Stochastic Consequential Life Cycle Assessment of Technology Substitution in the Case of a Novel PET Chemical Recycling Technology

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Abstract

The current traditional mechanical recycling of Polyethylene Terephthalate (PET) grinds the waste into granulate, yet the resulting secondary material quality is strongly dependent on the efficiency of the selection processes, leading to the requirement of an integration of fossil PET to assure the bottle-grade quality is reached. Instead, the novel chemical recycling gr3n technology depolymerizes the waste PET back into the constituent monomers with a resulting quality that is comparable to the virgin product, due to a more efficient separation of impurities. In order to estimate the environmental impacts related to the introduction of this technology in the related market, Consequential Life Cycle Assessment (CLCA) is particularly indicated. Among the consequential approaches, we adopt the Stochastic Technology Choice Model, as it is able to model the technological mixes typical of markets based on costs and production capacities, while its stochasticity suits the need to manage the uncertainty of future market conditions. Indeed, the assessment of the expected technological mixes contributing to the same function and the quality of the recycled material are key to evaluate the variation in marginal LCA impacts due to the introduction of the gr3n technology. We assess the marginal LCA impacts of the European bottle-grade PET market in two scenarios: one in which the gr3n technology is not available and one in which this technology is present. To correctly evaluate the difference between these two scenarios, we perform a paired simulation. Here we show that the populations related to this difference show more than 50% negative results in 12 out of 16 impact indicators and more than 75% of negative results in 9 out of 16 impact indicators. In particular, a median 0.13 kg $_{CO2\text{-}eq}$ per kg $_{\text{bottle-grade PET}}$ could be saved by the introduction of gr3n, equivalent to a 5% reduction. We show that the 5-95 percentiles range of the difference between the two scenarios is only 17.7% of the average range defined by the two separate scenarios distributions, confirming previous findings from the literature. The robustness of the results is tested through three sensitivity analyses. Therefore, policy makers should focus on limiting the increase in marginal demand of PET and on creating fair conditions for this chemical recycling technology to be deployed to complement mechanical recycling in reducing virgin PET production, thus decreasing potential environmental impacts and fostering a more circular economy. The positive performance of the novel technology is strongly related to the increased substitution of waste treatment processes, as incineration and landfill, and to the increased quality of the recycled product: this environmental profile could further improve as the novel technology will scale up industrially.

Keywords*:* Consequential Life Cycle Assessment; Plastic; Paired simulation; Stochastic simulation; Scenario analysis; Sensitivity analysis

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1. Introduction

Most plastics are produced from non-renewable petroleum-based feedstock and global plastics demand, which settled around 330 Mt (Megatons) in 2016, is expected to double again within 20 years and almost quadruple by 2050 (World Economic Forum, 2019). Plastic recycling constitutes a valuable strategy in reducing the Life Cycle Assessment (LCA) impacts of plastics (Zheng and Suh, 2019), since the raw material extraction phase accounts for a significant share of these impacts (Dormer et al., 2013). Therefore, the European agenda aims to increase the recycling of post-consumer plastic waste to promote a more circular economy (European Commission, 2020). Polyethylene terephthalate (PET) has gained interest in this aspect, due to its widespread utilization in the packaging sector (Welle, 2011), which covers most of its use and accounted for 7.7% of the polymers demand in Europe in 2018, without including fibers applications (PlasticsEurope, 2019). Thanks to an increasing recollection rate, the amount of recollected bottle-grade PET has steadily increased in the last decade in Europe (Welle, 2018). Recycling of this polymer can be done through mechanical or chemical recycling, with the former being the most common way due to cost effectiveness (Awaja and Pavel, 2005; Ragaert et al., 2017). Mechanical recycling requires a sorting phase to separate other polymers, washing and drying to remove impurities and then a grinding phase to produce the PET flakes. In the case of bottle-to-bottle recycling, this is followed by further decontamination steps and, usually, by an integration of virgin PET granulate (Welle, 2011). Different processes have been developed for chemical recycling of PET, which leads to its depolymerization into its monomers (Ragaert et al., 2017) and may allow for higher impurity separation (Crippa and Morico, 2019).

LCA has been widely used as a valuable methodology to assess environmental benefits in technology application to support decisions (Bernstad Saraiva et al., 2018). LCA has been widely applied in the waste management context; however, several elements like the definition of the functional unit, the system boundaries, the quality of the treated waste and the need for a consequential or attributional approach can seriously affect results (Laurent et al., 2014). In particular, Consequential LCA (CLCA) can model the reaction of the system to an action, such as a new recycling policy or the introduction of a new technology into the market (Herbert et al., 2016). However, results in CLCA studies seem to be dependent from (i) "context depending" factors such as the chosen substituted technology or the use of global or regional/national average data (Bernstad Saraiva et al., 2018) and (ii) "technology depending factors", such as the chosen virgin material substitution ratio and level of organic contamination (Lazarevic et al., 2010).

Several LCA studies have been carried out on PET recycling. Different authors assessed the impacts and compared to those of other materials typically used for bottles such as glass (Accorsi et al., 2015), polylactic acid (Papong et al., 2013) or bio-based PET (Chen et al., 2016). In (Lonca et al., 2020), it is demonstrated how adopting a systemic perspective to assess the optimal recycling pathways should be preferred to a study constrained to a single product. A comprehensive review of LCA of PET packaging in (Gomes et al., 2019) highlighted the importance to include CLCAs, but this approach was only carried out once (Accorsi et al., 2015). When assessing the impacts of new recycling technologies, it's important to model the effective market reactions to the introduction of a novel technology. This does not necessarily imply a complete substitution of traditional competing technologies by the novel one but rather the creation of a new equilibrium in the mix of technologies that compete to provide a similar service (Cucurachi et al., 2018). Nonetheless, LCA studies of PET chemical recycling of do not follow this suggested approach (BASF, 2020; CE Delft, 2019; Davidson et al., 2021; Meys et al., 2020). LCA studies should aim to assess full-market systems, while emerging technologies often are not deployed at scale and their environmental efficiency at this level cannot be measured (Faludi et al., 2017; Hung et al., 2020). Specifically, previous LCA studies on PET recycling technologies suggest that markets for recovered products, policy and regulations can play a prominent role (Chilton et al., 2010).

Our work examines a PET chemical recycling technology, namely the gr3n technology (Crippa and Morico, 2019), to assess its potential role at a European scale, which is relevant due to the extensive use of PET in Europe and due to the potential of chemical recycling to enable a circular economy (Ellen MacArthur Foundation, 2020). This technology adopts an alkaline hydrolysis in a microwave reactor, in a solution of ethylene glycol (MEG) and water to depolymerize the waste PET. After several steps, described in detail in section 3 of the supplementary information, a purification process is aimed at removing contaminants contained in the feedstock. The potential advantages of the gr3n technology are its ability to process PET trays and fibers, unlike mechanical recycling, and that the monomers of PET, namely MEG and purified terephthalic acid (PTA), are produced at a quality that is comparable to those obtained through the traditional process (Crippa and Morico, 2019).

Firstly, our aim is to perform the first CLCA of a PET chemical recycling technology, to assess the variation of marginal LCA impacts due to the introduction in the European bottle-grade PET market of the gr3n chemical recycling technology. Secondly, the present work aims to be the first application of the Stochastic Technology Choice Model (STCM) (Katelhon et al., 2016) to assess the introduction in a market of a novel technology. We adopt the STCM to be able to explicit market parameters such as costs and production capacities of the involved technologies with a consequential approach, while the stochasticity of the assessment is useful to manage the uncertainty that is related to technological and economic projections. Indeed, even if the gr3n technology has a TRL of 6-7 and is therefore still evolving, this study will not address the potential technological development, which is typical of ex-ante LCA (Cucurachi et al., 2018): rather, it will evaluate the potential market penetration and consequences due to the introduction of this technology at the current development stage. To test the influence on the results of the STCM, we alternately propagate the uncertainties related to the background Life Cycle Inventory (LCI) and to the STCM itself. Thirdly, we aim to produce the first study to include in the STCM the ecoinvent LCI through Brightway2 (Mutel, 2017). Compared to the two-step model of Larrea-Gallegos et al. 2019 (Larrea-Gallegos et al., 2019), our approach runs paired Monte Carlo simulations to ensure a fair modelling in which the simulations are fully dependent (Suh and Qin, 2017; von Brömssen and Röös, 2020).

Then, a specific focus will be devoted to sensitivity and correlation assessment between input parameters in order to avoid under- or over-estimation of the output variance (Groen and Heijungs, 2017) and to assure the robustness of the results. Such effort aims to emphasize the implications of the structure of the model and to further contribute to the decision-making process (Wei et al., 2015). Therefore, we perform three different sensitivity analyses to test the robustness of our results. These involve different hypotheses for the following parameters of the STCM: (i) the increase in demand of bottle-grade PET in Europe; (ii) costs; (iii) rate of suboptimal decisions.

2. Methods and modelling

2.1. Case study

In order to assess the consequences of the introduction of the chemical recycling technology, we project the current (2013-2018) trends of European bottle-grade PET demand up to 2030 and we evaluate the additional bottle-grade PET demand with respect to 2018. Both the assumption that bottle-grade PET constitutes 100% of this additional demand and data used for the projection are from PlasticsEurope (PlasticsEurope, 2019).

