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1. Document Info

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1.2. Revision history

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PU Public	**X**
CI Classified, as referred to Commission Decision 2001/844/EC	
CO Confidential, only for members of the consortium (including the Commission Services)	

2. Summary

Background	In order to comparatively assess the maximum potential environmental impact savings from the implementation of innovative biorefinery alternatives, the Territorial Metabolism-Life Cycle Assessment (TM-LCA) framework is implemented. The framework includes integrated life cycle assessment, territorial metabolism and dynamic LCA.
Objectives	To provide holistic decision support and large scale assessments before the implementation of new technologies.
Methods	Two biorefinery alternatives are assessed, one where only biogas is produced and another where biogas and polyhydroxyalkanoates (PHA) are co-produced. The feedstock processed by the biorefineries includes a mixture of wine pomace, liquid and solid cow manure. These alternative processes are assessed for two regions, one in Southern France and the other in Oregon, USA. The production of PHA is assessed as both a replacement for Polyethylene terephthalate (PET) and polylactide (PLA). Multiple dynamic energy provision and other dynamic inventory scenarios are assessed for both regions, and territorial scale impacts are assessed using both midpoint impacts and single score indicators.
Results & implications	It is determined that in all probable future scenarios, a biorefinery with PHA-biogas co-production is preferable to a biorefinery only producing biogas. Based on the results of this study, it can be concluded that when a biorefinery is installed in Oregon or Languedoc-Roussillon to handle a mix of grape mark and cow wastes, it is very likely that it would be environmentally beneficial to include PHA production in addition to energy and digestate. However, based on the results of the sensitivity analysis regarding transportation, special care needs to be taken in regards to assessing the potential increase of biomass transport; else, it is likely that all environmental benefit from the biorefinery will be offset by the induced impacts of transportation. Likewise, the induced environmental impact reductions cannot be ensured if the feedstock for the biorefinery is to be rerouted from another use. Thus, it is concluded that PHA production should be seen as a potentially valuable add-on for biogas platforms.

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3. Manuscript submitted in the Journal Sustainability

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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Abstract

In order to comparatively assess the maximum potential environmental impact savings from the implementation of innovative biorefinery alternatives, the Territorial Metabolism- Life Cycle Assesment (TM-LCA) framework is implemented. Two biorefinery alternatives are assessed, one where only biogas is produced and another where biogas and polyhydroxyalkanoates (PHA) are co-produced. These alternative processes are assessed for two regions, one in Southern France and the other in Oregon, USA. The production of PHA is assessed as both a replacement for Polyethylene terephthalate (PET) and polylactide (PLA). Multiple dynamic energy provision and other dynamic inventory scenarios are assessed for both regions, and territorial scale impacts are assessed using both midpoint impacts and single score indicators. It is determined that in all probable future scenarios, a biorefinery with PHA-biogas co-production is preferable to a biorefinery only producing biogas.

4. Introduction

Life cycle assessment (LCA) is a tool designed to assess the environmental impacts of products and services (International Organization for Standardization, 2006). Recent advances in the field of LCA, such as the inclusion of temporal dynamism (Sohn et al., in press) and the coupling of LCA to urban metabolism (Goldstein, Birkved and Quitzau, 2013) are a response to a growing body of knowledge, attempting to address its known limitations. These advances are an especially important input that can guide the transition into a sustainable bioeconomy. LCA of durable production systems, such as various agricultural production e.g. wine, cereal, meat, can benefit from adding some of the new developments, as the large inputs and outputs to these systems have great environmental implications when changes are implemented. As laid out in (Sohn, Vega and Birkved, 2018) assessing large systems, as the above mentioned, can be approached by defining the geographical boundaries in terms of a “producer territory” so that the LCA can be applied to a territory. The TM-LCA framework reduces data demand by aggregating individual areas of the production of, for example, a specific product, supply chain or waste treatment technology, while ignoring unchanging background systems. At the same time, representativeness is increased by merging local inventory data from individual producers with regional and nation-wide data to fill in data gaps. In this way, an improvement in the territory, due to e.g. the implementation of a new technology or new management technique, can be measured in the non-contiguous production area and be reflected in the territory results. When combined with dynamic LCA, this approach offers an extremely comprehensive assessment that gives temporally and geographically relevant results.

Moreover, it has the added utility of providing prospective insights that can more accurately support decision makers, production owners, and technology developers.

A point of departure for many LCAs is a static product system, where for example, technology A might be assessed against technology B, for the making of a product. The static nature of LCA is problematic when applied to products or system with long service lives (Sohn *et al.*, 2017) , due to inconsistencies in time horizons and changes in background systems (Pinsonnault *et al.*, 2014; Beloin-saint-pierre *et al.*, 2016). Previous work has demonstrated the importance of incorporating various types of dynamism into LCA, as this can significantly affect the results of the study (Pinsonnault *et al.*, 2014) In this regard, it is possible to add dynamism to the various stages of the LCA in a consistent manner, as outlined in (Sohn et al., in press) and shown in various other publications (Levasseur, Lesage and Margni, 2012; Beloin-saint-pierre *et al.*, 2016; Benetto, Tiruta-barna and Pign, 2016). In the TM-LCA framework, dynamism is added in a consistent manner from the start, which provides added information regarding the sensitivity of the system to background changes. Static systems rarely represent ever-changing reality, and results based on static systems can sometimes exhibit rank reversal, when compared to dynamic results (Vega, Sohn and Birkved, 2018). Thus, basing future decisions on static LCAs can result in building significant error into the models and associated results. Adding dynamic aspects to LCAs increases the analytical accuracy of results (Almeida *et al.*, 2015).

The added layers of information to the TM-LCA, mean that the interpretation phase becomes more resource intensive. This can be eased by the use of extra tools, such as multi-criteria assessment (MCDA). Midpoint results for 18 different impact categories of an LCA, are often difficult to synthesize into clear decision support. By adding dynamism, this translates into temporally specific results for each year of the time horizon, for each of the 18 impact categories. Out of the many MCDA methods that exist, one that has shown great capability in dealing with LCA results is Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981; Sohn, Kalbar and Birkved, 2017). The output from TOPSIS is given in the form of a single score performance index, which is used to derive preference between the scenarios being assessed. By checking a multiple criteria decision support tool used with equal weightings for all midpoint impacts, it is easy to develop an indication of burden shifting amongst the midpoint impact categories when used in conjunction with a visual inspection of internally normalized results. This is considered preferable, as using carbon footprint alone without checks has been shown to give potentially misleading results (Laurent, Olsen and Hauschild, 2012).

Present study aims to provide as comprehensive as possible an assessment by using the TM-LCA approach to assess the introduction of a new technology for the treatment of agricultural residues. A scenario of biogas production is compared to a scenario of combined biogas and Polyhydroxyalkanoates (PHA) production, which is currently being developed at pilot scale. Polyhydroxyalkanoates are naturally occurring polymers, produced by a consortium of bacteria, which can feed of the volatile fatty acid (VFA) stream generated by the acidogenic phase of anaerobic digestion (AD)(Cavinato *et al.*, 2017). The two scenarios are modeled with dynamics built into both foreground and background systems. The scenarios are then tested at a territorial scale, in two geographically dissimilar producing territories, to observe the effects of regional differences on territorial performance. Finally, MCDA is applied in the interpretation phase to prevent drawing incorrect conclusions from the use of global warming potential (GWP) as a single indicator and to help ease interpretation of results.

5. Methodology

5.1. TM-LCA Framework Application

The application of the TM-LCA framework is described in general terms here. A point of departure for the application of the TM-LCA framework is the functional unit. The functional unit, the treatment of one ton of feedstock of specific composition, is treated by two different technology alternatives, described in more detail below. From here, the following steps are applied and described through the methodology:

(a) Alternative technology is defined.
(b) The producer territory is defined and limited to systems interacting with the technological options being assessed within a geographical region.
(c) Temporal dynamics are incorporated into the systems, e.g., in dynamic background electricity energy provision and technological efficiency improvement.
(d) The assessment is scaled to encompass the whole region so that all feedstock available that may fulfill the functional unit is treated by the technological alternatives being assessed. However, only changes in systems and in the region are assessed.

5.2. Goal and Scope

In order to test the TM-LCA framework, two options for the treatment of agricultural residues were modelled. Advancements in biogas technology make it possible to treat a plethora of agricultural residues and recent innovation allows for the production of value-added products, in this case, the family of biopolymers known as polyhydroxyalkanoates (PHA). This innovative technology, which effectively creates a biogas-platform for new biorefineries, is a contender to conventional biogas production were the only products are biogas and digestate. The proliferation of biogas treatment centers make this new addition to anaerobic digestion a highly transferable technology, which can be implemented wherever agricultural residues are available. Because these types of biorefineries generally have a long service life (decades) and draw from large discontiguous areas, both territorial and dynamic aspects of this assessment are an advantage for decision makers considering biorefinery options for their region.

5.2.1. Scenarios

Two baseline scenarios were assessed with the OpenLCA (GreenDelta, 2019) software and the Ecoinvent 3.4 database (Wernet *et al.*, 2016). These were a point of departure to which the territorial and dynamic aspects were layered. The scenarios are:

5.2.1.1. *Biogas Only*

Conventional biogas production was modelled as the anaerobic digestion step of biogas production, which produces biogas and digestate. The biogas was assumed to be burned in a combined heat and power (CHP) engine, producing electricity and heat based on the energy content of the biogas. Process consumption was calculated to be 7% of the electricity output, based on data received from an industrial scale biogas plant in Northern Italy, while heat production is assumed to be wasted. This is due to the geographical areas of implementation of the scenarios, which are not expected to use the heat. Furthermore, adding the produced heat to this study would only change the magnitude of the savings from displaced energy production, and not the ranking of the scenarios, as seen in (Hamelin *et al.*, 2010), as the magnitude of heat production is similar across all scenarios. All other important operational parameters were also based on the data acquired from the abovementioned biogas plant and are available in the Supplementary Information (SI).

Areas where the scenarios are equal were left out of the assessment, as they would result in no relative difference. These include; emissions from feedstock storage, animal housing and digestate storage, as the feedstock used was the same and undergoes the same management practices, while the digestate nutrient content was next to equal. Similarly, phosphorus fertilizer replacement was left out because the starting content of P is the same, and processing is not expected to change this. Adding replacement of P fertilizer to the assessment would only elucidate differences between digestate and mineral fertilizer, which is not the focus of this study.

