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Attributional and consequential LCAs of a novel bio-jet fuel from Dutch potato by-products

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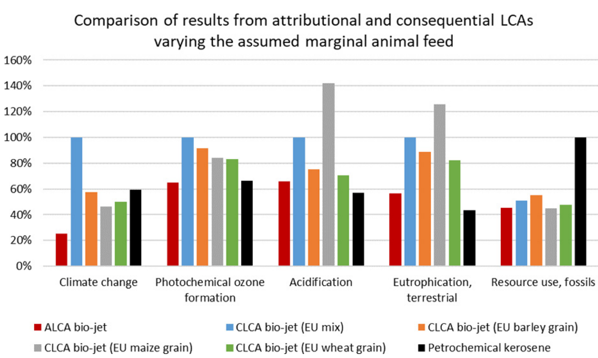
HIGHLIGHTS

- A comparison of attributional and consequential LCAs for an innovative bio-jet fuel from potato by-products is presented.
- The attributional additivity principle and the uncertainty of the consequential model were in focus.
- The consequential LCA calculated higher environmental burden than the attributional LCA.
- The diversion of potato by-products from the animal feed market was the major cause of uncertainty in the consequential LCA.

GRAPHICAL ABSTRACT



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ABSTRACT

To mitigate the climate change impact of aviation, jet fuels from bio-based by-products are considered a promising alternative to conventional jet fuels. Life cycle assessment (LCA) is a commonly applied tool to determine the environmental impacts of bio-jet fuels. This article presents both attributional and consequential LCA models to assess an innovative bio-jet fuel produced from potato by-products in the Netherlands. The two models led to opposite conclusions regarding the overall environmental performance of this bio-jet fuel. The attributional LCA showed that this bio-jet fuel could offer about a 60% GHG emissions reduction compared to conventional jet fuel. In comparison, the consequential LCA estimated either a much lower climate change benefit (5–40%) if the potato by-products taken from the animal feed market are replaced with European animal feed or a 70% increase in GHG emissions if also imported soybean meals are used to replace the feed. Contrasting conclusions were also obtained for photochemical ozone formation. Conversely, the attributional and consequential LCAs agree on acidification, terrestrial eutrophication and depletion of fossil fuels. Although the consequential LCA was affected by higher uncertainties related to the determination of the actual product displaced, it allowed understanding the consequence of additional animal feed production. This process was not included in the system boundaries of the attributional LCA.

1. Introduction

The substitution of petrochemical fuels with low-carbon fuels is necessary for reducing anthropogenic greenhouse gas (GHG) emissions. Although the direct emissions from the aviation sector were responsible for only 2% of pre-covid-19 worldwide GHG emissions (Crippa et al., 2019), the sector is expected to continue growing (IATA, 2020). The role of biomass for the aviation sector is essential as there are limited options for decarbonization, especially in the next twenty years (Doliente et al., 2020; Wei et al., 2019). Unlike road transport, it is challenging to equip aircrafts with electric-powered engines for long distances (Wei et al., 2019). Other alternatives such as hydrogen or other fuels based on renewable electricity and CO_2 are at the early stages of development (Arat and

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Sürer, 2020). Therefore, the decarbonization of aviation is still far away from practical implementation.

In the short term, the most promising option for GHG emissions reduction is using drop-in jet fuels from sustainable biomass feedstocks (Doliente et al., 2020; Wei et al., 2019). Bio-jet fuels can be blended with petroleum fuels and used in existing engines without modifications (Zemanek et al., 2020). Despite that, to date, hydroprocessed esters and fatty acids (HEFA) is the only commercial technology available for bio-jet fuels (Doliente et al., 2020). However, HEFA bio-jet fuel production volumes are still considerably limited, accounting for less than 1% of total jet fuels worldwide (EASA, 2019). The high production costs (2 to 6 times higher than conventional jet fuels) and strict sustainability requirements to be incentivized (60–65% GHG emissions' savings depending on the country) result in unfavorable industry development conditions (de Jong et al., 2015; IRENA, 2017; O'Connell et al., 2019). Currently, used cooking oil is the only alternative applied on industrial levels that is near cost-competitive and delivers low life cycle GHG emissions (O'Connell et al., 2019; Pavlenko et al., 2019). Nevertheless, the availability of used cooking oil is limited. Used cooking oil is also demanded for road and marine transport fuels and chemicals (Moretti et al., 2020b; Talens Peiró et al., 2010; Tsoutsos et al., 2016).

Many emerging bio-jet fuels have been recently certified by the American Society for Testing and Materials (ASTM, 2020). Among them, Fischer-Tropsch (FT) and alcohol-to-jet (ATJ) pathways are the production routes closest to commercialization (Wei et al., 2019).

For policy decision-making, it is crucial to assess the potential environmental benefits/impacts of bio-jet fuels compared to petrochemical jet fuels. Generally, these assessments are carried out using Life Cycle Assessment (LCA), a method for environmental assessments standardized by ISO 14041 and ISO 14040 (ISO, 2006a, 2006b). This article investigates the environmental performance of an innovative ATJ route developed in the Netherlands to use local potato by-products from the food processing industry. This low-price carbohydrate by-product is currently used mainly as animal feed but can be potentially transformed into valuable bio-based products such as biofuels, materials and chemicals (Achinas et al., 2019; Broeren et al., 2017; Mars et al., 2010).

Despite being a standardized approach, LCA results can be affected by significant variability. The option of different methodological assumptions can steer the life-cycle environmental impact of a process/product, even when assessing the same fuel and feedstock (Capaz et al., 2020; Zemanek et al., 2020). A recent review of LCAs for HEFA biofuels (Zemanek et al., 2020) identified the method used to deal with multifunctional processes and the inclusion/exclusion of land-use change (LUC) emissions as the most important sources of variability. For example, the GHG emission intensity of a bio-jet fuel could increase by 2–3 times using either a different allocation method or making a different assumption for LUC (Zemanek et al., 2020). Similar findings for bio-jet fuel pathways were also reported by Capaz et al. (2020). However, note that these issues also apply to other biofuels in general (Plevin, 2017; Stratton et al., 2011).

Multifunctionality practices and the inclusion of land-use changes depend on the specific LCA's goal and scope and consequently, the choice of modeling approach (Moretti et al., 2021; Plevin, 2017). In the literature, two main modeling approaches are distinguished: attributional and consequential LCAs (Curran et al., 2005). The attributional approach attempts to quantify the portion of global burdens associated with the specific products under assessment (Schaubroeck et al., 2021). The environmental impact of such products is determined by analyzing the production system using representative average data (Majeau-Bettez et al., 2018; Pelletier et al., 2015). Via attributional LCAs (ALCAs), the environmental impacts of each co-product are obtained by distributing the burden based on allocation parameters such as energy or market values (Moretti et al., 2020b; Pelletier et al., 2015; Sandin et al., 2015). In this way, the so-called additivity principle of ALCAs is respected i.e., summing ALCAs of all worldwide products should lead to the total environmental burdens worldwide (Schaubroeck et al., 2021). In attributional LCAs, looking at the status-quo and not to what has happened in the past or the future, (indirect) LUC is generally not included. However, when LUC is included, only direct LUC is addressed and indirect LUC is not considered (Plevin, 2017; Plevin et al., 2014; Schmidt et al., 2015). Consequential LCAs (CLCAs) focus on modeling the relative changes in the entire techno-sphere when the decision supported by the LCA is adopted. Hence, the CLCA provides information on both direct and indirect environmental impacts occurring due to the changes in demand for a product caused by such a decision (Schaubroeck et al., 2021). Therefore, a CLCA allows assessing all the causal-effect relations within the market by changing product demand using marginal data (Brando et al., 2017; Capaz et al., 2020; Majeau-Bettez et al., 2018). In CLCAs, multifunctionality is addressed by a substitution approach (or often referred to as "displacement method"), and both direct and indirect LUC are included in the life cycle inventory (Plevin, 2017; Plevin et al., 2014; Schmidt et al., 2015).

While there is plenty of methodological literature regarding the effects of the modeling approach on the LCA result, the practice of applying both modeling approaches to the same product system before drawing recommendations is rare. No more than 8% of the peer-reviewed LCAs on bioenergy products in the Scopus database applied both modeling approaches to their case study (Moretti et al., 2020a). Only 3% of peer-reviewed LCAs on bioenergy products declared to adopt a consequential modeling and the remaining studies used an attributional or unspecified modeling approach (Moretti et al., 2020a). A recent review of the 100 most cited LCAs of bioenergy products highlighted that ambiguous results in these LCAs are mainly due to choices in the inventory modeling approach that are inconsistent with the goal of the study (Agostini et al., 2019).

To our knowledge, there is only one peer-reviewed LCA applying both modeling approaches to a bio-jet fuel (Capaz et al., 2018). In their study, the CLCA resulted in an environmental benefit mainly due to the substitution of the power surplus. Their ALCA using allocation instead of substitution could not confirm such a benefit. While there is only one study applying both modeling approaches to a bio-jet fuel, there are several comparisons between the two modeling approaches for the case of animal feed (Schmidt and Weidema, 2008; Thomassen et al., 2008). Among them, a recent study by van Zanten et al. (2018) applied attributional and consequential modeling approaches to understand the environmental advantages of replacing soybean meal with an alternative protein source (peas or rapeseed meal) in pig diets. While their ALCA concluded that this practice could lead to environmental advantages, the CLCA concluded the opposite (van Zanten et al., 2018).

Given the lessons learned by the abovementioned literature regarding the effects of the modeling approach on LCA results, this study presents both attributional and consequential LCAs of this bio-jet fuel. In particular, the attributional LCA aimed to investigate the environmental impacts caused by the production of this jet fuel starting from the total environmental impact of the production system (i.e. the full pie). The attributional LCA of the bio-jet fuel attributes a piece of the pie to the bio-jet fuel. Technically, other practitioners could have a different aim leading to investigate one of the co-product of the same production system. These attributional LCAs attribute the remaining shares of the pie to the other system's co-products. The sum of each functional output's environmental impact corresponds to the total impact of the product system (additivity of these ALCAs). Hence, the ALCA modeling serves to answer the research question: how much each of the different product outputs is responsible for the production system's total environmental impact? Companies producing such bio-based products are usually interested in consulting these LCAs. The results of these ALCAs allow understanding the environmental performance of the entire spectrum of bio-based products produced, usually benchmarking with their petrochemical counterparts, as well as possible process improvements.

While attributional modeling has a producer perspective, consequential modeling has usually a policy perspective. Our CLCA aimed to answer the following research question: how could introducing the new bio-jet fuel to the market potentially change the overall environmental impact of the economic sectors affected by the change? For example, the consequential LCA in our study aimed to understand the environmental impact of this novel bio-jet fuel at the net of the effects of displacing the potato by-products from the animal feed market.

2. Materials and methods

2.1. Goal and scope definition

Both attributional and consequential LCAs aimed to assess the environmental impact of a novel bio-jet fuel. Based on this goal, a functional unit of 1 MJ of bio-jet fuel was defined. The results of the two LCAs were compared with the environmental impact of conventional jet fuel (assumed kerosene). Such a comparison was used to evaluate if the two modeling approaches lead to similar findings regarding the environmental performance of this novel bio-jet fuel. This exercise aimed not only to provide a comprehensive picture of environmental impacts of the bio-jet fuel using a food processing by-product, but also to join the current LCA debate about the influence of the type of modeling approach used on the environmental performance of bio-based fuels and materials using by-products with low economic significance or waste as resources (Moretti et al., 2020a; Plevin, 2017). Hence, the intended audience of this LCA includes both technology developers and the LCA community.

Since this novel bio-jet fuel has been developed in the Netherlands from a local feedstock, the geographic scope of the LCA is the Netherlands. The temporal scope is the year 2030, when this fuel could be commercialized on a large scale.