We distinguish technologies and pathways, with the latter being a collection of processes that include all the necessary steps to produce bottle-grade PET, starting from either waste PET or fossils. Within our model, three technological pathways compete against each other for bottle-grade PET production, whose system boundaries are shown in Fig. 1:

- The *gr3n pathway,* constituted by the gr3n technology, the waste PET sorting, the PTA and the traditional processes to transform the monomers, i.e. MEG and PTA, into the bottle-grade PET.
- The *mechanical recycling pathway,* constituted of 30% in weight by recycled bottle-grade PET content from mechanical recycling and of 70% by an integration of fossil PET, required to maintain high quality in the final product (Wernet et al., 2016).
- The *virgin PET pathway,* defined as traditional manufacturing of bottle-grade PET from the global market.

The functional unit is the production of 1 kg of bottle-grade PET granulate in Europe. Differently from fossil PET, the recycling technology pathways are assumed to be based on European processes. Moreover, the mix for the integration of fossil PET required by the *mechanical recycling pathway* is the result of a second competition, between European and extra-European producers.

Furthermore, to consider of the multifunctionality of the two recycling processes, the system is expanded to include the avoided impacts due to the substitution of a mix of European PET waste treatment technologies: namely, municipal incineration and sanitary landfill disposal. As the mix of the substituted technologies is not known a-priori, it is assessed by treating it as a competition, too.

Three layers of competition are assessed through the STCM:

- Production of bottle-grade PET: competition among the *gr3n pathway*, the *mechanical recycling pathway* and the *virgin PET pathway*;
- Production of fossil PET integration needed by the *mechanical recycling pathway*: competition between European and extra-European manufacturers.
- Avoided treatment of waste PET: competition between European processes of municipal incineration and sanitary landfills.

The value of gr3n technology expected capacity by 2030 was given by the manufacturer and is equal to 0.177 Mt of waste treatment. This would lead to the production of 0.155 Mt of bottle-grade PET (see Fig. S2). The different PET production technologies capacities were estimated through the projections of (EUNOMIA, 2020).

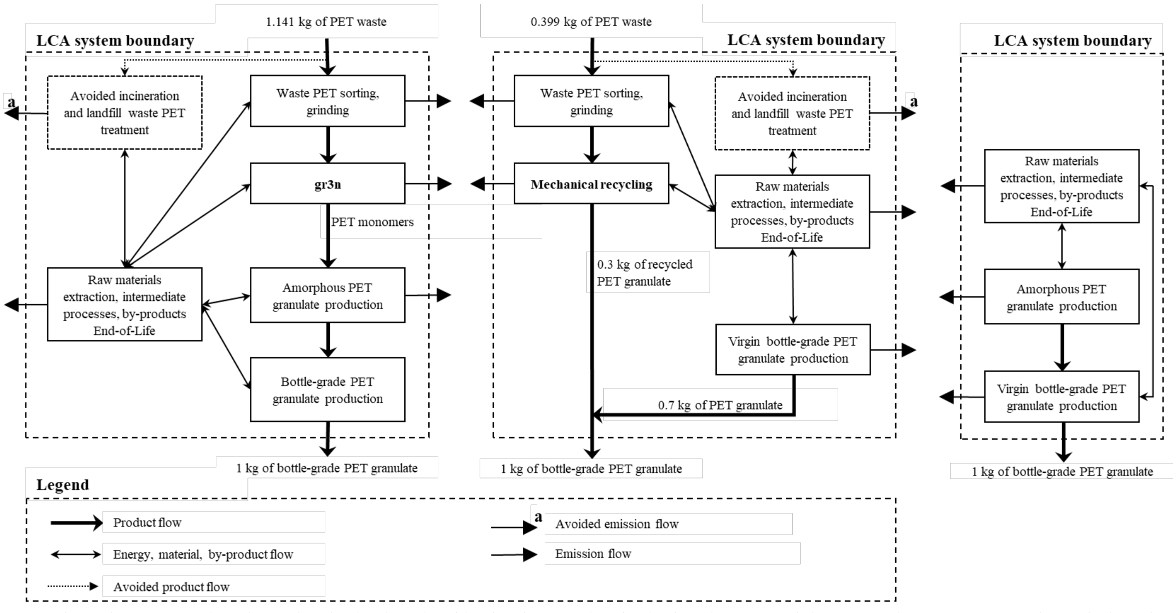

Fig. 1. Flow chart presenting the technologies involved in the three technological pathways and the respective LCA system boundaries: the *gr3n pathway* (left), the *mechanical recycling pathway* (center), and the *virgin PET pathway* (right). None of the waste PET sorting and grinding, the gr3n technology and the mechanical recycling processes include the avoided production of virgin PET.

The *mechanical recycling pathway* was assumed to have a 30% recycled PET content, as described in the ecoinvent database (Wernet et al., 2016): this limitation is due to the required quality of the final product. Table 1 summarizes the hypotheses on production capacities and costs used in the STCM, as well as their respective standard deviations and the sources. The first row of the table shows dummy values, as it refers to the operation of the bottle-grade PET market.

As far as LCI is concerned, primary data is only used in the gr3n technology model, while other foreground and background systems refer to the consequential dataset of ecoinvent 3.5 (Wernet et al., 2016).

Table 1. Summary of the capacity and cost vectors parameters, with the respective standard deviations.

	Capacity vector c [Mt]	Standard deviation of lognormal distribution of the capacity vector Sc	Source	Cost vector k [€/kg]	Standard deviation of lognormal distribution of the cost vector Sk	Source
Operation of bottle-grade PET production	20	2	Dummy	0	0	Dummy
Gr3n PET bottle-grade production	0.155	0.0776	gr3n developers	1.16	0.5812	80% lower than mechanical recycling pathway cost
Fossil PET bottle-grade integration from European plant	1.98	0.198	(EUNOMIA, 2020)	1.23	0.369	(*ICIS Global Petrochemical Index*, 2019)
Fossil PET bottle-grade integration from foreign plant	0.594	0.0594	(EUNOMIA, 2020)	1.23	0.369	(*ICIS Global Petrochemical Index*, 2019)
PET waste treatment, in gr3n	0.177	0.0885	gr3n developers	0	0	gr3n developers
PET waste treatment, in landfill	0.366	0.0366	(PlasticsEurope, 2019), (EUNOMIA, 2020)	-0.42	0.126	(International and RDC-Environment & Pira International, 2003)
PET waste treatment, in incineration	0.630	0.063	(PlasticsEurope, 2019), (EUNOMIA, 2020)	-0.378	0.1134	(International and RDC-Environment & Pira International, 2003)
PET production, mechanical recycling	1.14	0.228	(EUNOMIA, 2020)	0.592	0.1776	(International and RDC-Environment & Pira International, 2003)
PET waste treatment, in mechanical recycling	1.9	0.38	(EUNOMIA, 2020)	0	0	Model assumption
Virgin PET bottle-grade production	5	0.5	Dummy	1.845	0.1845	50% higher than Fossil PET integration cost

2.2. Implementation of the STCM

Here, we detail our approach to the implementation of the STCM, namely the differences to the original one by (Katelhon et al., 2016), described in section 2 of the supplementary information. These differences are due to the use of the uncertainty information included in the ecoinvent database, often based on the pedigree approach (Muller et al., 2016). The code is split in two parts and the related Jupyter notebooks can be found in the supplementary information. As illustrated in Fig. 2, in the first part of the code we adopt the open source LCA framework of Brightway2 (Mutel, 2017) to perform Monte Carlo simulations for those processes that have environmental impacts, while in the second part the results of the first one are fed into the STCM.

It is worth mentioning how it is frequent for two products to share parts of the background system, e.g. transports and electricity consumption processes. However, in Brightway2 it is possible to run paired Monte Carlo simulations that are fully dependent (Suh and Qin, 2017; von Brömssen and Röös, 2020). This means that the Monte Carlo simulation will sample in a coherent manner for the shared parts of the systems, thus avoiding miscalculations. Therefore, it is possible to treat the results of the Monte Carlo simulations of the assessed processes as independent information modules (Buxmann et al., 2009). Indeed, once the sampling is performed

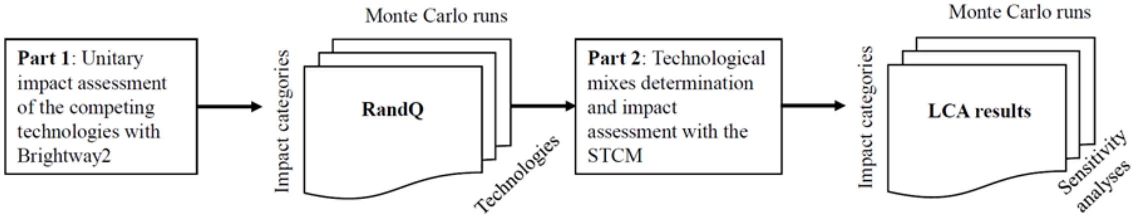

Fig. 2. Schematic representation of the structure of the code, whose two parts are processed in series. Both produce a 3-dimensional matrix, respectively RandQ and the LCA results. The number of impact categories dimension is common to the two matrixes. The number of Monte Carlo runs is 15,000 for RandQ and 100,000 for the LCA results, while the third dimension differs in meaning, as in the LCA results data is aggregated and not directly available for each technology.

in a paired and dependent manner, the results of each process can be considered independent and can be linearly combined as needed. To avoid double counting, the processes "PET market" and "PET for integration in mechanical recycling", are not assessed since they are linear combination of other independent information modules. The output of the first part of the code is a three-dimensional matrix, called **randQ** since it is the sequence of randomized Characterization Matrixes **Q**. The dimensions of the matrix represent respectively (i) seven dummy environmental flows, one for each assessed process, (ii) the selected sixteen ILCD 2.0 midpoint impact categories and (iii) the 15,000 Monte Carlo runs. The latter value was chosen in order to guarantee a sufficient stability of results and is further discussed in section 5 of the supplementary information. Indeed, this study adopts a selection of impact categories of the ILCD set, which was designed to support decision makers (Sala et al., 2012). Since no biogenic flow is part of the foreground system, the differences among Climate Change (i) biogenic, (ii) fossil, (iii) land use and land use change and the total indicator are negligible. Therefore, our list of indicators includes only the Climate Change, total impact category among those from this endpoint category.