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Field application of the digestate was also modelled and conventional ammonium nitrate fertilizer was assumed to be replaced. The nutrient content of the digestates, as well as emission factors for all N-related emissions, for digestates and mineral N fertilizer are presented in the SI.

5.2.1.2. *PHA-Biogas*

The second scenario represents a tweaking to the AD process, where AD is split so that the VFA production that occurs during the first days of digestion is diverted and used to produce and feed biomass capable of producing PHA. This change results in the co-production of biogas and PHA, albeit with a lower biogas production. Just as above, digestate continues to be produced and replaces mineral N fertilizer. Additionally, the extraction of PHB is included as the addition of extraction process energy consumption and hydrogen peroxide as extraction agent. All other model parameters are equal to the biogas scenario.

PHA production is assumed to be 100% polyhydroxybutyrate (PHB) and replaces the production of petroleum or bio-based polymers, the replacement polymer (RP). In the first run of the model PHB replaces PET at factory gate with a replacement ratio of 0.97:1 PHB to PET. Material properties, in this case, a performance index (PI) based on yield strength (σ) and density (ρ) was used to derive the replacement rate (RR) (Equation 1). The rate of replacement is tested in the sensitivity analysis so as to represent different applications of the polymer more accurately. The choice of polymer substitution is also tested, since PHA is a bio-sourced biopolymer, a sub-scenario with replacement of polylactide (PLA) is also presented. The RR ratio is 0.59 for PLA, based on Equation 1.

$$RR = \frac{PI_{PHB}}{PI_{RP}}, \text{ and } PI = \frac{\sigma}{\rho}$$

Equation 1: polymer replacement rate, where RR= replacement rate, PI=performance index, σ= yield strength, RP= replacement polymer and ρ= density

The addition of PHA production in this scenario is not burden free, inducing impacts from energy consumption and and the production of the extraction agent. However, due to missing data from the pilot plant the additional energy consumption was calculated using the process design software Superpro Designer ® (Intelligen Inc, 2018). This yields, an additional 7 kwh/FU. It was assumed that the energy consumption for PHA production could improve over time, so a 1% decrease in energy demand for PHA production was modeled for the assessed period. This represents the maturation of PHA extraction technology, which is a likely scenario as the implementation of PHA extraction in biorefineries becomes more widespread. This value is tested in the sensitivity analysis, to explore the possibility of faster and slower improvements to the process. Key parameters for the production of PHB are presented in the SI.

5.2.2. Functional Unit

The basis for the comparison of the two scenarios is the treatment of 1000 kg of feedstock. The feedstock is assumed to be agricultural residues of the following composition: 50% liquid cow manure, 15% solid cow manure, and 35% wine pomace. Feedstock characterization is based on laboratory tests performed on site at the Italian biogas plant, for the liquid and solid manure, while for wine pomace it is based on literature values. The feedstock physiochemical properties are presented in the SI.

5.2.3. System boundaries

The system boundary of the two scenarios extends from when the feedstock enters AD to the application of digestate onto the field,

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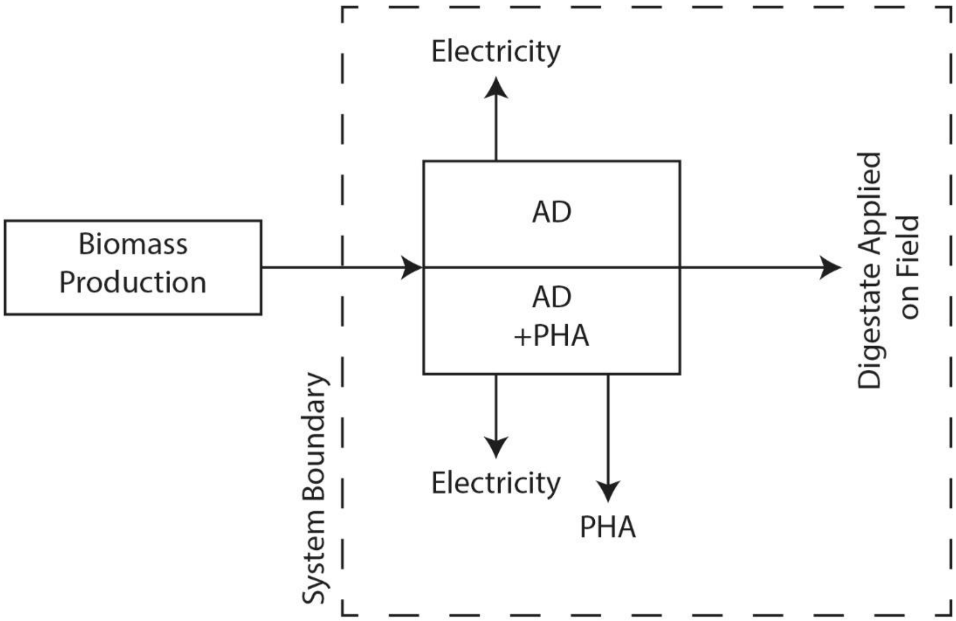

Figure 1: System boundary definition

Two geographic locations were chosen for this study, the Languedoc-Roussillon region in southeast France, and the Willamette, Umpqua, Rogue and Columbia valleys of Oregon State in the USA, in order to observe intercontinental differences in the background systems and sociopolitical context. Through a dynamic approach, all background and foreground processes are modified so that these two geographical areas are accurately represented for various future energy production scenarios.

5.3. Dynamics

Dynamic inventories of the electricity mix for the two locations, modelled for a period of 20 years from 2015-2035, were used in the analysis. Four different dynamic energy futures, developed by the French government, with yearly shifting percentages of contributing sources of energy (Figure 2) were used for all electricity provision in the scenarios for Languedoc Roussillon *(GENERATION ADEQUACY REPORT on the electricity supply-demand balance in Franc*>, no date). Likewise, three different dynamic energy futures were developed based on legislation for Oregon State (Figure 3), which regulates the share of renewables in Oregon's future energy grid (Oregon State, 2017). In order to develop future scenarios for electricity production in Oregon that meet the legislation, three energy future scenarios were developed. Qualifying renewables, i.e. renewable energy sources accepted by Oregon legislation on renewables, were introduced in varying amounts. Thus, (1) a scenario where biomass was increased more than other qualifying renewables, (2) a scenario where wind and solar were increased more than other qualifying renewables, and (3) a scenario where all qualifying renewables were increased evenly were developed.

To maintain consistency in the foreground and background systems, the electricity provision component of all Ecoinvent processes used in the assessment was exchanged with the dynamic mixes described. This included the electricity for fertilizer production, conventional polymer production, and the electricity replaced in the grid. This use of the local grid mix in the commodity production may not be representative of market reaction for the background systems and is discussed further in section 4.

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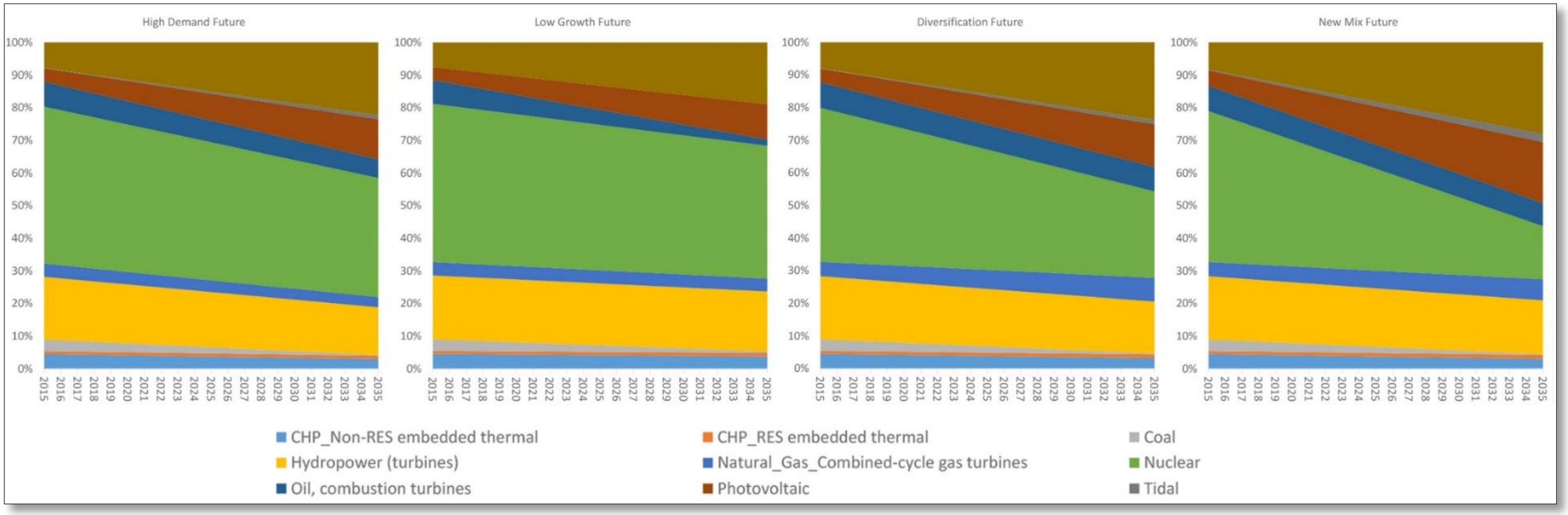

Figure 2: Evolution of French electricity grid based on future scenarios defined by Réseau de transport d'électricité (2014)

