Aviation biofuels: an economic and environmental assessment with an outlook on cost reduction potentials

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Abstract

The global awareness to reduce greenhouse gas (GHG) emissions from aviation and thereby make the overall aviation sector more environmentally friendly has increased in recent years. In this context, one main driver is seen in the development of advanced renewable jet fuels for aviation, which have already been used for some regular flights by various air carrier.

Therefore, this paper compares four different production processes for biokerosene located in northern Germany, investigating two different types of biomass feedstock for each process. These conversion processes are then assessed in terms of technical, economic and environmental criteria based on data retrieved from an extensive process simulation. Main outcome of this analysis are mass and energy balances, kerosene production costs and GHG emissions for the investigated conversion routes, including a rough analysis of future cost reduction potentials.

The results of the investigated criteria are scattering significantly; i.e. no "silver bulled" can be seen based on these findings. Nevertheless, the significant influence of the provision of the biomass feedstock becomes obvious. Generally spoken the more environmentally sound and economic viable the feedstock provision can be realized, the more promising is the resulting biokerosene related to the economic and environmental criteria assessed here. This result is more or less independent from the respective conversion route.

1. Introduction:

Today the aviation industry is emitting about 820 million tCO_2/a representing a total share of 2.5 % of the global CO_2 emissions [1]. These emissions are most likely to increase in the years to come, since the ascending living standards in emerging countries like China, India and Brazil (and thus the accelerating travel activities) as well as the strongly rising world trade flows will induce even more and longer flight operations per year. With regard to this development, the international aviation industry has developed a challenging self-commitment related to the further development of global CO_2 emissions from civil aviation. This includes a carbon neutral growth starting from 2020 leading to CO_2 emission reductions by 50 % in 2050 related to the year 2005 [2]. These ambitious goals have to be realized via more efficient aircrafts, optimized flight operations (e.g. single European sky) and renewable aviation fuels with a significantly reduced carbon footprint. According to these goals the largest CO_2 emission reduction is expected to be realized based on the market introduction of advanced bio- and/or power fuels for aviation.

Today civil aviation depends basically fully on Jet A-1 (kerosene) produced from crude oil. While for land transportation various alternative options are possible and partly already market mature from a technical point of view (e.g. biofuels, e-mobility, hydrogen and fuel cells, switch to rail roads and/or water ways) this is not the case for aviation (in a large scale) yet. Here research has just recently started to develop alternatives. These activities focus mainly on the development of the provision of alternative aviation fuels with low GHG emissions fulfilling the Jet A-1 specifications (so-called "drop-in" fuels). So far, most of these activities are strongly dedicated to fuels based on biogenic feedstock; but some early activities are carried out to use CO_2 (e.g. extracted from air) and electricity from renewable sources of energy for the provision of a synthetic kerosene (power to liquid (PtL) fuels).

The reason for this strong focus is that civil airplanes in commercial use today are usually operated with Jet A-1 kerosene and that their average technical lifetime is approximately 25 years and longer. Additionally, fuels used within airplanes should have a high energy density to minimize the necessary volume needed to operate a long-haulflight and a good combustion quality to allow for a highly efficient use. Beside this they should be characterized by a widespread or even global availability, fulfill numerous safety requirements, and have to be transported, stored and pumped easily. Kerosene resp. Jet A-1 fulfills all these requirements. Thus it is most likely that this fuel will stay in place also in the years to come especially due to the fact that the fuel characteristics of Jet A-1 are well adapted to the demands of an airplane turbine as well as the harsh conditions during a long distance flight roughly 10,000 m above ground.

So far, numerous options to produce kerosene from organic matter (i.e. biomass) have been and still are under investigation globally (see also [3]). Among these various options, no silver bullet has been identified for the time being. To get a better understanding of the various conversion processes, four conversion routes have been analyzed in more detail, regarding technical, economic and environmental criteria. Therefore a detailed process modelling simulation of these various processes is realized. Based on these results an overall economic assessment following the annuity method as well as a life cycle assessment (LCA) is conducted. Additionally cost reduction potentials are analyzed by extrapolating the process efficiency as well as the equipment cost reduction due to a large scale application to the medium (2030) and long-term future (2045). The results, i.e. mainly the kerosene production costs and the GHG emissions within the overall life cycle, are then compared to each other and to a fossil reference to draw some conclusions.

2. Concept and methodology:

The overall conceptual process designs for the four investigated process routes are given in Fig. 1 to 4 (see also [4] for more details on the process design). In the following section the main input parameters, as well as the applied methodology will be given.

The four different processes in combination with the two different feedstock given below, whereby the acronym for each combination will also be used in the following sections (see also Fig. 1 to 4).