In the second part of the code, the STCM is performed as in (Katelhon et al., 2016), with the only difference being that the sampling of the randomized Characterization Matrix **Q** draws from the already complete **randQ**. The random choice of a number between 0 and 14,999 allows to select the results of a Monte Carlo run. Therefore, the selection of the same run for the different processes guarantees the integrity of the paired sampling done in Brightway2. Moreover, this two-step procedure is computationally more efficient, since the Monte Carlo simulation in Brightway2, which deals with the large ecoinvent 3.5 consequential database and it is slower than the Monte Carlo of the STCM, needs to be performed only once. This procedure could be applied to every work in which the background uncertainty of the database needs to be propagated separately from the foreground uncertainty, as in the case of sensitivity analyses.

Thanks to the modular approach, only the foreground system is represented in the Technology Matrix (**A**) of the STCM. Here, the rows represent the functions and the columns represent the various processes that compete in order to fulfill the functions. Therefore, the three competitions among the technology mixes assessed by the STCM are modelled as two or more values with the same sign, in the same row. The system expansion has been modelled accordingly, with a row that includes information on displaced amount of PET waste treatment per kg $_{PET}$ produced by the different pathways (i.e. 1.141 kg and 0.399 kg from Fig. 1).

The Elementary Flow Matrix (**B**) is composed by unitary impacts linking each process to dummy elementary flows, one for each process present in **A** that is responsible for a non-null direct or indirect environmental burden. The avoided treatment processes are assigned a -1 value since their supply leads to an avoided impact. The *mechanical recycling pathway* is assigned a 0.3 coefficient which represents that only 30% of the supply of this technological pathway is to be related to the recycling technology.

The factor requirement matrix coefficients are all set to 1, apart from those relating to the waste treatment function of the two recycling pathways. Distributions are lognormal, apart from the last row of F which models the introduction of suboptimal decisions within the STCM. Variances of the matrixes coefficients are computed assuming ratios of the standard deviations of the underlying normal distributions to their average value. These ratios vary within 0.5, related to *gr3n pathway* costs and capacity which are considered highly uncertain, and 0.1, related to **A**, **B**, **F** matrices coefficients. The coefficients in **A** related to functional units of each process are given a 0 variance, in accordance to (Katelhon et al., 2016).

We have not considered environmental impact savings due to the recycling of waste PET in terms of avoided virgin PET production. To avoid a double counting in the *gr3n pathway*, the avoided virgin PET production present in the ecoinvent process “treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | waste polyethylene terephthalate, for recycling, unsorted | Consequential, U - Europe without Switzerland” was set to zero. The same approach was followed for the modelling of the *mechanical recycling pathway*. That is, we don’t consider an avoided production but a reduced one, in view of the competition managed through the STCM optimization. Indeed, we can assume that the pathways are elastic, since they will not be scaled more than their capacity, thanks to the constraints to the STCM optimization.

2.3. Coherent marginal impact assessment between scenarios

Here, we describe how we have assessed the marginal impacts due to the introduction of the *gr3n pathway*. Therefore, the STCM assesses the marginal impacts of the consumption of bottle-grade PET in Europe in the case that (i) the *gr3n pathway* has the expected production capacity and in the case that (ii) the *gr3n pathway* is not available. The expected value of the *gr3n pathway* capacity it set to zero Mt and 0.155 Mt, respectively for the two scenarios, that are named *No gr3n scenario* and *gr3n scenario.*

Each of the two scenarios has its own variability, yet we are interested in the differences between such scenarios. Therefore, in the sensitivity analyses the differences between the *gr3n* and *No gr3n scenarios* are assessed by means of equation 1:

$$Difference_{i,j} = (h_{i,j,gr3n} - h_{i,j,No\ gr3n}) \tag{1}$$

Where h is the impact for *i-th* the category*,* for the *j-th* Monte Carlo run.

For each chart focused on the difference of results, the charts showing results for the single *gr3n* and *No gr3n* scenarios will be provided in the supplementary information. Results are shown with boxplots, in which the whiskers indicate 5th and 95th percentile of the related distributions.

Each of the sensitivity analyses is articulated into different cases, in which the value of an investigated variable is changed. To highlight the most sensitive impact categories, we propose equation 2:

$$Relative\ impact\ variation_{i,z,stat} = \frac{Difference_{i,z,stat} - Difference_{i,base\ case,stat}}{\left(\frac{\left(h_{i,gr3n,stat} + h_{i,No\ gr3n,stat}\right)_{base\ case}}{2}\right)} \tag{2}$$

Where h is the impact for *i-th* the category, in the case *z* of a sensitivity analysis, and *stat* being either the median or the average of the considered quantities. That is, we account for the variation of either the medians or the averages of the population of differences, with respect to either the medians or the averages of the base case impacts. Further discussion about equation 2 is provided in section 6.1 of the supplementary information.

3. Results and Discussion

3.1. The role of gr3n in the European PET market development

Here we aim to assess the LCA impacts variation due to the availability of the *gr3n pathway*. In order to make the reader able to properly criticize the results, three pre-analyses are presented and discussed.

Fig. 3 shows the LCA results of the STCM simulation, internally normalized on the maximum value for each impact category (Laurent and Hauschild, 2015). The two bars represent the main technological *pathway*s, *the gr3n* and the *mechanical recycling pathways*, which are assumed to compete to satisfy the European PET bottle-grade demand. The *virgin PET pathway* is not shown in this graph since, under our assumptions, these technological pathways fulfill close to the totality of the additional demand. This is due to the relatively high cost of the *virgin PET pathway*, which is anyway useful to the model to avoid cases in which the sum of the production of the technological pathways is not sufficient to satisfy the overall demand.

For all the presented bars, the median value is lower than the average value, which indicates the presence of outliers on the right tail of the distributions, which are determined by both the background and the foreground system. For the *gr3n pathway*, the asymmetry is mostly due to the background uncertainty, as the supply array distributions of this process are almost symmetrical (see Fig. 4 and Fig. 8). Conversely, the fact that the median value of the PET integration from Rest-of-World is almost equal to 0 is due to the STCM. Indeed, in the competition between Europe and Rest-of-World markets in providing PET integration for the *mechanical recycling pathway,* Europe provides all the production in more than 50% of the cases, as shown in Fig. 4 (see also the discussion on Fig. S15 about this).

The *gr3n pathway* only presents the higher impacts for the Ionizing radiation, Ozone layer depletion and Land use categories, due to higher consumption of electricity. Such process affects these three category indicators, respectively by employing nuclear, natural gas and biomass sources within the European marginal mix. Further details can be found in section 6.1 of the supplementary information.

Therefore, in case of a one on one substitution rate, an increasing penetration of the *gr3n pathway* could reasonably lead to a decrease in the potential marginal impacts of the European PET market, for most of the analyzed categories, which results in an overall average decrease of 11.04%.

However, due to its multifunctionality, an increased penetration of the *gr3n pathway* would also lead to the substitution of the currently available waste PET treatment processes, namely landfill and incineration. Moreover, mechanically recycled PET cannot constitute more than 30% of the final PET bottle for this pathway, while this is not the case for gr3n monomers, which only require an integration of purified terephthalic acid of about 0.111 kg_{PTA}/kg_{PET} (see Fig. S1). A more efficient system for impurities separation translates in lower waste production, higher monomers output, higher bottle-grade PET output (0.876 $kg_{\text{bottle-grade PET}} / kg_{\text{unsorted PET waste}}$) and to a quality of the resulting PET that is not distinguishable from the virgin one.

Therefore, the *gr3n pathway* could proportionally displace a higher capacity of waste PET treatment processes, compared to the *mechanical recycling pathway*. This is shown by Fig. 4, which correlates the production of bottle-grade PET (positive values of the ordinates) with the respective displacement of waste PET treatment processes (negative values of the ordinates) across the *No Gr3n scenario* and *Gr3n scenario*. These values are the components of the supply vector from the STCM analysis, expressed in Mt. In addition, the penetration of the *gr3n pathway* leads to a reduction in the use of the *virgin PET pathway,* which shows higher unitary impacts than the *mechanical recycling pathway* across all impact categories (see Fig. S3) and is employed in the *No gr3n scenario* due to the bounded supply capacity of the *mechanical recycling pathway.*

European and Rest-of-World PET production processes are assumed to have the same cost; therefore, their respective share of the mechanically recycled PET integration is highly variable, due to the intense competition.

The resulting values are chosen according to the STCM costs sampling. This leads to their wide standard deviations, relatively to their supply amount (see Table S3).

