Science of the Total Environment 775 (2021) 145848

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

From agricultural (by-)products to jet fuels: Carbon footprint and economic performance

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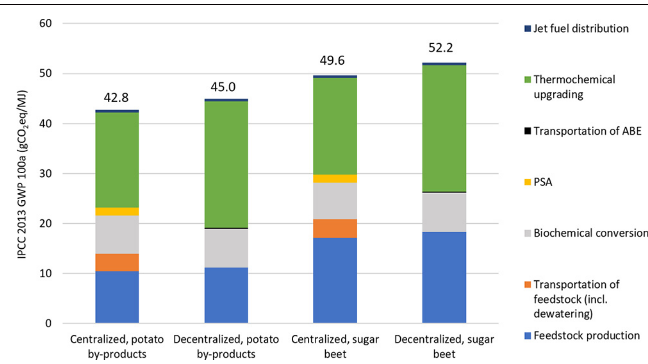
HIGHLIGHTS

- This article presents the early-stage economical and well to tank assessments of a novel bio-jet fuel.
- Centralized options lead to minimum selling prices of about 2250 and 1700 €/t respectively for potato by-products and sugar beet.
- Compared to petrochemical kerosene, 52% savings of GHG emissions can be achieved using potato by-product and 44% using sugar beet.
- A net-zero climate change impact could potentially be achieved by the centralized option permanently storing the biogenic carbon dioxide from fermentation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 January 2021
Received in revised form 9 February 2021
Accepted 10 February 2021
Available online 14 February 2021

Editor: Damia Barcelo

Keywords:
Biomass
Life cycle assessment
ABE fermentation
GHG emissions
Minimum selling price

ABSTRACT

This research assesses the well-to-tank (WTT) greenhouse gas (GHG) emissions and economic performance of an innovative bio-jet fuel via acetone-butanol-ethanol (ABE) fermentation. Dutch potato by-products from the food processing industry and sugar beets are explored as potential feedstocks. Four product systems differentiated by feedstocks, logistics and centralized/decentralized fermenters are investigated.

For both feedstocks, it is found that a centralized large-scale fermentation is preferable to decentralized small-scale fermentation (25–30% less expensive and 5% lower WTT emissions). Once commercialization is reached, the cost and carbon performance of this novel bio-jet fuel could be similar to that of other alcohol-to-jet fuels. Depending on the feedstock and configuration considered, the GHG emission mitigation potential of this novel jet-fuel was estimated between 41% and 52%. To meet the EU RED II 65% GHG reduction criterion, possible options could be using low carbon-intensive processing energy and hydrogen or storing permanently biogenic carbon dioxide from fermentation.

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1. Introduction

In 2018, the combustion of jet fuels was responsible for about 2% of all global greenhouse gas (GHG) emissions (Crippa et al., 2019; Larsson et al., 2019). In Europe (EU 28), about 59 million metric tonnes (Mt) of jet fuel were consumed in 2018 (EUROSTAT, 2020a). These led to a total

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https://doi.org/10.1016/j.scitotenv.2021.145848
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of approximately 250 Mt. of GHGs emitted, of which 75% was associated with direct jet fuel combustion (at 3.1 t CO_2 eq./t jet fuel) and 25% was caused by the indirect emissions of jet fuel production (0.7–0.9 t of CO_2 eq/t jet fuel) (Moretti et al., 2017).

The European Commission aimed to use 2 Mt. of biofuels for aviation by 2020 (European Commission, 2013), which is about 3.4% of the consumption of jet fuels in 2018. In addition, the latest EU Renewable Energy Directive (RED II) requires a 65% GHG emissions mitigation potential for biofuels produced in installations starting operation after 2021 to be incentivized (European Commission, 2016). However, the EU 2 Mt. target will not be reached (Kousoulidou and Lonza, 2016; O'Connell et al., 2019). This is due to the available volume of bio-jet fuels which is still limited.

The main reasons for the limited available volume of bio-jet fuels are high production costs (typically 3–10 times more expensive than petrochemical jet fuels) and limited GHG emissions savings (de Jong et al., 2017a). Commercial bio-jet fuels are currently produced mainly as hydroprocessed esters and fatty acids (HEFA) produced via hydroprocessing of oils and fats such as used cooking oil (UCO). A further production increase of HEFA with high GHG emissions mitigation potential is largely constrained by the availability of the waste oils and fatty acids (Karatzos et al., 2017). It is therefore important to continue exploring alternative routes for producing sustainable aviation fuels, which not only are economically competitive but also offer attractive savings of GHG emissions. Fig. 1 provides a summary of the five main routes to produce bio-jet fuels that presently have a technological readiness level (TRL) above 5.

In this study, we present the technology assessment of a novel alcohol-to-jet (ATJ) route developed in the Netherlands and aimed to use Dutch local feedstock (WUR, 2017). Contrary to conventional ethanol production through fermentation of C6-sugars, this route combines acetone–butanol–ethanol (ABE) fermentation with catalytic alcohol condensation and hydrotreatment. It has been tested using potato by-products as feedstock obtained from a Dutch food processing industry.

Before the 1950s, ABE fermentation was the main technique to produce butanol, but in the 1980s, the commercial process was abandoned due to the higher costs compared to the production of butanol from the petroleum refinery route (De Guido et al., 2019; Lodi and Pellegrini, 2016). In the last two decades, the increasing demand for biofuels has triggered some firms to invest again in ABE fermentation at large scales. However, a successful operation has been so far limited by several technical issues (Chemical and Engineering News, 2019), e.g. low productivity, product inhibition and high energy consumption of the downstream processes for the separation of the mixture of acetone, butanol, and ethanol (Cai et al., 2016; De Guido et al., 2019; Lodi et al., 2018).

In our approach, a pervaporation membrane is coupled to the bioreactor to increase productivity and reduce product inhibition levels. Pervaporation is an emerging separation technology that can allow higher selectivity compared to the other possible techniques for in-situ product recovery such as gas stripping or liquid extraction (Cai et al., 2016). To decrease the high energy consumption of the downstream processing, this process uses alcoholic condensation of the ABE products to avoid the separation into high purity alcohols and ketone end-products (Breitkreuz et al., 2014). At the time when this article is prepared, the overall TRL of our route is assessed as 6 (demonstration plant).

This article aims to assess the potential of this novel bio-jet fuel route to become a future certified route for producing sustainable aviation fuels achieving low life-cycle GHG emissions and competitive production costs. For this reason, based on lab-scale research, early-stage carbon footprint and Nth plant economic assessments of this novel bio-jet fuel have been conducted.

The two assessments presented in this article explore two feedstocks locally available in the Netherlands: potato by-products and sugar beet. In particular, potato by-products from the potato processing industry have attracted interest as a low-price carbohydrate source to produce biofuels such as ethanol (Arapoglou et al., 2010), biogas (Achinas et al., 2019) and hydrogen (Djomo et al., 2008; Mars et al., 2010). In the Netherlands, it is a feedstock that is continuously available all year long. A previous LCA showed that using this feedstock for biohydrogen offers climate change advantages over their current use as feedstock for animal feed (Djomo et al., 2008). For a broader perspective, sugar beet, which is the main sugar crop in the Netherlands (Rademaker and Marsidi, 2019), was also investigated using literature data.

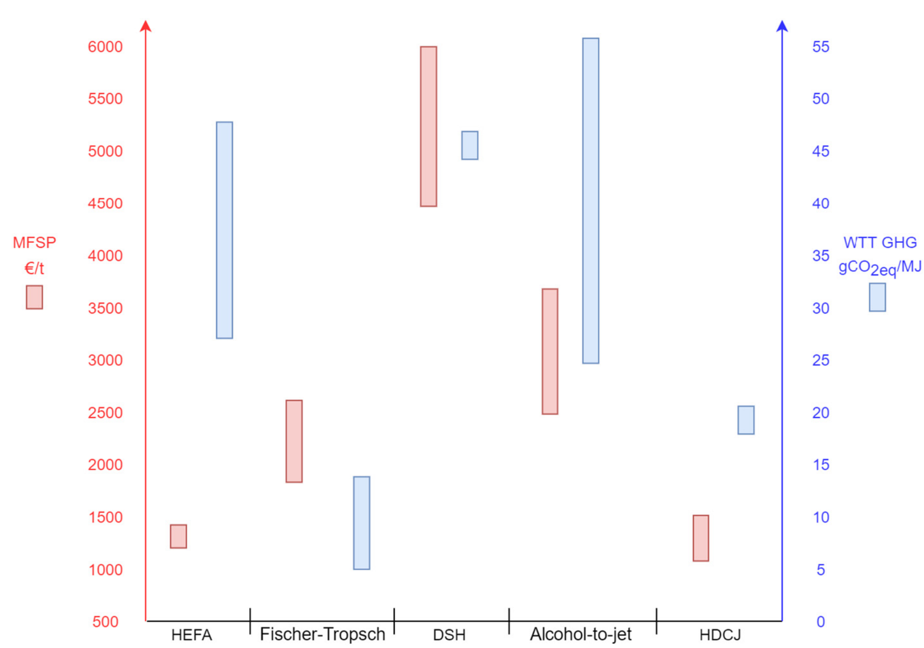

Fig. 1. Examples of well-to-tank (WTT) greenhouse gas (GHG) emissions (energy allocation) and minimum fuel selling prices for various conversion routes retrieved from de Jong et al. (2017b), Antonissen (2016) and (van der Hilst et al., 2019). The ranges represent various feedstocks. HEFA = hydroprocessed esters and fatty acids, DSH = direct sugar to hydrocarbons, HDCJ = hydrotreated depolymerized cellulosic jet.

2. Materials and methods

2.1. Goal of the study

The goal of the assessments was to investigate the potential of this novel fuel to become a future commercialized sustainable aviation fuel. Accordingly, it was necessary to identify the main sources of GHG emissions and the critical economic constraints to assist in minimizing the climate change impact and understanding the key parameters affecting the economic performance for future technology development. The LCA was conducted following ISO 14040 and ISO 14044 (ISO, 2006a, 2006b). The economic performance was assessed by modeling the minimum fuel selling price (MFSP, see Section 2.1.2).