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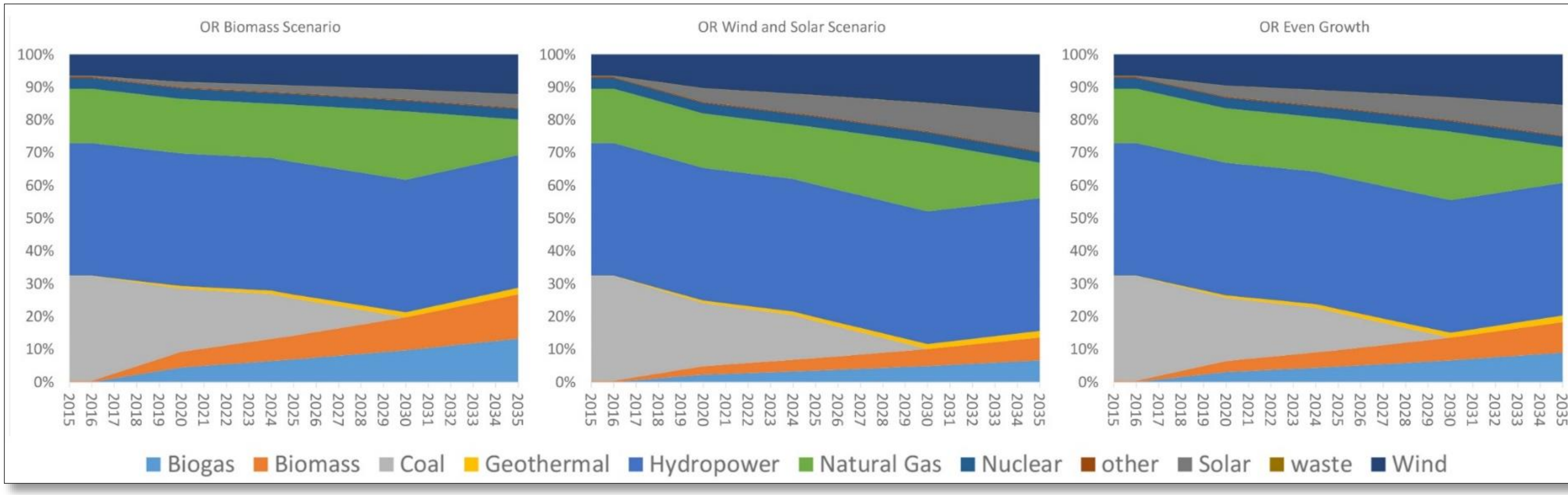

Figure 3: Evolution of Oregon electricity grid based on three possible future scenarios for fulfillment of legal requirements for decommissioning fossil based production facilities

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5.3.1. PHA process consumption

PHA production is at a more advanced level in the waste water treatment sector (Frison *et al.*, 2013; Morgan-Sagastume *et al.*, 2016) and also 1st generation PHA production from crops is at a higher tier level (Dietrich *et al.*, 2017) than 2nd generation biomass PHA production. Thus, the PHA production for 2nd generation biomass, as in the present study, will likely attain vast improvements in the future, eventually reaching a maturity level comparable to current AD production. To reflect this, dynamics in the PHA inventory were included in terms of the magnitude of electricity consumption, in addition to the dynamic electricity provision. Hence, while PHA production was modelled starting as 7 kwh/FU more burdensome than the Biogas-only scenario, thereafter, the process was modelled as becoming more energy efficient, improving by 1% annually for the 20 year period. This improvement rate was also tested to indicate its influence on total impacts (see section 5.6).

5.4. Implementation of Territorial Scale Assessment

In order to assess the implications of implementing PHA technology at a territorial scale, the two study regions, in France and Oregon respectively, were analyzed regarding ability to provide feedstock for application in the two assessed biorefinery scenarios. The territories were defined as the interacting areas of residue production and the treatment plants. However, as defined in (Sohn, Vega and Birkved, 2018), only the areas undergoing change are included in the assessment. In this case, the change is an average change reflected in the residue treatment centers. Therefore, it is not expected that this change will affect the production of the residues in any way, ergo feedstock producers are left out of the assessment in terms of environmental impact. Likewise, transport from producers to treatment centers is not expected to change, as the volume of residues produced will not change as a consequence of implementing PHA technology. Where there is potential for transport that would deviate from the status quo, namely in the transport of grape marc, impacts from transport were assessed (see 5.6, sensitivity analysis). These impacts were not included in the main results, as the induced impacts from transport would be equal in both the PHA-biogas and the Biogas-only scenarios.

5.4.1. Feedstock Provision

Several assumptions were used in determining the provisioning for feedstock. For the feedstock originating from wineries, it is assumed that grape marc is produced at a rate of 0.13 tons per ton of processed wine grapes (Torres *et al.*, 2002). It is further assumed that, in France where production data is reported in hectoliters of wine instead of mass of grapes at crush, that 140 kg of grapes are used to produce 1 hectoliter of wine (Robinson and Harding, 2015). And, for feedstock coming from cattle, it is assumed that all waste comes from dairy cattle and that dairy cattle produce waste at a rate of 54.5 kg per head per day (NW Natural, 2017).

Due to the relative scale of wine production and the cattle industry in Oregon, the production capacity of the biorefinery systems in Oregon is limited by the production grape marc, assuming that the co-digestion of cow waste and grape marc is not augmented with alternative feedstocks. With nearly 2.4 million tons of waste produced by dairy cattle annually (NW Natural, 2017) and only 8010 tons of grape marc produced annually, the treatment of all grape marc (at 35% of total treated biomass) would require appx. 1% of the dairy cattle manure provision capability of Oregon. However, the total production of this system might not be enough to provision a full industrial scale biogas plant, though it would be enough to provision a smaller scale plant, and implications of this are discussed in section 2.5.4.

Conversely, in regards to Oregon, the capacity of the biorefinery systems in Languedoc-Roussillon is limited by production of manure. With only 18,700 dairy cattle (France AgriMer, 2014),the region would

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only be able to supply appx. 0.37 million tons of the 0.39 million tons needed for co-digestion with the 0.21 million tons of grape marc produced in the region annually (CIVL - Languedoc Wines). This relationship, unlike that in Oregon, is fairly well balanced. However, unlike in Oregon, there are well-established uses for grape marc, so ability to provide grape marc as feedstock would therefore compete with existing demand. This is discussed further in section 4.

Table 1: Feedstock provision for Languedoc Roussillon and Oregon

	LANGUEDOC ROUSSILLON	OREGON
ANNUAL GRAPE MARC PRODUCTION (TONS AT CRUSH)	212,940	8,009
ANNUAL COW WASTES PRODUCTION (TONS)	372,300	2,389,091
MAX CO-DIGESTION FEEDSTOCK AVAILABILITY AT 35% GRAPE MARC (TONS/DAY)	1569	62
COW WASTE DEMAND AT 100% GRAPE MARC UTILIZATION (TONS)	395,460	14,875
GRAPE MARC DEMAND AT 100% COW WASTE UTILIZATION (TONS)	200,469	1,286,433
COW WASTE DEMAND AT 100% GRAPE MARC UTILIZATION (% OF AVAILABLE COW WASTE)	106%	0.62%
GRAPE MARC DEMAND AT 100% COW WASTE UTILIZATION (% OF AVAILABLE GRAPE MARC)	94%	16,060%

5.5. Impact Assessment Method

The ReCiPe 2016 Hierarchist method was used for impact assessment (Goedkoop *et al.*, 2009). Impacts were assessed at the midpoint level with a time horizon of 100 years from the time of emission. All impact categories were included in the assessment of the dynamic system model and in all scenarios.

While all impact categories were modelled, using all indicators creates difficulty for interpreting results. To avoid this issue, GWP was chosen as an indicator impact. In order to check for burden shifting when using GWP as an indicator impact, TOPSIS was applied with equal weighting to all impact categories. Ranking was then performed in a pairwise fashion i.e. within each energy mix future, for the two scenarios, Biogas-only and PHA-biogas using both GWP as a single score indicator and TOPSIS. Only in extreme scenarios tested in the sensitivity analysis (those deemed to be outside of what might be considered possible real world scenarios) did the technology preference differ between analysis using GWP and TOPSIS as single score indicators.

5.6. Sensitivity Analysis

Important modelling parameters and assumptions were tested through a sensitivity analysis. These include:

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5.6.1. PHA Process consumption

Process consumption for PHB, which was calculated using process design software, was tested to see if results were sensitive to this parameter. Thus, a scenario where the energy consumption of PHB production does not improve over time was tested. To contrast, a scenario where processing improves by 5% per year was also explored.

5.6.2. Replacement rate conventional polymers

Replacement rates in the first model run were based on yield strength (σ), which applies to brittle polymers that are loaded in tension. This is done in order to relate the polymer matrix to its final application, which is unknown for this case study. Thus, by choosing a handful of material properties, it is possible to estimate more realistic RR that apply to desired properties. Replacement ratios of PHB to PET and PLA were estimated using the following material property indices: tensile strength, and the average between tensile strength (TS) and yield strength (YS). The values used of the RR estimation are presented in Table 2.

Table 2 Material properties, performance indices of PET, PLA and PHB. Replacement rates are derived from the material properties, tensile strength and yield strength using Equation 1. Add TS YS

	PET[a]	PLA[b]	PHA[c]
Yield strength, σ (Mpa)	2410.0	3830.0	2200.0
Tensile strength (Mpa)	38.8	48.0	32.0
Density (kg/m^3)	1.3	1.2	1.2
Performance index YS	1882.8	3088.7	1833.3
Performance index TS	30.3	38.7	26.7
Average performance	956.6	1563.7	930.0
RR, YS	0.97	0.59	
RR, TS	0.88	0.69	
RR, AVG	0.97	0.59	

[a] average PET http://www.matweb.com/search/datasheet.aspx?MatGUID=a696bdcdff6f41dd98f8eec3599eaa20
[b] NatureWorks® Ingeo™ 3001D Injection Grade PLA http://www.matweb.com/search/datasheet.aspx?MatGUID=a696bdcdff6f41dd98f8eec3599eaa20
[c] Bastioli, Catia, 2016

5.6.3. Feedstock provisioning scenarios

In both regions there is potential for increased ground transportation in order to transport grape marc, as present transport for grape marc is, in most cases, non-existent in Oregon and to spread among various end-users in France. This means that implementing the PHA producing biorefinery would either route or re-route the grape marc needed as feedstock. To account for this, the system was modelled with ground transport by lorry of the grape marc. This was done for various potential transport distances ranging from 50-500 km for the PET replacement scenario.

6. Results

Results showed the PHA scenarios outperformed the Biogas-only scenarios in almost every impact category with a few exceptions (Figure 4). Exceptions included the Fine Particulate Matter Formation (PM), Terrestrial Acidification (TA), and Land Use Change (LUC), though LUC had an instance where PHA-biogas performed better than Biogas-only. Biogas-only had higher savings for the Ionizing Radiation (IR) impact category, though this is only true for the French scenarios.