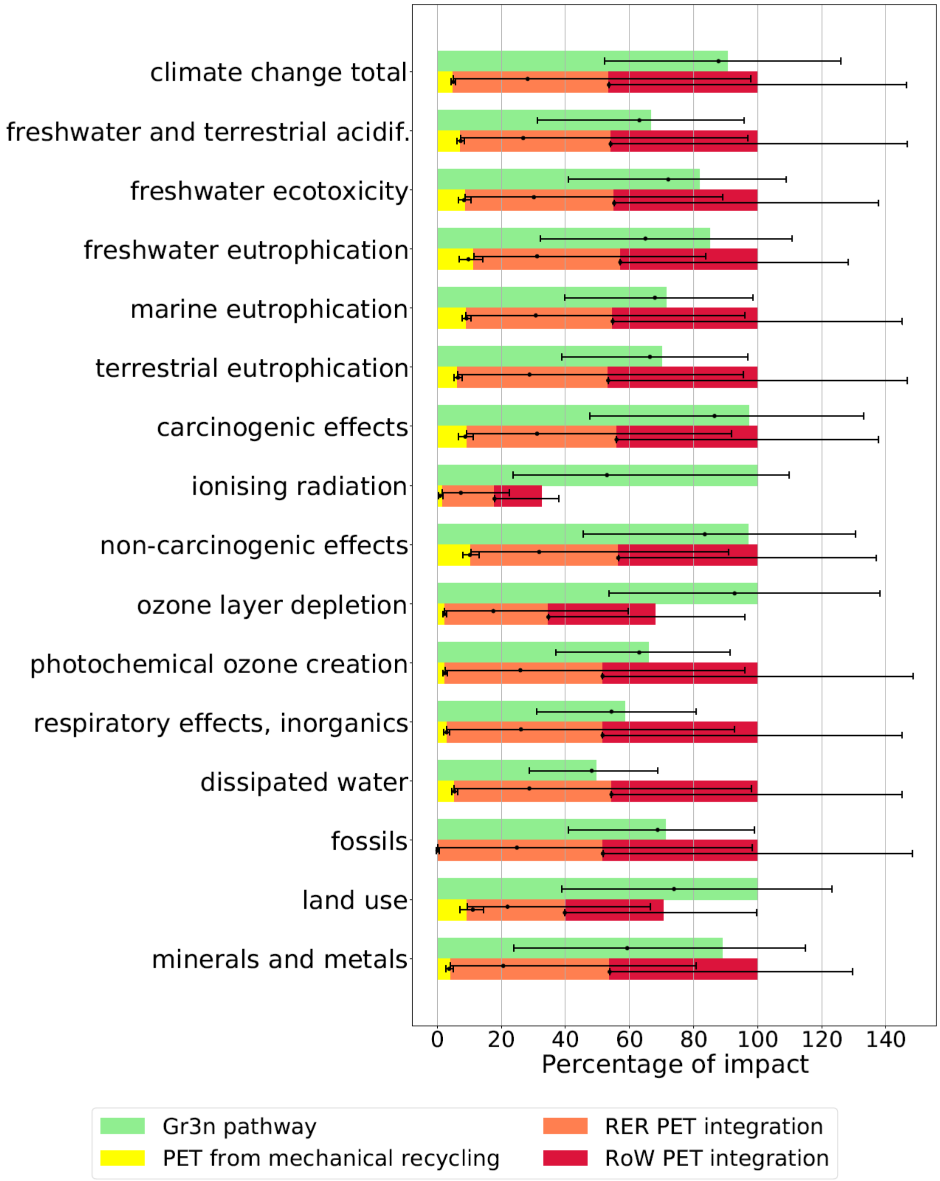

Fig. 3. Relative contribution of average impact indicators for the two main technological pathways, with their respective median (black dot of the error bar) and 25th and 75th percentiles, represented by the error bar caps. On the higher green bar, the contribution of the *gr3n pathway*. On the lower bar, the stacked contributions of the mechanical recycling (yellow) with the integration of bottle-grade PET from European (RER, orange) and extra-European (RoW, red) producers. RER and RoW error bars were slightly shifted to avoid overlapping.

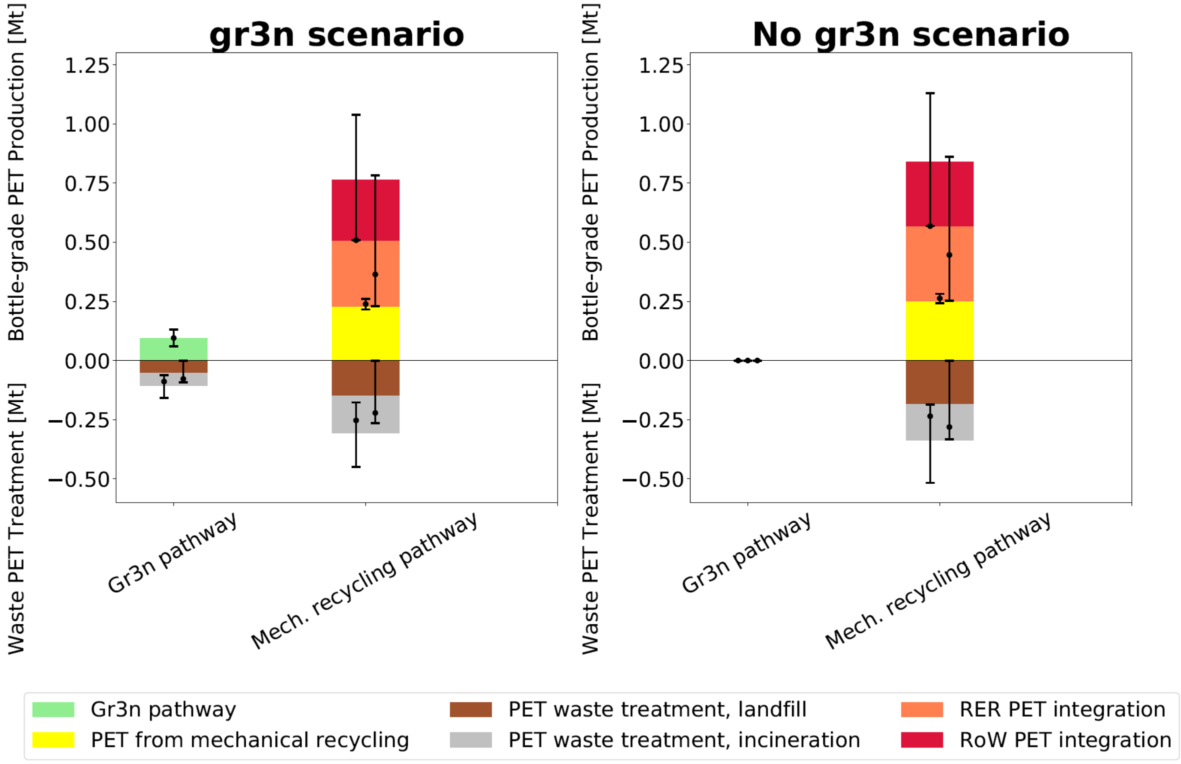

Fig. 4. Consequences of the introduction of the *gr3n pathway* in the two main scenarios, respectively from left to right: *gr3n scenario* and *No gr3n scenario*. While the positive values on the ordinates represent the Mt of production per technology, the negative values represent the avoided treatment of waste PET, in Mt. The avoided treatment is allocated to the technology pathways that are providing the waste PET treatment service as a by-product. Error bars are partially shifted to avoid overlapping; they are centered on the black dots, which represent the relative median contribution, while the caps represent the 25^{th} and 75^{th} percentiles.

Furthermore, a comparison between the unitary impacts of the displacement of landfill and incineration waste treatment technologies is performed. Fig. 5 shows the potential environmental impacts for the displacement of the treatment of 1 kg $_{\text{PET waste}}$, from the STCM simulation, relative to the maximum absolute value for each midpoint impact category. While displacing landfill waste treatment leads to a reduction in impacts across all the analyzed impact categories, this is not true for incineration. Displacing the latter would only lead to decreases in the following impact categories: Freshwater ecotoxicity, Climate change total, Dissipated water and Freshwater eutrophication. This is due to the consequential modelling hypotheses: incineration is assumed to displace the production of heat and electricity. Moreover, incineration absolute unitary impacts are relatively high, compared to the landfill values, apart from the Marine eutrophication category. However, within the STCM, the most expensive technology tends to be firstly displaced; therefore, in the *gr3n scenario* most of the incineration technology is displaced when landfill is approaching maximum capacity. As Fig. 4 shows, landfill is displaced in higher amounts than incineration. Due to the discussed consequences, landfill avoided impacts might be able to overcome the incineration increased burden across some categories, while increasing impacts might be seen in others.

The incineration process shows a peculiar trend in the Freshwater Eutrophication category. Indeed, 50% of the distribution values are relatively close to the median value, which is positive, yet the average value is negative. This is due to the presence of negative outliers: see Fig. S4 for a representation showing the 95th and 5th percentile.