2.1.1. LCA: well-to-tank assessment

The well-to-wheel methodology (WTW) is the main tool adopted for the EU biofuels policy decision context (Agostini et al., 2019; Edwards et al., 2014, 2017) and, for this reason, was used to assess the carbon footprint of this novel fuel. The WTW methodology is an attributional LCA method that focuses on defined stages i.e. feedstock production, conversion processes, transportation and distribution stages and combustion of the fuel (Moretti et al., 2017; Rocco et al., 2018). Compared to broader LCA, in WTW models, the production of the vehicles and plants and their decommissioning are neglected (Moretti et al., 2017; Orsi et al., 2016). According to the EU legislation, the sustainability of biofuels is measured in terms of GHG emissions' mitigation potential based on a functional unit of 1 MJ of fuel. The EU GHG emissions' mitigation potential is calculated as the difference between the well-to-tank (WTT) GHG emissions of the biofuel and a default value (the so-called fossil fuel comparator) for the fossil fuel. A WTT assessment is an LCA following WTW methodology whose scope ends at the distribution of the fuel. The fossil fuel comparator is as well calculated with WTT assessment but combustion emissions based on the carbon content of the fossil fuel counterpart are added.

This study presents the well-to-tank (WTT) assessment of our bio-jet fuel. The life cycle GHG emissions were calculated using the IPCC 2013 global warming potential (100 years) method (Hartmann et al., 2013). The WTW or WTT approach assumes that 1) there is a "perfect substitution of one product for another and that activity and emission levels scale linearly with the quantities required for meaningful levels of climate-change mitigation, with no indirect effects" (Plevin et al., 2014) and 2) the direct CO_2 emitted from the combustion of biofuels is carbon neutral. The current study follows the simplified WTT assessment (see Section 5.1 discussing the limitations behind this approach).

The life cycle stages included in this WTT assessment are *feedstock production, transportation (feedstocks or intermediates), ABE fermentation (biochemical conversion), thermochemical upgrading (alcoholic condensation and hydrotreatment) and the distribution of the final fuel.*

Based on the project that developed this novel fuel, the geographic scope is defined as the Netherlands. Nevertheless, when a specific inventory for the Netherlands was not available, European average data were used (see detailed inventory description in Section 2.3). The technological scope is the specific technology producing this fuel projected in the near-future temporal scope when it is expected that a first large-scale commercial plant could be ready in 2030.

2.1.2. Economic assessment: minimum fuel selling price (MFSP)

The production cost of bio-jet fuels is calculated with the so-called minimum fuel selling price (MFSP). This indicator is used for comparing the levelized cost of bio-jet fuels with the market price of petrochemical kerosene (de Jong et al., 2015; Tao et al., 2017).

MFSP or the levelized cost of fuel is the minimum price of the fuel at which the cost and benefits break even, leading to a net-zero present value. Eq. (1) shows the calculation of the MFSP. The economic data and assumptions used for various product systems are described in Section 2.3.

$$MFSP = \frac{\sum_{t=0}^{L} \frac{CAPEX_t + FS_t + U_t + IT_t + F_t + O_t + T_t + L_t - N_t}{(1+r)^t}}{\sum_{t=0}^{L} \frac{E_t}{(1+r)^t}} \quad (1)$$

where:

- $CAPEX_t$ is the capital expenditure (including working capital) in year t.
- FS_t is the cost of the biomass feedstock.
- U_t represents the cost of energy, utilities and other raw materials.
- IT_t is the interest and taxes payments in year t.
- F_t is the fixed costs including local taxes, insurance, general plant overhead, administrative costs and marketing.
- O_t represents other semi-variable costs (e.g. patent and royalties).
- T_t is cost of transport and blending.
- L_t is the labor cost.
- N_t is the sum of revenues which are generated by the sales of co-products and Dutch green certificate incentives i.e. Hernieuwbare Energieeenheden (HBE).[1]
- E_t is the annual production of fuel expressed in mass terms (t).
- r is the discount rate.

2.2. Conceptual system design

2.2.1. Centralized and decentralized configurations

Two types of system configurations were distinguished in this study, namely, centralized and decentralized systems, for both potato by-products and sugar beet, as illustrated in Fig. 2.

In the centralized systems, potato by-products or sugar beets are transported to a centralized location where ABE fermentation and upgrading to jet fuel take place on the same site. The most important advantage of the centralized systems is the scale effect: the large scale conversion process could likely result in lower specific investment costs. Also, there are other potential benefits of high overall system efficiency and more possibilities for utility recycling.

In the decentralized systems, the biomass feedstocks are directly fermented into ABE nearby the location where they are collected. The fermenter sizes are smaller. The ABE produced from scattered fermenters is then shipped to an upgrading center to be converted into jet fuel. The most important advantage of the decentralized systems is avoiding the potential burden of long-distance transportation of high water content (76–88%) biomass feedstock. The tradeoff could be that smaller size fermenters could be costly (and requires the transport of ABE).

2.2.2. Sizes and capacities

In this study, the system sizes were determined by the maximum amount of biomass that potentially available for bio-jet fuel production in the Netherlands. The potato by-products are a mix of potato steam peels, grey starch and press-pieces. We assumed that 80% of the total availability of Dutch potato by-products (about 1000 kt/year based on industrial project partner data) could be in theory collected and made available for jet fuel production. For sugar beet, in 2018–2019, the total annual Dutch production was about 6.5 Mt. (EUROSTAT, 2020b). In 2017, the production of sugar beet in the Netherlands was almost 8 Mt. (EUROSTAT, 2020b). Based on this historical data, we can assume that in the best possible scenario, compared to the production in the last couple of years, 1.5 Mt. can be additionally produced in the

[1] HBE are the biofuel certificates in the Netherlands and are traded between the obligated parties that have to buy the right amount of HBEs and the producers of biofuels generating a surplus of HBEs (Nederlandse Emissieautoriteit, 2020).

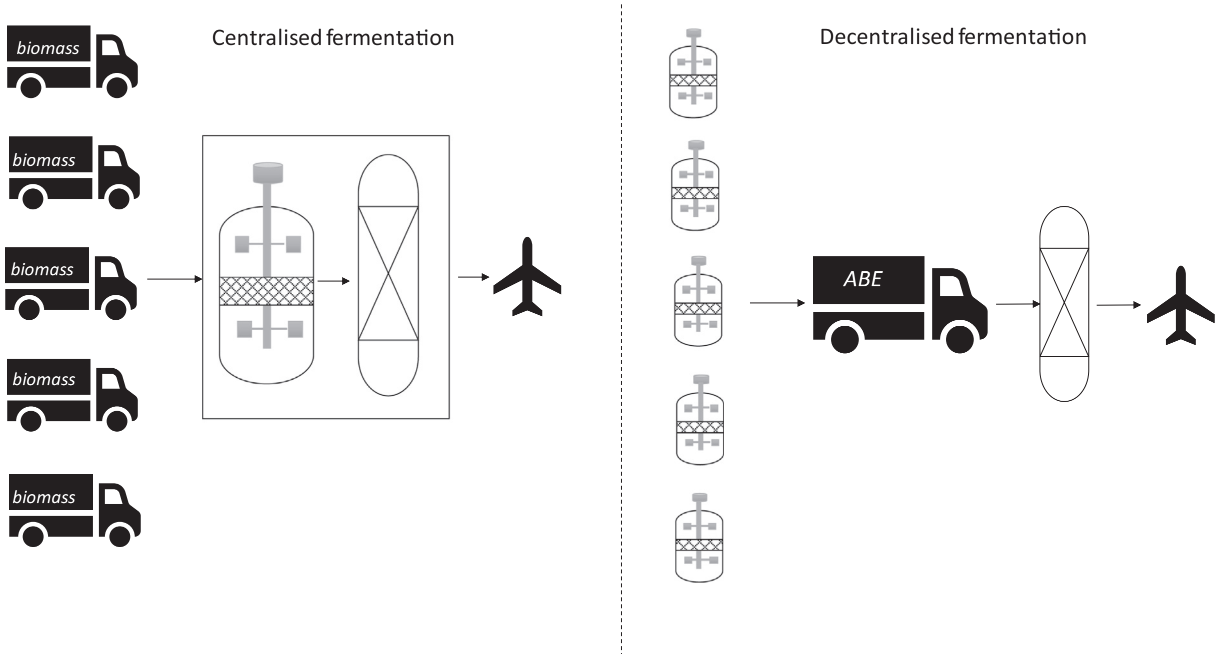

Fig. 2. Two system design concepts: centralized fermentation and decentralized fermentation.

Netherlands. A summary of the availability and composition characteristics of the potato by-products can be found in Table 1.

In the centralized system using potato by-products, it was assumed that a large scale fermenter can handle 800 kt feedstock per year. For the large scale fermenter, it was estimated that 16.2 kt per year of ABE can be produced (see detailed assumptions on yield in Section 2.3.3). Assuming that the plant operates for 8000 h per year (Pyrgakis et al., 2016), a production rate of 2025 kg/h of ABE is required.

In the *decentralized* configuration, the size of the fermenters is based on the average production capacity in terms of potato by-products of the Dutch potato processing plants (100kt/y) where each fermenter is assumed to be located. The assumed size is also representative of worldwide average production capacities per plant (Achinas et al., 2019). For this reason, fermenters are assumed to be 1/8th the size of the centralized fermenter.

Similar to the cases with potato by-products, for the **sugar beet** system with a *centralized* configuration, all the sugar beet collected is assumed to be processed in a centralized location. In the decentralized case, as for potato by-products, it is assumed that 100 kt/y of sugar beet are processed in each decentralized location. In total, it was assumed that there are 15 locations distributed in the most productive provinces in the Netherlands.

Table 2 summarizes the main characteristics of the four product systems differentiated per type of configuration (centralized/decentralized) and feedstock (potato by-products/sugar beet).

2.3. Inventory analysis: data and assumptions

Fig. 3 shows the detailed process diagrams of the centralized and decentralized systems using potato by-products as the feedstock. The process diagrams of the systems based on sugar beet largely resemble these based on potato by-products. The detailed inventory description per life cycle stage is explained in the following sub-sections.