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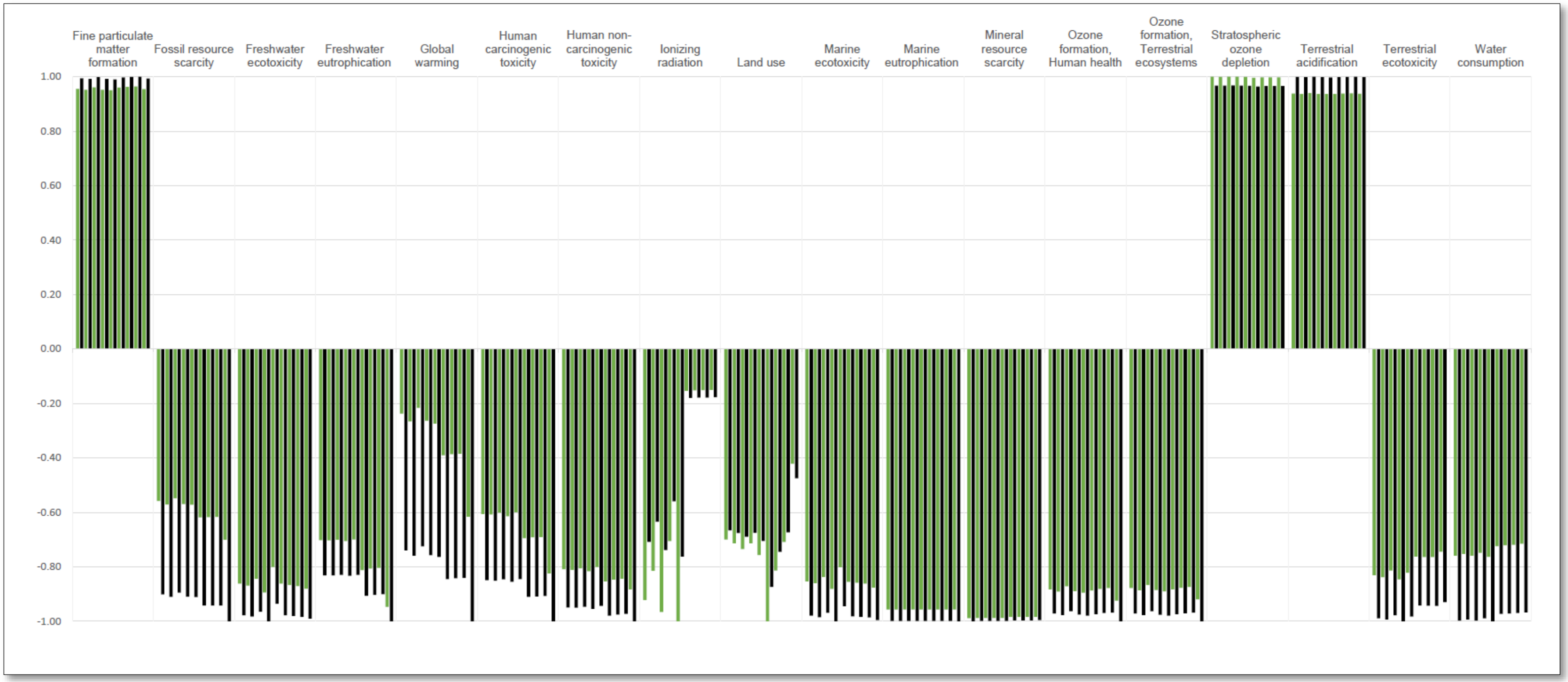

Figure 4 Cumulative midpoint level impacts for all 18 impact categories, ReCiPe 2016 (H). Black bars show combined PHA-biogas production, while green bars show Biogas-only. To the left, the first 10 bars correspond to Languedoc energy mixes, while the 8 from the right correspond to Oregon scenarios.

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It is worth noting that in some of the impact categories the difference between the two scenarios is so small (~4% difference) that, keeping in mind the uncertainty of the assumptions, it is fair to say that both PHA-biogas and Biogas-only are equally good or bad. This is true for the PM, Marine Eutrophication (ME), LUC, Mineral Resource Scarcity (MRC), and Stratospheric Ozone Depletion (SOD) impact categories. The remaining impact categories show a greater difference were it is clear that the PHA scenarios are preferable.

The baseline shown in Figure 4 had PET as the conventional polymer to be replaced by PHB. Results did not change for any of the impact categories If the polymer is to be replaced is PLA, but the magnitude of the savings or burdens changes slightly. For example, savings are higher for PHA-biogas when PET is the replacement polymer, rather than PLA. Figures and tables for the PHA-biogas results for PLA are shown in the SI.

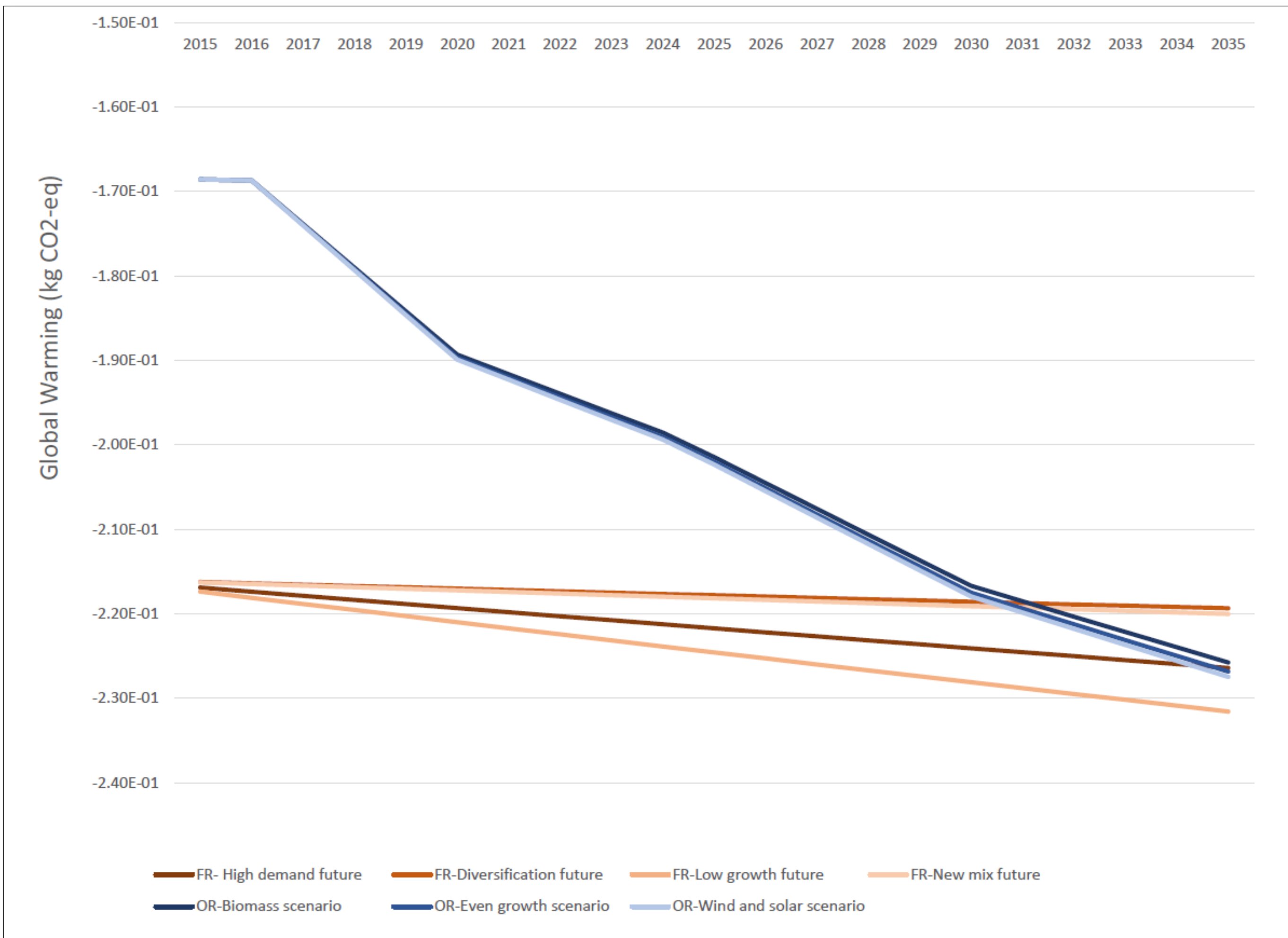

Figure 5 Difference in Global Warming potential between combined PHA-biogas and Biogas-only scenarios. Negative values show PHA-biogas has higher savings throughout the full 20 year period.

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Figure 5 shows the difference between PHA-biogas and Biogas-only scenarios i.e. PHA-biogas CO2-eq *minus* Biogas-only, in CO2-eq. For all twenty years, the PHA-biogas scenario induces greater savings than the Biogas-only scenarios, which is why the results are always negative. More interestingly, it is possible to observe the difference between plans for energy grid development in the two locations. Hence, Oregon scenarios show a steeper slope i.e. a drastic pull back from the use of fossil fuels and more specifically the use of coal. In contrast, the French slopes are less pronounced, as improvements to the grid are more subtle, because there is already a large share of renewable energy in use in France. The difference between the two scenarios is larger at the beginning of the period, getting smaller in time as the grids progressively increase their share of renewable energy.

6.1. Sensitivity results

The robustness of model results was checked by varying different parameters, as described in the methodology. None of the sensitivity parameters changed the ranking of the two scenarios, and combined PHA-biogas continued to show greater savings. After each change, indicators were checked with TOPSIS and GWP single indicators, but still there was no change to the preference ranking of the scenarios, and PHA-biogas continued to perform better. Thus, it can be said that the model results are robust in regards to the parameters checked.

More in detail, changes to the replacement rate according to different material properties, as discussed in 5.6.2, was shown to be moderately sensitive. A 5% change in the replacement rate lead to a 3-4% change in results for PHA-biogas with PET (Figure 6), and a 4-5% change in results for PHA-biogas PLA. Thus, it can be said that a general trend is observed of lower savings with lower RR (or higher saving with higher RR), while the effect of the change is nearly proportional to the change seen in the results.