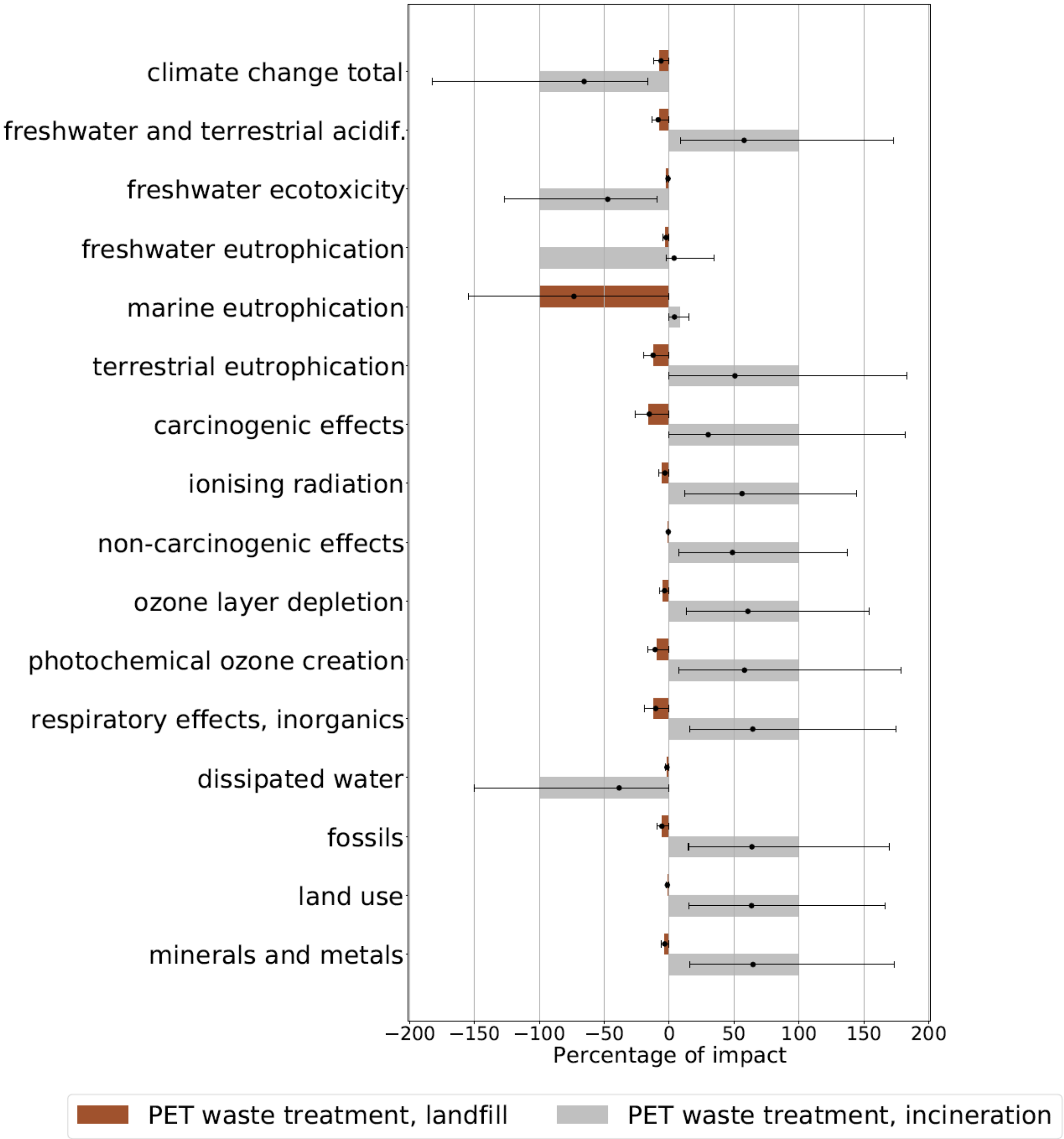

Fig. 5. Relative contribution to average ILCD impact indicators for the two displaced waste treatment pathways. Black dots represent the relative median contribution, while error bar caps represent the 25th and 75th percentiles. On the higher brown bar, the contribution of the displacement of landfill. On the lower silver bar, the contribution of the displacement of incineration.

Finally, Fig. 6 represents with boxplots the probability distributions of the selected midpoint impact indicators for the two scenarios. Namely, Fig. 6 shows that both the average and median potential impacts of the marginal European bottle-grade PET demand between 2018 and 2030 decrease in 12 of the 16 impact categories, when comparing the *No gr3n scenario* with the *gr3n scenario*, which implies the beneficial role of the introduction of the *gr3n pathway*.

This means that the lower impact indicator values of the *gr3n pathway* overcome the increase in impact indicator values due to incineration substitution in most impact categories. However, the Ionizing radiation, Ozone layer depletion and Land use categories do show a respective median impact increase of about 17%, 6% and 10% when shifting from the *gr3n* to the *No gr3n* scenario. This is due to either the *gr3n pathway* higher unitary impact (see Fig. 3) or the higher displacement of incineration (see Fig. 4) or the combination of the two. Moreover, the median Non-carcinogenic effects impact indicator shows an increase of 2% between the two scenarios, due to the high impact of substituting incineration. Considering the remaining impact indicators, the decreases of median values span from 7% (Dissipated water) to 0.3% (Carcinogenic effects), apart from the Freshwater ecotoxicity indicator, which decreases by 27%. The median impact within the Climate change total category decreases by 6%: from 2.73 kg $_{CO2\text{-}eq}$ / kg $_{PET}$ to 2.57 kg $_{CO2\text{-}eq}$ / kg $_{PET}$. Results of each of the analyzed scenarios show high standard deviations, being them on average equal to 64.67% of the median value and up to 247.44% of the median value and overall, standard deviations do not substantially change across scenarios. Fig. S7 outlines the drivers of impact indicator results, for the 2 analyzed scenarios.

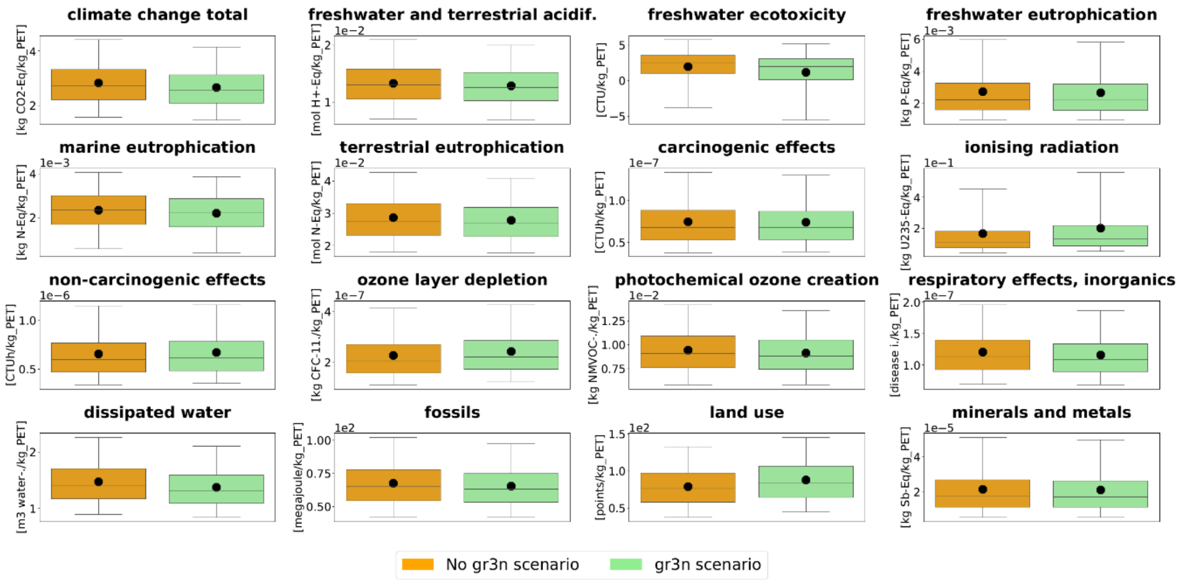

Fig. 6. Boxplots representing the probability distribution of the selected LCA impact categories, assessed across two scenarios to determine the consequences of the introduction of the *gr3n pathway*. The left orange boxplots represent the *No gr3n scenario*, while on the right green there is the *gr3n scenario*. Results are relative to the marginal PET demand. Outliers have been removed for clarity, see Fig. S5 for the full chart.

3.2. Uncertainty propagation: background and foreground influences

It is useful to understand how the results are affected by the uncertainty information related to the ecoinvent database and the uncertainty propagated by the STCM, which respectively represent the background and the foreground systems. To assess which is the prevalent source of uncertainty, we compare three cases. Firstly, the differences between the previously described *gr3n scenario* and *No gr3n scenario*, named *Base case delta.* Secondly, in the *Foreground variability only* case the STCM does not sample from the complete **randQ** but every process is represented by its average LCA impacts. Thirdly, in the *Background variability only* case the STCM samples from **randQ**, as in the *Base case delta,* but is different as the variance of all the STCM matrixes is set to zero. That is to say, we alternatively remove the propagation of uncertainty: in the *Foreground variability only* case from the background system, while in the *Background variability only* case from the foreground system.

Fig. 7 shows the 3 boxplots of the described cases. Looking at the Base case delta boxplots, the whiskers define a range that is only 17.7% of the average range of the whiskers of the gr3n scenario and No gr3n scenario shown in Fig 6, in accordance with the findings of the literature (von Brömssen and Röös, 2020). Still referring to this case, more than 50% of the population of the differences of LCA indicators are negative in 12 of the 16 indicators, meaning that the presence of the *gr3n pathway* in the technology mix tends to reduce potential environmental impacts. In 9 of these 12 indicators, the impacts are negative for 75% of the population, which signals a higher certainty of the goodness of the introduction of the *gr3n pathway.* Moreover, economies of scale and future R&D improvements, have the potential to further improve the environmental profile due to the introduction of the *gr3n pathway* in Europe.