A cradle-to-grave scope was adopted in the two LCAs of the bio-jet fuel. The respective process flow diagrams are shown in Fig. 1. For both ALCA and CLCA, the common unit processes included are: acetone-ethanol-butanol (ABE) fermentation, swing adsorption, alcoholic condensation, hydrotreatment, distribution and combustion. The production of the aircrafts and the biorefinery plant and their decommissioning were neglected in both models. The exclusion of capital goods (including infrastructures) and their end of life is common practice for LCAs of biofuels in the EU. In fact, the well-to-wheel approach, which is the main tool adopted for the EU biofuels, excludes the production of the vehicles and plants and their decommissioning from the LCA scope (European Commission, 2016; European Parliament, 2015). The reason is that the contribution of capital goods on the total life cycle of fuels is expected to be small and very similar for biofuels and conventional fuels (Edwards et al., 2017; JRC et al., 2014). The exclusion of capital goods from this LCA is also in line with the update of the EU Product Environmental Footprint (PEF) recommending the exclusion of capital goods from the LCA "unless there is evidence from previous studies that they are relevant" (Zampori and Pant, 2019).

In the attributional LCA, the flow diagram starts with potato cultivation and the potato processing industry generating the potato by-products. In the CLCA modeling, the unit processes representing the production of the feedstock (cultivation and potato industry) are not included because they are not affected by the change that the CLCA aims to assess. In fact, if the potato by-products were not used for this application, they would be produced anyway. The use of potato by-products for this application changes neither the raw potatoes inputs nor the utilities utilized by the factory per tonne of the main food product. Hence, introducing this bio-jet fuel as a substitute for petrochemical kerosene (i.e. the change assessed) does not affect these processes.

In the Netherlands, the potato by-products that can be used for this fuel are made of potato peels (80%), grey starch (15%) and press-pieces (5%) (Moretti et al., 2021). Most potato by-products (potato peels and potato pieces) are currently used in animal feed. Grey starch might be used for

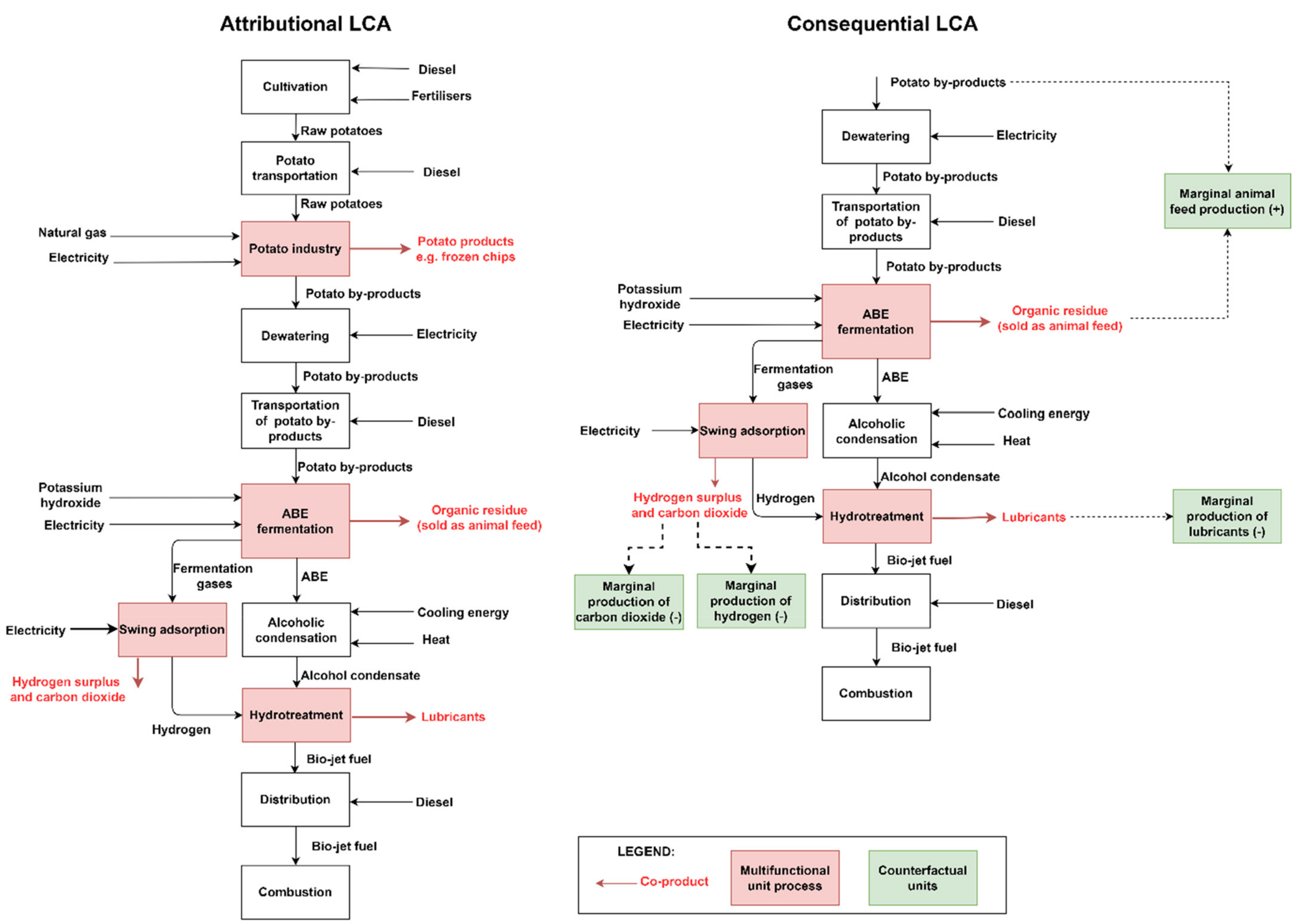

Fig. 1. Cradle-to-grave process flow diagram detailing inputs and co-products for attributional (left) and consequential (right) LCAs of the investigated bio-jet fuel.

Table 1
Environmental impact categories and impact assessment models.

Impact category	Unit	Impact assessment models (European Commission, 2018)
Climate change	kg CO2eq	IPCC 2013, GWP 100a with carbon climate feedback (Hartmann et al., 2013)
Photochemical ozone formation	kg NMVOC eq	(van Zelm et al., 2008)
Acidification	molc H+ eq	(Posch et al., 2008)
Terrestrial eutrophication	mol N eq	(Goedkoop et al., 2009)
Depletion of fossil fuels	MJ	(van Oers et al., 2002)

other purposes (Feednavigator, 2013). Since grey starch represents only 15% of potato by-products, we can assume that taking away the potato by-products used as feed affects mainly the animal feed supply. If the animal feed demand is to be maintained, additional feed needs to be supplied from other sources. For this reason, the flow diagram of the CLCA includes the unit process named "marginal animal feed production", representing the production of such additional animal feed from other sources.

Furthermore, attributional modeling was also used to determine the environmental impact of the co-products in the value chain, namely animal feed (from fermentation residue), bio-based hydrogen, bio-based carbon dioxide and biolubricants. In this way, it is possible to transparently present how the environmental impact of each process contributes (i.e. is allocated) to the environmental impact of each function delivered by the system. The impacts between the main product (jet fuel) and these by-products are partitioned by physical or economic relations. The allocation choices between the co-products can be found in the next section. For CLCA, system expansion is applied to these by-products. The by-products are assumed to replace the marginal productions of the same or similar products (see Section 2.2); therefore, the environmental impacts of the individual co-product cannot be quantified.

In the ALCAs, the environmental impacts of each co-products were compared with their current market benchmarks. This comparison is in the interest of the producer of such bio-based products. The company wants to avoid burden-shifting between their co-products i.e. producing one bio-based product with a good environmental performance at the expense of a bad environmental performance for the other bio-based products produced. In case of opposite conclusions between the two LCAs of the bio-jet fuel for certain impacts, it is possible to use the results of the other ALCAs to immediately understand if the main reason is linked to the allocation method. For example, we could notice if most of the environmental impact in that category is caused by a certain unit process and was allocated mainly to a co-product instead of the bio-jet fuel. If this is not the case, we can exclude this effect of allocation and look for other reasons not linked with the allocation applied in the ALCA. For example, a reason can be the inclusion of a different process in the system boundaries (e.g. animal feed displacement effect) or marginal versus average data.

The selection of the market benchmarks for the ALCAs and the substituted products in the CLCA can be found in Sections 2.2.5 and 2.2.7.

For the attributional LCAs of the bio-based co-products of the jet-fuel, the functional units were defined as 1 kg of each product, i.e., 1 kg of animal feed or 1 kg of hydrogen or 1 kg of carbon dioxide or 1 kg of lubricants (see Table 3 and Table 4 for the actual production ratios). Since these co-products are delivered at the bio-jet fuel production process gate and are usually not combusted, their LCA follows a cradle-to-gate scope. Given the additivity principle of ALCA, summing the environmental impact of the functional units of all ALCAs conducted leads to the total environmental impact of the system shown in Fig. 1 on the left.

Five midpoint impact categories were selected (see Table 1). Besides climate change and depletion of fossil fuels, which are priority indicators in the current environmental decision-making (Höök and Tang, 2013), other four impact categories were considered. Among them, photochemical ozone formation, acidification and terrestrial eutrophication are recognized as key environmental problems linked to nitrogen oxides in the Netherlands (Stokstad, 2019). These three categories are acknowledged as important impacts for bio-based products' policy and investment decisions. Previous work showed that a fair comparison with petrochemical products with reasonable uncertainties is possible for these five impact categories (European Commission, 2019; Vural Gursel et al., 2021). As for the sustainability assessment of bio-based fuels used in the European Union (European Commission, 2016; European Parliament, 2015; JRC et al., 2014), the direct biogenic carbon dioxide emitted to the atmosphere from the combustion biofuels was considered carbon neutral. Based on the European legislation for biofuels and supporting documents (mentioned above), the only exception regards the consequences of land use changes on the soil organic carbon (biogenic). Accordingly, the carbon removal from the original biomass matter was neglected except for net effects related to LUC (for details regarding the data used for LUC modeling, please refer to Section 2.2.6).

2.2. Life cycle inventory

2.2.1. Feedstock production (ALCA) and transportation

Potato by-products are a low economic significance by-product of the potato processing industry. In the flow diagram of the ALCA (see Fig. 1), the product system starts with the cultivation of potatoes. After the raw potatoes are harvested, they are sent to the potato industry to be processed into food products. The main inputs to the potato industry are electricity and heat. The quantities are reported in Table 2. Economic allocation was applied to the potato industry unit process (for details, see Section 2.2.4).

The dewatered potato by-products are then transported by lorry (16–32 t) to the refinery, which is assumed in Rotterdam. Based on the location of potato processing factories in the Netherlands, the potato by-products need to be transported on average for 105 km (Moretti et al., 2021).

2.2.2. From potato by-product to bio-jet fuel

At the refinery location, the potato by-products are processed via ABE fermentation, which produces a mix of valuable alcohol/ketone made of butanol and acetone with a minor fraction of ethanol. Table 3 reports on the ABE fermentation process's inputs and output, which uses pervaporation for in-situ butanol recovery, increasing the ABE yield (Van Hecke et al., 2018; Van Hecke and De Wever, 2017).

Table 2
Mass and energy inputs of the potato industry per tonne of potato by-products and background data sources for these inputs. Processed potatoes output based on confidential data from the industry and not disclosed.

Activity level data	Quantity per tonne of potato byproduct	Foreground data sources	Background data
Inputs			
Raw potatoes, wet (t)	4.6	(Ponsioen and Blonk, 2011).	Agri-footprint 5.0 (Potatoes, market mix, at regional storage/NL) This dataset already includes the average transportation of potatoes in the Netherlands.
Heat (GJ)	12.4	(Ponsioen and Blonk, 2011).	Heat, district or industrial, natural gas {Europe without Switzerland}|heat production, natural gas, at boiler condensing modulating >100 kW|APOS, from ecoinvent 3.6.
Electricity (kWh)	558.9	(Ponsioen and Blonk, 2011).	For electricity, the dataset Electricity, medium voltage {RER}|market group for APOS from ecoinvent 3.6 was used updating the shares of electricity by fuel mix based on the 2030 EU reference scenario for the Netherlands (Carpos et al., 2016).