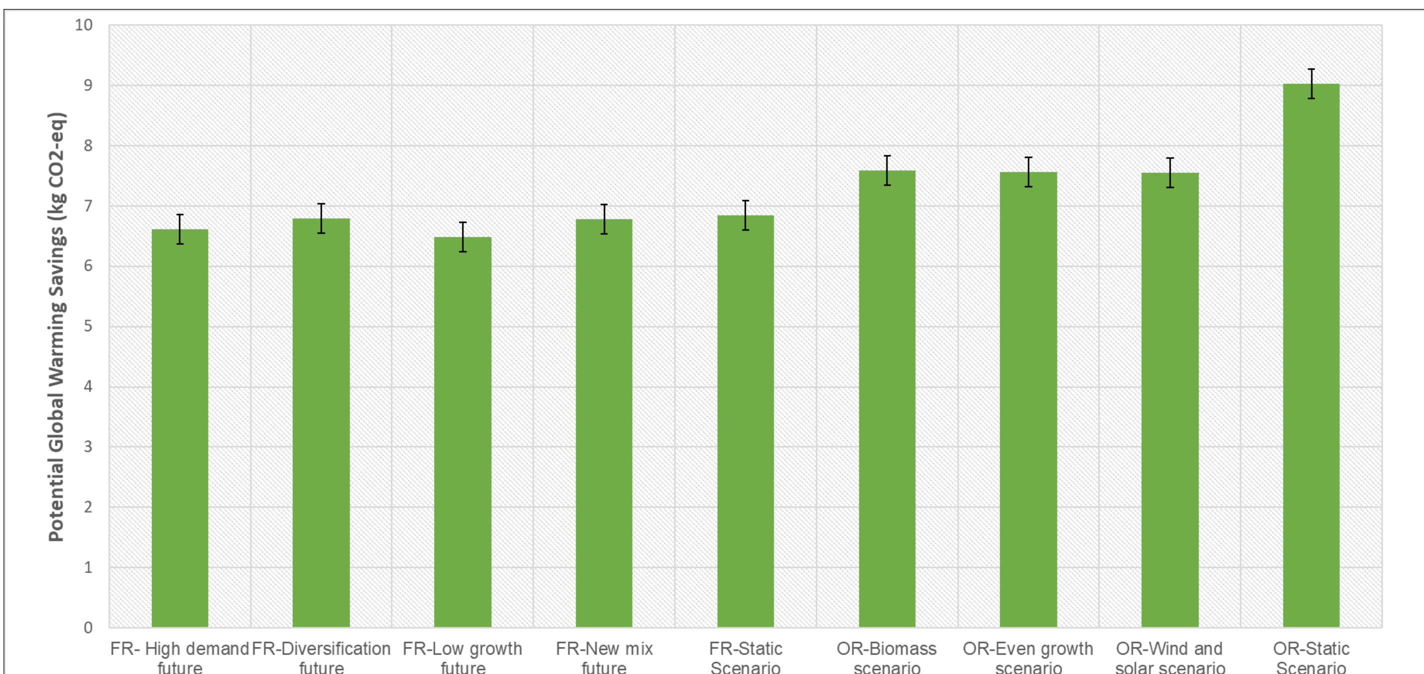

Figure 6 Sensitivity analysis of replacement rate of conventional polymers by PHB. Global warming potential savings for replacement of PET by PHB. Green bars represent an average of performance indices, while the upper limit of the black bar are based on yield strength. PHA scenarios only.

Interestingly, the upper bar of RR for PET represent yield strength, while the lower bar represents tensile strength. This is reversed for PLA, figure in SI.

The sensitivity to energy consumption during processing was also tested and it is shown in the SI. This parameter showed to have very little effect on overall model results, with GWP changing in the range of 0.5%-1.3%.

6.2. Territorial scale application

Application of the biorefinery alternatives at a territorial scale would lead to potential reductions in regional scale environmental impact. In order to give a measure of scale to the potential savings induced by the implementation of the two scenarios, the GWP impacts were normalized using carrying capacity based normalization factors. Assuming a 985 kg CO_2 eq. per person year (PY) carrying capacity (C.Cap) (Bjørn and Hauschild, 2015), and assuming that PHA replaces PET with a 97% RR and that the PHA process improves in terms of energy efficiency at 1% annually, the production of PHA induces an average reduction in GWP impacts equating to over 2500 PY of C.Cap. Using the same assumptions except exchanging the RP with PLA production at a 59% RR, then the production of PHA-biogas induces an average impact reduction of 768 PY of C.Cap when compared to production of Biogas-only.

Table 3: Carrying capacity normalized GWP reduction for maximum application of the PHA-biogas and the Biogas-only biorefinery alternatives in France and Oregon based on replacement of PET with 97% RR and a 1% annual energy efficiency improvement for PHA production

	GWP Reduction/Fu	PY of C.Cap Reduction Daily	PY of C.Cap Reduction Annually
Fr- high demand future_biogas	2.20	4	1280
Fr- high demand future_pha	6.86	11	3987
Fr-diversification future_biogas	2.46	4	1433
Fr-diversification future_pha	7.04	11	4093
Fr-low growth future_biogas	2.01	3	1168
Fr-low growth future_pha	6.72	11	3910
Fr-new mix future_biogas	2.44	4	1418
Fr-new mix future_pha	7.02	11	4082
Fr-static scenario_biogas	2.54	4	1476
Fr-static scenario_pha	7.09	11	4122
Or-biomass scenario_biogas	3.62	6	2107
Or-biomass scenario_pha	7.83	12	4555
Or-even growth scenario_biogas	3.59	6	2085
Or-even growth scenario_pha	7.81	12	4540
Or-wind and solar scenario_biogas	3.56	6	2072

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Or-wind and solar scenario_pha	7.79	12	4531
Or-static scenario_biogas	5.71	9	3318
Or-static scenario_pha	9.27	15	5390

6.2.1. Sensitivity analysis of transport at territorial scale

At 200 km, the transport reduces average impact savings from the various biorefinery-location scenarios by 41%, inducing impacts of a maximum of appx. 305% and a minimum of 66%of the GWP savings induced by the biorefinery scenarios. At 50km, all scenarios except the French low growth future electricity scenario show reductions in GWP, and at 100km, all PHA production scenarios induce GWP savings while some biogas only production scenarios induce increased GWP. At 500km, all scenarios induce increased GWP impacts.

Table 4: sensitivity to inclusion of transport in percentage change to midpoint impacts without transport

	50KM	200KM	500KM
Average change amongst all impact categories	10.3%	41.3%	103.2%
Average change in gwp	37.3%	149.2%	373.0%
Max change in gwp	76.2%	305.0%	762.4%

7. Discussion

7.1. Polymer replacement rate

Overall, model results were robust and indicate that implementing PHA technology is preferable to conventional AD, when the functional unit is 1 ton of feedstock treated. Combined PHA-biogas scenarios, whether with PET or PLA as the replaced polymer, performed better almost across every impact category. This is largely due to the added benefit of replacing conventional polymers, which was an important parameter in the model. As evidenced by the RR sensitivity analysis, decreasing or increasing the amount of PHB needed to equate the function of PET or PLA resulted in a proportional effect in the outcome. RR would have to decrease by around 80% and be as low as 0.2 before there is rank reversal in some of the impact categories. This was confirmed by single score indicators, which did not flip until reaching this very low level of replacement i.e. before Biogas-only is the preferred choice over PHA-biogas by TOPSIS and GWP. Furthermore, the single score indicators employed generally agreed on PHA-biogas being the preferred choice across all energy futures when RRs were higher than 0.2 (Table 4). It is worth noting that such a low replacement rate is not expected, as the material properties of PHB are good for various applications (Bastioli, Catia, 2016).

Table 5. Single indicator preference, by TOPSIS with equal weights or GWP. Sensitivity values shown. For energy demand of calculated PHA production, values start with 10 times the calculated energy needed. For RR, values are shown for a replacement rate lower than 42%; above this value, PHA-biogas is always preferred.

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		FR-High Demand Future	FR-Diversification Future	FR-Low Growth Future	FR-New Mix Future	FR-Static Scenario	OR-Biomass Scenario	OR-Even Growth Scenario	OR-Wind and Solar Scenario	OR-Static Scenario
Energy Demand for PHA Production (kWh/FU)										
70.70	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
	TOPSIS Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
77.70	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
	TOPSIS Preference	PHA	PHA	PHA	PHA	Biogas	PHA	PHA	PHA	PHA
84.84	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
	TOPSIS Preference	Biogas	Biogas	Biogas	PHA	Biogas	Biogas	PHA	PHA	PHA
98.98	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	PHA	PHA	PHA
106.10	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	PHA	PHA
113.12	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	Biogas
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	PHA	PHA
127.26	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	Biogas
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	PHA
226.34	GWP Preference	PHA	PHA	PHA	PHA	PHA	Biogas	Biogas	Biogas	Biogas
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas
388.85	GWP Preference	PHA	PHA	PHA	PHA	Biogas	Biogas	Biogas	Biogas	Biogas
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas
537.32	GWP Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas
Polymer replacement ratio (PHB:PET)										
42%	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
	TOPSIS Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
32%	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA
	TOPSIS Preference	PHA	PHA	PHA	PHA	Biogas	Biogas	Biogas	Biogas	PHA
22%	GWP Preference	PHA	PHA	PHA	PHA	PHA	PHA	PHA	PHA	Biogas
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas
12%	GWP Preference	PHA	Biogas	PHA	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas
	TOPSIS Preference	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas	Biogas

7.2. PHA process energy consumption

Unlike replacement rate, improvements in process consumption for the production of PHA lead to very small changes in results. If there is no improvement in process consumption, meaning production of PHA takes 7kwh more per FU than Biogas-only, results still stay the same. The limit of this value is high i.e. it takes 12 times this value, before TOPSIS single indicator shows preference for Biogas-only over PHA, and even then this is true for only one of the pairwise comparisons of energy futures. Moreover, it takes 30 times this value before it is possible to observe a flip in a few of the impact categories and 40 times the value so that GWP is reversed for Oregon. For France, it is not until PHA-biogas uses 70 times this value before there is a flip for GWP in two of the energy future scenarios. Thus, it is possible to

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conclude that there is large leeway in process consumption for PHA-biogas before the results are altered. As exemplified here, this is also dependent on the share of renewables in the future energy grid, which is why results are more robust for France, in terms of GWP i.e. requiring 70 times 7kWh/FU, before seeing a change in GWP impact category.

7.3. Dynamic inventory

Using dynamic energy grids for the background is a powerful tool in this type of assessment. Many nuances come from the predicted changes in the share of renewable energy for the different locations. The most obvious of these subtleties can be observed in the IR category, where it is evident that there is a higher share of nuclear energy in the French background system than in Oregon. As seen in Figure 5 the evolution of the energy gird shows a sharp decrease for Oregon, while France's energy grid stays somewhat flat. This is due to legal requirements in Oregon, which will increase the share of renewables from 15% to 50% by 2040 (Oregon State, 2017). Greening of the energy grids reduces the difference between Biogas-only and PHA-biogas in the future, as is exhibited by the converging lines in Figure 5. Despite the increasing environmental importance of plastic replacement, as opposed to electricity replacement, it is worth restating that PHA-biogas is always preferable in terms of GWP i.e. negative values throughout the assessment period.