The prevalence of either the foreground or the background model uncertainty in determining the variability of the differences depends on the assessed impact category. The propagation of the uncertainty in the ecoinvent database is responsible for the highest share of the variability within categories such as Freshwater ecotoxicity, Freshwater eutrophication, Carcinogenic effects, Ionising radiation, Non carcinogenic effects, Land use and Minerals and metals. Across the remaining categories, the STCM and the ecoinvent database are about equally responsible for the results variability. See Tables S6 and S7 for variations of average, median and standard deviations across these 3 cases.

Moreover, the *Background variability only* case shows different average and median points with respect to the *Foreground variability only* case. This is because, within the *Background variability only* case, market mixes are optimized with the average values of costs, factors requirements and capacities, instead of stochastic values. Consequently, gr3n penetration occurs up to its full capacity and landfill is fully displaced before displacing incineration (see Tables S8 and S9). Therefore, the difference between the supply array components of the *gr3n* and *No gr3n* scenarios increases, and the related variability increases, too. This is the reason why boxplots of the 6 categories whose variability appears to be more influenced by ecoinvent actually show a larger interval between whiskers in the *Background variability only* case, with respect to the *Base case delta*, even if the STCM uncertainty information is set to 0.

Further discussion on these results can be found in section 6.2 of the supplementary information.

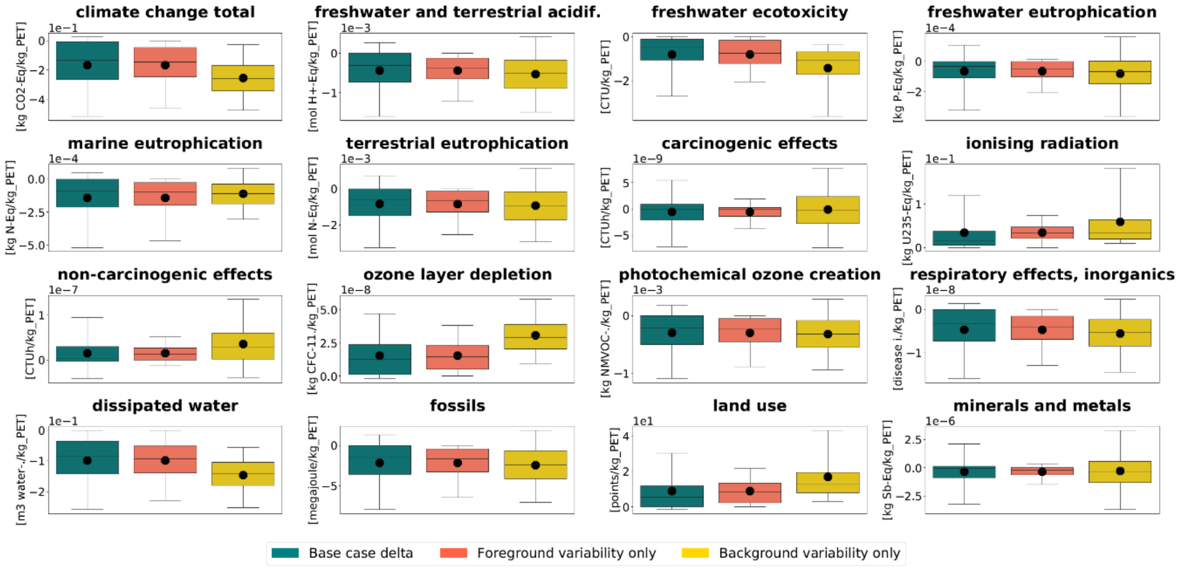

Fig. 7. Sensitivity analysis on the differences of ILCD impact indicators across the *gr3n scenario* and *No gr3n Scenario* due to different sources of variability in the LCI. On the left in teal, the *base case delta*. At the center in coral, the STCM is the only source of variability, because ecoinvent impacts are attributed their mean value. On the right in yellow the only source of variability is the ecoinvent database, because the coefficients of the STCM matrices were given zero variance.

Therefore, the background system, or the ecoinvent database, is responsible for a larger amount of the results variability, while the foreground system, or the STCM, is mostly responsible for the determination of averages and medians.

3.3. Sensitivity analysis

One of the novelties of our approach to the STCM is that we can incorporate the uncertainty distributions that are built-in in the ecoinvent database, which adopts the pedigree approach. Since the pedigree approach was found to underestimate the variability of market processes (Kuczenski, 2019), we examine if the addition of the STCM analysis might increase the robustness of the conclusions. Therefore, we perform three kinds of sensitivity analysis on key parameters to avoid presenting inaccurate results. A detailed discussion on the supply vector sensitivity to the parameters analyzed in sections 3.3.2 and 3.3.3 can be respectively found in sections 6.3, 6.5 and 6.6 of the supplementary information, with section 6.4 explaining the sensitivity to an additional parameter not presented here.

3.3.1. Different levels of marginal bottle-grade PET demand by 2030

The investigated variable in this analysis is the different amount of marginal PET demand by 2030, which has been varied in the domain [0.1, 1.72] Mt with a 0.27 Mt step, around the 0.91 Mt value of the *Base case,* based on PlasticsEurope (PlasticsEurope, 2019). We limit the analysis to the [0.1, 1.72] Mt interval of marginal bottle-grade PET demand. Since the STCM cannot evaluate at the same time positive and negative marginal demands, the lower bound of the investigated domain is chosen as a small but positive amount. On the other hand, the upper bound was determined so that the *Base case* would be the central one among the 7 that we assess and after having tested that relevant impact variations due to the gr3n pathway are not excluded by the 1.72 Mt limit. As Fig.9 shows, the variations of LCA indicators due to the introduction of the *gr3n pathway* are negligible after this value.

Fig. 8 shows the variations of the differences of supply vector components depending on the investigated variable. For what concerns the *gr3n pathway* only, looking at the variation of the differences is equal to looking at the *gr3n scenario* trends, as the supply array of this technology in the *No gr3n scenario* is set to 0. The lower the marginal demand, the higher the share of *gr3n pathway* in the PET supply mix increases, reaching 72% (see Table S10) at 0.1 Mt of PET marginal demand (yellow boxplots). Then, the *gr3n pathway* supply almost saturates at 0.37 Mt, with a further increase of only 0.015 Mt between the *0.37 Mt* and the *1.72 Mt cases*. Thus, between the latter cases, the marginal PET demand is mostly covered by the *mechanical recycling pathway* and by the *virgin PET pathway*. This is the reason behind the trends of the differences for the *mechanical recycling pathway* supply, which firstly decreases, due to the penetration of the *gr3n pathway,* and then progressively shifts towards zero, as this pathway reaches saturation in both the *gr3n* and *No gr3n* scenarios. The Europe and Rest-of-World PET integration accordingly show the same trend. The *virgin PET pathway* differences become lower than zero already in the *0.64 Mt case*, which means that already from this case, this pathway shows a higher penetration into the market, in the *No gr3n* scenario, with respect to the *gr3n* scenario.

Therefore, the introduction of the *gr3n pathway* reduces the use of the fossil RER and RoW PET integrations when the marginal demand is low. This can be further understood by looking at the symmetry between the *gr3n pathway* and the *mechanical recycling pathway* in the 0.1 Mt, 0.37 Mt and 0.64 Mt cases. Moreover, the introduction of such *pathway* decreases the production of the *virgin PET pathway.* Again, this translates into a symmetry, between the *gr3n pathway* and the *virgin PET pathway*, in the 1.72 Mt case. These observations demonstrate the potential of the gr3n technology to reduce the dependence in Europe on fossil production and to enable a more circular economy (Ellen MacArthur Foundation, 2020).

Finally, the differences of the two waste treatment avoided supplies are always positive, due to the higher displacement related to the penetration of the *gr3n pathway* in the *gr3n* scenario. Landfill avoided treatment firstly increases due to the higher penetration of the *gr3n pathway,* and then reaches a constant difference of about 0.02 Mt. Conversely, incineration differences do not significantly vary between *0.1 Mt* and *0.64 Mt cases*, while they show an increase due to the higher penetration of the *virgin PET pathway* in the *No gr3n scenario*.

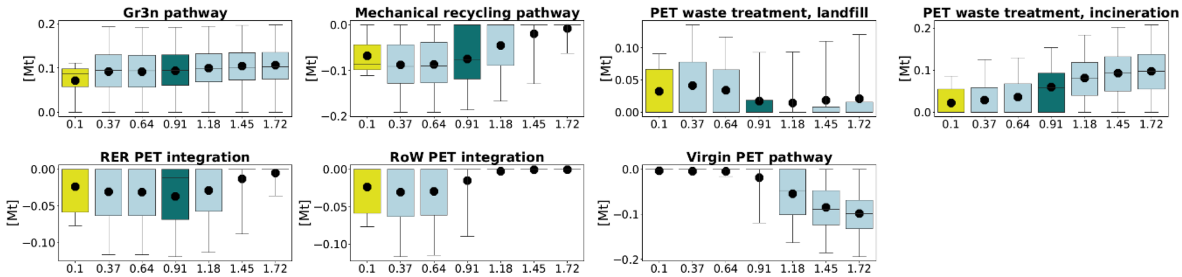

Fig. 8. Boxplots of the differences of supply vector components of *gr3n*, *mechanical recycling pathway*, avoided landfill and incineration, European and Rest-of-World PET integration and *virgin PET pathway*, between the *gr3n scenario* and *No gr3n scenario* are here plotted with respect to different levels of marginal European bottle-grade PET demand. The *Base case delta* is highlighted in teal (0.91 Mt), while the 0.1 Mt case is represented in yellow.