AtJ-WS: Alcohol-to-Jet using wheat straw

AtJ-WG: Alcohol-to-Jet using wheat grains

Bio-GtL-SM: Biogas-to-Liquids using biogas produced from the German product mix

Bio-GtL-Ma: Biogas-to-Liquids using biogas produced from manure

BtL-WS: Biomass-to-Liquids using wheat straw

BtL-Wi: Biomass-to-Liquids using willow wood chips from short rotaition coppice

HEFA-JO: Hydrogenated Esters and Fatty Acids using jatropha oil

HEFA-PO: Hydrogenated Esters and Fatty Acids using palm oil

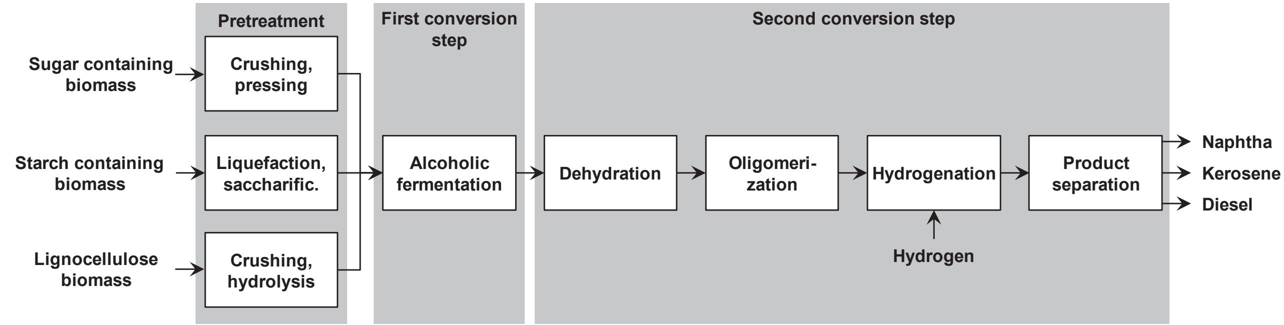

Fig.1 Process conversion chain for an alcohol-to-jet (AtJ) process

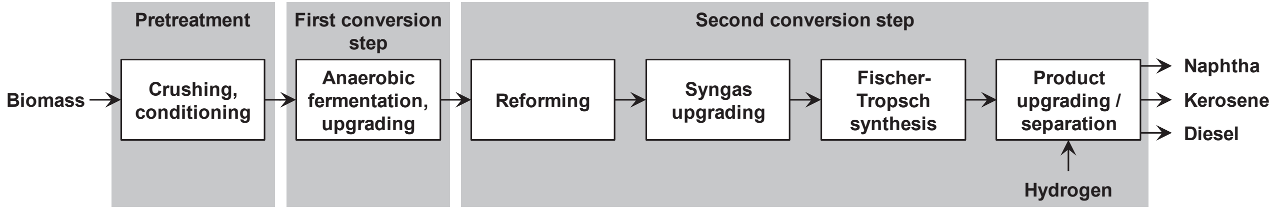

Fig.2 Process conversion chain for a biogas-to-liquids (Bio-GtL) process

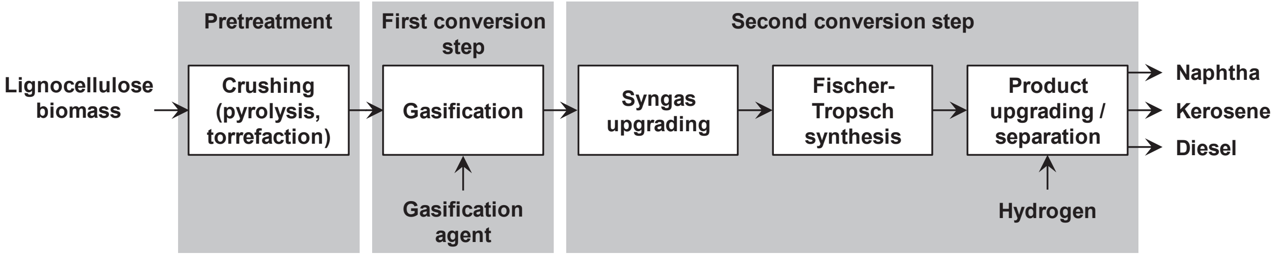

Fig.3 Process conversion chain for a biomass-to-liquids (BtL) process

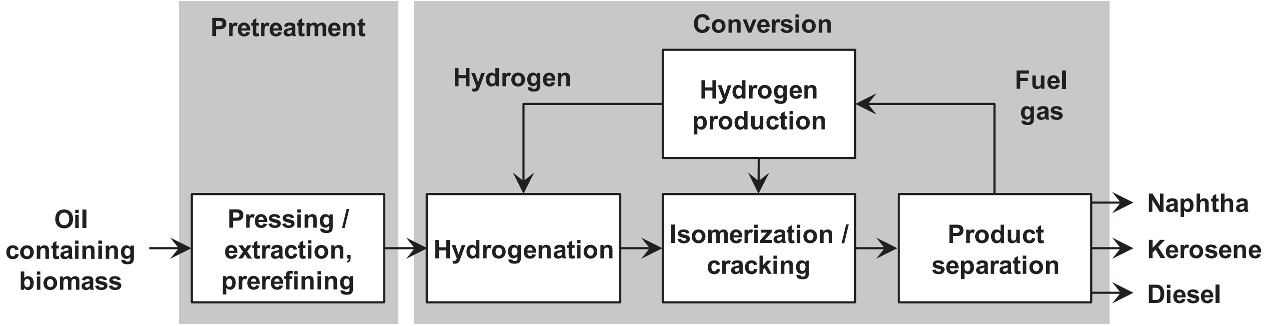

Fig.4 Process conversion chain for a hydrogenated esters and fatty acids (HEFA) process