7.4. Exceptions to technology preference

The few exceptions where Biogas-only is moderately better than PHA-biogas include the Terrestrial Acidification (TA) impact category. This is due to higher ammonia emissions after field application sludge from the PHA-biogas system relative to the Biogas-only system. This is in turn due to a higher rate of conversion of organic matter during PHA processing and thereby, higher content of mineral N, which is available for ammonia emission. It is important to highlight that this result is based on modelling of field emissions so it should be taken with a grain of salt. Field emissions are highly complex and interdependent, and though there is evidence for higher ammonia emissions from biogas digestate (Gericke *et al.*, 2012; Möller and Müller, 2012), it remains to be proven with field experiments if the same holds true for PHA sludge. Furthermore, it is worth remembering that field emissions largely depend on management practices and weather conditions at the time of application. Different management practices have not been tested here, but should affect both sludges in the same way so results are not expected to change because of this. Uncertainty of N2O emissions after digestate application has also been shown to be high in several LCAs (Croxatto Vega *et al.*, 2014; ten Hoeve *et al.*, 2014, 2016). Due to the closeness in results for biogas and PHA scenarios it can be concluded that both sludges act more or less the same way in the model. Results were also tested without the field emissions and remained the same.

7.5. Feedstock provisioning effects

One area where there is potential for inducing impacts that would eliminate the environmental benefits of the system is in transport. Due to the relatively low energy and chemical value density in grape marc, increases in present transport of grape marc greater than 200km cause induced impacts in all biogas only scenarios when replacing PET and in all scenarios, both PHA-biogas and Biogas-only except for the PHA-biogas scenario with static energy grid in Oregon. While the PHA production scenario remains clearly preferable, this does underline the need to assess potential re-routing of the feedstock, if a new biorefinery technology were to be implemented.

It is also notable that the present use of feedstock, omitted in the results of this study as the impacts would be equal in both the PHA-biogas and the Biogas-only scenarios, varies significantly between the two assessed territories. In France, there is a well established market for distillation of wine residues, and in Oregon the wine residues are often used as compost. This said, it is also important to highlight that the feedstock mix used in this assessment can also be changed, as the PHA producing technology

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is compatible with all types of organic waste e.g. organic fraction of household waste, waste-water treatment waste, other animal slurries, other crop residues etc. The option to change the feedstock mix was not investigated in this study, as it would change the functional unit and was thus omitted from the present work. However, it is quite possible that there is further exploitable feedstock in both assessed regions. A good indication of feasibility is the biogas plant e.g. if there is an industrial sized biogas plant already in operation in the region, which would indicate that there is already feedstock enough to run PHA production. Though, it is important to keep in mind that the use of crops has not been investigated in this report and so this study's conclusions do not apply if the feedstock is food crops.

7.6. Dynamic inventory

One major area discussion regarding the dynamic inventory is the use of local energy mix scenarios in commodity replacement. It is likely that the increased production of PHA would have no direct effect on the production of PET or PLA in Oregon or France. However, by using a local instead of global process, it is possible to develop processes that are treated equally, in terms of system dynamism, for their inventory development. Furthermore, this is seen as a cautious choice, as the localized dynamic processes for the replaced polymers exhibit lower impacts than the global average. Thus, it is possible that this inclusion slightly under-represents the potential impact reduction gains from increased PHA production and is unlikely to over-state impact reduction gains.

8. Conclusions

Based on the results of this study, it can be concluded that when a biorefinery is installed in Oregon or Languedoc-Roussillon to handle a mix of grape marc and cow waste, it is very likely that it would be environmentally beneficial to include PHA production in addition to energy and digestate production. When relating the impact reductions between PHA-biogas and biogas-only, based on the maximum potential implementation capacity of the specific region, to planetary boundaries-based carrying capacity, it is shown that the impact reductions correspond to up to nearly 2500 person years in France and up to nearly 90 person years in Oregon. This corresponds to 1.59 and 1.40 person years of avoided GWP per ton of treated feedstock per day in France and Oregon, respectively. However, based on the results of the sensitivity analysis regarding transportation, special care needs to be taken in regards to assessing the potential increase in biomass transport; otherwise, it is likely that all environmental benefit from the biorefinery will be offset by the induced impacts of transportation. Likewise, the induced environmental impact reductions cannot be ensured if the feedstock for the biorefinery is to be rerouted from another use. Thus, it is concluded that PHA production should be seen as a potentially valuable add-on for biogas platforms.

The TM-LCA framework has the added benefit of elucidating the influence of potential future energy provision and the impact this has on potential environmental benefits. As indicated by the results, the benefit of including co-production of PHA in biogas plants increases as energy grids become greener, an element that can have significance in terms of decision support for its implementation from the regional planning or governance perspective. The framework also provides perspective on the scale of potential benefits (in person years) and added emphasis on single score indicators that point out possible burden shifting to environmental problems other than global warming.

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9. Fair Data Management

All data used for the production of this publication is either publicly available through the Ecoinvent Database or directly available in the Annex. The publication is available through Open Acess and has been published in the journal of Sustainability **https://doi.org/10.3390/su11143836**.

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11. Annexes

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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Methodology

Feedstock and Digestate 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

Individual Feedstock Characterization

	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

Values for wine marc, based on (Scoma *et al.*, 2016).

Biogas and PHA Operating Parameters

Yield of PHA (biomass growth& PHA accumulation)	0.11	kgCOD/kgCOD-VFA	(Valentino *et al.*, 2018)
PHA as 100% PHB	1.67	kgCOD/kgPHB	(Valentino *et al.*, 2018)

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Yield as PHB	0.07	kgPHB/kgCOD-VFA	(Valentino *et al.*, 2018)
CH4 in Biogas	60	%	
Heat Value CH4	9.94	kWh/Nm3	
Biogas Yield	0.70	m3 biogas / kg VS	
Electricity output motor	40.8	%	

Field Emissions and Assumptions

	Sludge PHA	Sludge Biogas	Mineral fertili-zer	Unit	Reference
N2 emission rate	9.40%	9.40%	5.60%	% tot N	SIMDEN Model, (Vinther, 2005)
N2O emission rate	1.22%	1.22%	0.79%	% tot N	SIMDEN Model, (Vinther, 2005)
NH3 emission rate	14.70%	14.70%		% TAN	ALFM Model, (Søgaard *et al.*, 2002)
NH3 emission rate	10.01%	9.46%	2.00%	% N tot	(Nemecek, Kägi and Dübendorf, 2007)
NO3 loss rate	13.65%	14.19%	25.89%	% tot N	Calculation
Crop N uptake rate	65.73%	65.73%	65.73%	% tot N	(Khaledian *et al.*, 2012; Plaza-Bonilla *et al.*, 2017)
N rate balance	100.00%	100.00%	100.00%	%	Calculation

N application rate was assumed to be 139.3 kg N/ha based on Khaledian *et al.*, 2012. Digestates were assumed to be incorporated within 12 hours of application, with trailing hose. Soil is clay loam.