Table 3
Mass and energy inputs and outputs of ABE fermentation (including in-situ recovery pervaporation) per t pure ABE from Moretti et al. (2021) and background data sources for the LCA.

Flow	Amount	Comment/background data
Inputs		
Potato by-products (t) wet	46.6	As the output from the potato processing industry. Corrected based on dry base content for the data source (Ponsioen and Blonk, 2011).
Enzymes (kg)	2.2	Electricity (1.9 kWh per kg of enzyme) and steam (4 MJ per kg of enzyme) to produce α-amylase enzymes based on Dunn et al. (2012). For electricity in the attributional modeling, the dataset Electricity, medium voltage {RER}|market group for|APOS from ecoinvent 3.6 was used to update the shares of electricity per source based on the 2030 EU reference scenario for the Netherlands (Carpos et al., 2016). For electricity in the consequential modeling, Electricity, medium voltage {NL}|market for|Conseq was used. For steam, the dataset Heat, from steam, in chemical industry {RER}|market for heat, from steam, in chemical industry|APOS or Conseq from ecoinvent 3.6 was used.
Potassium hydroxide (t)	0.1	Potassium hydroxide {RER}|production|APOS or Conseq from ecoinvent 3.6.
Electricity (kWh)	1000	For electricity in the attributional modeling, the dataset Electricity, medium voltage {RER}|market group for|APOS from ecoinvent 3.6 was used to update the shares of electricity per source based on the 2030 EU reference scenario for the Netherlands (Carpos et al., 2016). For electricity in the consequential modeling, Electricity, medium voltage {NL}|market for|Conseq was used. The marginal electricity dataset, which was based on 2014 data, was not modified since marginal technologies are more stable in time than data based on average technologies (Weidema et al., 1999).
Nitrogen (kg)	2.8	Nitrogen, liquid {RER}|market for|APOS or Conseq from ecoinvent 3.6
Co-outputs (Details about allocation are reported in Section 2.2.4)		
Organic residue (t)	3.5	Sold as animal feed.
Part of fermentation gases made of hydrogen (t)	0.05	Partly used for hydrotreatment while the surplus is sold.
Part of fermentation gases made of biogenic carbon dioxide (t)	1.6	Sold.

The mix of ABE alcohols is then processed through alcohol condensation (Breitkreuz et al., 2014), avoiding an important part of energy consumption to separate the alcohols and acetone to purity (Lodi et al., 2018; Van Hecke et al., 2018). The water produced by alcohol condensation is recycled back to a second pervaporation membrane for water separation, which needs to be treated before being discharged to the environment. In parallel, the fermentation gases (a mix of carbon dioxide and hydrogen) are separated via swing adsorption, with 344 kWh of electricity consumed per t of carbon dioxide separated (Cloete et al., 2020). The alcoholic condensate is then further deoxygenized via hydrotreatment using part of the separated bio-hydrogen (Breitkreuz et al., 2014; Moretti et al., 2021). Table 4 reports on the inputs and outputs of the thermochemical upgrading to bio-jet fuel.

2.2.3. Distribution and combustion

For the distribution of the bio-jet fuel and petrochemical kerosene to the “tanks”, a distance of 65 km was assumed, representing the transportation from Rotterdam to Amsterdam. As background data, the process Transport, freight, lorry >32 metric ton, EURO4 {RER}|transport, freight, lorry >32 metric ton, EURO4|APOS or Conseq from ecoinvent 3.6 was used. The technology under assessment is similar to the ATJ-synthetic paraffinic kerosene pathway where isobutanol or ethanol are upgraded to jet fuel via alcohol dehydration and condensation reaction followed by hydrotreatment (Gevo, 2019). For this reason, the combustion emissions for the bio-jet fuel were assumed to be the same as ASTM-certified synthetic paraffinic kerosene. The carbon dioxide from the bio-jet fuel is biogenic and was assumed carbon neutral as currently assumed in biofuels' sustainability calculations according to the EU legislation (European Commission, 2016; European Parliament, 2015). The inventory for distribution and combustion can be found in Table 5. The lower heating value (LHV) of the bio-jet fuel was assumed to be 44.1 MJ/kg, which is typical of synthetic paraffinic kerosene (Elgowainy et al., 2012). An LHV of 43.2 MJ/kg was assumed for petrochemical kerosene (Elgowainy et al., 2012). Combustion emissions were based on a single-aisle passenger aircraft operating on an average distance and with an average payload for both jet fuels. With these assumptions, the so-called payload fuel energy intensity is 8.62 $kJ/kg_{payload}$-$km_{great\text{-}circle\ distance}$ for the bio-jet fuel (Elgowainy et al., 2012) and 8.65 $kJ/kg_{payload}$-$km_{great\text{-}circle\ distance}$ for conventional jet fuel.

Table 4
Mass and energy inputs and outputs of the thermochemical upgrading (alcohol condensation plus hydrotreatment) per t of bio-jet fuel from Moretti et al. (2021) and background data sources for the LCA.

Flow	Data	Background data
Inputs		
Pure ABE	1.5 t	
Heat	4.6 GJ	Heat, district or industrial, natural gas {RER}|market group for|APOS or Conseq from ecoinvent 3.6.
Cooling energy	1.7 GJ	Cooling energy {CH}|from natural gas, at cogen unit with absorption chiller 100 kW|APOS or Conseq from ecoinvent 3.6.
Bio-hydrogen	36.5 kg	From swing adsorption.
Co-outputs		
Lubricants	41.7 kg	Mass allocation. Details in Section 2.2.4.
Wastes		
Wastewater	0.6 t	Wastewater, average {Europe without Switzerland}|market for wastewater, average|APOS from ecoinvent 3.6

2.2.4. Multifunctionality in the attributional model

In attributional modeling, the allocation method was based on each unit process's “causality mechanism” as recommended by ISO 14044:2006. The purpose of the potato industry is to produce revenues selling potato food products. Hence, an economic allocation was used. Based on Ponsioen and Blonk (2011), approximately 1% of the environmental impact of the potato industry was allocated to the potato by-products (based on the five-year average price).

For the ABE fermentation process, energy allocation was applied because the process is driven to produce an energy product, even though the fermentation residue used for animal feed has a higher mass content compared to the alcohols. The following allocation factors were retrieved

Table 5
Inventory of combustion emissions per kg of jet fuel retrieved from Elgowainy et al. (2012).

Emissions to air	Data (grams/kg) for bio-jet fuel	Data (grams/kg) for petrochemical kerosene
CO_2	3100	3151
CO	4.0	4.0
N_2O	0.01	0.01
NO_x	14.5	15.5
SO_x	0	1.4
CH_4	0.005	0.005

from Moretti et al. (2021): 34.4% to ABE, 6% to the fermentation gases and 59.6% to the animal feed.

The swing adsorption process aims to remove the fermentation gases continuously and separate carbon dioxide and hydrogen. Between these two co-products, carbon dioxide is more significant from both economic and mass perspectives. Given that this unit process's main product is not an energy product, economic allocation was also applied for this multi-output process. As a result, allocation shares of 59.4% and 40.6% were calculated respectively for carbon dioxide and hydrogen (Moretti et al., 2021).

Together with the bio-jet fuel, the hydrotreatment process also delivers a minor co-product (i.e., lubricants). The goal of the hydrotreatment process is to generate bio-jet fuel (energy). Energy allocation could be applied to the hydrotreatment process. Since the lower heating value of the lubricants is unknown, a mass allocation was used as a proxy for energy allocation resulting in 4% of the environmental impact allocated to lubricants. Since lubricants are a minor product, the allocated environmental impact to each t of fuel is only slightly affected by the applied allocation method. Conversely, the impact of the lubricants is more affected by the allocation method based on how different is the actual lower heating value of the lubricants compared to the one of the bio-jet fuel.

2.2.5. Multifunctionaility in the consequential model

2.2.5.1. By- and co-products. The consequential modeling included avoiding the production of all bio-jet fuel's co-products in the system boundaries through the so-called system expansion by substituting marginal production. For most commodity products, the marginal production data were taken from the Ecoinvent Consequential datasets. Lubricants were substituted with Lubricating oil {RER}|production|Conseq. The surplus of hydrogen was substituted with Hydrogen (reformer) E from PlasticsEurope since nowadays hydrogen production mainly comes from steam reforming of natural gas (Di Marcoberardino et al., 2019). The current market demand for carbon dioxide is mainly for the promotion of plant growth, the creation of inert environments or as a heat transfer medium, as a refrigerant, or as a chemical for the production of a variety of other chemicals (Althaus et al., 2007; Topham et al., 2014). For these markets, commercial carbon dioxide is obtained as a “waste gas” from ammonia and hydrogen production processes (Althaus et al., 2007; Topham et al., 2014). In the ammonia production process, an intermediate mix of gases made of hydrogen, nitrogen and carbon dioxide is produced. However, only the first two gases are required to make ammonia. So, carbon dioxide needs to be removed from the gas stream. A gas with a similar composition that needs to be separated is also generated in hydrogen production from reforming natural gas.

The impact associated with CO_2 production is led by extraction and purification of the abovementioned “waste” gas (that comes burdens-free) (Althaus et al., 2007). In our LCA, it was assumed that the CO_2 is extracted and purified from the waste gas of ammonia production using monoethanolamine (MEA), which is a common practice (Althaus et al., 2007; Young et al., 2019). Based on Young et al. (2019), 3.56 MJ of heat are necessary to separate 1 kg of CO_2 from waste gas from ammonia production using MEA as extraction solvent. For heat from natural gas, the process *Heat, district or industrial, natural gas {Europe without Switzerland}|heat production, natural gas, at industrial furnace > 100 kW | Conseq* from ecoinvent 3.6 was used. The amount of MEA, losses of MEA to air and water flows of carbon dioxide separation using MEA were retrieved from ecoinvent 3.6 dataset *Carbon dioxide, {RER}|production|Conseq.* This modeling could be considered also a good proxy for the purification of carbon dioxide using MEA from gases from other industrial processes and not only from ammonia production. The electricity input for carbon dioxide liquefaction was not considered since the carbon dioxide delivered by the swing adsorption process is in a gas state.

2.2.5.2. Additional animal feed to replace potato by-products. Concerning the additional animal feed production, it was necessary to identify the mix of marginal technologies that will fulfill such marginal demand. A decision tree is typically used to determine the marginal technologies, i.e., the technologies affected by a small change in market demand (Weidema et al., 1999). Since the additional production of animal feed affects a market more than a specific process, it is necessary to understand the trend in the volume of the affected market (Weidema et al., 1999).

Potato peels are a balanced feed with good fibre, starch and protein contents (Duynie, 2021). The dry content and starch content (on a dry basis) of this mix of potato by-products were measured as 12.3% and 55.7%, respectively (Moretti et al., 2021). It could be argued that potato peels are also used to provide calorific values of the feed for its high content of starch. Hence, potato peels have a specific function in the animal feed sector's supply-demand equilibrium that would be affected by a displacement effect. The production amount of potato by-products sold on the market cannot be independently varied since it is linked to the production of potato food products. The market price of potato peels is about 106 €/t dry matter (Moretti et al., 2021). We used generic feed market information about potato peel-based feed to determine the types of displacement feed. In the baseline analysis, the protein content is used to quantify the equivalent function of different types of animal feeds because the nutrient value of feed is determined by the protein content.