In Fig. 3, the co-products of each unit process are highlighted. Their production quantities per type of configuration and feedstock can be found in Table 3.

2.3.1. Feedstock production

For the potato by-products, the production of the feedstock starts with the cultivation of the potatoes (see Fig. 3). The inventory for the production of the market average harvested potatoes in the Netherlands was retrieved from Agri-footprint 5.0 (Potatoes, market mix, at regional storage/NL). These harvested potatoes are processed into food products such as packaged frozen chips by the potato industry. The potato by-products (mainly peels, see Table 1) are an industrial by-product of this

Table 1
Availability and characteristics of potato industry by-products and sugar beet in the Netherlands (NL = Netherlands and DM = dry matter).

Biomass feedstock	Estimated availability in NL (kt/y)	Dry matter (DM) (%)	Starch content (as %DM)	Starch availability from potato by-products (kt/y)
Steam peels	800[a]	11.2[b]	55.0[b]	48.4
Grey starch	~140[a]	17.9[b]	59.2[b]	14.4
Press-pieces	~50[a]	15.5[b]	57.7[b]	4.4
Total potato by-products (mix) in the Netherlands	~1000	12.3	55.7	67.6
Potato by-products (mix) assumed to be used for bio-jet fuel for this assessment	~800	12.3	55.7	55.0
			Sugar (sucrose) content	Fermentable sugar available
Sugar beet assumed to be used or bio-jet fuel for this assessment	1500	23.5[c]	71.1[d]	250.5

[a] Availability of potato by-products: information obtained from industrial partners of the project.
[b] Dry matter and starch content of the potato by-products: information obtained from the lab measurements from the project.
[c] Data source: (Edwards et al., 2017).
[d] Data source: (Bietenstatistiek, 2019).

Table 2
Main characteristics of the conceptual designs of the product systems.

Parameter	Potato by-products (800 kt/y)		Sugar beet (1500 kt/y)	
	Centralized, large scale	Decentralized, small scale	Centralized, large scale	Decentralized, small scale
Number of fermenting facilities	1	8	1	15
Capacity of the fermenting facility (kt feedstock/y/fermenting facility)	800	100	1500	100
Sugar production (kt of starch or sucrose/y/fermenting facility)	55	7	250	17
ABE production (kt ABE/y/fermenting facility)	16.2	4	68	4.5
Bio-jet fuel production (total kt/y)	10.7	10.7	44.7	44.7

process (see Section 2.3.6 for detailed information on the allocation applied). To process 1 t of harvested potatoes, it requires 70 Nm^3 of natural gas and 120 kWh of electricity and delivers about 213 kg of wet potato by-products (Ponsioen and Blonk, 2011). For the cultivation of the sugar beet in the Netherlands, the inventory dataset was also retrieved from Agri-footprint 5.0 (Sugar beet, at farm/NL).

2.3.2. Dewatering and transportation (feedstocks or intermediate ABE)

For centralized systems, the biomass feedstocks (potato by-products or sugar beet) are dewatered from 88% to 65% by centrifuging and decanting on-site before transport. The amount of electricity for dewatering was provided with personal communication by the industrial producer and is kept confidential. The cost and climate change impact of dewatering (minor) were incorporated in the feedstock transportation.

In the centralized systems using potato by-products as the feedstock, the distance for transporting the feedstock to the refinery (assumed in Rotterdam) is 105 km, which is based on the actual locations and capacities of the factories owned by the industrial project partner. This average distance is assumed to be representative of the whole supply chain of this type of potato by-products in the Netherlands. For sugar beet, the same average distance is assumed.

In the decentralized systems, the decentralized fermenters are located next to the potato (or sugar beet) processing plants. So, the transportation of the feedstock (few kilometers) is assumed to be negligible from both environmental and cost perspectives. The ABE transport distance to the biorefinery where the upgrading to jet fuel occurs is 105 km as for the centralized case.

For transportation, the background dataset *Transport, freight, lorry 16–32 metric ton, EURO4 {RER}| APOS* was retrieved from ecoinvent 3.6.

2.3.3. Biochemical conversion (ABE fermentation and concentration)

The biochemical conversion process starts with potato by-products hydrolysis. For sugar beet, hydrolysis is not necessary. In the hydrolysis reactor, the starch of the potato by-products is converted into sugars (maltodextrins) by alpha-amylase enzyme preparation. These sugars are then fed to a fed-batch fermenter to be converted into ABE. For both feedstocks, it is assumed that the unfermented dry matter remaining in the fermentor after the production process is sold as animal feed.

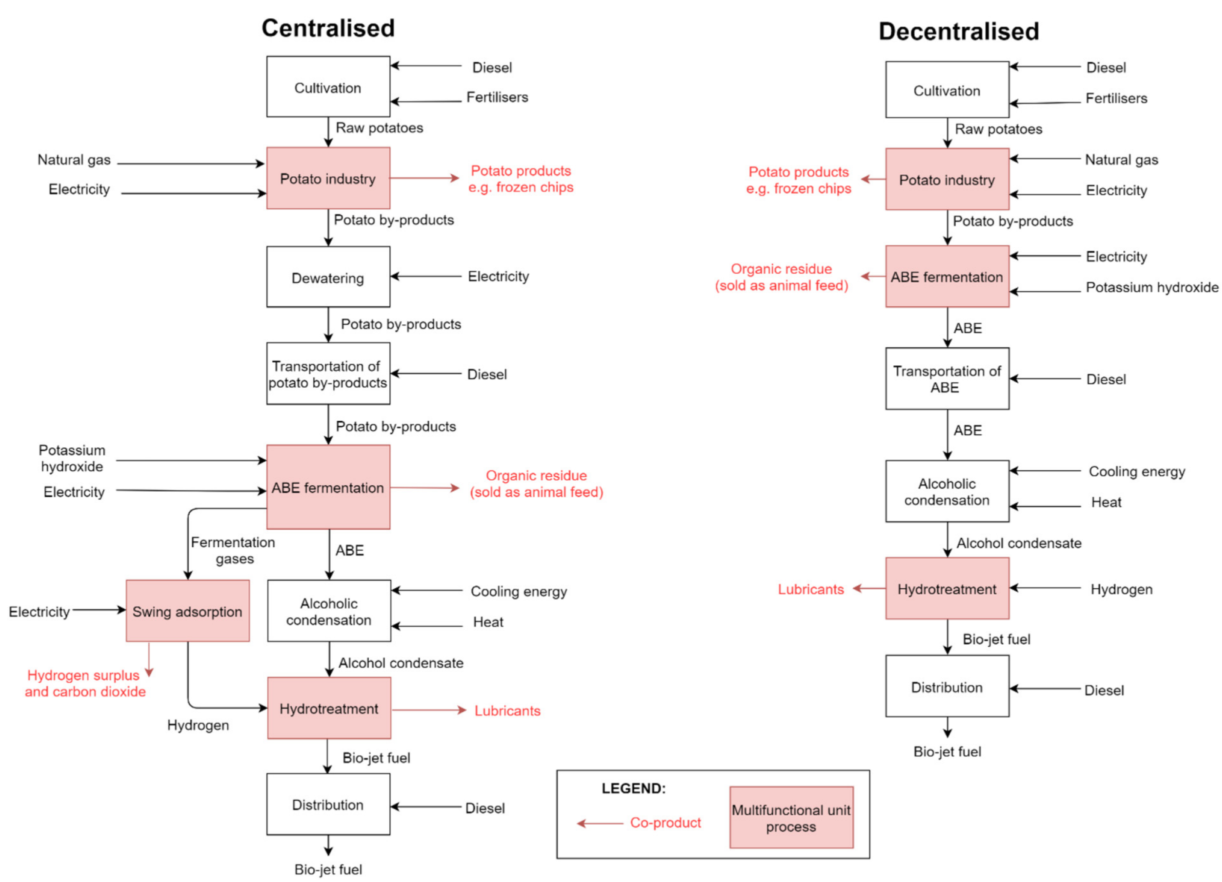

Fig. 3. Process flow diagrams detailing inputs and co-products (multifunctional unit processes have been highlighted) for the centralized and decentralized configurations using potato by-products. The flow diagrams using sugar beet differ for the absence of the (potato) industry unit process.

Table 3
Total production of bio-jet fuel and co-products per feedstock and configuration. n.d = not disclosed.

Co-product	Potato by-products (800 kt/y)		Sugar beet (1500 kt/y)	
	Centralized, large scale	Decentralized, small scale	Centralized, large scale	Decentralized, small scale
Bio-jet fuel (kt/y)	10.7	10.7	44.7	44.7
Potato products (e.g. frozen chips)	n.d.	n.d.	n.d.	n.d.
Organic residue (sold as animal feed) (kt dry/y)	56.3	56.3	165.6	165.6
Carbon dioxide (sold) (kt/y)	25.4	0	115.7	0
Hydrogen surplus (kt/y)	0.4	0	1.9	0
Lubricants (kt/y)	0.4	0	1.9	0

ABE fermentation is a biological process that allows the conversion of sugars into ABE using Clostridium bacteria (Jones and Woods, 1986). By using pervaporation to recover ABE from the fermentation broth and thereby avoiding product inhibition, based on lab experiments, it is possible to achieve yields (g/g) of 29.5% for starch or glucose to ABE (potato by-products) and 27% for sucrose to ABE[2] (sugar beet).

The centralized fermenter is accompanied by two membranes for removal of the ABE products: a first one to separate ABE from the fermentation broth (after solid-liquid separation) and a second one to separate water from the ABE-containing permeate. The permeate from the first membrane, composed of water and volatiles ABE, goes to the second membrane for dewatering. The retentate from the first membrane containing residual sugars is recycled to the fermenter. The main objective of the second membrane is to remove the high amount of water that is present in the permeate along with ABE. This membrane removes the water to a maximum content of 10% water before alcohol condensation.

This concentrated ABE permeate flow is then fed into the alcohol condensation process. In the decentralized systems, the two aforementioned membranes are decentralized with the fermenters. The ABE permeates from the last membranes of each fermenter are then transported to Rotterdam where the downstream processing (alcoholic condensation plus hydrotreatment) is assumed to occur.