All process concepts are designed with an annual production capacity of 800 000 t/a of liquid products and include a decentralized biomass pretreatment to increase the energy density of the feedstock and thereby decrease the transportation intensity. This includes the production of isobutanol via a fermentation process for AtJ, biomethane production via anaerobic digestions for Bio-GtL, pyrolysis respectively torrefaction for BtL and vegetable oil pre-refining for the HEFA concepts (see [4] for a detailed concept description). The conversion plants as well as all pretreatment steps are located and operated in northern Germany, next to a port. The same is true for the biomass cultivation; the only exception are jatropha and palm oil, which are imported from Mozambique resp. Malaysia via ship

For the techno-economic analysis, mass and energy balances of all processes have to be provided. This is done by modelling and simulating all processes in Aspen Plus V8.6 [5]. Heat integration was carried out via pinch analysis using the Aspen Energy Analyzer V8.6 [6]. Details about the included methodology, simulation structure and databases of Aspen can be found in the respective manuals. Based on these results the overall process efficiency for each process is calculated using Eq. 1.

$$\eta_{tot} = \frac{\sum \dot{W}_{Products} + P_{el}}{\sum \dot{W}_{Educts} + P_{el,own}} \qquad \text{Eq. 1}$$

with	η_{tot}	Overall process efficiency
	$\sum \dot{W}_{Products}$	Sum of product energy flows
	P_{el}	Generated electrical power
	$\sum \dot{W}_{Products}$	Sum of educt energy flows
	$P_{el,own}$	Consumed electrical power

All investigated conversion plants have been modelled and assessed using the n^{th} plant theory. According to this theory, plant economics are to be interpreted as the costs for a commercial scaled technology. That implies that several commercial plants have been built and are operational; i.e. the overall conversion pathway is market mature. This allows a fair comparison of technologies from different development stages. The economic analysis is based on the annuity method, following [7] and using the general assumptions giving in Table 1. All costs are calculated for the year 2017, using the chemical engineering plant cost index (CEPCI) for annualization [8].

Parameter	Unit	Value
Base year	-	2017
Plant availability	h/a	7 500
Plant lifetime	a	20
Rate of interest	%	4

Tab.1: Overall financial frame assumptions

Biomass prices are based on published data including all aspects of the feedstock provision. The assumed prices are given in Table 2. Prices for all other auxiliary material or energy flows (e.g. process water, chemical and bio-catalysts as well as electricity) included in the calculations are given in [4].

Parameter	Price	Source
Biomethane from grid	0.070 €/kWh resp. 913 €/t	[9]
Biomethane from manure	0.055 €/kWh resp. 717 €/t	[9]
Jatropha oil	1 250.0 €/t	[10]
Palm oil	639.9 €/t	[11]
Wheat grain	160.0 €/t	[12]
Willow wood chips	50.0 €/t	[13]
Straw	85.0 €/t	[14]

Tab.2: Assumed feedstock prices

To give a rough overview of the potential future cost reduction potential of the investigated production routes results of the techno-economic assessment are extrapolated to the near future (2030 and 2045. Therefore the result of the technical assessment, i.e. the calculated process efficiency is extrapolated following a saturation model, based on research and industry developments. In a second step the potential cost reduction due to learning and scaling effects is calculated using learning curves based on comparable process developments, leading to reduced capital costs. The described approach is visualized Figure 1.

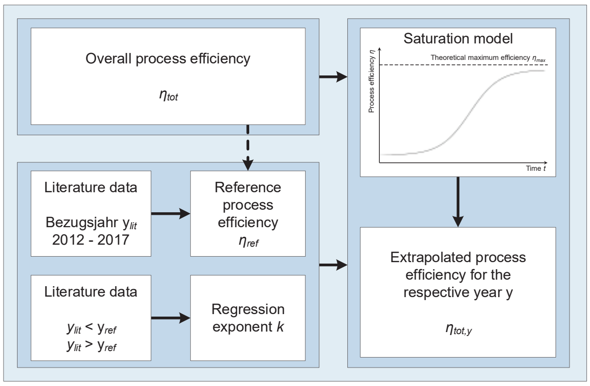

Fig.1: Methodological approach for the technical process extrapolation

Based on this approach, the results of the process assessment for the year 2017 can be extrapolated to 2030 and 2045 using Eq. 2. The respective regression exponent is calculated according to Eq. 3 and Eq. 4 according to the base year of the comparative literature case

$$\eta_{tot,y} = \eta_{max} - (\eta_{max} - \eta_{ref}) \cdot e^{-k\cdot(y-y_{ref})} \qquad \text{Eq. 2}$$

with		
	$\eta_{tot,y}$	Extrapolated process efficiency for the respective year
	η_{max}	Theoretical maximum efficiency
	η_{ref}	Process efficiency for the reference year
	k	Regression exponent
	y	Extrapolated year
	y_{ref}	Reference year

$$k = \frac{-1}{y_{ref} - y_{lit}} \cdot ln\left(\frac{\eta_{max} - \eta_{ref,m}}{\eta_{max} - \eta_{lit}}\right), \quad y_{lit} < y_{ref} \qquad \text{Eq. 3}$$

$$k = \frac{-1}{y_{lit} - y_{ref}} \cdot ln\left(\frac{\eta_{max} - \eta_{lit}}{\eta_{max} - \eta_{ref,m}}\right), \quad y_{lit} > y_{ref} \qquad \text{Eq. 4}$$

with		
	y_{ref}	Reference year
	y_{lit}	Base year of the literature source
	η_{max}	Theoretical maximum efficiency
	$\eta_{ref,m}$	Mean reference efficiency
	η_{lit}	Efficiency of the literature source

The detailed applied methodology is described in [4].