The protein content (on a dry basis) was measured only for the sample of potato peels as 16.0%. In this study, the protein content of potato peels (being the main fraction) was assumed for the entire mix of potato by-products. Potato by-products are a minor amount in the Dutch animal feed market currently used mainly for pigs (Feedipedia, 2019; Ncobela et al., 2017) and cattle (Duynie, 2021; Nelson, 2010). In the Netherlands (and nearby countries), the compound feed production for pigs is declining and for cattle is stagnating (CBS, 2020; Heuvelmans and Vogel, 2017). Therefore, there is a potential to provide a marginal increase in production since the production system is not saturated, and thus the current market is the marginal technology. The animal feed produced in Europe is made mostly of grains produced in Europe (71%) and imported oil meals (24%) (Heuvelmans and Vogel, 2017). The grains are mostly made of wheat (32%), corn (30%) and barley (25%), while soybean meal makes 58% of all the oil meals used in the EU and is mainly imported from Argentina (58%) and Brazil (33%). These major crops were considered to build the marginal market that can be found in Table 6. The sensitivity of the choices made the marginal feed production is discussed in Section 4.2.

2.2.6. Land use changes

There are still many concerns around the sustainability of biofuels' production; many of these are related to direct or indirect carbon stock changes from land-use transitions (van der Hilst et al., 2018). The induced direct carbon stock changes from bio-jet fuel production are proven to play a critical role in their environmental performance (Zhao et al., 2021). Simultaneously, the role of carbon stock changes becomes increasingly relevant when the impact on other lands from the displacement effect of biomass production is accounted for (indirect land-use change) (Ahlgren and Di Lucia, 2014). Therefore, it is paramount to include such direct and indirect effects of land-use change (iLUC) from biofuels systems.

In our study, LUC impacts were retrieved from the Ecoinvent database (version 3.6) and Agri-footprint database (version 5.0). Under these databases, LUC is assessed following the methodological principles recommended by PAS2050 (BSI, 2011). A 20-year time horizon for carbon pools to reach equilibrium is considered (IPCC, 2006). Carbon stock changes are addressed over the four main carbon pools (Donke et al., 2020): aboveground biomass, belowground biomass, dead organic matter and soil organic carbon. Note that the LUC Ecoinvent model follows the WFLDB Quantis adapted version (country-level perspective) of the Blonk tool to assess direct LUCs (van Zeist, 2016). The LUC model of Agri-footprint 5.0 used for the direct land-use change of potato product relies on the Blonk tool (van Zeist, 2016).

To illustrate, carbon stock change effects from potato production within the same country are accounted for directly as they occur on the same land as the potato production land use. In the ALCA model, no indirect effects are generated from the current potato production as there is no effect of using land already dedicated for this purpose.

Table 6
Animal feed actual/average (used for the comparison conducted in the ALCA) and marginal market proportions (used for the CLCA) based on Heuvelmans and Vogel (2017) and background sources; n.a. = not applicable.

Flow	Actual/average market (%)	Marginal (%) market based on the rescaling of the major crops	Amount assumed (kg) for the marginal animal feed modeling in the CLCA[a]	Background data sources for ALCA (benchmark used for comparison) and CLCA (marginal animal feed used in system expansion)
Barley grain (EU)	17.8%	23.9%	1.5	Barley grain {DE}|barley production|APOS or Conseq
Corn gran (EU)	21.3%	28.6%	1.8	Maize grain, Swiss integrated production {CH}|production|APOS or Conseq
Wheat grain (EU)	22.7%	30.5%	1.9	Wheat grain {DE}|wheat production|APOS or Conseq
Other grains	9.2%	0%	0	Oat grain {FI}|oat production|APOS
Total grains	71%	83%	5.2	n.a.
Soybean meal (AR)	8.1%	10.9%	0.7	Soybean {AR}|soybean production|APOS or Conseq. Soybean production used as proxy for soybean meal.
Soybean meal (BR)	4.6%	6.2%	0.4	Soybean meal {BR}|market for soybean meal|APOS or Conseq
Other oil meals	11.3%	0%	0	Rapeseed, at farm/NL Economic from Agri-footprint 5.0. Rapeseed production as a proxy for rapeseed meal.
Total oil meals	24%	17%	1.1	n.a.
Neither gains nor oil meals	5.0%	0%	0	Neglected

[a] To obtain 1 kg of total protein considering the (typical) dry matter and protein content of the product modeled in the dataset used as background data.

In contrast, in the CLCA model, animal feed production's displacement effects outside the production country's boundaries are accounted as indirect. The upstream displacement effects of the potato by-products attributed to the marginal animal feed production are assumed with a direct casual-effect relationship. Consequently, the displacement effect from the marginal feed (corn, wheat, barley, and soybean) production and derived carbon stock changes in the EU, Brazil and Argentina are attributed 100% to this displacement effect and accounted for entirely in this supply chain. The data of carbon stock exchanges of the marginal feed produced in the EU, Brazil and Argentina are obtained from ecoinvent version 3.6.

2.2.7. Petrochemical kerosene and other reference products

For petrochemical kerosene, the dataset *Kerosene {Europe without Switzerland}|kerosene production, petroleum refinery operation* from the libraries of ecoinvent 3.6 named APOS and Conseq respectively for the ALCA and CLCA. This dataset represents the European production of kerosene at the factory gate of the oil refinery. Distribution and combustion were modeled as detailed in Section 2.2.3. The process flow diagram detailing inputs and co-products for petrochemical kerosene can be found in the supplementary materials.

For the other co-products, the comparison was conducted with the following reference products:

- for hydrogen, the dataset *Hydrogen (reformer) E from PlasticsEurope* (PlasticsEurope, 2005);
- for carbon dioxide, the inventory was modeled as illustrated for the marginal carbon dioxide using average data i.e. 1) assuming that 3.56 MJ of heat are necessary (*Heat, district or industrial, natural gas {Europe without Switzerland}|heat production, natural gas, at industrial furnace > 100 kW|APOS* from ecoinvent 3.6) and 2) retrieving the amount of MEA, losses of MEA to air, water flows of carbon dioxide separation using MEA from the ecoinvent 3.6 dataset *Carbon dioxide, {RER}|production|APOS.*
- for lubricants, the dataset *Lubricating oil {RER}|production|APOS* from ecoinvent 3.6;
- for animal feed, the average European mix has been considered and can be found in the second column of Table 6.

3. Results

The results section is structured as follows. First, the environmental impact hotspots of the ALCA of the bio-jet fuel are presented. Second, the environmental hotspots of the CLCA of the bio-jet fuel are presented. Third, the environmental impacts of the bio-jet fuel assessed with both modeling approaches are compared to petrochemical kerosene. Afterward, the results of the ALCAs of the bio-based co-products are presented, along with a comparison with market benchmarks. The last section of the Results (Section 3.4.4) reports on the "attributional pie", showing how much each co-product contributes to the environmental impact of the entire product system.

3.1. ALCA: identification of the environmental hotspots

The overall breakdown of the cradle-to-grave environmental impact of 1 MJ of bio-jet fuel is illustrated in Fig. 2 (numerical results can be found in the supplementary information).

From Fig. 2, it can be observed that feedstock production is a relevant environmental hotspot (23–30% of the cradle-to-grave environmental burden) in all categories except for photochemical ozone formation. Both biochemical conversion and alcohol condensation generate about 30% of climate change and depletion of fossil resources, adding up to 60% of the environmental impact for these two categories. The bio-jet fuel combustion dominates the photochemical ozone formation, acidification and terrestrial eutrophication impacts (60–80% of the cradle-to-grave impact in these categories).

Heat from natural gas used for feedstock production contributes to 45% of the impact share for climate change and 56% for the depletion of fossil fuels. The impact of electricity for feedstock production is relatively small for all categories (less than 18%) and minor (3%) for acidification. Conversely, for all categories, raw potato production represents a significant impact share of feedstock production. This share ranges from 25% in depletion of fossil fuels to up to 94% in acidification. The main environmental impact sources from raw potato are the cultivation stage and their transport to the processing industry. The transport process is responsible for 20% of climate change impact and 35% of fossil fuel depletion. For climate change, 45% of the impacts in the cultivation stage are caused by dinitrogen monoxide emissions to air. These emissions result from applying fertilizers, manure and crop residues. In addition, 20% of the impact is caused by diesel use in agricultural machinery and 14% by calcium ammonium nitrate production. The acidification and terrestrial eutrophication from feedstock production are related to ammonia emissions from fertilizer application. The diesel burned in agricultural machinery also represents 38% of the depletion of fossil fuels caused by feedstock production. Regarding the small impact (5%) of the feedstock production on the cradle-to-grave photochemical ozone formation, it is mainly caused by the transportation of the potatoes to the processing food industry and by the diesel burned in the agricultural machinery during the cultivation phase. The direct carbon stock change caused by the cultivation of potatoes processed in the Netherlands has a negligible impact since there is no displacement effect. Long-term established agricultural land is used in the EU for the production of potatoes. Thus, the carbon stock changes within this land are relatively small as the land is already dedicated for agricultural purposes.

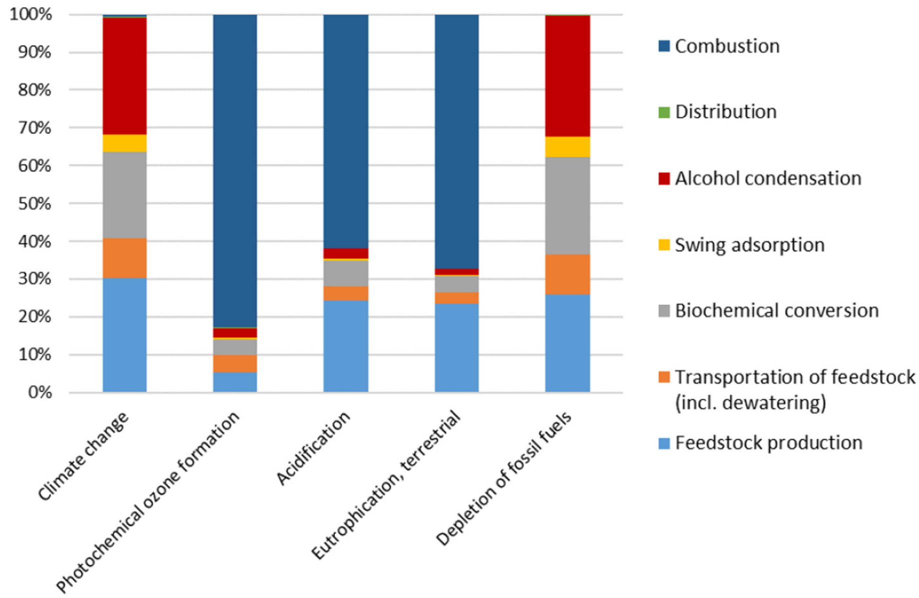

Fig. 2. Breakdown of the cradle-to-grave attributional environmental impact of 1 MJ of bio-jet fuel per key-unit process.

In all categories, biochemical conversion is important and has high impact especially for climate change and fossil fuel depletion. The environmental impact of this process is caused mainly by the production of electricity (44–72%) and potassium hydroxide (26–51%). The impact of alcohol condensation represents 30% of climate change and depletion of fossil fuels, respectively, and 12% of photochemical ozone formation. For these impact categories, the main sources of impact are the production of steam (55–56%) and cooling energy (43–45%). The production of steam impact is related to the combustion of natural gas. Swing adsorption impact is minor and generated by the allocated electricity (1–5%). Since hydrogen is the only consumable of hydrotreatment and comes from a closed-loop flow, hydrotreatment has no impact. The environmental impact of hydrogen production is already accounted for in the biochemical conversion and the swing adsorption process.

Feedstock transport is an important environmental hotspot for climate change (9%), photochemical ozone formation (18%) and use of fossil resources (9%), mainly due to the production and combustion of diesel. The distribution of the bio-jet fuel to the tank has a negligible contribution to the cradle-to-grave environmental burden in all categories. The combustion of the bio-jet fuel releases nitrogen oxide emissions resulting in high photochemical ozone formation, acidification and terrestrial eutrophication.

