SWAFEA

Environmental impact analysis report

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SUMMARY

Context

From a European perspective, the reduction of Green House Gas emissions is a major driver for the introduction of alternative fuels in aviation. The continuous traffic growth, with its inevitable increase of emissions, leads to consider the contribution of aviation to the 10% target of renewable energy in transport set by the Renewable Energy Directive (RED) for 2020. Furthermore, aviation will be integrated in the Emission Trading Scheme (ETS) in 2012 which could be an incentive for the introduction of fuels with reduced carbon impact such as biofuels. The aviation community also calls for a reduction of the sector emissions with the IATA aspirational target of dividing by two the emissions level in 2050 compared to 2005, a target which requires the use of biofuels.

Regulations introduced in Europe (RED), but also in the United States of America (EISA[1]), to promote the use of renewable energies have defined thresholds for GHG emissions reductions that should be achieved by biofuels. In Europe the threshold is a reduction of 60% from 2018. Those regulations in addition define sustainability criteria that biofuels should respect, duties being placed on the producer to demonstrate their compliance.

In parallel, numerous initiatives are actively working on sustainability frameworks and certification schemes. Among others, the Round table for Sustainable Biofuels (RSB) receives a strong adhesion from the aviation community and has developed a complete set of sustainability criteria. The International Sustainability and Carbon Certification System (ISCC) is another initiative that has been recognised by Germany, the first European country to transpose the RED into its national laws.

Scope of the analysis

Sustainability of alternative fuels in aviation has been studied from two separate points of view:

- The assessment of environmental impacts and sustainability aspects of the fuel production and distribution, which is the "Well To Tank" or "Field to Tank" part of the sustainability assessment;
- The analysis of the specific atmospheric impacts of aviation, especially because of the particular altitude at which aviation's emissions take place.

For the "field to tank" part, considering the critical importance of GHG emissions in the selection of an alternative fuel[2], the focus has been mainly put on biofuels for which a much wider scope of parameters also enters in the sustainability assessment. The analysis covers the "sustainable"

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[1] Energy Independence and Security Act

[2] From the preliminary State of the Art performed in SWAFEA, fossil based alternative fuels didn't offer potential for GHG emissions reductions.

availability of the biomass for the biofuels production, their Life Cycle Analysis and a review of their other environmental and societal impacts.

For the atmospheric impacts of aviation's emissions, the analysis addresses both local air quality around airports and the more global impacts on high atmosphere through contrails formation or ozone balance modifications.

Biomass availability for biojetfuel production

The two current leading processes for biojetfuel production, the Fischer-Tropsch synthesis and the hydroprocessing of oil or fats, allow the use of a very wide scope of feedstocks including lignocellulose crops, oil seeds, forestry and residues biomass or more futuristic algae. The availability of these feedstocks has been assessed by production sectors: agriculture, forestry, residues and waste, and algae which involve completely different ways of cultivation. A proper study has been carried out for agriculture resources while figures for the other sources stem from a literature review.

The biomass availability is assessed against the global energy demand as projected by the International Energy Agency[3] and against the aviation demand. Two aspirational scenarios have been considered: a carbon neutral growth of aviation from 2030 at the emissions level of 2020, and the more ambitious IATA target of a 50% reduction of the emissions in 2050 compared to 2005. A preliminary remark is that both targets represent an enormous challenge. Limiting aviation to its emission level of 2020 from 2030 implies a very strong ramp-up of biofuels production by 2030 to provide, only for aviation, the equivalent of 170% of the current total biofuel production, meaning 31% of the biofuels production projected by IEA at that time in its Scenario 450[4].

A conservative approach has been retained to assess biomass availability. The highest technological scenario was not selected for agriculture production and the lower bound of evaluations ranges was chosen for forestry and residues. For agriculture, priority was given to food security, energy crops (including lignocellulose and oil seeds) being only considered on remaining croplands and grazing lands. Sustainability constraints were also introduced: only perennial crops were considered on grazing lands, 30% of which were preserved as grazing land, deforestation being excluded.

The largest contributor to energy biomass is by far agriculture. Forestry biomass presents a potential from a technical point of view, but the introduction of economical or ecological constraints can annihilate it, even leading to a shortage of wood for industry and woodfuel.

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[3] World Energy Ooutlook 2009

[4] Voluntary scenario to limit CO_2 content of the atmosphere to 450 ppm and temperature increase to 2°C.

		Reference Scenario		Scenario 450	Blue Map Scenario
EJ/year	2009	2030	2050	2030	2050
Primary energy demand	502	705	977	604	750
Primary biomass demand	*51*	67	90	82	150
Biomass share	10%	10%	9%	14%	20%
Final energy demand	347	482	664	427	443
Transport final energy demand	95	140	204	126	112
Biofuels demand in transport	2.2	5.6	4.5	11.7	29.1
Share of biofuels in transport	2%	4%	2%	9%	26%

Projection of energy demand

Reference scenario: continuation of present policies

Scenario 450: voluntary scenario limiting CO_2 in the atmosphere to 450 ppm and temperature increase to 2℃

Blue Map: scenario reducing emission by 50% in 2050 compared to current levels

EJ/year	2010	2030	2050
Total final energy consumption	8.6	14.7	24.4
"IATA carbon neutral growth" from 2030			
Biojet consumption	0	4.6	16.7
Biojet share	0.0%	31.3%	68.4%
IATA 50% reduction target in 2050			
Biojet consumption	0	4.6	24.4
Biojet share	0.0%	31.3%	100.0%

Projection of aviation energy demand

(Assuming life cycle emissions reduction of 80% for biofuels)

EJ/y	Agriculture	Forestry	Residues	Total
Primary energy	162.2	4.6	16.6	183.4

Total biomass primary energy potential in 2050

Compared to the primary energy demand, the biomass potential represents 18.8% of the total demand in the reference scenario, and 24.5% of the aggressive "Blue Map" scenario. This is a significant percentage which nevertheless evidences the strong need for other energy sources. In the same time the biomass contribution to the global energy mix projected in the IEA's Blue Map scenario is not so far from the total biomass potential assessed in our study.