To determine the GHG emissions of the different processes a lifecycle analysis (LCA) of the overall conversion process is conducted. Following the common procedure within such an LCA defined by the International Organization for Standardization different alternatives of a product or service can be compared related to their environmental impacts [15, 16]. This includes the conversion or production process as well as the respective pre-chains (e.g. biomass cultivation and transportation); additionally, recycling processes are taken into consideration if they are realized. For such a total product life cycle the terminology "from cradle to grave" is widely used.

Therefore, the system boundary includes the cultivation of the feedstock, its transportation, all pretreatment and conversions steps as well as the distribution and use of the final product (see Figure 2). The respective biokerosene production plant is located in Germany, the functional unit all upstream emissions are related to is 1 MJ kerosene. The overall emissions assessed here are allocated; i.e. they are subdivided on the main product kerosene and all other byproducts on an energy basis.

For calculation the environmental impacts of the pre-chains prior to the biokerosene production data from the ecoinvent database V3.5 is used [17]. Additional data from [18] was used for enzyme production, from [19] for alpha and gluco-amylase production and from [20] for jatropha cultivation and oil prerefining. The catalyst production has not been included in the inventory analysis, since information about the detailed composition of the catalyst material is not available due to IP reasons.

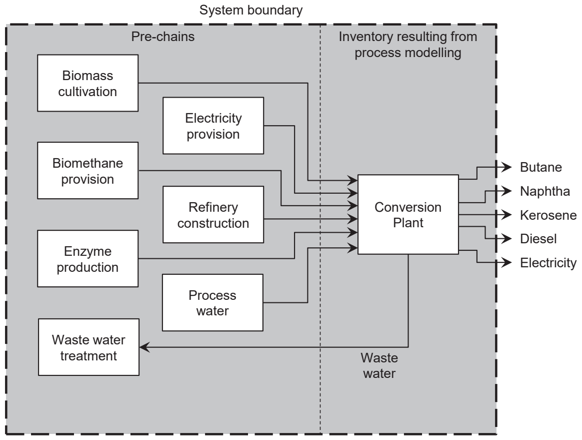

Fig.2: System boundary for the life cycle assessment

During the impact assessment, the results from the inventory analysis are allocated to different impact categories. Here the impact category "global warming potential" with a time scope of 100 years (GWP100) is applied, using the ReCiPe 2016 Midpoint (H) method [21]. The results for the different biofuels are compared to the fossil reference defined by the European Renewable Energy Directive II (EU RED II) of 94.0 g_{CO2eq}/MJ [22].

3. Results and discussion

The results based on the process modeling of the four investigated processes are discussed below. This includes the general mass and energy balances for each process, the overall costs related to the defined calculation method leading to the biokerosene production costs as well as the CO_{2eq} emissions resulting from the life cycle analysis performed according to the frame conditions and methodology defined above. Additionally the cost reduction potential for the years 2030 and 2045 due to the process extrapolation is discussed briefly.

The mass flow of the main input and output parameters as well as the related energy flows and the resulting process efficiencies calculated via the lower heating value are shown in Table 3. The overall mass flow of the kerosene fraction shows the lowest values for the Fischer-Tropsch processes (i.e. Bio-GtL and BtL) with approx. 58 to 60 t/h followed by the AtJ route resulting in a kerosene production of approx. 66 t/h and the HEFA option with the highest kerosene mass fraction of approx. 72 t/h.

In terms of energy efficiency the results show a much higher deviation. Again the HEFA processes show the highest overall efficiencies of 90 to 91 % as well as a kerosene efficiency of 58 to 60 %.

All other processes are characterized by significantly lower values, starting with the Bio-GtL route (with 57 % resp. 26 %) followed by the AtJ-WG process showing an overall efficiency of 53 % and a kerosene specific efficiency of 32 %. The three process alternatives using lignocellulosic feedstock (i.e. AtJ-WS and both BtL concepts) are characterized by the lowest energy efficiencies; the overall efficiency ranges from 35 to 38 % and the kerosene efficiency varies between 19 and 24 %. The comparatively low process efficiencies regarding the BtL concepts is mainly related to the high energy demand of the air separation unit, needed to provide pure oxygen as gasification agent, significantly reducing the overall efficiency.

All in all it can be said, that the more the natural synthesis performance (by the different plants) can be used, the higher is the overall processes efficiency. E.g. the chain length of vegetable oils and the one of kerosene are relatively close to each other. As a result, only minor modifications in the biopolymers are necessary and a large part of the vegetable oil molecules synthesized by the plants is found almost unchanged in the fuel. This leads to the high overall efficiencies of HEFA the concepts. If, on the other hand, the biopolymers of the biomass are initially decomposed thermally into very small molecules (hydrogen and carbon monoxide) in order to then be reassembled with the appropriate technical effort to the desired fuel molecules, this leads to lower overall efficiencies, as e.g. in the BtL process.

Based on the process simulation results stated above the various process routes can be analyzed economically. The results of this economic assessment are presented in Figure 3. All details regarding the calculation of the equipment costs can be found in [4]. Following these data large variations can be seen, with the largest bandwidth in terms of total investment costs as well as operation-linked costs.