3.2. CLCA: potential environmental impacts due to changes in demand

Fig. 3 shows the breakdown of the cradle-to-grave CLCA. Similar to the results from the ALCA, the environmental impacts caused by the utilities in the biochemical conversion are high in most of the impact categories. Similarly, the impact of alcoholic condensation is high in climate change and

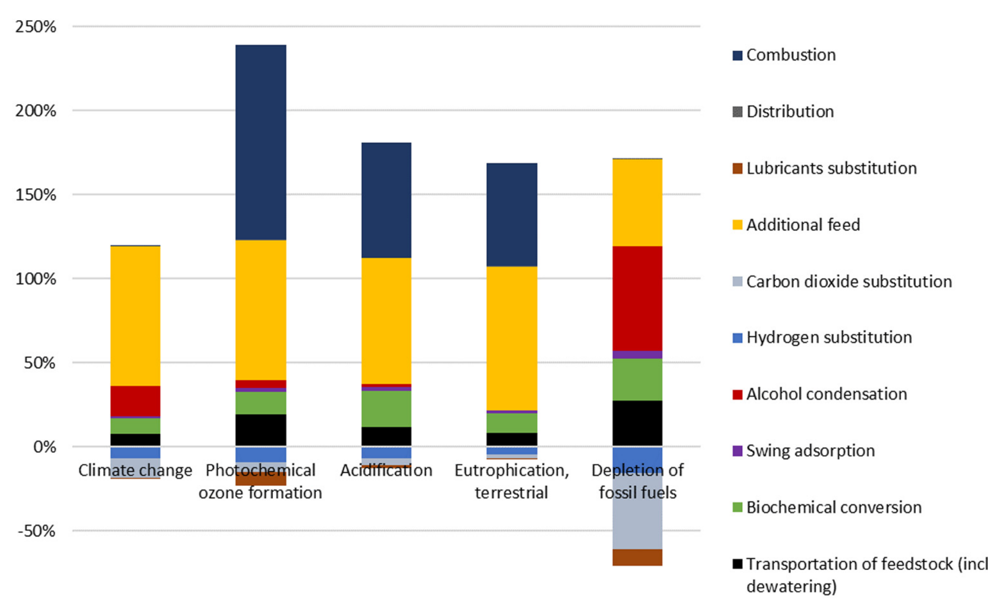

Fig. 3. Breakdown of the cradle-to-grave consequential environmental impact of 1 MJ of bio-jet fuel per key-unit process. Numerical results can be found in the supplementary materials (see Table 7 for LUC contribution).

depletion of fossil resources (marginal data did not change that). The environmental impact caused by the combustion of the bio-jet fuel remains important also for the CLCA for photochemical ozone formation, acidification and terrestrial eutrophication.

Different from ALCA, the consequential modeling leads to the result that the additional amount of animal feed is one of the most important contributors of impact for all impact categories. The impact of the additional animal feeds can be divided into biomass production and LUC (see Table 7).

For biomass production, producing fertilizers and resulting field emissions from their application are the major environmental impacts. For barley, the impact of producing nitrogen fertilizers is high in all categories, ranging from 32% for photochemical ozone formation to 79% for acidification. Similarly, for wheat grain, the production of nitrogen fertilizers contributes between 39% (photochemical ozone formation) and 93% (acidification) of the environmental impact. Tillage is also an important source of environmental impact for barley in three categories i.e., photochemical ozone formation (26%), acidification (19%) and depletion of fossil fuels (13%). The impact of tillage is also high in these categories for wheat grain (but with slightly lower percentages for wheat grains). For maize production, direct field emissions cause 33% of climate change due to dinitrogen monoxide and carbon dioxide released into the air. They also cause 86% of acidification and 80% of terrestrial eutrophication (80%), mainly due to ammonia to air.

The effects of LUC are relevant for climate change, photochemical ozone formation, acidification and terrestrial eutrophication. The LUC impacts are attributed primarily to soybean production. LUC is responsible for 94% and 74% of the climate change impacts of Argentinian and Brazilian soybeans, respectively. The LUC climate change impact of the Argentinean soybeans is higher than that of the Brazilian soybeans, given the larger share of high carbon stock lands converted to arable land. For Argentina, the land-use transition to arable land involves mainly removing forest land, from which 85% is secondary and 8% is primary. A lower share of forest removal characterizes the land-use transition in Brazil, with 75% clear-cutting of primary forest. In addition, 5% of the land-use transition is attributed to the removal of grasslands. Grasslands contain considerably lower carbon stocks than forests.

For photochemical ozone formation, 18% of the impact of marginal animal feed is caused by LUC. Of this 18%, 13% is caused by clear-cutting of secondary forest to arable land in Argentina and 4% by clear-cutting of primary forest to arable land in Brazil while the remaining 1% by clear-cutting of primary forest to arable land in Argentina. For clear-cutting of secondary forests in Argentina (and similarly for Brazil with slightly different shares), the photochemical ozone formation impact is caused by air emissions of ethene (29%), nitrogen oxides (21%), formaldehyde (11%) and propene (9%) due to the burning of vegetation, for 7% by diesel combustion in tractors and for 5% by petrol combustion in power sawing.

The small acidification and terrestrial eutrophication impacts caused by LUC is mainly due to Argentinian soybeans (see Table 7). More than 90% of acidification and terrestrial eutrophication related to Argentinian soybeans' LUC is due to the clear-cutting of secondary forests converted into arable land. The acidification due to such clear-cutting is caused by ammonia emissions to air (61%) and nitrogen oxides (26%) due to the burning of vegetation. For terrestrial eutrophication, these percentages become 64% for ammonia emissions and 34% for nitrogen oxides.

The marginal production of carbon dioxide (given the high amount of carbon dioxide produced) is the main environmental credit for climate change, depletion of fossil fuels and photochemical ozone formation. In these three categories, the credit is mainly caused by avoiding the production and combustion of natural gas with smaller credits for the avoidance of the production of the MEA solvent used for carbon dioxide separation.

The credit for substituting the surplus of hydrogen is lower than the one for carbon dioxide in climate change and depletion of fossil fuels, because the quantity of the surplus H_2 is much smaller than that of CO_2. Nevertheless, the surplus H_2 offers environmental credits for photochemical ozone formation (98% caused by avoided nitrogen oxides emissions to air from fuel combustion) and acidification (70% nitrogen oxides and 30% sulfur dioxide to air from fuel combustion).

However, in the future, the production of hydrogen and carbon dioxide and other chemical products might become less carbon-intensive (see Sections 4.1 and 4.2 for discussion regarding the uncertainties on future benchmark technologies).

The credit for the substitution of lubricants is high only for photochemical ozone formation and depletion of fossil fuels. 90% of such credit is caused by the avoidance of direct air emissions of non-methane volatile organic compounds (NMVOC) during the production of the lubricants. For depletion of fossil fuels is caused by avoided production of crude oil (75%).

3.3. Comparison with petrochemical kerosene

As shown by Fig. 4, the environmental performance of the bio-jet fuel compared to conventional jet fuel is very different depending on the LCA modeling selected.

Based on both ALCA and CLCA results, The bio-jet fuel assessed offers a lower fossil fuel depletion impact compared to petrochemical kerosene (55% reduction based on ALCA and 49% based on CLCA).

For climate change, the ALCA and CLCA models lead to different conclusions. The ALCA model shows benefits for the bio-jet fuel (58% lower impact), whereas the CLCA calculated a 68% higher climate change impact than conventional jet fuels. In the CLCA model, LUCs due to the additional animal feed production is influential for climate change (47% of the cradle-to-grave climate change) but not significant for the depletion of fossil fuels (see Table 7).

For photochemical ozone formation, the differences between the bio-jet fuel and the petrochemical jet fuel are insignificant (1% difference) based on the ALCA model, whereas based on the CLCA model, a 50% higher impact is observed for the bio-jet fuel compared to petrochemical kerosene. In the CLCA model, the credits for photochemical ozone formation from co-products substitution are only 30% of the impact from the additional production of animal feed. Moreover, the impact of the transportation of potato by-products becomes 3 times higher in all categories (with slightly different percentages 2.9–3.1 times given the shift from average to marginal data). The reason is two-fold: 1) this impact is no more allocated to the co-products but entirely apportioned to the bio-jet fuel and 2) this unit process does not have co-products to substitute.

The bio-jet fuel has a higher impact on acidification than the petrochemical jet fuel (10% in ALCA and 75% higher in CLCA). In the CLCA model, the benefits from co-product substitution do not compensate for

Table 7
Breakdown of the environmental impacts of the additional feed needed to replace the potato by-product, contributed by biomass (crop) production and land use changes.

Impact category	Biomass (crop) production					LUC		Total
	Barley grain (EU)	Maize grain EU	Soybean from Argentina	Soybean from Brazil	Wheat grain EU	Soybean from Argentina	Soybean from Brazil	
Climate change (%)	11	9	3	4	16	46	11	100
Photochemical ozone formation (%)	18	16	17	9	23	13	5	100
Acidification (%)	10	52	12	4	14	6	2	100
Eutrophication, terrestrial (%)	18	40	5	0	27	7	2	100
Depletion of fossil fuels (%)	26	21	12	2	36	0	0	100

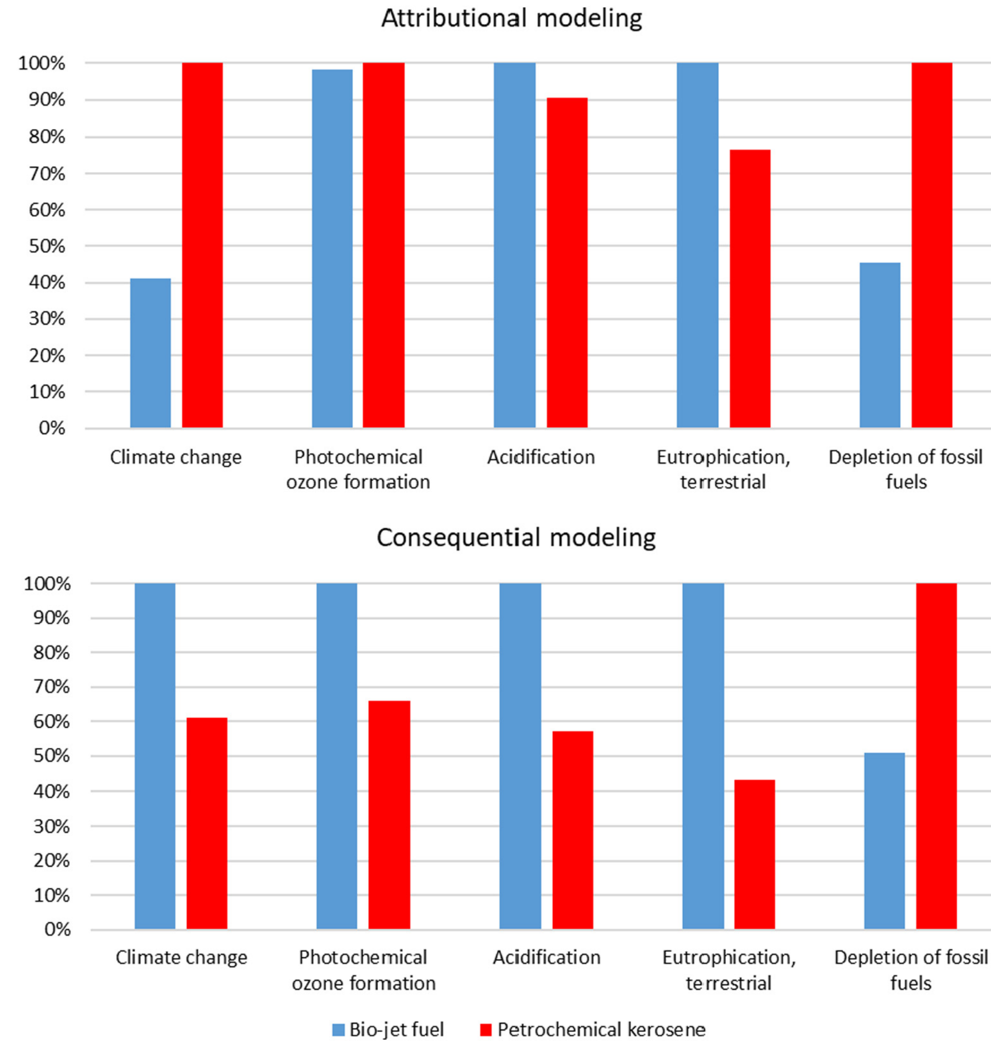

Fig. 4. Comparing the cradle-to-grave environmental impacts of 1 MJ bio-jet fuel from potato by-products: the attributional model (top) and the consequential model (bottom). Characterized impacts can be found in the supplementary information.

the impact of the additional animal feed production i.e. the benefits are only 17% of the additional impact from animal feed production. Similar patterns are observed for terrestrial eutrophication between the results of ALCA and CLCA.