Fig. 9 shows the consequent intensive (i.e. per kg of PET delivered) differences of LCA impacts results. The trends are similar across the different impact categories, with the 0.1 case showing distributions significantly different from zero, essentially due to the high shares of the *gr3n pathway* and substitution of landfill in this case. The higher the marginal PET demand, the lower the intensive differences between the *gr3n* and *No gr3n* scenarios are, while the opposite is true for the absolute differences (see section 6.3 of the supplementary information). Excluding the *0.1 Mt case*, the relative impact variations, respectively computed with the medians and the averages according to equation 2, span at most by 17.92% and 26.41%, and by 1.99% and 2.47% on average. Therefore, the intensive differences gradually tend to zero, either from the positive side (Ionising radiation, Land use and Ozone layer depletion, which showed an increase of unitary impacts in the *Gr3n scenario*) or from the negative side. On the other hand, Fig S27 shows how extensive impact differences grow in absolute value with the increase in demand. Within this general trend, small fluctuations may appear due to counterbalancing effects related to the unitary impacts of the different processes involved in the STCM. For instance, an increased penetration of the *gr3n pathway* makes the Non carcinogenic effects indicator decrease, while an increased avoided supply of incineration makes the considered impact indicator increase. In the *0.1 Mt case*, the former effect is more relevant, while the opposite happens in the *1.72 Mt case.*

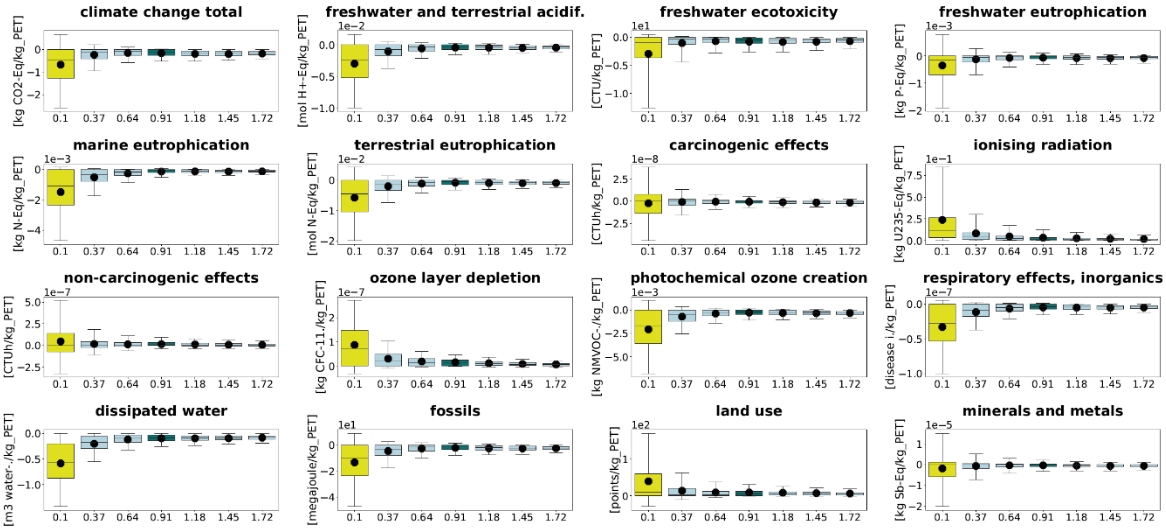

Fig. 9. Boxplots showing the sensitivity analysis of the distributions of the differences between the *gr3n scenario* and *No gr3n scenario* of the selected ILCD impact indicators, related to a change in marginal demand of the STCM. Demand was varied between 0.1 and 1.72 Mt by steps of 0.27 Mt. The left boxplots are highlighted in yellow since in the *No gr3n scenario* close to the totality of the PET production is generated by the *gr3n* pathway. In the middle in teal, the *Base case delta*. Impacts are normalized on the amount of marginal demand of PET in the European market in each case.

3.3.2. Different assumptions on technology cost

Here we investigate the consequences on LCA indicators related to different assumptions on the relative cost of gr3n and *mechanical recycling pathways*.

The investigated variable in this analysis is the ratio of the costs of *gr3n* to *mechanical recycling pathways*, which has been varied from 0.6 to 1.2, with 0.8 being the *Base case* assumption. These values aim to realistically model the competition: lower values of the cost ratio would not be realistic, while higher values would limit the production of the gr3n pathway and would be decreasingly interesting to assess the impact of introducing such option.

Fig. 10 shows that the differences between the two scenarios *gr3n* and *No gr3n* are relatively limited, especially comparing with Fig. 9 charts. Concerning this parameter, the variation of differences is only driven by variations within the *gr3n scenario*, as the *No gr3n scenario* cannot be influenced by this parameter.

The sensitivity of differences, evaluated through equation 2, shows the highest values for the Freshwater ecotoxicity and Ionizing radiation categories. Such categories show relative variation of average difference, respectively equal to -6.18% and +2.48% in the *0.6 case* and equal to +15.40% and -5.92% in the *1.2* case (see Table S17), the same considerations are valid for the median as well. The Freshwater ecotoxicity deviations are mostly due to changes in the avoided incineration treatment supply, which decreases as the mechanical recycling pathway supply increases, rather than directly to changes in the fulfilment of the European PET demand. The ionizing radiation decrease in the *1.2 case* is mostly due to the lower supply of *gr3n pathway*. Landfill displacement slightly decreases when shifting to the *1.2 case*, which makes Marine eutrophication increase. Thus, the change in incineration displacement is the main driver behind impact variation due to different values of the investigated variable.

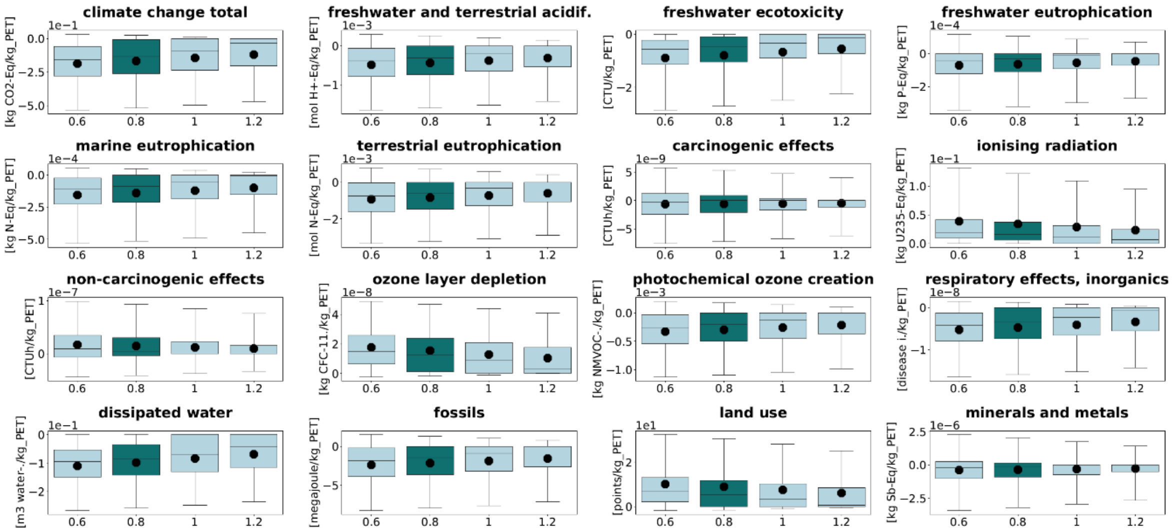

Fig. 10. Variations of the probability distribution of differences of LCA midpoint indicators due to different assumptions on the ratio of the cost of the *gr3n pathway* on the cost of the *mechanical recycling pathway*. In teal, the *Base case*.

3.3.3. Rate of suboptimal decisions

Here we analyze the dependence of LCA results on the rate of suboptimal decisions. This parameter models the noise in the composition of technology mixes that is due to decisions that do not follow the cost optimization process (Katelhon et al., 2016). Thus, the investigated variable is the parameter *i*, which is varied from 0 to 0.3, with 0.1 being the *Base case* assumption. In general, increasing *i* results in higher shares of costlier choices, such as virgin PET production.

Setting i=0 increases the *gr3n pathway* supply only by 0.001 Mt and in general, variations occurring due to a change of the analyzed parameter do not significantly alter results, as Fig. 11 shows. Within our model, the influence of *i* is lower than the influence of the other STCM stochastic parameters. The only noticeable variation across the analyzed cases concerns the interquartile range, which increases when *i* reaches 0.3, due to a higher random error in the optimizations.