	AtJ		**Bio-GtL**	**BtL**		**HEFA**	
	AtJ-WS	**AtJ-WG**		**BtL-WS**	**BtL-Wi**	**HEFA-JO**	**HEFA-PO**
Mass flow [kg/h]							
Feedstock	-675 000	-510 000	-204 900	-875 000	-650 000	-127 500	-129 000
Methane[a]	-5 104	-5 179	0	0	0	-11 398	-10 340
Butane/Naphtha	9 317	9 405	25 478	25 269	24 916	27 322	27 323
Kerosene	66 208	66 628	59 359	58 806	57 663	69 666	71 863
Diesel	31 725	32 186	22 190	23 569	23 122	9 676	7 481
Energy flow [MW]							
Feedstock	-3 300	-2 414	-2 676	-3 636	-3 233	-1 322	-1 333
Methane[a]	-67	-68	0	0	0	-149	-135
Electricity[b]	-17	-13	-83	-132	-152	-7	-8
Electricity[c]	0	0	260	0	0	19	25
Butane/Naphtha	112	113	309	306	302	338	338
Kerosene	797	809	729	723	709	855	882
Diesel	385	391	271	288	282	118	91
Energy efficiency [%]							
Overall process	38	53	57	35	38	90	91
Kerosene fraction	24	32	26	19	21	58	60

[a]: Methane is used for hydrogen production via steam methane reforming

[b]: Gross electricity consumption of the conversion process

[c]: Electricity production due to implementation of excess process heat in a steam power process

Tab.3: Mass and energy flows as well as resulting energy efficiencies for the investigated conversion routes (Negative values are related to input parameters, positive values are output parameters)

This is especially true for the biokerosene production costs for the different processes as well as for the same process with a different feedstock.

- The highest production costs are calculated for both Bio-GtL processes, resulting in 2 854 €/t for the Bio-GtL-GSM concept and 2 178 €/t for Bio-GtL-Ma under the given constraints and assumptions.
- The lowest production costs could be achieved with the HEFA-PO, the BtL-Wi and the AtJ-WS process, resulting in 978 €/t, 992 €/t and 1 016 €/t, respectively.
- The AtJ-WG route results in production costs of 1 249 €/t, more or less in the middle of the overall cost bandwidth calculated here.
- With costs of 1 687 €/t and 2 096 €/t for BtL-WS and HEFA-JO these options are located in the upper half of the cost bandwidth opened up by all investigated options