Based on the comparison of the results obtained with CLCA and ALCA approaches (see Fig. 4), it can be concluded that the recommendations for producing this bio-jet fuel would be very different depending on the approach used with respect to climate change and photochemical ozone formation impacts. In fact, for these categories, the bio-jet fuel has a significantly higher impact once the additional production of marginal animal feed is considered. The attributional modeling overlooks this aspect.

3.4. ALCA: environmental performance of the other bio-based products

This section presents the ALCA comparisons between the environmental impacts of the co-products of the bio-jet fuel production process and their reference products.

3.4.1. Animal feed (organic residue)

Fig. 5 shows the cradle-to-gate comparison between the organic residue from ABE fermentation sold as animal feed and the average European animal feed consumed (see Table 6). In four out of five impact categories, environmental benefits ranging between 65% and 87% were observed. A 38% higher impact was observed for the depletion of fossil fuels (see Fig. 5 for the sources of impact). Fig. 5 also shows the shares of the contribution of the various unit processes to the cradle-to-gate environmental impact of the animal feed co-product. We can observe that, since the allocation is applied only after subdividing the process as much as possible, the animal feed is not responsible for any environmental impact caused by either the swing adsorption process or alcohol condensation process. Similar considerations also apply to the other co-products. For this reason, the environmental impact of each co-product has its own “recipe” of environmental burdens' contributors, which differ among them.

3.4.2. Bio-based carbon dioxide and bio-based hydrogen

Fig. 6 shows the cradle-to-gate comparison between the carbon dioxide separated via swing adsorption and conventional carbon dioxide (see Section 2.2.7). In three out of five impact categories, environmental benefits ranging between 16% and 65% were observed. However, the acidification and terrestrial eutrophication caused by the bio-jet fuel are higher than for conventional jet fuel (see Fig. 6 for the impact sources).

Fig. 7 shows the cradle-to-gate comparison between the bio-based hydrogen separated via swing adsorption and conventional hydrogen from reforming (see Section 2.2.7). In four out of five impact categories, environmental benefits ranging between 45% and 78% were observed compared to reforming hydrogen (see Fig. 7 for process contributions). For bio-hydrogen, the breakdown of the environmental impact corresponds to the one of bio-based carbon dioxide since

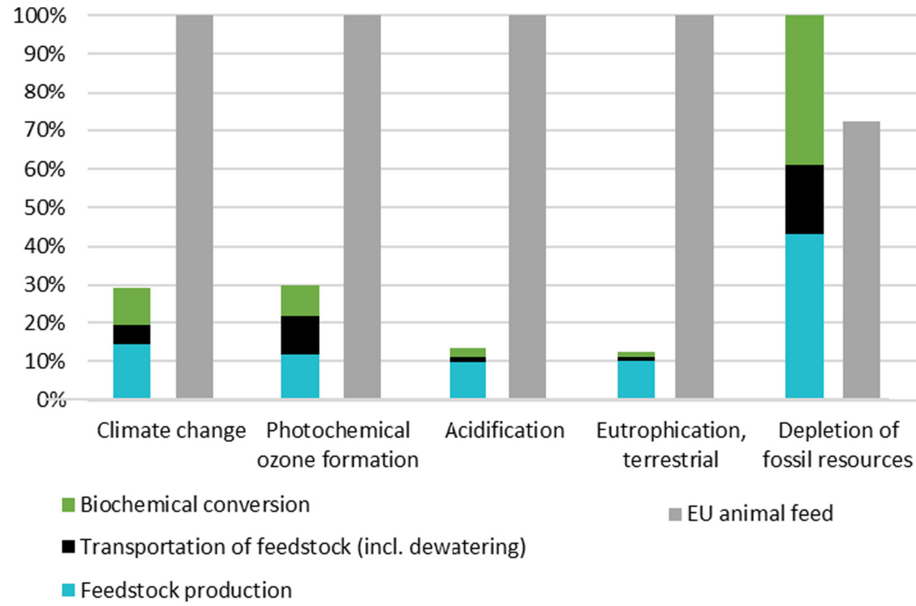

Fig. 5. Cradle-to-gate comparison between the animal feed by-product (left bar) obtained from the bio-jet fuel production process (with process contributions highlighted) and the average European animal feed. Values are normalized taking the most impacting value per each category as the reference.

they are both co-products leaving the system from the swing adsorption process.

3.4.3. Biolubricants

Fig. 8 shows the cradle-to-gate comparison between the biolubricants produced from hydrotreatment and petrochemical lubricants (see Section 2.2.7 for petrochemical lubricants). In four out of five impact categories, environmental benefits ranging between 12% and 88% were observed compared to petrochemical lubricants. For climate change, the impact of biolubricants was 18% higher than petrochemical lubricants (see Fig. 8 for process contributions). For bio-hydrogen, the breakdown of the environmental impact corresponds to the one of bio-based carbon dioxide since they are both co-products leaving the system from the swing adsorption process.

3.4.4. The "attributional pie"

By summing up the environmental impacts of each bio-based product (i.e. each piece of the pie), it is possible to visualize their contributions to the total pie i.e., the environmental impact of the entire "attributional" product system shown in Fig. 1. Fig. 9 shows the whole pie with its pieces.

The bio-jet fuel is the main cause of the environmental impact of the investigated product system. In fact, being responsible for the existence of the

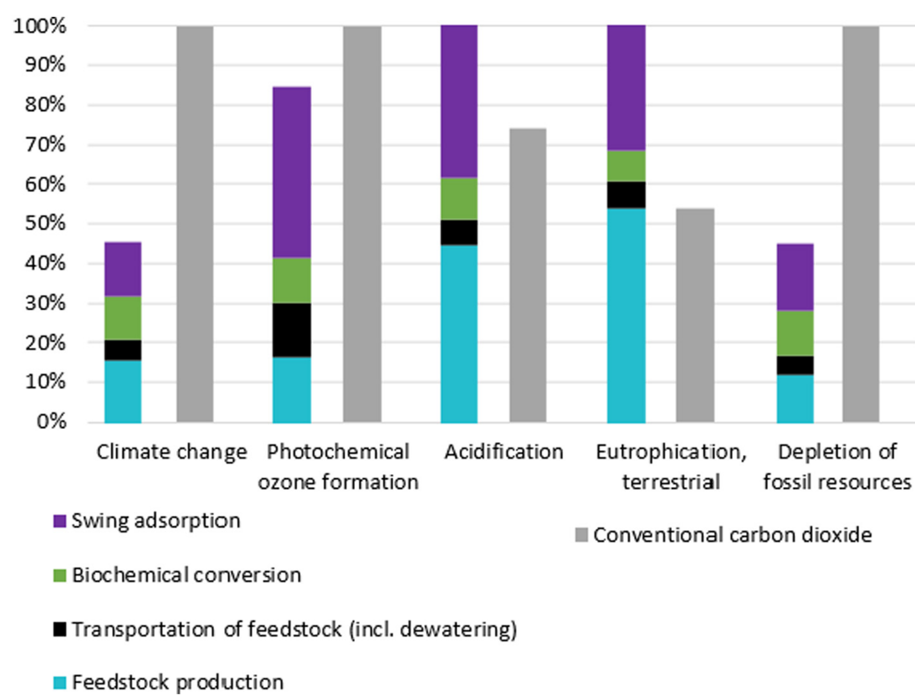

Fig. 6. Cradle-to-gate comparison between the bio-based carbon dioxide (left bar) delivered by this innovative process (with process contributions highlighted) and conventional carbon dioxide. Values are normalized taking the most impacting value per each category valued as 100%.

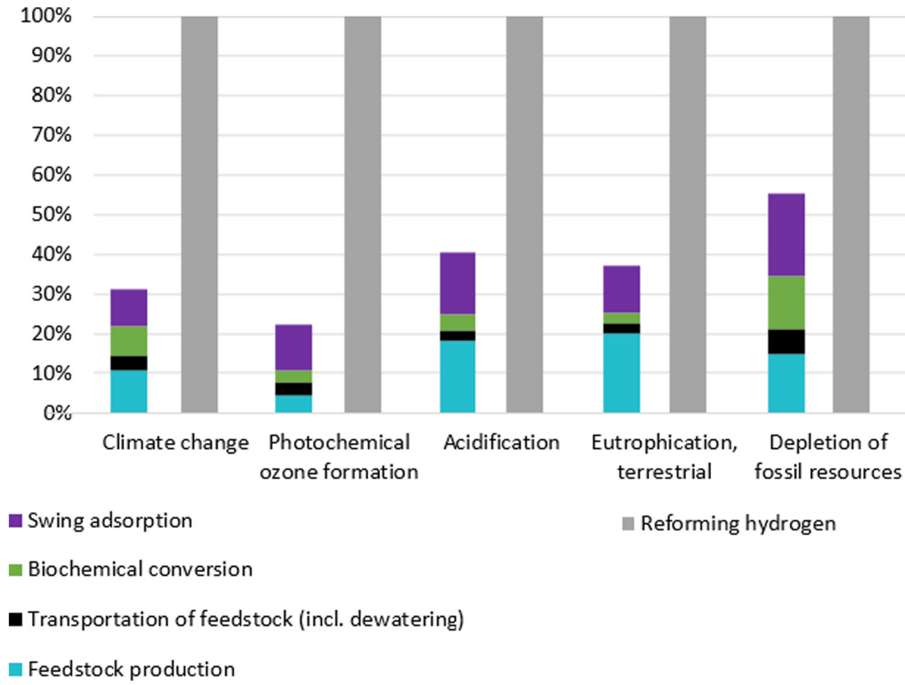

Fig. 7. Cradle-to-gate comparison between the bio-based hydrogen (left bar) delivered by this innovative process (with process contributions highlighted) and reforming hydrogen. Values are normalized by taking the most impacting value per category valued as 100%.

entire system product, the bio-jet fuel is the product that got allocated the environmental impact of all unit processes in the system (at least partially). The animal feed obtained as the organic residue also received a significant fraction of the environmental impact of the product system. The reason is that it got allocated most of the environmental impact at the level of the ABE fermentation due to its significant mass ratio compared to the other co-products (e.g. >5 kg of animal feed/kg of bio-jet fuel). The other co-products have minor “responsibilities” instead.