Results

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 688338

Midpoint results, PET as RP, 1% improvement process consumption, RR 97%

	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
	kg PM2.5 eq	kg oil eq	kg 1,4-DCB	kg P eq	kg CO2 eq	kg 1,4-DCB	kg 1,4-DCB	kBq Co-60 eq	m2a crop eq	kg 1,4-DCB	kg N eq	kg Cu eq	kg NOx eq	kg NOx eq	kg CFC11 eq	kg SO2 eq	kg 1,4-DCB	m3
FR- High demand future_Biogas	9.67E-02	-3.85E+00	-5.33E-01	-6.11E-03	-2.20E+00	-3.95E-01	-1.67E+01	-3.98E+00	-6.69E-01	-7.66E-01	-7.29E-01	-7.36E-01	-7.13E-02	-7.18E-02	3.25E-04	9.71E-01	-6.11E+01	-1.60E-01
FR- High demand future_PHA	1.01E-01	-6.23E+00	-6.04E-01	-7.24E-03	-6.86E+00	-5.54E-01	-1.96E+01	-3.06E+00	-6.37E-01	-8.81E-01	-7.62E-01	-7.45E-01	-7.85E-02	-7.94E-02	3.15E-04	1.03E+00	-7.28E+01	-2.10E-01
FR-Diversification future_Biogas	9.63E-02	-3.95E+00	-5.37E-01	-6.12E-03	-2.46E+00	-3.97E-01	-1.67E+01	-3.52E+00	-6.83E-01	-7.72E-01	-7.29E-01	-7.36E-01	-7.20E-02	-7.24E-02	3.25E-04	9.70E-01	-6.17E+01	-1.58E-01
FR-Diversification future_PHA	1.00E-01	-6.29E+00	-6.07E-01	-7.24E-03	-7.04E+00	-5.55E-01	-1.96E+01	-2.74E+00	-6.47E-01	-8.85E-01	-7.62E-01	-7.45E-01	-7.90E-02	-7.99E-02	3.15E-04	1.03E+00	-7.31E+01	-2.09E-01
FR-Low growth future_Biogas	9.72E-02	-3.79E+00	-5.22E-01	-6.10E-03	-2.01E+00	-3.92E-01	-1.66E+01	-4.18E+00	-7.02E-01	-7.52E-01	-7.29E-01	-7.36E-01	-7.04E-02	-7.08E-02	3.25E-04	9.73E-01	-5.99E+01	-1.60E-01
FR-Low growth future_PHA	1.01E-01	-6.18E+00	-5.97E-01	-7.23E-03	-6.72E+00	-5.52E-01	-1.96E+01	-3.20E+00	-6.60E-01	-8.71E-01	-7.62E-01	-7.45E-01	-7.79E-02	-7.87E-02	3.15E-04	1.04E+00	-7.19E+01	-2.10E-01
FR-New mix future_Biogas	9.64E-02	-3.93E+00	-5.53E-01	-6.14E-03	-2.44E+00	-4.01E-01	-1.69E+01	-3.05E+00	-6.83E-01	-7.92E-01	-7.29E-01	-7.36E-01	-7.19E-02	-7.23E-02	3.25E-04	9.70E-01	-6.23E+01	-1.57E-01
FR-New mix future_PHA	1.00E-01	-6.28E+00	-6.18E-01	-7.26E-03	-7.02E+00	-5.58E-01	-1.97E+01	-2.42E+00	-6.47E-01	-8.98E-01	-7.62E-01	-7.45E-01	-7.89E-02	-7.98E-02	3.15E-04	1.03E+00	-7.36E+01	-2.08E-01
FR-Static Scenario_Biogas	9.61E-02	-3.95E+00	-4.95E-01	-6.09E-03	-2.54E+00	-3.91E-01	-1.65E+01	-4.32E+00	-7.23E-01	-7.20E-01	-7.29E-01	-7.36E-01	-7.23E-02	-7.27E-02	3.25E-04	9.69E-01	-6.05E+01	-1.61E-01
FR-Static Scenario_PHA	1.00E-01	-6.29E+00	-5.78E-01	-7.22E-03	-7.09E+00	-5.52E-01	-1.95E+01	-3.30E+00	-6.75E-01	-8.49E-01	-7.62E-01	-7.44E-01	-7.92E-02	-8.01E-02	3.15E-04	1.03E+00	-7.24E+01	-2.10E-01
OR-Biomass scenario_Biogas	9.71E-02	-4.27E+00	-5.33E-01	-7.07E-03	-3.62E+00	-4.54E-01	-1.76E+01	-6.61E-01	-9.57E-01	-7.68E-01	-7.29E-01	-7.33E-01	-7.17E-02	-7.21E-02	3.24E-04	9.70E-01	-5.61E+01	-1.52E-01
OR-Biomass scenario_PHA	1.01E-01	-6.51E+00	-6.04E-01	-7.89E-03	-7.83E+00	-5.94E-01	-2.02E+01	-7.76E-01	-8.36E-01	-8.82E-01	-7.62E-01	-7.42E-01	-7.87E-02	-7.96E-02	3.14E-04	1.03E+00	-6.93E+01	-2.05E-01
OR-Even growth scenario_Biogas	9.74E-02	-4.26E+00	-5.36E-01	-7.02E-03	-3.59E+00	-4.52E-01	-1.75E+01	-6.57E-01	-7.78E-01	-7.71E-01	-7.29E-01	-7.33E-01	-7.12E-02	-7.17E-02	3.24E-04	9.72E-01	-5.62E+01	-1.52E-01
OR-Even growth scenario_PHA	1.01E-01	-6.51E+00	-6.06E-01	-7.86E-03	-7.81E+00	-5.93E-01	-2.01E+01	-7.73E-01	-7.13E-01	-8.84E-01	-7.62E-01	-7.43E-01	-7.84E-02	-7.93E-02	3.14E-04	1.04E+00	-6.94E+01	-2.04E-01
OR-Wind and solar scenario_Biogas	9.75E-02	-4.26E+00	-5.38E-01	-6.99E-03	-3.56E+00	-4.51E-01	-1.74E+01	-6.55E-01	-6.78E-01	-7.74E-01	-7.29E-01	-7.33E-01	-7.10E-02	-7.14E-02	3.25E-04	9.73E-01	-5.63E+01	-1.51E-01
OR-Wind and solar scenario_PHA	1.01E-01	-6.51E+00	-6.08E-01	-7.84E-03	-7.79E+00	-5.92E-01	-2.01E+01	-7.72E-01	-6.44E-01	-8.86E-01	-7.62E-01	-7.43E-01	-7.83E-02	-7.92E-02	3.14E-04	1.04E+00	-6.94E+01	-2.04E-01
OR-Static Scenario_Biogas	9.66E-02	-4.84E+00	-5.44E-01	-8.24E-03	-5.71E+00	-5.38E-01	-1.82E+01	-6.49E-01	-4.03E-01	-7.87E-01	-7.29E-01	-7.32E-01	-7.47E-02	-7.51E-02	3.25E-04	9.71E-01	-5.48E+01	-1.51E-01
OR-Static Scenario_PHA	1.01E-01	-6.90E+00	-6.12E-01	-8.70E-03	-9.27E+00	-6.53E-01	-2.06E+01	-7.68E-01	-4.54E-01	-8.95E-01	-7.62E-01	-7.42E-01	-8.08E-02	-8.17E-02	3.14E-04	1.03E+00	-6.84E+01	-2.03E-01

Midpoint results, PLA as RP, 1% improvement process consumption, RR 59%

	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
	kg PM2.5 eq	kg oil eq	kg 1,4-DCB	kg P eq	kg CO2 eq	kg 1,4-DCB	kg 1,4-DCB	kBq Co-60 eq	m2a crop eq	kg 1,4-DCB	kg N eq	kg Cu eq	kg NOx eq	kg NOx eq	kg CFC11 eq	kg SO2 eq	kg 1,4-DCB	m3
FR- High demand future_Biogas	9.67E-02	-3.85E+00	-5.33E-01	-6.11E-03	-2.20E+00	-3.95E-01	-1.67E+01	-3.98E+00	-6.69E-01	-7.66E-01	-7.29E-01	-7.36E-01	-7.13E-02	-7.18E-02	3.25E-04	9.71E-01	-6.11E+01	-1.60E-01
FR- High demand future_PHA	1.04E-01	-4.21E+00	-5.41E-01	-6.67E-03	-3.79E+00	-4.23E-01	-1.72E+01	-2.95E+00	-1.71E+00	-7.77E-01	-7.64E-01	-7.40E-01	-7.37E-02	-7.45E-02	3.06E-04	1.04E+00	-6.26E+01	-4.11E-01
FR-Diversification future_Biogas	9.63E-02	-3.95E+00	-5.37E-01	-6.12E-03	-2.46E+00	-3.97E-01	-1.67E+01	-3.52E+00	-6.83E-01	-7.72E-01	-7.29E-01	-7.36E-01	-7.20E-02	-7.24E-02	3.25E-04	9.70E-01	-6.17E+01	-1.58E-01
FR-Diversification future_PHA	1.04E-01	-4.28E+00	-5.45E-01	-6.68E-03	-3.98E+00	-4.24E-01	-1.72E+01	-2.62E+00	-1.72E+00	-7.81E-01	-7.64E-01	-7.40E-01	-7.42E-02	-7.49E-02	3.06E-04	1.04E+00	-6.30E+01	-4.10E-01
FR-Low growth future_Biogas	9.72E-02	-3.79E+00	-5.22E-01	-6.10E-03	-2.01E+00	-3.92E-01	-1.66E+01	-4.18E+00	-7.02E-01	-7.52E-01	-7.29E-01	-7.36E-01	-7.04E-02	-7.08E-02	3.25E-04	9.73E-01	-5.99E+01	-1.60E-01
FR-Low growth future_PHA	1.05E-01	-4.17E+00	-5.34E-01	-6.66E-03	-3.66E+00	-4.21E-01	-1.71E+01	-3.08E+00	-1.73E+00	-7.66E-01	-7.64E-01	-7.40E-01	-7.30E-02	-7.38E-02	3.06E-04	1.04E+00	-6.17E+01	-4.11E-01
FR-New mix future_Biogas	9.64E-02	-3.93E+00	-5.53E-01	-6.14E-03	-2.44E+00	-4.01E-01	-1.69E+01	-3.05E+00	-6.83E-01	-7.92E-01	-7.29E-01	-7.36E-01	-7.19E-02	-7.23E-02	3.25E-04	9.70E-01	-6.23E+01	-1.57E-01
FR-New mix future_PHA	1.04E-01	-4.27E+00	-5.56E-01	-6.69E-03	-3.96E+00	-4.27E-01	-1.73E+01	-2.29E+00	-1.72E+00	-7.95E-01	-7.64E-01	-7.40E-01	-7.41E-02	-7.49E-02	3.06E-04	1.04E+00	-6.34E+01	-4.09E-01
FR-Static Scenario_Biogas	9.61E-02	-3.95E+00	-4.95E-01	-6.09E-03	-2.54E+00	-3.91E-01	-1.65E+01	-4.32E+00	-7.23E-01	-7.20E-01	-7.29E-01	-7.36E-01	-7.23E-02	-7.27E-02	3.25E-04	9.69E-01	-6.05E+01	-1.61E-01
FR-Static Scenario_PHA	1.04E-01	-4.28E+00	-5.15E-01	-6.66E-03	-4.03E+00	-4.20E-01	-1.70E+01	-3.19E+00	-1.75E+00	-7.44E-01	-7.64E-01	-7.39E-01	-7.44E-02	-7.51E-02	3.06E-04	1.04E+00	-6.21E+01	-4.11E-01
OR-Biomass scenario_Biogas	9.71E-02	-4.27E+00	-5.33E-01	-7.07E-03	-3.62E+00	-4.54E-01	-1.76E+01	-6.61E-01	-9.57E-01	-7.68E-01	-7.29E-01	-7.33E-01	-7.17E-02	-7.21E-02	3.24E-04	9.70E-01	-5.61E+01	-1.52E-01
OR-Biomass scenario_PHA	1.04E-01	-4.50E+00	-5.41E-01	-7.35E-03	-4.80E+00	-4.64E-01	-1.78E+01	-6.01E-01	-1.91E+00	-7.78E-01	-7.64E-01	-7.37E-01	-7.39E-02	-7.47E-02	3.05E-04	1.04E+00	-5.90E+01	-4.05E-01
OR-Even growth scenario_Biogas	9.74E-02	-4.26E+00	-5.36E-01	-7.02E-03	-3.59E+00	-4.52E-01	-1.75E+01	-6.57E-01	-7.78E-01	-7.71E-01	-7.29E-01	-7.33E-01	-7.12E-02	-7.17E-02	3.24E-04	9.72E-01	-5.62E+01	-1.52E-01
OR-Even growth scenario_PHA	1.05E-01	-4.50E+00	-5.43E-01	-7.31E-03	-4.77E+00	-4.63E-01	-1.77E+01	-5.98E-01	-1.79E+00	-7.80E-01	-7.64E-01	-7.37E-01	-7.36E-02	-7.44E-02	3.05E-04	1.04E+00	-5.91E+01	-4.05E-01
OR-Wind and solar scenario_Biogas	9.75E-02	-4.26E+00	-5.38E-01	-6.99E-03	-3.56E+00	-4.51E-01	-1.74E+01	-6.55E-01	-6.78E-01	-7.74E-01	-7.29E-01	-7.33E-01	-7.10E-02	-7.14E-02	3.25E-04	9.73E-01	-5.63E+01	-1.51E-01
OR-Wind and solar scenario_PHA	1.05E-01	-4.50E+00	-5.45E-01	-7.29E-03	-4.75E+00	-4.62E-01	-1.77E+01	-5.97E-01	-1.72E+00	-7.82E-01	-7.64E-01	-7.37E-01	-7.34E-02	-7.42E-02	3.06E-04	1.04E+00	-5.91E+01	-4.05E-01
OR-Static Scenario_Biogas	9.66E-02	-4.84E+00	-5.44E-01	-8.24E-03	-5.71E+00	-5.38E-01	-1.82E+01	-6.49E-01	-4.03E-01	-7.87E-01	-7.29E-01	-7.32E-01	-7.47E-02	-7.51E-02	3.25E-04	9.71E-01	-5.48E+01	-1.51E-01
OR-Static Scenario_PHA	1.04E-01	-4.91E+00	-5.50E-01	-8.18E-03	-6.27E+00	-5.24E-01	-1.82E+01	-5.93E-01	-1.52E+00	-7.91E-01	-7.64E-01	-7.37E-01	-7.61E-02	-7.68E-02	3.06E-04	1.04E+00	-5.81E+01	-4.04E-01