Table 4 summarizes the main process inputs of the fermentation process (including pervaporation). The data are reported per t of pure ABE produced.

2.3.4. Thermochemical upgrading (alcoholic condensation plus hydrotreatment)

The upgrading of the ABE stream to aviation fuel consists of an alcoholic condensation process followed by hydrotreatment.

Alcoholic condensation is based on catalytically combining short-chain alcohols and ketones to produce mono-oxygenated long-chain hydrocarbons (Breitkreuz et al., 2014). During this process, a large amount of water is produced (see Table 5). In the centralized configuration, the water is designed to be recycled back to the second pervaporation membrane. In the decentralized configuration, there is a third small membrane dedicated to treating this flow. The alcoholic condensate is then further deoxygenized via hydrotreatment to produce long alkane chains in the range of jet fuel blending components (Breitkreuz et al., 2014). Based on pilot-scale experiments, ABE is converted into alcohol condensate with 75% yield and the alcohol condensate is converted to aviation fuel with a yield of 88% (plus 4% lubricants) by hydrotreating in a fixed bed reactor. Hydrotreating was performed with a commercial catalyst designed for fats and oils. All high boiling material not fitting the jet fuel boiling range fell fully into the diesel boiling range. Since no diesel quality tests were conducted, this aromatic-free fraction was assumed to be used as a specialty lubricant.

[2] Based on the experience of the technical experts involved in the project, a reasonable maximum yield sucrose to ABE is 30% in weight.%. In single batch fermentation, not all glucose will be consumed, but with recycling or another set up, 90% consumption of glucose could be reached. Accordingly, an overall maximum (and even feasible) yield of 27% was considered for the baseline calculations.

Table 5 envelopes the inputs and outputs of the thermochemical upgrading (alcoholic condensation plus hydrotreatment). Since the amount of hydrogen produced from ABE fermentation is enough to satisfy the need for hydrotreatment (see Table 4), hydrogen is assumed to be recovered in the centralized configuration (ABE fermentation and hydrotreatment occur in the same location). Since the centralized location is in an area of bio- and oil refineries, there is a local demand for the hydrogen surplus, which is sold. To recover this hydrogen, it is necessary to separate the carbon dioxide from the fermentation gas (otherwise the fermentation gas is usually released to the air). It is assumed that the carbon dioxide is separated by using swing adsorption reactors (SARs). Based on Cloete et al. (2020), 344 kWh of electricity is assumed to be needed to separate one t of carbon dioxide from flue gas. The separated carbon dioxide was assumed to be sold as well.

2.3.5. Blending and distribution

Once the fuel is produced, it is blended with petrochemical kerosene and distributed. Estimations of blending costs were retrieved from de Jong et al. (2015). The distribution of bio-jet fuels (blended with petrochemical kerosene) and petrochemical kerosene is assumed to be the same. Distance and mode of distribution of the jet fuel to the “tanks” were assumed to be the same as the average EU petrochemical kerosene (Moretti et al., 2017). Distribution costs were provided by a Dutch supplier of sustainable aviation fuels.

2.3.6. Multifunctionality in the well-to-tank model

Four multifunctional unit processes of the potato by-product based jet fuels are highlighted in Fig. 3, namely, potato industry (potato processing), ABE fermentation, swing adsorption and hydrotreatment. According to ISO 14044:2006 and the attributional approach adopted in the study, subdivision was applied every time possible and the allocation method was selected based on the parameter better representing the “physical causality” relationships of the unit process and co-products produced (Moretti et al., 2020a).

The impact of ABE fermentation was allocated to the co-products with energy allocation since ABE fermentation occurs to generate energy products. The allocation shares applied and LHVs assumed can be found in Table 6.

The impact of the swing adsorption unit was allocated between carbon dioxide and hydrogen based on their economic value. For the calculation of the economic allocation shares, the prices reported in Table 7 were used. The resulting allocation shares were 59.4% for carbon dioxide and 40.6% for hydrogen. This method was preferred to 1) energy allocation since carbon dioxide has no LHV and 2) mass allocation since the hydrogen mass fraction is negligible but it represents the entire energetic fraction.

For hydrotreatment, there is a minor by-product (lubricant) that has an LHV (which has been so far not measured) but lubricants are not used for their energy content. Since lubricants are a minor by-product, the type of allocation used has a minor impact on the results of the main product (Sandin et al., 2015). Mass allocation was considered as a good proxy allocation for energy allocation (and was applied to apportion the impact between the bio-jet fuel (96.0%) and lubricants (4.0%).

Table 4
Mass and energy inputs and outputs of ABE fermentation (including pervaporation) per t pure ABE and background data sources for the LCA.

Flow	Data for potato by-products	Data for sugar beet	Foreground data sources	Background data sources
Inputs				
Feedstock (t)	49.3	22.2		
Enzymes (kg)	2.2	0	Based on laboratory experiments. Enzymes used for starch hydrolysis, which is not needed for sugar beet. 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, the dataset Electricity, medium voltage {RER}| market group for | APOS, U from ecoinvent 3.6 was used updating the shares of electricity per source based on the 2030 EU reference scenario for the Netherlands (Carpos et al., 2016). For steam, the dataset Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | APOS, U from ecoinvent 3.6 was used.
Potassium hydroxide (t)	0.1	0.04	Based on laboratory experiments.	Potassium hydroxide {RER}| production | APOS from ecoinvent 3.6.
Electricity (kWh)	1000	1000	Based on (Van Hecke et al., 2018) for ABE fermentation with pervaporation.	For electricity, the dataset Electricity, medium voltage {RER}| market group for | APOS, U 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).
Nitrogen (kg)	2.8	1.1	based on laboratory experiments.	Nitrogen, liquid {RER}| market for | APOS from ecoinvent 3.6
Co-outputs (energy allocation)				
Organic residue (t)	3.5	2.5	Lab data. Details about allocation are reported in Section 2.3.6.	
Part of fermentation gases made of hydrogen (kg)	47.5	51.9	Lab data. Hydrogen generated by fermenting the feedstock. In the centralized configuration, this hydrogen is recovered and partly used for hydrotreatment while the surplus is sold. In the decentralized configuration, the hydrogen produced is released to the atmosphere together with the biogenic CO_2.	
Part of fermentation gases made of biogenic carbon dioxide (t)	1.6	1.7	In the centralized configuration, the carbon dioxide is sold. In the decentralized configuration, carbon dioxide is released to the atmosphere together with hydrogen.	

The main aim of the potato industry unit process is to produce revenues and not to produce residues to be converted into fuels. According to the ISO causality criterion for the selection of the allocation method, economic allocation was chosen. An allocation factor of 1% was retrieved from (Ponsioen and Blonk, 2011), who used five-years average prices for potato peels and potato products. A sensitivity analysis for this allocation factor was performed and can be found in Section 4.1.

2.3.7. Input data and key assumptions of the economic analysis

In the economic analysis, a lifetime of 25 years and 8000 h per year of operation was assumed for the plant. In the first year, the production was assumed to be 30% of the total capacity, while in the second year this value could be increased to 70% (Towler and Sinnott, 2012). The total investment occurs with the following shares and timing: 30% two years before the first year of production, 50% one year before production, and 20% in the first year of production. Cost growth factors for the first pioneer plant were not considered. So, the calculated MFSPs refer to a future Nth plant built when the technology will be considered mature. We can expect that, as for alcohol to jet fuel routes, the costs of the first pilot plant could be up to double compared to an Nth plant. Transportation costs were provided by the project partner (15–20 € per t of feedstock depending on the distance of the single plant from Rotterdam). The financial parameters to determine the annual cash flows are reported in Table 7. Table 7 summarizes also the main cost parameters used to determine the CAPEX and OPEX of this novel fuel. To update all price/cost data used to 2019, indexation was applied using EU Harmonized Index of Consumer Prices for the Netherlands (EUROSTAT, 2020c).

3. Results

3.1. Well-to-tank GHG emissions

Fig. 4 shows the well-to-tank global warming potential of producing one MJ of bio-jet fuels with centralized and decentralized configurations

Table 5
Mass and energy inputs and outputs of alcoholic condensation plus hydrotreatment that are in common for centralized and decentralized configurations and the two feedstocks assessed. Data per t of aviation fuel.

Flow	Data	Foreground data sources	Background data sources
Inputs			
Pure ABE	1.5 t		
Heat	4.6 GJ	Based on pilot-scale experiments	Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | APOS from ecoinvent 3.6.
Cooling energy	1.7 GJ	Based on pilot-scale experiments	Cooling energy {GLO}| market for | APOS from ecoinvent 3.6. Mainly, cooling energy from natural gas, at cogen unit with absorption chiller of size 100 kW.
Hydrogen	36.5 kg	Based on project partner's directions, the value from NESTE's NEXBTL technology was used (Moretti et al., 2020b)	From SAR for centralized configuration. Hydrogen (reformer) E from PlasticsEurope (PlasticsEurope, 2005) for decentralized configuration
Co-outputs			
Lubricants	41.7 kg	Based on pilot-scale experiments	Mass allocation. Details in Section 2.3.6.
Wastes			
Wastewater	0.6 t	Based on pilot-scale experiments. 52% of this water was generated by the alcohol condensation reaction.	Wastewater, average {Europe without Switzerland}| market for wastewater, average | APOS from ecoinvent 3.6

Table 6
Energy allocation shares and LHVs assumed for allocating the impact of ABE fermentation to the organic residue sold as animal feed and fermentation gases; n.a = not applicable.

Co-product	LHV (MJ/kg)	Allocation shares			
		Potato by-products		Sugar beet	
		Centralized, large scale	Decentralized, small scale	Centralized, large scale	Decentralized, small scale
ABE	32.8 (Boundy et al., 2011)	34.4	36.6	41.82	45.4
Fermentation gases	3.5 calculated as weighted average between 120.2 (Boundy et al., 2011) for hydrogen and carbon dioxide which has no LHV.	6.0	n.a.	7.95	n.a.
Organic residue (sold as animal feed)	16.4 per 1 kg of dry potato pulp pressed animal feed (Durlinger et al., 2017) and 16.1 per 1 kg of sugar beet pulp sold as animal feed (Edwards et al., 2017)	59.6	63.4	50.23	54.6

for the two investigated feedstocks. For both feedstocks, the difference of impact between the centralized and decentralized options is minor (5%). Although the centralized systems lead to a high impact of feedstock transportation, the decentralized systems have a much higher impact for the thermochemical upgrading (external hydrogen supply). The impact of the hydrogen from ABE fermentation in the centralized systems is 35–40% (depending on the feedstock) of the impact of producing the same amount of hydrogen by steam reforming from natural gas (in the decentralized systems).