4. Discussion

4.1. Uncertainties in the attributional model

The ALCA has modeling uncertainties that are usually related to the application of a different allocation method or the price fluctuation for economic allocation. Applying energy or mass allocation at the level of the potato processing industry would mean a significant increase of the

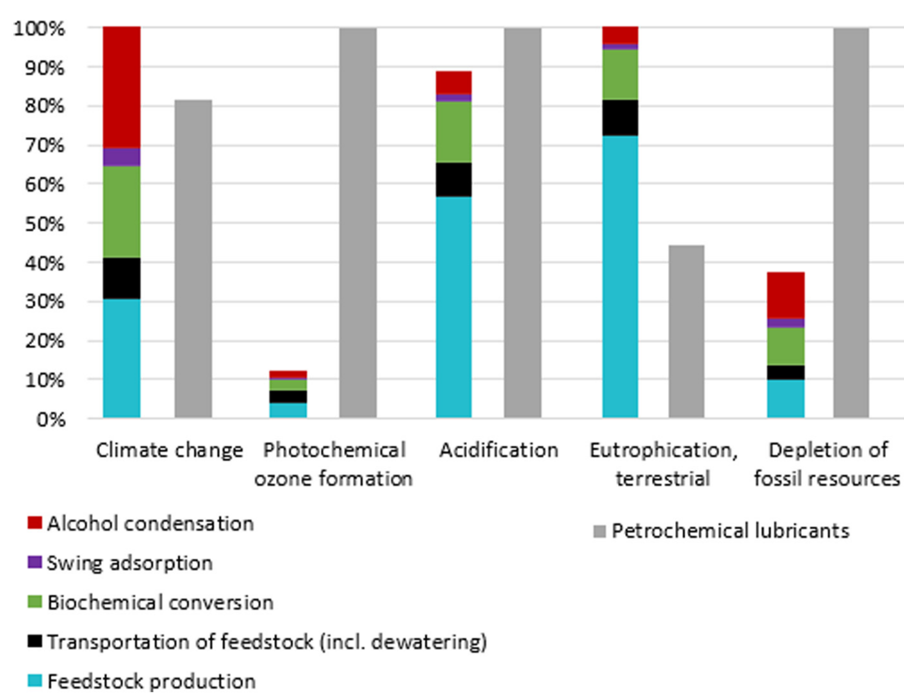

Fig. 8. Cradle-to-gate comparison between the biolubricants (left bar) delivered by this innovative process (with process contributions highlighted) and petrochemical lubricants. Values are normalized taking the most impacting value per each category valued as 100%.

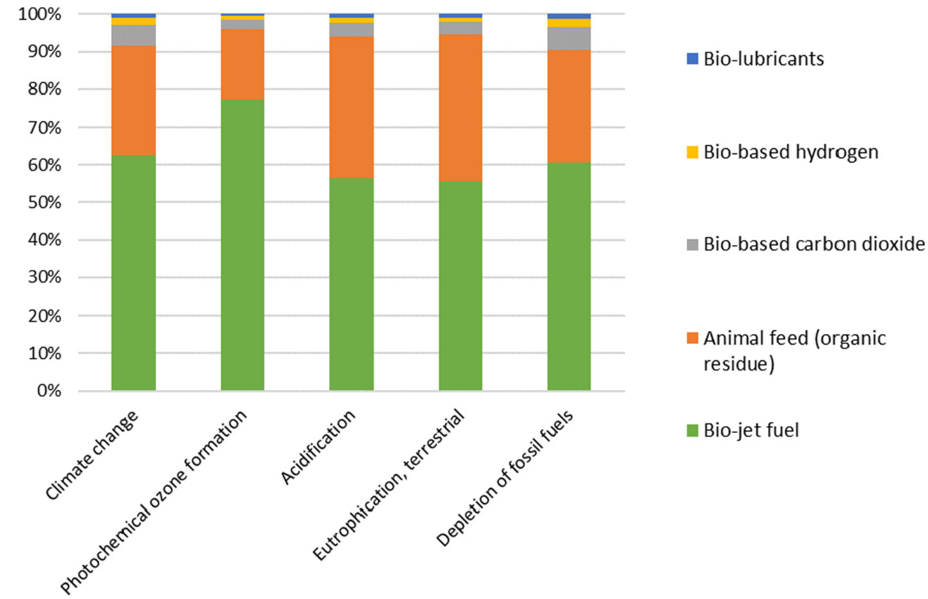

Fig. 9. The attributional environmental impact of the overall production system and its allocation to each of the bio-based co-product.

environmental impact of the potato by-products since they have physical characteristics similar to the main food products but much lower market price. As we argued in our earlier work (Moretti et al., 2021), such a type of allocation leads to distorted results and would not respect the ISO causality principle that the allocation criterion should reflect. Regarding the price fluctuation of potato by-products, the market trend of the last five years showed a small variation (order of 3%) that would have a negligible effect on the results of the ALCA. The economic allocation factor applied at the level of the swing adsorption unit is also affected by uncertainties related to the prices of carbon dioxide and hydrogen. For both these products, novel technologies with a lower carbon footprint and/or using greener energy are expected to take place in the next decade. Carbon capture and storage (CCS) might also play a role in many chemical and energy processes in the longer term (e.g. the next two decades). Despite the deployment of CCS has been very slow so far (accounting for less than 0.5% of global investment in clean energy), robust climate targets could increase CCS investments (IEA, 2021). Greener energy and CCS could affect the price of carbon dioxide and/or hydrogen, affecting the allocation share applied. Uncertainties also apply to the allocation factors regarding the fermentation residue sold as feed and lubricants, but they are not affected by future price fluctuations since based on energy and mass values respectively. The environmental impact of petrochemical kerosene is also influenced by the allocation applied at the level of the oil refinery, but with a minor effect on the overall environmental impact, for two reasons: 1) combustion emissions dominate the environmental impact of conventional kerosene (70–90% of cradle-to-grave impact) in all categories except depletion of fossil fuels and 2) there is small difference in energy, mass or economic shares for European kerosene over the total EU refinery system output (Moretti et al., 2017).

4.2. Uncertainties in the consequential model

It is still challenging to address (without significant uncertainties) the historical question (Thomassen et al., 2008) "which feed ingredient will meet the increased protein demand?". A different answer to this question can significantly impact the final numerical results of the LCA (van Zanten et al., 2018).

For our study, taking different animal feeds to replace potato by-products does change the conclusion for climate change (see Fig. 10). In fact, the climate change impact of the bio-jet fuel could become between

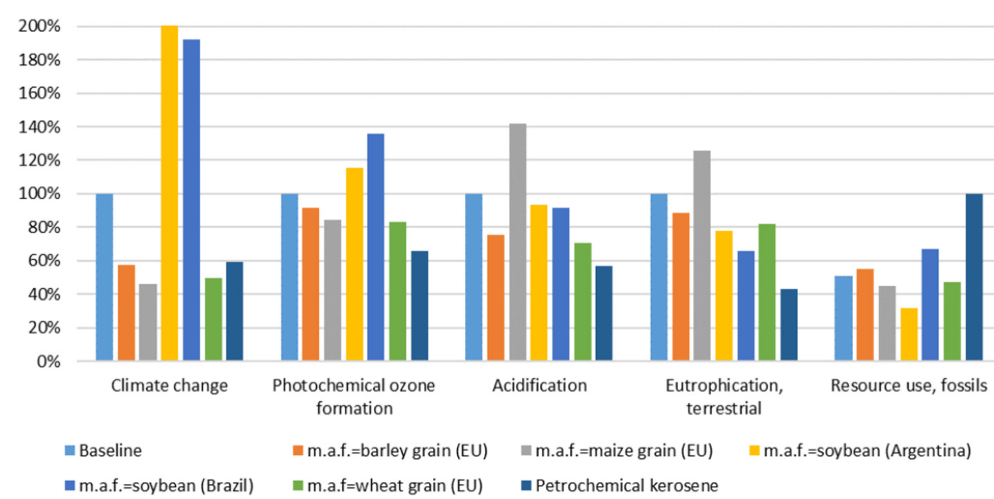

Fig. 10. Consequential cradle-to-grave comparison between the innovative bio-jet fuel from potato by-products and petrochemical kerosene for 1 MJ of fuel varying the type of marginal animal feed (m.a.f.). Values are normalized taking the most impacting value per each category between the bio-jet fuel with baseline calculations and petrochemical kerosene (i.e. 100% taken as Fig. 4).

4% and 23% lower than petrochemical kerosene if the company currently utilizing the potato by-products replaced them with European animal feed only. Conversely, the climate change impact of the bio-jet fuel could double than calculated for the baseline scenario (and therefore significantly higher than petrochemical kerosene) importing soybean from South America to replace the potato by-products diverted from the European animal feed market. For the other four categories, the conclusions of the CLCA regarding the comparison between the bio-jet fuel and petrochemical kerosene are unaffected by the market displacement from the animal feed market. However, the numerical results could change significantly depending on the type of animal feed assumed and the impact category considered.

Moreover, in our study, the displacement of animal feed with potato by-products was made on a protein basis. Alternatively, an energy basis could be assumed since animals do not need only proteins from the feed but also energy (the same apply to humans, who are the final user of the food products). The gross energy of potato by-products is 17.2 MJ/kg_{dry} (Ncobela et al., 2017). Keeping the same composition of the marginal mix, the mass of animal feed to be substituted would increase by 10% mainly because soybean meals have much higher protein content than potato by-products but only slightly higher energy content. Alternatively, if one type of animal feed only were consumed as an alternative for potato by-products on the market, it should be considered what follows. Assuming that the primary function of potato by-products used as animal feed is to provide calorific energy and not protein to animals, it would be incorrect to compare 1 MJ of soybean meal only with 1 MJ of potato by-products. In fact, what matters is the primary function and the causality mechanism behind the provision of such a function (FAO, 2010; International Dairy Federation, 2015). For the same amount of energy, soybean meal would also provide a much higher amount of nutrients (proteins) to animals than the original potato by-products (hence, the primary function of soybean meal is to provide proteins). This means that the product's primary function that is included in the system boundaries would no more correspond to the primary function of the displaced product. Fig. 11 shows the sensitivity analysis results where the market displacement was assumed based on energy as the primary function.

As for the previous sensitivity analysis, what emerges is that the outcome of the CLCA on the better or worse performance between the bio-jet fuel and conventional jet fuel was affected only for climate change. However, the environmental performance of the bio-jet fuel for photochemical ozone formation, acidification and terrestrial eutrophication can change significantly. The case of potato by-products displaced by maize is the best scenario for climate change and depletion of fossil resources. In particular, almost 40% reduction of climate change impact could be achieved compared to petrochemical kerosene. On the other hand, the acidification and eutrophication impacts would increase in the case of maize compared to barley and wheat grains.

Given the temporal scope (the year 2030), the production method of the products substituted in the CLCA based on market trends such as the surplus of hydrogen and carbon dioxide are affected by uncertainty. In fact, in the future, environmental impact reductions could be achieved if carbon dioxide and hydrogen production will be produced on a large scale using renewable energy (see discussion in Section 4.1 for future effects on benchmark technologies). CLCAs with a future scope need to be revised if a significant market shift occurs and such shift was not accounted. Otherwise, such LCAs would consider an outdated production method instead of the one actually affected (Schmidt and Weidema, 2008). In the results of our CLCA, the credits for substituting carbon dioxide and hydrogen were (much) lower than the environmental impact of the marginal production of animal feed in four out of five categories. However, there is high uncertainty in the impacts of the additional animal feed (see Fig. 10 and Fig. 11). In the future, more sustainable animal feeds might be marketed e.g., food waste enriched with proteins using insects (Dou et al., 2018), or the market demand for meat may decline due to a switch in diet choices (Rust et al., 2020). Furthermore, we assumed that the entire fraction of potato by-products are taking away feed from the animal feed supply. However, as detailed in Section 2.1, 15% of potato by-products are not used as animal feed and would need waste treatment or can be used for lower-value applications.

4.3. Indirect land use change

The iLUC impacts from the displacement effects from potato by-products accounted for almost 45% of the climate change impact category in the baseline calculations. The results suggest that iLUC impacts steer to a large extent the biofuel environmental performance. However, iLUC impacts are subject to high uncertainty (Plevin et al., 2015) and were significant only for imported soybeans. Carbon stock changes from land-use transitions were directly retrieved from publicly available LCA databases and not modeled directly, given the scope of the study. Therefore, impacts from carbon stock changes are conditioned by the assumptions and methods carried out in such databases.

Ecoinvent (WFLDB Quantis-adapted version of the Blonk tool) assumes that mainly forests are converted to arable land. For Brazil, 75% of the total converted land corresponds to forests. However, recently it's been suggested that the effect of soybean as an (in)direct driver from forest loss in Brazil is more significant than previously understood (Song et al., 2021). Therefore, if a larger share of forest loss were accounted for, the share increase would lead to higher carbon losses and overall CO_2 emissions.