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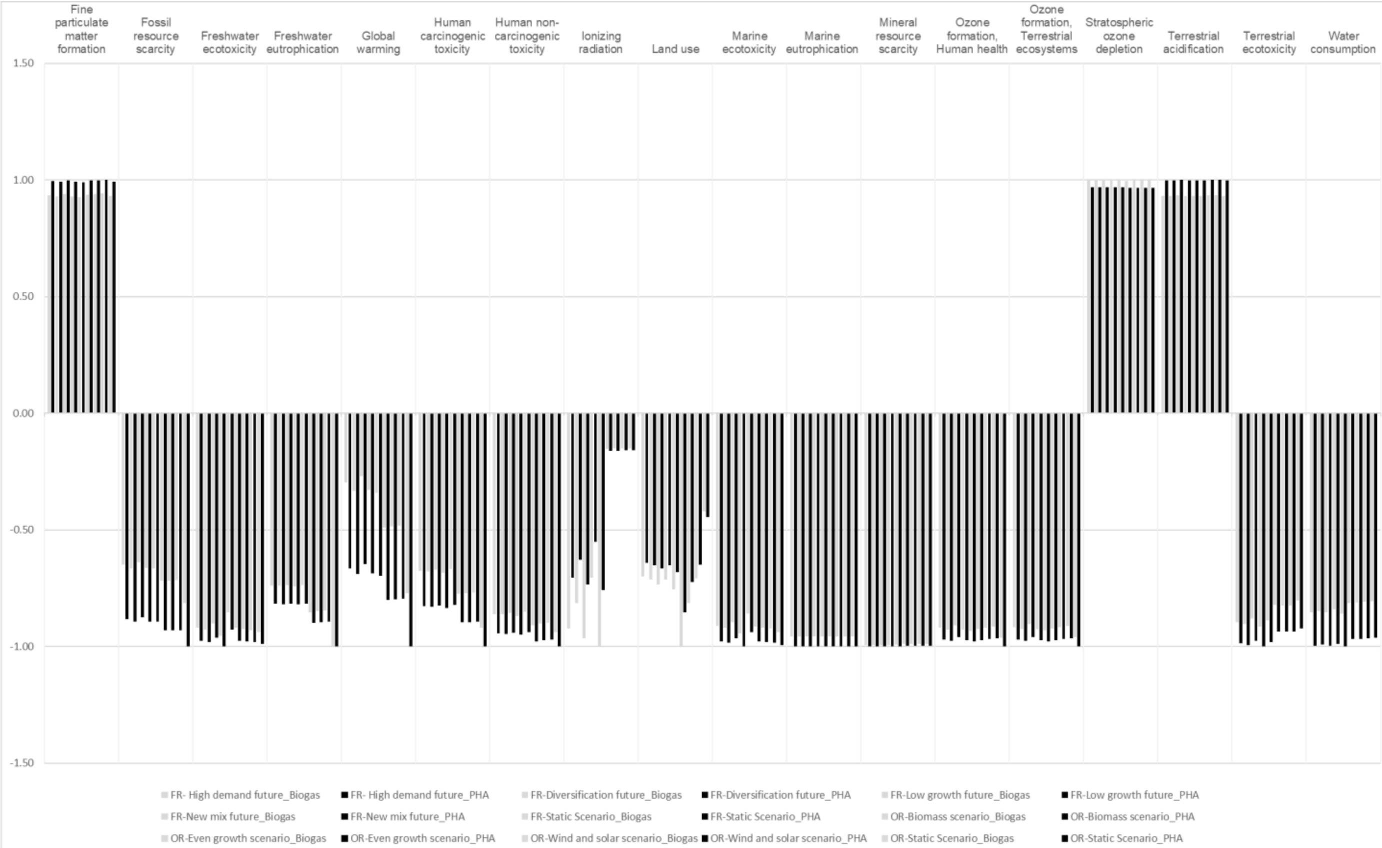
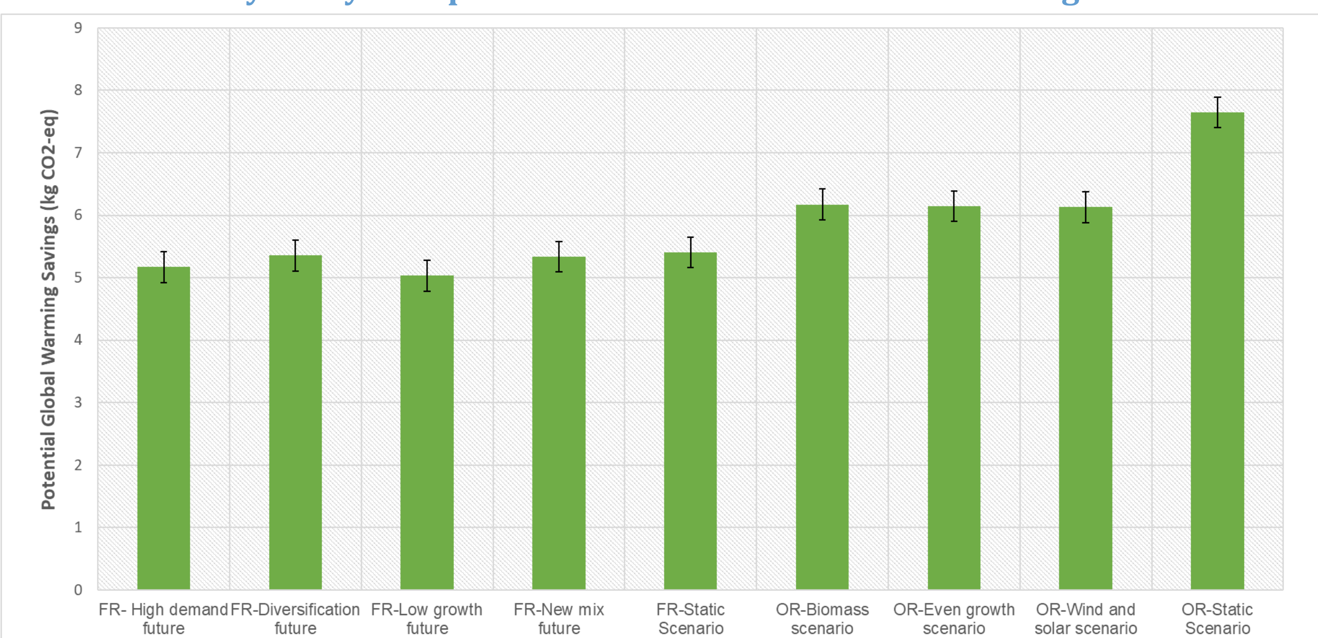
Midpoint impacts PLA



Sensitivity Analysis replacement rate PLA for Global Warming



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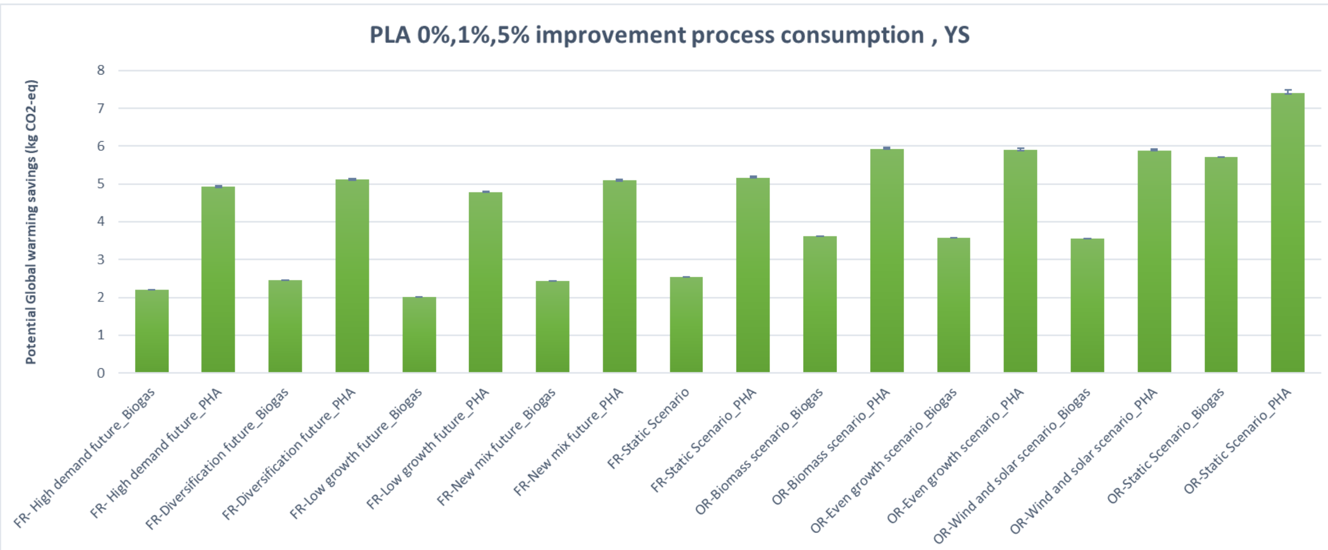
Sensitivity analysis improvement in process consumption, tested values are 0% and 5%



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