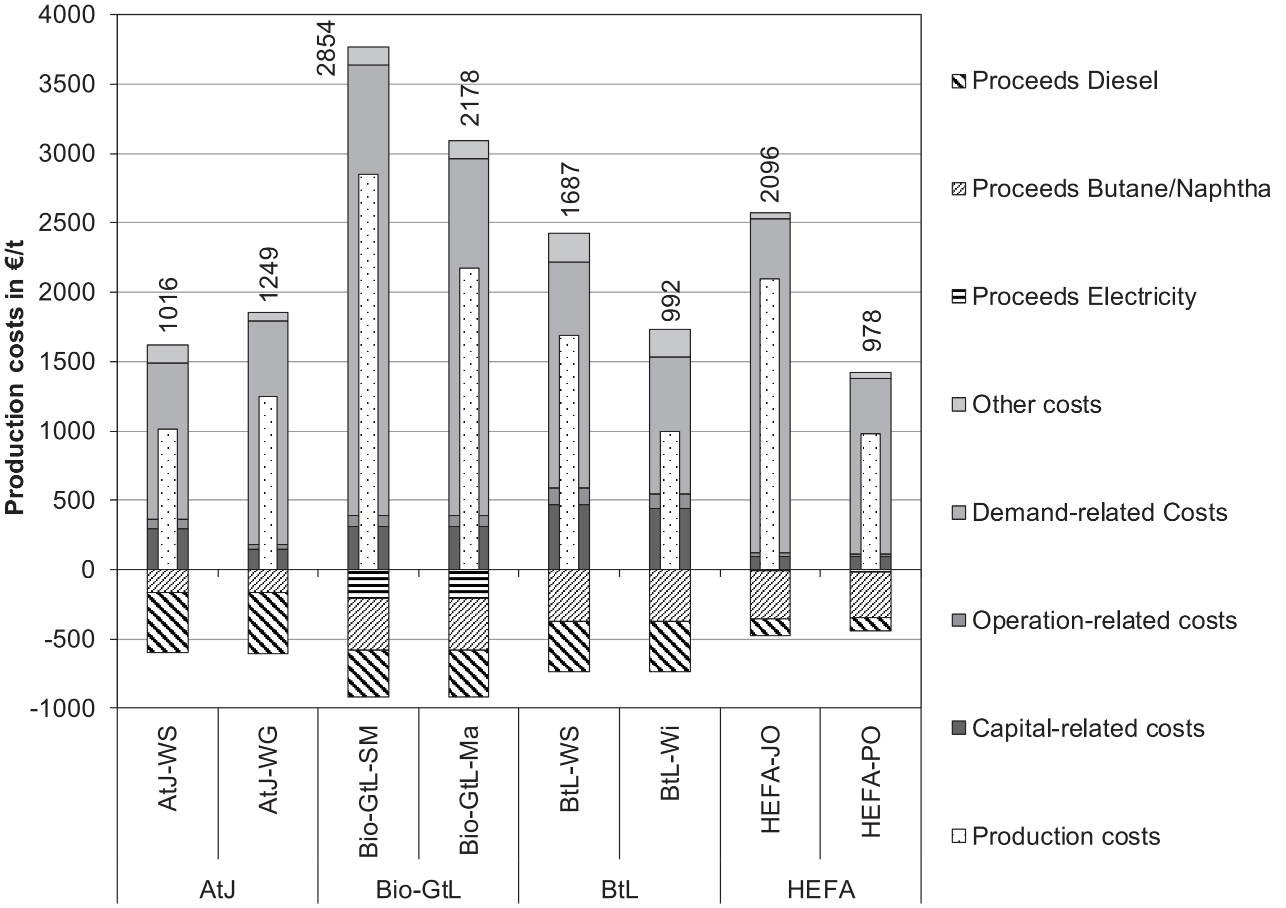

Fig.3: Production costs for the four different investigated biokerosene production routes with two different biomass resources for each route

Under the given assumptions and conversion routes none of the investigated pathways could produce biokerosene cost competitive to fossil kerosene with a price of roughly 560 €/t for the first half of 2019 [23]. Therefore, on the one hand side the production costs have to be reduced; the most important option to do so is to realize lower feedstock costs due to an optimized agricultural production. On the other hand side, the price for fossil fuel might increase as it has been the case in the beginning of this century. Additionally and/or alternatively, compensation payments or penalties for CO_2 emissions from fossil fuel energy might be used to compensate at least a part of this considerable price gap.

In comparison to the cost analysis, the overall greenhouse gas (GHG) emissions for all investigated processes are given in Figure 4 and are discussed below.

Following these results the GHG emissions of the different production routes show a very broad bandwidth. For most processes the emissions from biomass cultivation dominate the overall GHG emissions; this is not true for the processes based on lignocellulosic biomass. Due to the optimized, decentralized biomass pretreatment emissions resulting from biomass or intermediate product transportation are rather low compared to previous calculations [24].

The lowest GHG emissions can be realized with the AtJ-WS concept, resulting in total emissions of roughly 17 $g_{CO2eq}/MJ_{Kerosene}$ or an emission reduction potential of roughly 80 % compared to the fossil reference. The BtL and HEFA concepts are related to GHG emissions between 28 and 38 $g_{CO2eq}/MJ_{Kerosene}$ respectively emission reductions between 60 and 70 %. The highest emissions are related to both Bio-GtL processes as well as the AtJ concept using wheat grains, only resulting in emission reductions between 10 and 32 %.

Huge deviations related to the emissions of the actual biofuel production, i. e. the conversion of the biomass into final fuels can be seen. Although the Bio-GtL processes show the highest overall emissions, the emissions related conversion process are marginal. Both AtJ and HEFA concepts show higher emissions for the conversion step, which are mainly related to the use of methane for hydrogen production via steam reforming. Again, the high electricity demand for the air separation unit included in the BtL concepts results in comparatively high emissions for the conversion step. These emissions may be reduced by using renewable electricity instead of grid electricity, as assumed for this analysis.