For all the product systems, the impact of the thermochemical upgrading (see Fig. 4) is contributed by steam production (12.1 gCO_2eq per MJ of fuel), cooling energy (6.2 gCO_2eq). For the decentralized configurations, an additional impact of 6.95 gCO_2eq is caused by the production of the hydrogen (steam reforming of natural gas) for hydrotreatment. The climate change impact of the biochemical conversion (see Fig. 4) is mainly (70–80%) caused by electricity production (for pervaporation).

The transportation of ABE of the decentralized systems and the distribution of jet fuels represent a minor GHG impact.

Comparing the two feedstocks, jet fuels based on sugar beet have 14% higher GHG emissions than jet fuels made from potato by-products for both centralized and decentralized systems.

The impact of the production of the feedstock contributes about a quarter of the total impact of the fuel in the case of potato by-products and a bit more than one-third (35%) of the total impact in the case of sugar beet. The cultivation of sugar beet causes a high amount of direct emissions of dinitrogen monoxide (59% of the impact of sugar beet) by the use of N-fertilizers, manure and crop residues. Because sugar beet is not a by-product, all impacts associated with the cultivation and harvesting of sugar beet are attributed to the jet fuel.

In contrast, the impacts caused by the potato processing industry are mainly (99%) allocated to the final food-potato products. Specifically, the impact of the potato processing industry is dominated by the use of utilities, i.e. natural gas consumption to produce process heat (46%) and electricity consumption (14%). The remaining impact (40%) is caused by the cultivation of potatoes (76% of the impact of potatoes) and transport to the plant (24% of potatoes' impact).

The impact of the feedstock is also affected by the yield assumed for the ABE fermentation process and the economic allocation factor applied to the potato industry. In particular, the fermentation yield affects the amount of potato by-products (or sugar beet) used to obtain one t of bio-jet fuel; while the allocation factor determines the fraction of the impact of the potato by-products. The influence of the yield and allocation factors are assessed by sensitivity analysis (see Section 4.1).

3.2. Minimum fuel selling price

Fig. 5 shows the MFSP and its cost build-up for the four jet fuel product systems investigated.

For both jet fuels made from potato by-products and sugar beet, the MFSP of the decentralized options is higher than that of the centralized ones. Hence, for both feedstocks, the increase in the CAPEX caused by using smaller fermenters is not compensated by the reduction in the transportation costs.

For the centralized configuration based on potato by-products, the feedstock represents the highest source of cost (42%), followed by the CAPEX (28%), transportation costs (16%) and fixed costs (15%). The CAPEX consists of the fermenter (36%), the first pervaporation membrane (16%) and the downstream upgrading equipment including the second pervaporation membrane (38%). The CAPEX of the SAR is small (4%). The transportation costs are the third major source of cost due to the high water content (65%) of the feedstock transported.

For the decentralized configuration using potato by-products, the CAPEX represents the highest source of cost (32%), followed by the cost of the feedstock (32%) and fixed costs (15%). In particular, the cost of the feedstocks is the same in absolute value (because of the same fermentation yield assumed), while the CAPEX is 50% higher for the decentralized fermenters compared to the centralized ones. For the decentralized option, the fixed costs are 33% higher than for the centralized one since they are assumed to be proportional to the CAPEX (which is much higher in the decentralized case). The transportation costs are 78% lower in the decentralized case because a much smaller mass (ABE plus residual water) needs to be transported.

For both sugar beet systems, the feedstock is the most important cost accounting for 48–64% of the MFSP (see Fig. 5). The cost to acquire sugar beet (1167 $€_{2019}$ per t of bio-jet fuel) is higher than the cost of potato by-products (973 $€_{2019}$ per t of bio-jet fuel). The main reasons are the lower yield assumed for sucrose to ABE (27%) compared to glucose to ABE (29.5%), and the higher cost per t of sugar in the case of sugar beet compared to starch (208 $€_{2019}$ /t of sucrose from sugar beet vs. 189 $€_{2019}$ /t of starch from potato by-products). Both parameters, i.e., the fermentation yield and the sugar liberation costs, were further investigated by sensitivity analysis (see Section 4.1).

Overall, the MFSP is lower when using sugar beet compared to potato by-products for the same configuration. The main reason is the lower CAPEX. As a consequence, all other costs proportional to CAPEX are all influenced by the input data for CAPEX. The CAPEX in the sugar beet case is lower because 1) the higher amount of feedstock available allows processing units of larger size (fermenter and/or upgrading units) and 2) the yield ABE/feedstock (t/t) is higher when sugar beet is processed by the fermenters. Combining the two feedstocks is also possible but minor decreases of MFSPs are expected (see Section 4.2).

3.3. Comparison with other bio-jet fuels and petrochemical kerosene

From well to tank, the investigated fuel from potato by-products emits 42.8–45.0 gCO_2 eq./MJ and 49.6–52.2 g CO_2 eq./MJ from sugar beet. These emissions are similar to jet fuels produced via ATJ using corn, HEFA using Camelina and FT jet fuel from sugarcane (de Jong et al., 2017a). However, the WTT GHG emissions of the investigated

Table 7
The main data used and assumptions made to estimate the minimum fuel selling prices.

Flow	Data	References on which these data are based on and notes
Main financial parameters		
Depreciation period	10 y	Based on industrial partners' estimations for the Netherlands
Rate of principal investment	15 y	Based on (de Jong et al., 2015).
Debt to equity ratio	2	Based on industrial partners' estimations for the Netherlands
Interest rate on debt	6%	Based on industrial partners' estimations for the Netherlands
Corporate tax rate	25%	Based on (de Jong et al., 2015)
Discount rate	10%	Based on (de Jong et al., 2015)
Main CAPEX parameters		
Constant scaling factor	0.7	The constant standard values used for chemical plants are usually 0.6 or 0.7 (Ereev and Patel, 2012). For sugar processing equipment with a biomass input between 400 kt/y and 3500 kt/y, which includes our range of investigation, the scaling factor could range between 0.634 and 0.767 (Tribe and Alpine, 1986). The value of 0.6 is well representative of vessels and fermenters (Tribe and Alpine, 1986) while for membranes and adsorbent materials, a higher value is expected. For this reason, between the two values proposed by Ereev and Patel (2012), we assumed 0.7.
Capital cost of semi-batch fermenters	22.4 $M€_{2019}$	For the production of 18 kt ABE per year, which is similar to our size with potato by-products, Pyrgakis et al. (2016) calculated the cost of the fermentation semi-batch reactors as 30.5 M€. However, based on Van Hecke et al. (2018), for the same configuration of semi-batch reactors of Pyrgakis et al. (2016), the cost could be 12.1 M€.
Installed cost pervaporation membrane (incl. vacuum pumps) for in-situ recovery of solvents	28.3 $M€_{2019}$	From (Van Hecke et al., 2018) for a size of 80 kt ABE permeate/y (assuming 8000 h/y operation and that all the ABE produced is processed though pervaporation) for year 2016.
Capital cost of fuel upgrading processing units	58.9 $M€_{2019}$	Based on process simulations for a size of 50 kt/y of hydrotreated products (jet fuel plus lubricants) using real data from pilot scale experiments at Fraunhofer. The downstream processing units include the pervaporation membrane for water separation, the alcohol condensation unit and the hydrotreatment unit.
Working capital	5%	(Ereev and Patel, 2012)
Operation and maintenance factor	3%	Estimation of CAPEX-dependent variable based on (Ereev and Patel, 2012)
Operation supplies factor	15%	Estimation of CAPEX-dependent variable based on (Ereev and Patel, 2012)
Local taxes factor	1.5%	Estimation of CAPEX-dependent variable based on (Ereev and Patel, 2012)
Insurance factor	1%	Estimation of CAPEX-dependent variable based on (Ereev and Patel, 2012)
CAPEX cost SAR	660 $€_{2019}$ /t	2019 CAPEX cost per ton of hydrogen produced by SAR based on average value for carbon dioxide adsorption reported in Cloete et al. (2020) assuming that this value is applicable for the reference size of 18 kt ABE/y used as reference size for the fermenter.
Main OPEX parameters		
Price of potato by-products	106 $€_{2019}$/t dry matter	2016 price of potato steam peels that are the most abundant fraction. Based on the industrial partner's data.
Price of sugar beet	35 $€_{2019}$/t wet matter	Price of 2019 in the Netherlands (EUROSTAT, 2020d).
Animal feed price	79.2 $€_{2019}$/t dry matter	All the dry matter which is not starch and the starch not fermented are assumed to be sold as animal feed. The market value of this flow is assumed to be 25% lower than the one of the original potato by-products.
Lubricants price	2113 $€_{2019}$/t	Sales price of aromatic free specialty lubricant fractions in 2016 used in Fraunhofer model.
Carbon dioxide	98 $€_{2019}$/t	Assumed to be sold to a greenhouse in horticulture sector in the Netherlands. In 2015, the market price for the supply of external carbon dioxide was between 90 and 100 € (average value used) (Mikunda et al., 2015).
Green certificate incentives (HBE)	8 $€_{2019}$/GJ	Based on the industrial partner's data for 2016
Hydrogen price	2210 $€_{2019}$/t	Price of hydrogen from the average EU refinery in 2010 (Moretti et al., 2017). The surplus of bio-hydrogen from the centralized configuration is also assumed to be sold at this price.
Electricity price (NL)	0.092 $€_{2019}$/kWh	Industry electricity price in the Netherlands in 2019 (EUROSTAT, 2020e)
Heating price	7.4 $€_{2019}$/GJ	2016 price for pressurized steam (~ 400 °C) for the alcohol condensation reactors in a refinery environment used in Fraunhofer model.
Cooling price	1.1 $€_{2019}$/GJ	2016 price for "normal" water cooling towers operated with river or cooling pond water typical in chemical production sites used in Fraunhofer model.
Dutch labor cost	36.4 $€_{2019}$/h	Eurostat data for 2019 in Netherlands (EUROSTAT, 2020f)
Cost of electricity used by SAR per t of hydrogen	1045 $€_{2019}$/t	Based on the electricity consumption to separate carbon dioxide from cement plant flue gas using swing adsorption from Cloete et al. (2020) and Electricity price (NL). The same electricity cost (about 1000 $€_{2019}$/t per t of hydrogen) was estimated also by Di Marcoberardino et al. (2018) for producing hydrogen from raw biogas using swing adsorption.

jet fuel are much higher than the emissions of jet fuels made from used cooking oil (27 g CO_2 eq./MJ) or forestry residues (max. 20 g CO_2 eq./MJ) but lower than ATJ fuel from corn (de Jong et al., 2017a). For sugar beet, the impact of the investigated technology is 32–39% higher than conventional ATJ route using the same feedstock (Antonissen, 2016). Among the main reasons for this, compared to sugar beet ethanol fermentation (Edwards et al., 2014), we can find the three times higher consumption of electricity (due to pervaporation to avoid product inhibition).