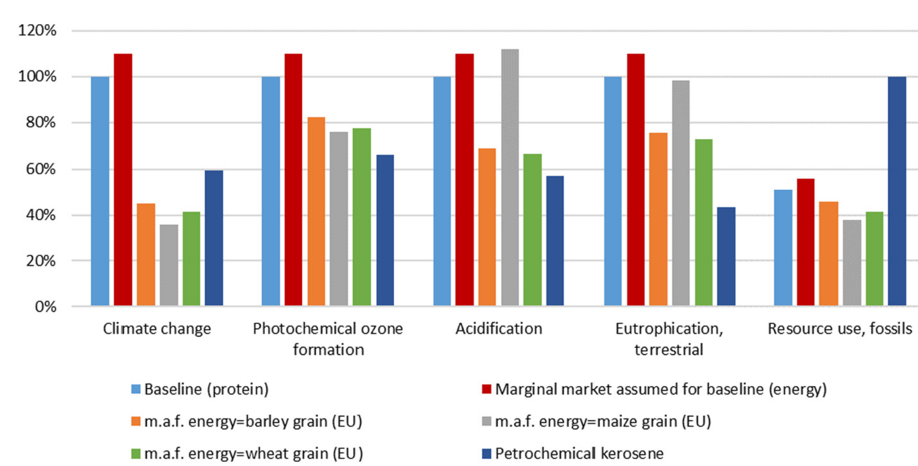

Fig. 11. Sensitivity analysis results based on energy as the primary function. Consequential cradle-to-grave comparison for 1 MJ of fuel varying the type of marginal animal feed (m.a.f.). Values are normalized taking the most impacting value per each category between the bio-jet fuel with baseline calculations and petrochemical kerosene (i.e. 100% taken as Fig. 4).

Forest contains considerably higher carbon stocks than other land categories such as grasslands, shrublands, or cropland (IPCC, 2006). Contrastingly, the change from any of the mentioned categories towards soybean would result in a lower iLUC impact. Inherently, iLUC occurs somewhere else where biomass is produced and often with a significant time-related lag effect (Fritsche et al., 2010). Therefore, attributing causality from displacement effects is extremely challenging.

In this paper, we attributed 100% of the carbon stock change impacts to the displacement effect. However, several economic, social, and environmental variables affect such direct casual effect attribution. Therefore, in reality, the displacement effect between shifting the land use in one location to the marginal animal feed production in another one is submitted to numerous conditions such as market conditions (Schmidt et al., 2015). Thus, the causal-effect relationship might not be as direct as assumed in this study, and the potential impacts from carbon stock changes could decrease. In addition, land-use carbon stock changes are highly location and context-specific. These conditions can vary considerably driven by biophysical characteristics (e.g., temperature), management practices (e.g., land intensification), and socio-economic conditions, which can vary significantly even within the same region (van der Hilst, 2018; Vera et al., 2020). Thus, the real iLUC impact from bio-jet fuel production due to displacement effects is difficult to determine. Still, when accounted for in biofuels, iLUC generally results in an unfavorable environmental performance (Wicke et al., 2012). Note that iLUC processes and impacts are valid for any land-based service. Future research should focus on including adequate measures to estimate the percentage of attribution from iLUC process that help to reduce the uncertainty nature from these processes and understand better the overall performance of biofuel supply chains.

4.4. Advantages and disadvantages of attributional or consequential LCAs

There has been an open discussion, for more than 20 years, on which modeling approach (attributional or consequential) is better for environmental product labeling and policy making (Brando et al., 2017; Moretti et al., 2020a). Currently, two (or even more) well-established “internally consistent but mutually exclusive schools” exist (Pelletier et al., 2015). Each of these schools claims that there is “general agreement in the literature” (Weidema et al., 2020) that supports their modeling choices over

Table 8
Summary of aims, product systems, multifunctionality, uncertainty and application of attributional and consequential modeling approaches in general and in our study.

Most critical difference	Attributional LCA (ALCA)	Consequential LCA (CLCA)
Aim		
General	“Provide information on what portion of global burdens can be associated with a product (and its life cycle). In theory, if one were to conduct attributional LCAs of all final products, one would end up with the total observed environmental burdens worldwide” (UNEP and SETAC, 2011).	“Provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product)”(UNEP and SETAC, 2011).
In our case study	Investigate the environmental impacts caused by the production of an innovative bio-jet fuel starting from the total environmental impact of the production system (i.e. the full pie). LCAs of the other co-products of the bio-jet fuel aimed to understand how much each of the co-product is responsible for the production system's total environmental impact.	Investigate how introducing an innovative bio-jet fuel to the market could potentially change the overall environmental impact of the supply chain of bio-jet fuel production and the economic sectors affected by the change. Hence, the aim was to understand the environmental impact of this novel bio-jet fuel at the net of all the displacement effects i.e. the potato by-products from the animal feed market and the products potentially replaced by the co-products of the bio-jet fuel.
Product system definition		
General	“The systems analysed ideally contain processes that are actually directly linked by (physical, energy, and service) flows to the unit process that supplies the functional unit or reference flow” (UNEP and SETAC, 2011).	“The systems analysed in these LCAs are made up only of processes that are actually affected by the decision, that is, that change their output due to a signal they receive from a cause-and-effect chain whose origin is a particular decision” (UNEP and SETAC, 2011).
In our case study	The most critical aspect was the choice to incorporate additional animal feed production within the system boundaries in the consequential LCA. Conversely, the ALCA accounted for the impact of producing the potato by-products but did not include the effect on the animal feed market.	
Multifunctionality		
General	Allocation of the inputs and outputs of processes among co-products based on certain allocation keys.	The approach aims to reflect cause-and-effect chains including the expansion of the system to include affected unit processes outside the supply chain and substitution i.e. avoided burden effect due to the effects of introducing co-products in the market leading to the displacement of conventional market products.
In our case study	Various allocation methods were applied at unit process-level (for details, see Section 2.2.4)	Our setup is driven by the change in potato by-products' final use. Currently, potato by-products are used as animal fed. However, shifting the use for bio-jet fuel production results in a supply-side deficit, which requires to be covered by producing additional feed. Substitution was applied to the co-products
Uncertainty related to product system definition and multifunctionality		
General	The modeling uncertainties in ALCAs are often related to the application of a different allocation method or the price fluctuation for economic allocation.	The fact that CLCAs are more sensitive to uncertainties than ALCAs due to the inclusion of market prospects is already broadly acknowledged by the literature (Capaz et al., 2018; Giuntoli et al., 2019; Thomassen et al., 2008).
In our case study	For this specific case study, the uncertainty of the allocation practices on the outcome of the study can be considered minor (for details, see Section 4.1). The inclusion of the additional animal feed production in the system boundaries of the CLCA was affected by high uncertainties depending on both the type and functionality of the animal feed assumed (for details, see Section 4.2) as well as uncertainties regarding indirect land use changes (for further details, see Section 4.3).	
Applications		
General	Attributional LCAs have been broadly applied for ecolabeling and policy support since ALCA results are usually less sensitive to assumptions and have lower uncertainties (Agostini et al., 2019; Sala et al., 2021; Weidema et al., 2020). Regarding policy application, results from attributional LCAs have been used in EU legislation to place thresholds on GHG emissions savings.	Consequential LCA have been applied mainly for policy support on understanding consequences of possible policy decisions especially for biofuels. The production of biofuels and current drastic changes in the energy and materials sectors are occurring due to policy interventions. Although the consequences of a decision might be uncertain, policy interventions could be supported to prevent unwanted effects from happening.
In our case study	Consequential modeling becomes a key tool to avoid unintended effects that might lead to significant environmental damages. In fact, an ALCA could not prevent the chance that diminishing the environmental impact of the aviation sector could push up the impact somewhere else e.g. increasing the impacts of meat production due to shifts in the animal feed market. For this reason, while ALCA could be a proper tool for market regulation, both ALCA and CLCA should be used to support policy making. For example, if the current user of potato by-products shifts towards maize as animal feed to replace potato by-products, 40% GHG savings can still be reached by this bio-jet fuel compared to conventional jet fuel. The directives of such a shift are in the hands of policy making.	

the rest (Weidema et al., 2019, 2020). However, other researchers believe that both attributional and consequential modeling approaches are necessary and should be kept well distinguished (Adams et al., 2015; Brander, 2019; Moretti et al., 2020a; Pelletier et al., 2015). As shown by our LCA investigation and highlighted by previous literature (Capaz et al., 2020; Plevin et al., 2014; Zemanek et al., 2020), attributional and consequential LCAs of the same product or system could lead to different conclusions in several impact categories.

Table 8 shows a summary of major differences between attributional and consequential LCAs in general and in our case study. In our case, the two modeling approaches led to contrasting results for climate change and photochemical ozone formation (see Section 3.3). The ALCA showed that the bio-jet fuel and its co-products offer environmental impact reductions in most categories compared to their conventional counterparts. A similar conclusion was drawn by Djomo et al. (2008), who concluded that "using potato steam peels to produce hydrogen along with feeding animals with its by-products offer more environmental benefits than using the potato steam peels directly for animal fodder". However, like our ALCA, the LCA of Djomo et al. (2008) and other peer-reviewed LCAs investigating bio-based products from potato by-products (Hijazi et al., 2019; Moretti et al., 2021; Ochs et al., 2010) overlooked the effects of diverting potato by-products from the animal feed market. However, the fact that we do not know precisely which animal feed market the potato peels are mainly sold for and with what feed would be probably replaced is a major uncertainty in our study. On the other hand, checks on the consequences linked with the indirect effects of biofuels production (and resulting environmental impacts) are needed for a policy perspective aiming to avoid unintended counterfactual effects.

From our case study, we have learned what follows. Contradictory trends in the outcome of attributional and consequential LCAs of a fuel from a bio-based by-product can be expected in certain impact categories if the three circumstances are in place. The first one is that the by-product feedstock is already marketed to be utilized by another process. The second is that the process from which the by-product feedstock is diverted is not part of the processes delivering the final bio-based product (the bio-jet fuel in our case). In our case study, the two LCAs would have led to less contradictory outcomes, e.g., if the potato industry itself would be the current user of the potato by-products they generate e.g., to produce biogas used internally. In that case, the potato industry would need to replace that biogas with an alternative energy input that both types of LCA would include. Third, the displacement of a by-product from its current use leads to more contradictory results between the two LCAs if their conversion process does not have a high yield. Consequently, i.e. requiring a large amount of by-product feedstock per t of the final product (the bio-jet fuel in our case).

5. Conclusions

The main goal of this article was to compare the results of attributional and consequential LCAs to evaluate a future bio-jet fuel produced in the Netherlands.

For this specific case study, the environmental burdens were higher when using consequential modeling than attributional modeling, leading to contrasting conclusions in this fuel's environmental performance than conventional jet fuels. The reason was that, besides the major environmental hotspots related to the bio-jet fuel conversion processes, the impact of the production of additional animal feed could be much higher than the credits from co-product displacement in the consequential LCA.

So, even if the results of consequential LCAs by including market prospects and indirect land-use changes are more sensitive to uncertainties than attributional LCAs, we believe that both LCAs are necessary for decision making to mitigate possible indirect effects on the affected markets. In this specific case, our consequential LCA highlights the environmental issues arising if the potato by-products diverted from the European animal feed market to produce the bio-jet fuel are replaced (in part) with imported soybean meals from South America. Such an aspect was instead overlooked using attributional modeling. To mitigate indirect environmental impacts on the animal feed market, it is necessary that the market is steered with a holistic perspective and both ALCA and CLCA become necessary.

The technology investigated in our study is at a pilot scale and was successfully tested using potato by-products. However, other bio-based residual streams could be converted via ABE fermentation. Further research may provide data for assessing the operation of this innovative technology with other feedstocks.

CRediT authorship contribution statement

Christian Moretti: Conceptualization, Methodology, Software, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Ivan Vera:** Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Martin Junginger:** Conceptualization, Methodology, Data curation, Supervision, Funding acquisition, Resources, Writing – review & editing. **Ana López-Contreras:** Data curation, Formal analysis, Investigation, Writing – review & editing, Project administration, Funding acquisition. **Li Shen:** Conceptualization, Methodology, Project administration, Funding acquisition, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.152505.

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