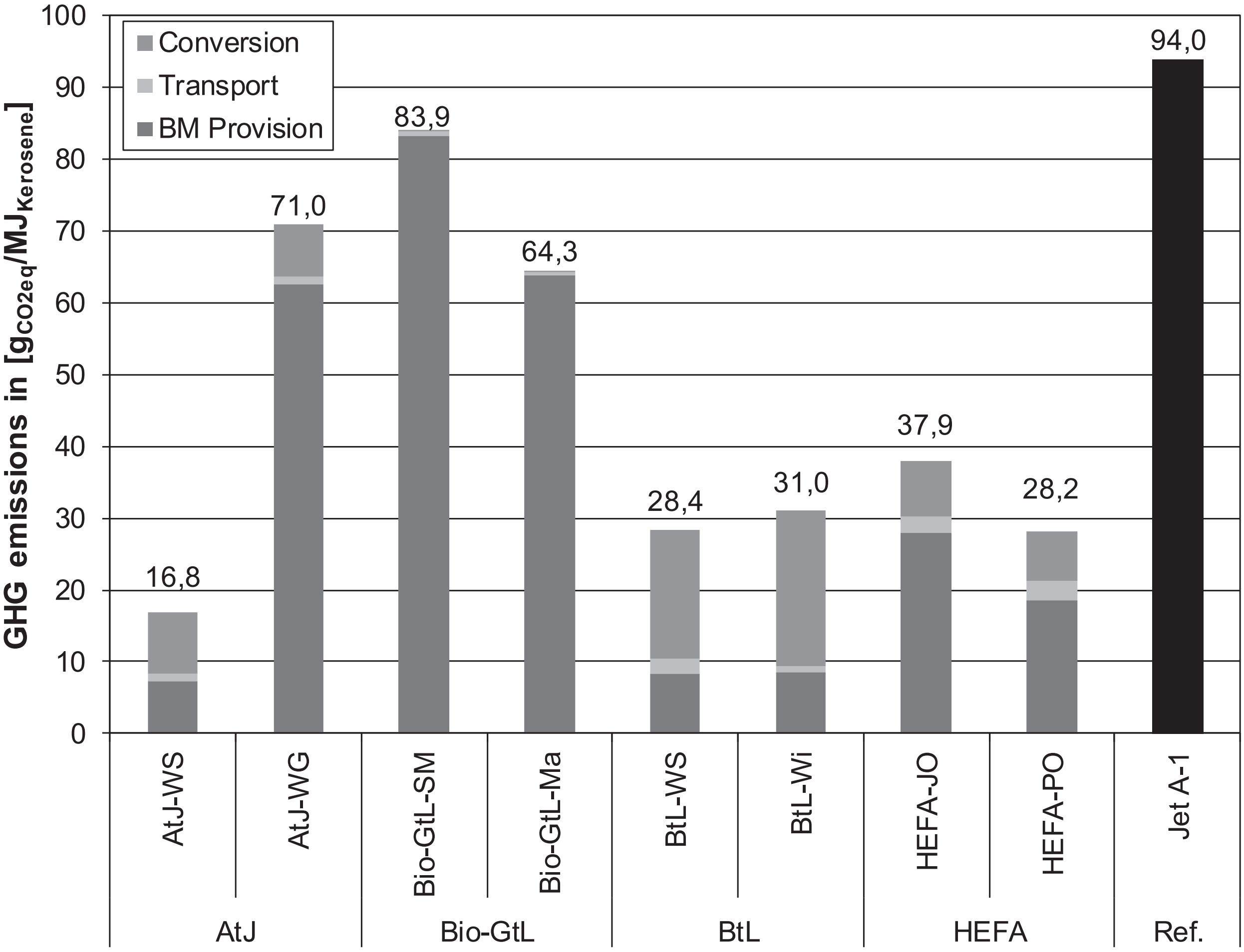

Fig.4: GHG emissions of the investigated biokerosene production routes in comparison to a fossil Jet A-1 reference (BM = biomass; fossil Jet A-1 reference according to the EU RED II [22])

Interpreting the GHG emissions one always has to keep in mind, that they result from a rather rough estimation of the overall life cycle emissions and might therefore be connected with high uncertainties. This is especially true for the comparatively good results of the HEFA processes, since the production of (especially tropical) vegetable oils like jatropha or palm oil might come in hand with land-use change (LUC) effects leading to much higher emissions than calculated here. As such effects are very sensitive to the related assumptions and may strongly vary for different plantation locations, they have not been investigated here in detail.

To give a rough estimation of the future development of the investigated processes, the potential cost reduction is shown in Figure 5, mainly resulting from two different effects, applied to estimate future developments. On the one hand side, a potential efficiency increase due to a large scale implementation of the production technology calculated following a saturation model including assumed increasing production capacities for the next years has been implied. Additionally equipment costs and thereby the overall investments might decrease due to learning effects coming along with the capacity build up, estimated by applying experience curves and the corresponding progress ratios.