Moretti et al. (2017) calculated the fossil fuel comparator for European petrochemical jet fuel in the range 89.1–91.6 g CO_2eq/MJ. The International Civil Aviation Organization (ICAO) uses the benchmark value of 89 CO_2 eq./MJ (ICAO, 2019). Compared to 89 g CO_2 eq./MJ, the investigated jet fuels can offer modest GHG emission savings: 42–52%. However, for the recently revised Renewable Energy Directive (RED II), the minimum GHG saving requirement is 65% for biofuels produced in installations starting operation after 2021 (see Section 5.4 for possible options for carbon footprint improvement).

According to the baseline assumptions, the MFSP of the investigated bio-jet fuels is about 2250–3000 €/t if potato by-products are used as feedstock and 1700–2450 €/t if sugar beet is used. These MFSPs are of the order of twice as much as the ones of commercial bio-jet fuels, (HEFA using UCO, 1289 €/t) (de Jong et al., 2015) and 4–5 times higher than petrochemical jet fuel (550 €/t) (IATA, 2019).

On the other hand, the investigated bio-jet fuels are competitive with many bio-jet fuels under development (see Fig. 1). For example, the MFSP of the studied bio-jet fuels is in the range of MFSP of bio-jet fuels from forestry residues or wheat straw produced by using FT

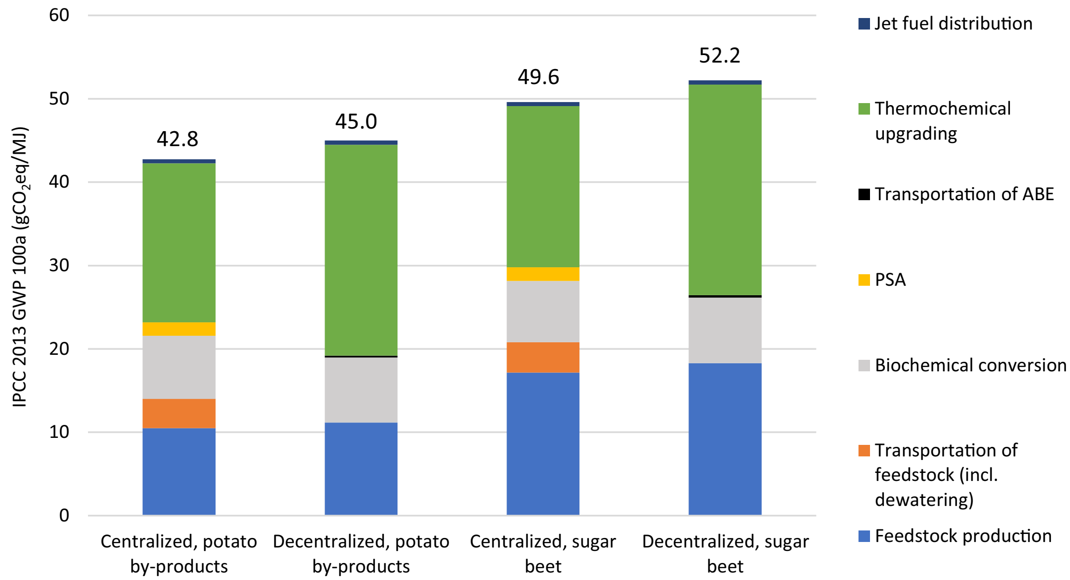

Fig. 4. Well-to-tank breakdown of climate change impact assessed as global warming potential (GWP) over 100 years (g CO_2eq) per one MJ of bio-jet fuel. Feedstock transportation includes a minor impact caused by dewatering for the centralized options.

technology (1800–2700 €/t) or by alcohol fermentation (2500–3500 €/t) (de Jong et al., 2017b).

4. Sensitivity analyses

One of the main challenges of ex-ante assessments is the uncertainty of the assumptions that are needed to overcome the lack of high-quality data from the actual plants. In this section, the influence of the main assumptions affecting the main sources of costs and carbon footprint are scrutinized.

From the baseline results of both carbon footprint and MFSP, what emerged was the importance of the feedstock acquisition (sensitivity assessed in Section 4.1) and the CAPEX (sensitivity assessed in Section 4.2) on the MFSP. Beyond the feedstock used, the selection of the best configuration in terms of carbon footprint performance was mainly influenced by hydrogen production. Hence, it is important to conduct a sensitivity analysis to evaluate the effect of the assumptions behind the impact of hydrogen production by steam reforming and by recovery through SAR (see Section 4.3).

4.1. Feedstock

The impact of the feedstock is affected by two main assumptions, namely the feedstock prices and fermentation yields (which determines the amount of feedstock needed per t of bio-jet fuel).

4.1.1. Feedstock prices

The current price of the potato by-products was provided by the industrial project partner (see Table 7). The potato by-products are currently sold as valuable ingredient for animal feed. Hence, their variation

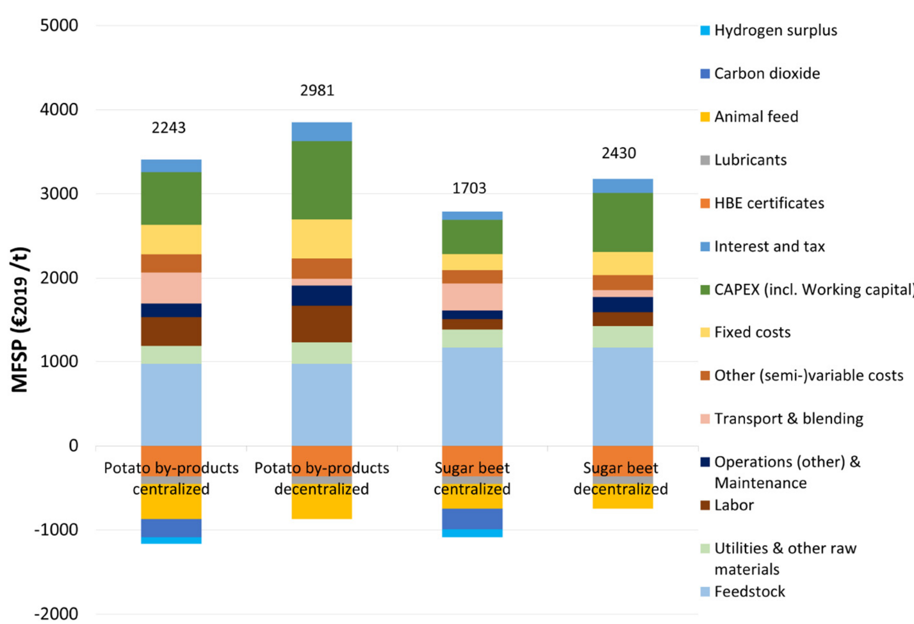

Fig. 5. Cost build-up (€$_{2019}$) and resulting MFSP (on top of each bar) for one t of jet fuel produced from 800 kt/y potato by-products and 1500 kt/y sugar beet. 25 years lifetime and 10% discount rate assumed.

in the price probably corresponds to the price variation of the main potato-based animal feed. Over the past ten years, this price varied between −16% and +17% compared to the 10-year average price (WUR, 2020). These percentage variations are applied to the price of the potato by-products to assess the variation in the MFSP of the bio-jet fuel. These variations in the prices have a limited influence on MFSP (±5%).

As mentioned in Section 3.1, the impact of the potato by-products (feedstock) is affected by the allocation factor applied to the potato processing industry. The allocation factor applied depends on the price of the potato by-products, which, as most of the prices, fluctuates based on the market demand and supply. In LCA, to limit the influence of the price fluctuation, the economic allocation factors are recommended to be averaged over the previous 3–5 years (ISO, 2012). The difference between the five year-average prices of 2009–2013 and 2014–2018 of this type of animal feed from potato by-products was only 3.1% (WUR, 2020). Such a variation would have a negligible effect on the LCA results. However, the variation in the price of the potato-food products, which are the main product of the potato processing industry, also affects the allocation factor. In the sensitivity analysis, the allocation factor (1.8%) used in the Agri-footprint 5.0 database for a similar product i.e. potato pulp pressed animal feed (plus silage)[3] was applied. For climate change, applying this allocation factor, the impact of the investigated bio-jet fuel can increase by about 20%. Hence, the allocation factor of potato by-products is very sensitive for the carbon footprint of the jet fuels.

The price of sugar beet has fluctuated significantly in the past decade. In the Netherlands, the 2018 price (€34.96 per t sugar beet) was used in the model (EUROSTAT, 2020d). This price was one of the lowest prices registered in the previous ten years. From 2007 to 2017, the price fluctuated between €36.90 (2007) and €61.00 (2012) per t. The average price over these 10 years was €45.04 per t. Compared to this average price, the 2018 price used in the model is 22% lower. Accordingly, we considered a variation of ±22% in the price of sugar beet for the sensitivity analysis. It was found that the MFSP of the beet-based jet fuels produced with a centralized configuration will be affected by ±15% by this variation while for the decentralized option, this figure becomes 10% since the total MFSP is higher.