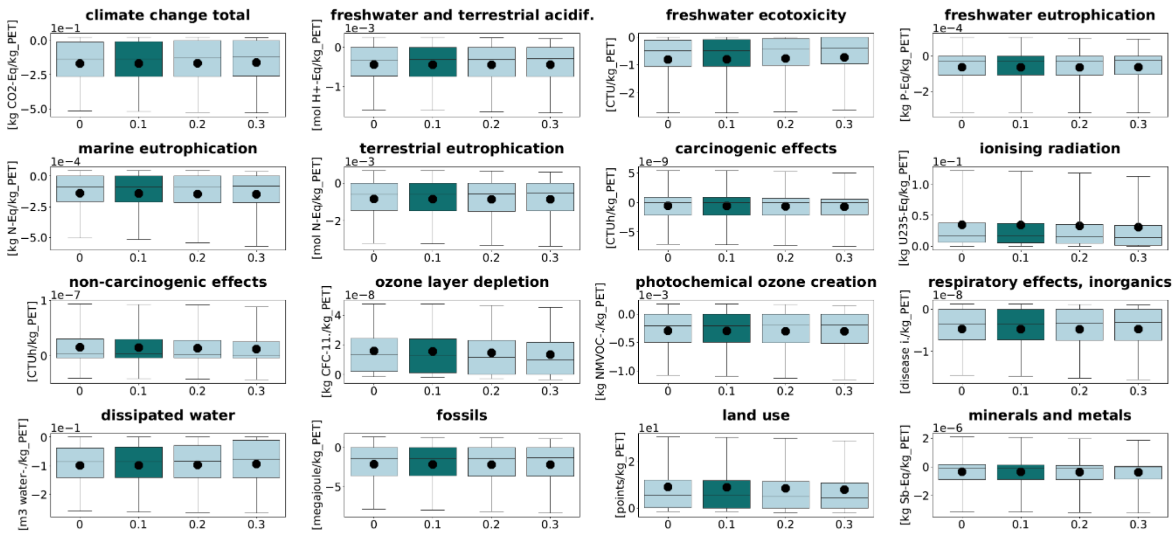

Fig. 11. Variations of the probability distributions of the differences of LCA midpoint indicators due to different assumptions on the parameter *i*, which represents the amount of suboptimal decisions. The *Base case* is represented in teal, at *i*=0.1.

3.3.4. Sensitivity analysis summary

Impact indicators show the highest sensitivity to assumptions on additional PET demand, especially when this variable approaches 0.1 Mt, with average variations of differences, computed with equation 2, of 19.85% and 34.04% respectively for the medians and the averages in such case.

Variations in the *i* parameter modify the results to a higher degree when *i* is increased, rather than decreased. Yet the variability in impacts indicators due to variations in the *i* parameter is systematically lower than the variability due to variations in *gr3n pathway* and *mechanical recycling pathway*. The most sensitive categories are the most closely related to *gr3n pathway* (Ionizing radiation) and waste treatment processes (above all are Freshwater ecotoxicity, Land use and Marine eutrophication).

Table 2 summarizes the percentages of relative deviations from the *Base case* of the medians of the extreme cases of the sensitivity analysis*,* for a selection of LCA impact indicators. Freshwater and terrestrial acidification, Terrestrial eutrophication, Photochemical ozone creation and Respiratory effects, inorganics follow a pattern which is very similar to the climate change one, which is shown in Table 2. The impact categories are chosen according to the average variation of the difference of results across the performed analyses and are sorted by a decreasing value of such relative deviations. For the sake of completeness, such table provides both indications on the medians and on the averages, yet medians should be regarded as the best indications within the present study. Indeed, the distributions of the single *gr3n* and *No gr3n scenarios*, together with the distribution of the differences between them, are skewed and a wide range of outliers was found (see from Fig. S21 to Fig. S24). According to the literature indications (von Brömssen and Röös, 2020), Table 2 shows that variations based on averages are more sensitive to changes in the analyzed input parameters.

Table 2. Summary of the widest relative impact variations found in the three sensitivity analyses, i.e. variations of average (or median) values of the differences of the selected ILCD categories with respect to the base case, relative to the average of the base case average (or median) values, computed with equation 2. For each cell, the first and second values are respectively computed using the medians and the averages.

	Ionising radiation	Freshwater ecotoxicity	Marine eutrophication	Dissipated water	Climate change total
Demand variation – widest decrease	-5.89; -8.45	-22.50; -134.00	-43.70; -59.50	-34.70; -34.30	-11.90; -18.50
Demand variation – widest increase	82.70; 110.00	9.06; 4.83	-0.16; 0.55	0.51; 0.86	1.24; 0.45
gr3n/ mechanical recycling cost – widest decrease	-7.97; -5.92	-4.29; 6.18	-0.88; -0.66	-0.77; -0.83	-0.89; -0.71
gr3n/ mechanical recycling cost – widest increase	2.63; 2.48	15.10; 15.40	3.47; 1.75	3.04; 2.05	3.83; 1.75
i widest decrease	-2.10; -1.84	-0.50; -0.50	-0.01; -0.26	-0.03; 0.02	-0.04; -0.01
i widest increase	0.29; 0.24	3.95; 4.36	0.40; 0.12	0.40; 0.33	0.52; 0.25
Main drivers	gr3n supply	gr3n supply, avoided incineration supply	avoided landfill supply	gr3n supply, avoided incineration supply	gr3n supply, avoided incineration supply

4. Conclusions

This study aims to evaluate the impact of the introduction of a novel chemical recycling technology in the European bottle-grade PET market by 2030. In this perspective, we look at the difference in the marginal LCA impacts of such market in case the gr3n technology is and is not available, through the Stochastic Technology Choice Model. Moreover, we assess how much of the variability of the LCA results is due to the propagation of the uncertainty related to the background LCI and how much is due to the uncertainty propagated within the STCM. Finally, we test the robustness of our results with three sensitivity analyses on key STCM parameters.

According to our hypotheses, 12 of the 16 selected ILCD impact categories show a clear decrease due to the introduction of the *gr3n pathway* (see Fig 7), as 12 indicators show more than 50% negative values of the population of the differences of results, computed with equation 1. Of these 12, 9 indicators are negative for at least 75% of their population. On the contrary, Ionizing radiation, Land use and Ozone layer depletion increase. The potential impacts of Non-carcinogenic effects also increase, due to incineration displacement. Freshwater ecotoxicity shows the largest relative decrease on median values, -27%, while a median 0.13 $kg_{CO2\text{-}eq}/kg_{\text{bottle-grade PET}}$ could be saved by the introduction of gr3n, equivalent to a 5% reduction. Results of each of the analyzed scenarios show high standard deviations, being them on average equal to 64.67% of the median value and up to 247.44% of the median value, for the Freshwater ecotoxicity category. The boxplots whiskers of the difference of results (Fig. 7) define a range that is only 17.7% of the average interval defined by the *gr3n scenario* and *No gr3n scenario* (Fig. 6). Therefore, to determine the environmental consequences of introducing a new technological pathway, it is important to coherently assess the differences between two such scenarios. In general, a larger part of the variability in LCA results is found to be related to the propagation of the uncertainty from the ecoinvent database, while the rest is traced to the STCM. Moreover, the latter is responsible for the shift of both average and median impact values towards new equilibria, due to the optimized technology mixes.

In the sensitivity analysis on different levels of additional PET demand, results are found to be particularly sensitive to the 0.1 Mt additional PET demand case, with the relative impact variations, respectively computed with the medians and the averages according to equation 2, being equal to 19.85% and 34.04% on average across the selected impact categories. For the other cases in this analysis, the same quantities, span at most by

17.92% and 26.41%, and by 1.99% and 2.47% on average. For all the selected 16 ILCD impact categories, average absolute value of variation of the differences of medians with respect to the average impact of the *Base case* is not particularly sensitive to assumptions on additional demand (excluding the 0.1 and 0.37 Mt cases), costs of PET production pathways and to assumptions on the rate of suboptimal decisions. Indeed, excluding the 0.1 and 0.37 Mt cases, the relative impact variations, respectively computed with the medians and the averages according to equation 2 are at most equal to 15.10% and 15.40%. Categories such as Ionizing radiation, which is greatly influenced by the *gr3n pathway* supply, and those impact categories most closely related to the avoided waste treatment processes show the highest sensitivity to the analyzed parameters. Across the performed sensitivity analyses, the relative impact variations, respectively computed with the medians and the averages according to equation 2, are equal to 3.10% and 4.34% on average.

Our contribution is threefold. Firstly, this is the first consequential LCA of the gr3n technology and, to the best of our knowledge, the first for a PET chemical recycling technology. Secondly, this is the first study to utilize the STCM to assess the introduction in a market of a novel technology. Thirdly, this is the first study to include in the STCM the ecoinvent LCI through Brightway2, to properly account in the Monte Carlo simulations for the correlations within the life cycle systems of the assessed processes and to propagate separately and coherently uncertainties from the background and from the foreground systems.

Therefore, the results of this study could inform policy makers on the potential marginal LCA impact savings due to the introduction of the gr3n technology at a European level. Moreover, the positive environmental impacts, together with the high displacement of incineration, landfill and virgin PET production could further improve with economies of scale and research and development. The sensitivity analyses show that our results are reasonably robust for most of the impact categories and can be used to inform on potential trade-offs among them. Particularly in the case of a limited increase of European bottle-grade PET demand by 2030, the gr3n technology could play a significant role in reducing most of the marginal LCA impacts. Therefore, policy makers should focus on limiting the increase in marginal demand of PET and on creating fair conditions for this chemical recycling technology to be deployed to complement mechanical recycling in reducing virgin PET production, thus decreasing potential environmental impacts and fostering a more circular economy.

CRediT authorship contribution statement

Simone Cornago: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Davide Rovelli:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Carlo Brondi:** Writing – original draft, Writing – review & editing. **Maurizio Crippa:** Resources. **Barbara Morico:** Investigation, Data curation. **Andrea Ballarino:** Supervision. **Giovanni Dotelli:** Methodology, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maurizio Crippa is the Co-founder and CEO of gr3n SA, the company that owns the intellectual property of the gr3n technology (Patent n. ITMI20111411A1).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi. org/10.1016/j.jclepro.2021.127406.

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