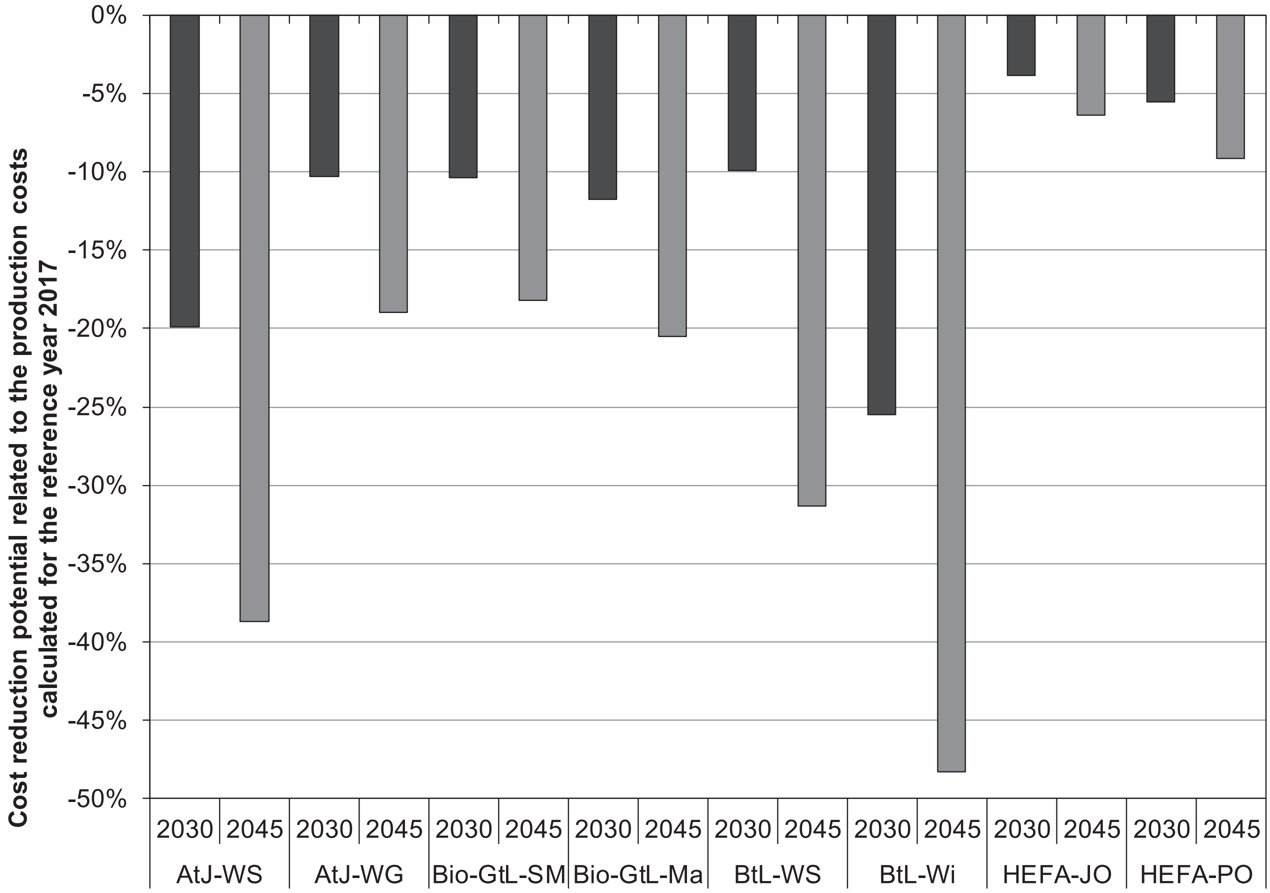

Fig.5: Relative cost reduction potential of the kerosene production costs related to the reference year 2017

Already in the medium term (2030), significant production cost reductions can be observed. The lowest cost reduction of approx. 4 % is calculated for the HEFA concept with jatropha oil (HEFA-JO), the highest reduction of approx. 25 % can be observed for the BtL process based on willow wood as raw material (BtL-Wi). The influence of the reduced investment becomes particularly clear in the case of the BtL processes, since they contribute to a higher share of the production costs than for the other concepts (see Figure 2).

For the long-term concepts (2045) an even greater reduction in production costs is to be expected. The lowest cost reductions of approx. 6 and 9 % respectively are expected for the HEFA concepts. This is due to the already very efficient conversion of raw materials and the comparatively low mass-based demand for raw materials. For the Bio-GtL processes, the cost reduction is calculated to be between 18 to 21 %. Depending on the feedstock and the combination with the corresponding pretreatment processes, the AtJ and BtL processes can result into significantly different reduction potentials.

For the AtJ process based on wheat grain (AtJ-WG) the predicted reduction is roughly 19 %, for the AtJ-WS concept, the kerosene production costs can be reduced by almost 40 %. Although the BtL process based on wheat straw (BtL-WS) is expected to show the lowest absolute costs by 2045, the relative cost reduction of 31 % is significantly lower than the expected reduction of 48 % for the BtL process using willow wood (BtL-Wi) as.

4. Conclusion and Outlook

The overall goal of this paper is to present an extensive assessment of different production pathways for biokerosene in terms of technical, economic and environmental aspects. Therefore, four different processes with two kinds of biogenic feedstock each have been modelled using a commercially available process simulation software. The results have been assessed based on the overall process efficiency (technical parameter), the biokerosene provision costs (economic parameter) and the GHG emissions occurring within the overall life cycle (environmental parameter). As an outlook, the production cost reduction potential has been investigated, based on a rough process extrapolation. The presented overall results show a broad variety for the different conversion routes and assessed criteria.

- In terms of energy efficiency the HEFA processes seem to have the best performance characteristics (91 % overall and 60 % kerosene efficiency). In addition, the HEFA process based on palm oil results in comparatively low production costs (978 €/t) and relatively low GHG emissions of 28 $gCO_{2eq}/MJ_{Kerosene}$. Nevertheless, it is most unlikely that large-scale palm oil production will be realized in an environmental friendly and sustainable way in the future since this would most likely lead to a clearing of virgin land to meet the increasing plant oil demand, which would be connected with LUC effects resulting in way higher GHG emissions.
- All processes based on lignocellulosic biomass (namely AtJ-WS and both BtL concepts) show good results from a GHG-reduction point of view (17 to 31 $gCO_{2eq}/MJ_{Kerosene}$). At least two of these process routes, namely BtL-Wi and AtJ-WS additionally result in comparatively low production costs (992 resp. 1 016 €/t). But they show rather poor energy efficiencies due to high losses during the overall conversion process induced by the manifold of chemical conversion reactions each characterized by obligatory losses.
- Considering the potential future cost reduction, except for the HEFA concepts all processes show a high reduction potential above 18 %. Again, the conversion routes using lignocellulosic biomass show the highest potential to be cost competitive in the near future, resulting into cost reductions roughly varying between 30 and 50 %.

Following these results, an ideal production process for biokerosene cannot be identified solely based on the assessed criteria. According to the current state, the combination of the AtJ process with straw and the BtL process with willow wood and thus two processes using lignocellulosic biomass as feedstock seem to have the greatest economic potential. Thus, in the future, kerosene might be produced at almost the same cost using two different processes with different and thus non-competitive raw materials under the given assumptions, which can have a positive effect on the market stability. However, this is always strongly linked to the actual local raw material availability and further (partly political) framework conditions.

For all processes, the selected raw materials determine the results of the assessed criteria. This applies to the technical efficiency of the different conversion processes, to the great influence of raw material costs on the kerosene production costs as well as on the GHG emissions related to the fuel production. This is due to the different characteristics, growing conditions, and the logistical challenges for the provision of biomass. Therefore, sustainable and efficient biomass provision is essential for the cost-effective production of biofuels.

Under current regulatory conditions, the use of biokerosene in aviation does not seem realistic from an economic point of view. In addition, if a reduction in greenhouse gas emissions from aviation is desired, appropriate framework conditions must be enacted to create an economic incentive for the use of biokerosene in order to make it competitive with fossil kerosene.

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