4.1.2. Fermentation yields

The yields of the ABE fermentation process were assumed as 29.5% for glucose (liberated from potato starch) and 27.0% for sucrose (from sugar beet). The ranges of the values observed in the literature (Jiang et al., 2014) are 27–32% for glucose and 25–36% for sucrose. Based on these ranges, a sensitivity analysis was conducted for both MFSP and climate change impact and the results are shown in Table 8. By increasing the fermentation yield to 36% for sucrose, it is possible to reduce the MFSP of the fuel produced from sugar beet significantly (for the centralized configuration by about 23% reaching about 1300 €/t). The increase in yield in the case of potato peels has a much lower effect on the MFSP. The carbon footprint is unaffected by the variation of yield. The main reason is that increasing the yield means increasing the amount of ABE produced per kg of feedstock. However, this means that less animal feed is produced and more electricity is needed for the pervaporation membrane (which is proportional to the ABE output and not to the amount of feedstock processed).

Table 8
Summary of the sensitivity analyses on fermentation yield. For baseline calculations, the assumed yields were 29.5% for glucose and 27.0% for sucrose. Based on the literature, these values were varied in the ranges of 27–32% for glucose and 25–36% for sucrose.

Assessment	Potato by-products (800 kt/y)		Sugar beet (1500 kt/y)	
	Centralized	Decentralized	Centralized	Decentralized
MFSP	−4% to +9%	± 5%	−23% to +7%	−15% to +5%
Climate change	± 0.1%	± 0.3%	± 0.1%	± 0.3%

4.2. CAPEX

The CAPEX turned out to be an important source of the production cost. The CAPEX is based on the size of the components and their prices.

4.2.1. Size of the components

The dimensions of the different process units were based on the maximum availability assumed for the two feedstocks in the Netherlands. This assumption was revisited and the effect of varying the amount of feedstock processed on the MFSP is shown in Fig. 6.

Fig. 6 shows that if it were possible to collect 1000 kt potato by-products per year (which is all the availability of potato by-products in the Netherlands), the MFSP would decrease further (2130 €/t for centralized and 2910 $€_{2019}$ /t for the decentralized system). However, if the available potato by-products are constrained, the MFSP would drastically increase (2980–3500 $€_{2019}$ /t if only 300 kt potato by-products would be available).

For the sugar beet-based jet fuels, if it were possible to collect 3000 kt per year of sugar beet for this use (which is of the order of half of the current Dutch annual production), the MFSP of the jet fuel produced via the centralized system would decrease to 1540 $€_{2019}$ /t, which is an attractive price for a novel bio-jet fuel. From the figure, it can also be observed that regardless of the feedstock, the centralized configuration is always preferable compared to the decentralized one in terms of economic performances. On the other hand, Fig. 6 accounts only for the variation of CAPEX and related costs (e.g. fixed and maintenance costs) but not for possible increases in the transportation distances. In particular, for sugar beet, the average distance for transporting all sugar beet produced in the Netherlands to Rotterdam is 190 km (Vera et al., 2020), which is almost double compared to 105 km assumed. Varying the distance, both costs and the environmental impact of feedstock transportation would change proportionally. Moreover, increasing significantly the amount of sugar beet to produce biofuels, which is a crop competing directly with food supplies e.g. for water availability and land allocation, raises ethical and sustainable development issues that should not be overlooked (Callegari et al., 2020).

The production of this fuel is limited by the availability of the feedstock, which is also one of the main current limits of further production of HEFAs and generally of bio-jet fuels. A possibility is to combine the use of the two feedstocks (potato peels and sugar beet) to increase the production capacity of this fuel. In this way, the CAPEX could be further reduced but less importantly than for the range 1000–1500 kt/y since the curve of the MFSP decreases less when the system capacity is larger than 2000 kt per year and the curve using potato by-product has always a higher MFSP for the same capacity. For the decentralized option, already after 1500 kt/y, the curve becomes flat.

4.2.2. Cost of fermenters

In the baseline analysis, the average value found in the literature was assumed for the cost of the fermenter (see Table 7). A sensitivity analysis was conducted to assess how the MFSP of the bio-jet fuel would vary by using a different value among the ones (± 40%) observed in the literature reported in Table 7. After performing such a sensitivity analysis, we observed that the MFSP would vary in the range between ±5% for the centralized systems and ±10% for the decentralized systems.

4.3. Hydrogen

For the centralized option, the recovery of hydrogen using SAR from the product gas of the fermentation process was assumed. For the baseline calculations, the average electricity consumption of the SAR process was retrieved from Cloete et al. (2020). According to the values reported in Cloete et al. (2020), electricity consumption can vary in the order of ±

[3] Potato pulp pressed fresh+silage, from wet milling, at plant/NL Economic.

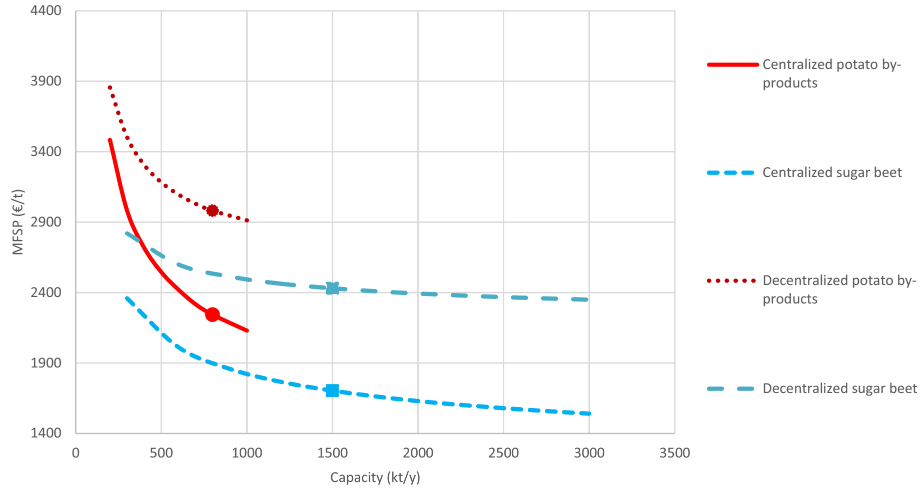

Fig. 6. MFSP (€$_{2019}$) dependency on the capacity (expressed in terms of kt of feedstock per year) for centralized and decentralized configurations, keeping the scale factor constant (0.7). In the baseline calculations, 800 kt per year of potato by-products and 1500 kt per year of sugar beet were assumed to be used for this technology.

15%. The SAR process represents only 6–7% of the carbon footprint of the fuel, this uncertainty leads only to a variation of ±1%.

For the decentralized option, the hydrogen required for upgrading was assumed to be produced from steam reforming of natural gas and is responsible for 13–15% of the carbon footprint of the bio-jet fuels. For hydrogen from steam reforming, the dataset was retrieved from (PlasticsEurope, 2005). Based on the inventory of such a dataset, producing 1 kg of hydrogen emits 9.4 kg CO_2eq. This value is aligned with the range observed in the literature (Bhandari et al., 2012) for the steam reforming of natural gas (8.9 to 12.9 kg CO_2 eq./kgH_2). According to this range, the climate change impact of the bio-jet fuel produced with the decentralized configurations could vary insignificantly, i.e. in the range of −1% to 5% (for both feedstocks).

4.4. Enzymes

In this study, the production of the enzyme, alpha-amylase, was not a sensitive parameter of the LCA since it contributes to only 1.5 g CO_2eq per MJ of jet fuel produced from potato by-products. This contribution in line with MacLean and Spatari (MacLean and Spatari, 2009) who estimated 1.1 g CO2 eq. per MJ of ethanol from corn caused by enzymes. Moreover, their cost was neglected since alpha-amylase has a very low cost (Schubert, 2006). For example, to produce 1 t of ethanol, the cost of the amylase needed is less than 10 euro per t of ethanol, which is about 3% of the cost of ethanol from corn (Schubert, 2006).

However, other enzymes could be more expensive. If more expensive enzymes in the future will be considered more suitable for potato by-products than alpha-amylase (which is the enzyme used at the current stage of development), their cost might affect the MFSP of this fuel. In particular, the cost of hydrolytic enzymes like a mixture of cellulases, hemicellulases and cellobiases can be up to 10 times higher than that of amylase (Barrera et al., 2016). Based on the cost for these enzymes (3 €/kg) assumed by (Barrera et al., 2016), the change of enzymes would put an additional cost of 63 euro per t on our bio-jet fuel (i.e. the cost would be about 2–3% higher than estimated in the baseline calculations). This value is a bit lower than the 90 euro cost of enzymes per t of ethanol calculated by (Barrera et al., 2016) but is in line with (Liu et al., 2016) who calculated between 17 and 100 euro per t of ethanol depending on the type of enzymes and feedstock used to produce ethanol.

Concerning the carbon footprint, the energy utilities for various types of enzymes are quite uncertain (Dunn et al., 2012) but for cellulase, it is expected to be of the same order of magnitude as amylase (Dunn et al., 2012). With a conservative scenario based on the enzyme emissions data published by (MacLean and Spatari, 2009), we can expect that the enzyme contribution to the carbon footprint of this new jet fuel could rise from 1.5 gCO_2eq per MJ of jet fuel to the 3–4 gCO_2eq per MJ of fuel, which would lead to an increase of 3–5% of the WTT carbon footprint of the jet fuel.

5. Discussion

5.1. General limitations of the WTW method

As mentioned in Section 2.1.1, the WTW method applied to biofuels 1) is based on the assumption that there is a perfect substitution of petrochemical fuels, 2) does not account for indirect effects and 3) neglects the impact caused by the capital goods such as the production of machinery, infrastructures and ancillary activities.

