impact category. N_2O emission factors from Yoshida et al, 2015.

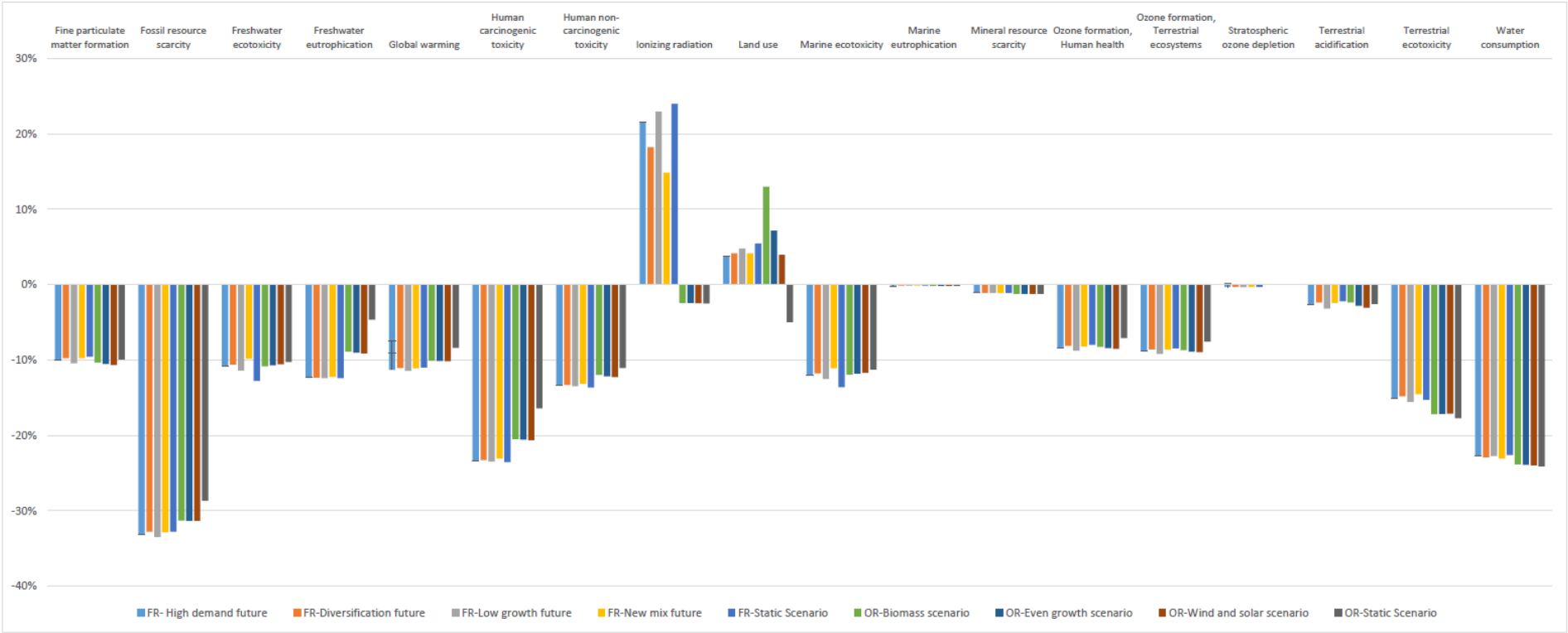

Figure S5. Cumulative difference for all impact categories for PHA-biogas minus Biogas-only scenarios. PHA-biogas continues to outperform Biogas-only in almost every impact category though the difference lessens. N_2O emission factors from Yoshida et al, 2015.

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