While the last point should lead only to the addition of a small impact to both biofuels and petrochemical fuels, the assumption of direct substitution and consideration of indirect effects could affect significantly the carbon footprint of biofuels. Using the WTW method (or more generally an attributional LCA approach) to estimate the GHG emissions savings offered by this novel bio-jet fuels implies the avoidance of the "entire life cycle of a functionally equivalent quantity" of kerosene with no indirect effects "in any system anywhere in the world, at any time" (Plevin et al., 2014). In reality, biofuels do not perfectly substitute fossil fuels (biofuels somehow affect the price and consumption of fossil fuels) and there is no empirical proof that indirect effects are negligible for biofuels (Plevin et al., 2014). Moreover, the avoidance of consumption of a refined product e.g. gasoline does not always lead to a decrease in the corresponding quantity of crude oil (Plevin et al., 2014).

Consequential LCAs could provide a more detailed answer to policymakers about the indirect effects by assessing the actual changes in production and consumption in a policy region (Moretti et al., 2020a; Plevin et al., 2014). For this study, consequential thinking would have allowed to include, for example, the impact of land-use change linked to the use of sugar beet and the market consequences of using potato peels for bio-jet fuels instead than for animal feed.

Assessing indirect land-use change impacts, however, is not straightforward. The potatoes production (from which the by-products are derived) is driven by the demand for food and feed, not the demand for bio-jet fuels. So, direct land-use change can be considered negligible for potato by-products. On the other hand, the feed market could be disturbed if we take away the potato by-products for producing bio-jet fuel. Somewhere, there will be additional production to meet the feed demand, and there will be land-use required. Hence, indirect land-use changes might be significant due to this additional demand for animal feed. Future research should, therefore, evaluate the indirect land-use changes for production systems that are land-intensive in the sugar beet supply chain and the marginal production of animal feed.

5.2. Allocation and RED methodology

In Europe, the Renewable Energy Directive (RED) and Fuel Quality Directive (FQD) recommend performing energy allocation based on the lower heating value (LHV) and no credits are given or impact allocated to by-products that do not have an LHV in principle (European Commission, 2016; European Parliament, 2015). On the other hand, in our carbon footprint assessment, energy allocation was applied only to ABE fermentation and ISO "physical causality criterion" was preferred for the selection of the allocation method for each specific unit process. The aim of the food processing industry is not to produce energy products and potato peels themselves are often not an energy product. If energy allocation were applied to the potato industry, the impact of the potato by-products would have been distorted; they would be approximately the same as for the potato food products because of the similar LHV. From Section 4.1, it is observed that the allocation factor is very sensitive to the climate change impact. In reality, the potato by-products represent a negligible fraction of economic revenues (1%) for the potato industry. The (very) low economic value of potato peels needs to be reflected in the allocation in such an LCA. Under these circumstances, the allocation rules defined by RED II does not work.

According to RED II, no impact was apportioned to carbon dioxide, which has no LHV. However, carbon dioxide is the main product in both terms of physical (mass) and economic significance of the swing adsorption process. So, it would have been unfair to use energy allocation and apportion all impact of the swing adsorption unit to hydrogen (which is the only product with LHV). Moreover, hydrogen has a very high energy value and economic value compared to its mass. This aspect would have not been reflected by mass allocation.

5.3. Food processing by-product as feedstock for energy production

Potatoes are the fourth most consumed crop worldwide (Pathak et al., 2018). As mentioned in Section 2.3.1, 20% of the processed potatoes become a by-product ("waste" if not sold to the animal feed industry), which can be converted into value-added products. Based on 2018 data (FAO, 2020), the Netherlands is the fourth country in EU28 for production quantity with more than 6000 kt/y of potatoes produced. Despite Germany produces the highest quantity in EU28 (almost 9000 kt/y), the Netherlands is a much smaller country and has the second-highest yield for potatoes in EU28 (FAO, 2020). For these reasons, the Netherlands can be considered the most interesting country for potato by-products. However, using all the 1000 kt/y of t of potato by-products (800 kt/y assumed in our baseline calculations) could allow to generate only 13.4 kt/y of bio-jet fuel via ABE fermentation. Considering that about 4000kt of jet-fuels are consumed per year by Dutch aviation (EUROSTAT, 2020a), only 0.3% of the Dutch demand for jet fuels could be satisfied using the investigated bio-jet fuel. Using also 1.5 Mt. of sugar beet, 1% of total demand could be reached. So, this novel bio-jet fuel cannot be considered a game-changer but a possible minor contribution to future aviation decarbonization. Moreover, potato by-products are currently sold to the animal feed industry and multiple other uses for bioenergy/chemicals are also investigated. Outside the EU, there are very few countries with higher availability of potato by-products. Among them, Ukraine with more than 22,500 kt/y of potatoes produced (FAO, 2020) could be an attractive country in terms of availability and to decrease the costs (from feedstock price to labor cost).

5.4. Future perspective towards 2030

For the investigated fuel, room for improvement is still needed to fulfill the EU 65% GHG savings requirement. Given the scope of 2030, some options that could be also combined are the use of renewable electricity, blue/green hydrogen for hydrotreatment and storing the biogenic carbon dioxide separated by swing adsorption. The impact of blue hydrogen from natural gas calculated with an attributional approach is between 2.6 and 5.8 kg CO_2eq per kg of hydrogen depending on the production and type of carbon capture process (Antonini et al., 2020). The impact of blue hydrogen is 40–70% lower than hydrogen produced using steam reforming of natural gas assumed. This decrease of impact makes hydrogen from natural gas with carbon capture on par with green hydrogen produced using renewable electricity (Antonini et al., 2020), which is also an option for the future. Using blue or green hydrogen could therefore lead to about 10% reduction of the carbon footprint of the bio-jet fuel produced with the decentralized configuration. Moreover, in the centralized configuration, improvements in the carbon footprint (further 2%) can be also achieved using renewable electricity (assumed photovoltaics in the Netherlands) for the swing adsorption process. A further 10% decrease in carbon footprint can be achieved in all options using green electricity for pervaporation (and another 2–3% if green electricity is used for the potato processing industry). On the other hand, MFSPs could increase using low carbon process electricity or hydrogen. Another aspect that was not considered is that the carbon dioxide separated (2.4–2.6 t of carbon dioxide per t of bio-jet fuel produced) and assumed to be sold to Dutch greenhouses is biogenic and might have a much higher market price than assumed (the same applies to the surplus of bio-based hydrogen); or could it be stored and credited as negative emission if permanently stored (at net of the climate change impact allocated to the separated carbon dioxide, the credit would be up to 50 gCO_2eq per MJ of bio-jet fuel produced), compensating (almost or in total) the climate change impact generated by the production of the fuel. Of course, also the oil refinery industry is expected to benefit from future technological improvements such as carbon capture. Near future improvements could potentially decrease refining carbon emissions by about 10% (Zhao et al., 2020). On the other hand, 80% of the carbon footprint of conventional jet fuels is caused by their combustion emissions (Moretti et al., 2017). So, the effects of the decarbonization of the oil refining industry on the overall carbon footprint of jet fuel will be less significant.

6. Conclusions

The results of this study indicated that, in the Netherlands, the minimum fuel selling price (MFSP) of bio-jet fuel produced via ABE fermentation using potato by-products or sugar beet is about double compared to currently commercialized bio-jet fuels (HEFA) and of the same order of other alcohol-to-jet fuel routes.

For both the feedstocks analyzed, the centralized systems are less expensive (about 30% lower in MFSP) compared to the decentralized systems. The techno-economic analysis showed that the MFSP can be decreased by increasing the yield of the ABE fermentation so that the feedstock requirement can be reduced. The fermentation yield improvement can lead to up to a 5% decrease in MFSP in the case of potato by-products and up to 23% for sugar beet. The MFSP can also be decreased (order of 10%) by increasing the capacity of the plant components trying to collect as much feedstock as possible. Furthermore, a less expensive fermenter can decrease the MFSP of the bio-jet fuel by another 5–10%. Moreover, if the price of sugar beet continued to drop in the next years, the centralized configuration might reach a price that is competitive with HEFA.

The jet fuels made from potato by-products were identified as the preferred option in terms of the wheel-to-tank emissions (43–45 gCO_2eq per MJ of bio-jet fuel). When sugar beet is used, the climate change impact is 16% higher compared to the potato by-product systems mainly because of the difference in the impact of the feedstock used. For the jet fuels made from sugar beets, the impact of cultivating sugar beet is mainly (59%) caused by the high amount of direct emissions of dinitrogen monoxide released to air due to the use of fertilizers, manure and crop residues. Beyond the high direct emissions of dinitrogen monoxide, the main reason for the higher impact for the fuel produced from sugar beet compared to potato by-products is the fact that all impact caused by cultivation is entirely assigned to sugar beet because it is a dedicated crop.

Overall, for both feedstocks, the centralized option resulted in being preferable to the decentralized one from both environmental and economic perspectives since 1) it allows to recover hydrogen and carbon dioxide produced by ABE fermentation and 2) relies on a single fermentation unit of larger size, which decreases the CAPEX.

Depending on the feedstock considered, this fuel could offer 41–52% GHG emissions savings compared to petrochemical kerosene. Given the scope of 2030, decarbonization practices such as using renewable electricity and blue/green hydrogen could allow to achieve the RED II target of 65% GHG emissions savings. If possible, storing the biogenic carbon dioxide from ABE fermentation could also further increase the GHG emissions savings and potentially lead to net-zero carbon emissions. Beyond high costs, as for other bio-jet fuels investigated in the literature, the main bottleneck to become an important environmental game changer is the availability of the feedstock limiting the production volume.

CRediT authorship contribution statement

Christian Moretti: Conceptualization, Methodology, Software, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Ana López-Contreras:** Data curation, Investigation, Visualization, Funding acquisition, Project administration, Writing – original draft, Writing – review & editing. **Truus de Vrije:** Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Axel Kraft:** Methodology, Data curation, Formal analysis, Investigation, Writing – review & editing. **Martin Junginger:** Conceptualization, Data curation, Supervision, Funding acquisition, Resources, Writing – review & editing. **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.

Acknowledgement

This work is financially supported by the Dutch Ministry of Economy Affairs and Climate Policy through the TKI-BBEG program (grant: TEBE116223). We would like to thank all our project partners.

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