If fully converted into biofuel, assuming BTL process and oils hydroprocesssing, this biomass can produce about 112 EJ/y of final energy, which represents 16.9% of the final energy total demand of the reference scenario, and 25% of the Blue Map's one. This potential biofuel production covers the total transport final energy demand of this second scenario, and is significantly higher than the contribution of 29 EJ/y projected by IEA for biofuel in transport.

From the 112 EJ/y of biofuels, up to 32 EJ/y can be jet fuel if jet fuel is targeted in priority in oils hydroprocessing. These figures have to be compared with the jet fuel demand ranging from 16.7 EJ/y for the carbon neutral growth scenario, and 24.4 EJ/y for the 50% emissions reduction target, when a 80% "carbon intensity" is assumed for biofuels[5], which is already an aggressive value with view to the results of the life cycle analysis.

Finally with this 80% biofuels "carbon intensity" assumption, reaching the 50% emissions reduction in 2050 would mean to use about 76% of the total biomass potential to make biofuels.

In such a scheme, 24.4 EJ/y of jet fuel would lead to the production of 61 EJ/y of co-produced non jet fuels, nearly the double of the projected biofuel contribution in transport of the IEA's Blue Map scenario. More generally, using the BTL conversion ratio, the Blue Map scenario projects only the use of 54 EJ/y (i.e. 36%) of the biomass primary energy for biofuels, meaning that 96 EJ/y (64%) of the primary biomass demand is dedicated to other uses. When 76% of our assessed biomass is used for biofuels, only 43 EJ/y are left for other uses. Reaching the IATA 50% reduction target thus means to displace a significant part of the other world biomass demands toward other sources of energy.

From this point of view, the carbon neutral growth scenario is probably more realistic whilst still very demanding. With 16.7 EJ/y of jet fuel, it requires 52% of the biomass to be processed into biofuels which is much closer to IEA's projection. This scenario would lead to 41.6 EJ/y of co-produced biofuels, a global share of biofuel in transport final energy demand of 52%, and would let 88 EJ/y for other uses.

However, it should be underlined that this potential corresponds to a theoretical potential associated to strong uncertainties, even if the most conservative values have been selected at each step of the assessment. Achieving this potential requires a significant effort and development of the agriculture production, meaning high investments in infrastructure, education and also the availability of manpower. If "realistic" figures have been selected for the potential yields increases, it does not

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[5] Emissions from biofuel = 20% of kerosene emissions

ensure that the agriculture production can ramp-up following the time schedule considered in this assessment.

The analysis at European level shows that Europe is likely to be a net importer of either biofuels, either raw materials. Its own biomass resources could cover the production of about 38% of the amount of biofuels uplifted from Europe in the neutral carbon growth scenario, assuming that European agriculture is mainly oriented toward self sufficiency which may represent a significant change compared to the current trade situation.

The additional potential of algae

In addition to the classical raw materials considered in the assessment of biomass availability, new type of feedstocks can be expected in the future through the development of algae that promise higher yields than terrestrial crops and induce low requirements on land quality avoiding a direct competition with food.

Algae are nevertheless still at research and development stage, the main challenges being to confirm at large scale the high performances obtained in laboratory or pilots, and to reach competitive production costs for energy production. Reaching these goals implies progress at all the steps of algal oil production chain, harvesting of algae and extraction of the oil being often recognized as the most pressing technical challenges. It also calls for a high integration of the process and the development of synergies with other application and coproducts. Indeed, economical, environmental and energetic balances of the production can be greatly improved if the CO_2 required for algae growth comes from flue gases and if the nutrients can be obtained from wastewater. The co-production of high value biomass is also essential to support the commercialization of algae based fuels.

As a conclusion, considering the early stage of algae production, drawing conclusion about their future contribution to biofuel production seems premature. Research and demonstration at significant scale are still required and emergence of commercial large scale production may take time. However, their potential advantages clearly justify the continuation and the development of research in the field.

Life cycle analysis

Based on the methodological guidelines set by the European Directive on the promotion and use on renewable energy (2009/28/CE), assessments have been made within the SWAFEA study on greenhouse gases (GHG) emitted for the production and use of alternative fuels and on energy consumption associated to the various fuel chains on the whole life cycle.

Fuel chains from fossil feedstock and biomass feedstock have been evaluated that were supposed to be relevant for the European Union in the middle term (~2020-2030):

- Conventional Jet fuel and FT fuel from natural gas (GtL);
- Hydrotreated Renewable Jet (HRJ) fuel from rapeseed, camelina, oil palm, jatropha and algae;

- FT fuel from lignocellulosic biomass (BtL) including miscanthus, switchgrass and wood from short rotation coppices (SRC).

The results of the assessment have first confirmed that GTL leads to an increase of GHG emissions compared to kerosene, even in case carbon capture and sequestration is applied. If GTL can have a significant effect on the fuel security of supply for aviation by giving access to extended fossil resources, there is no hope that it could provide environmental benefit from the green house gas effect point of view.

At the contrary, all the considered biofuels pathways demonstrate a potential for GHG emissions reduction. Nevertheless, their ability to reach the RED's targets of 60% in terms of emissions thresholds depends strongly on the process and on the cultivation pathway which is the major contributor due to the use of agrochemical inputs.

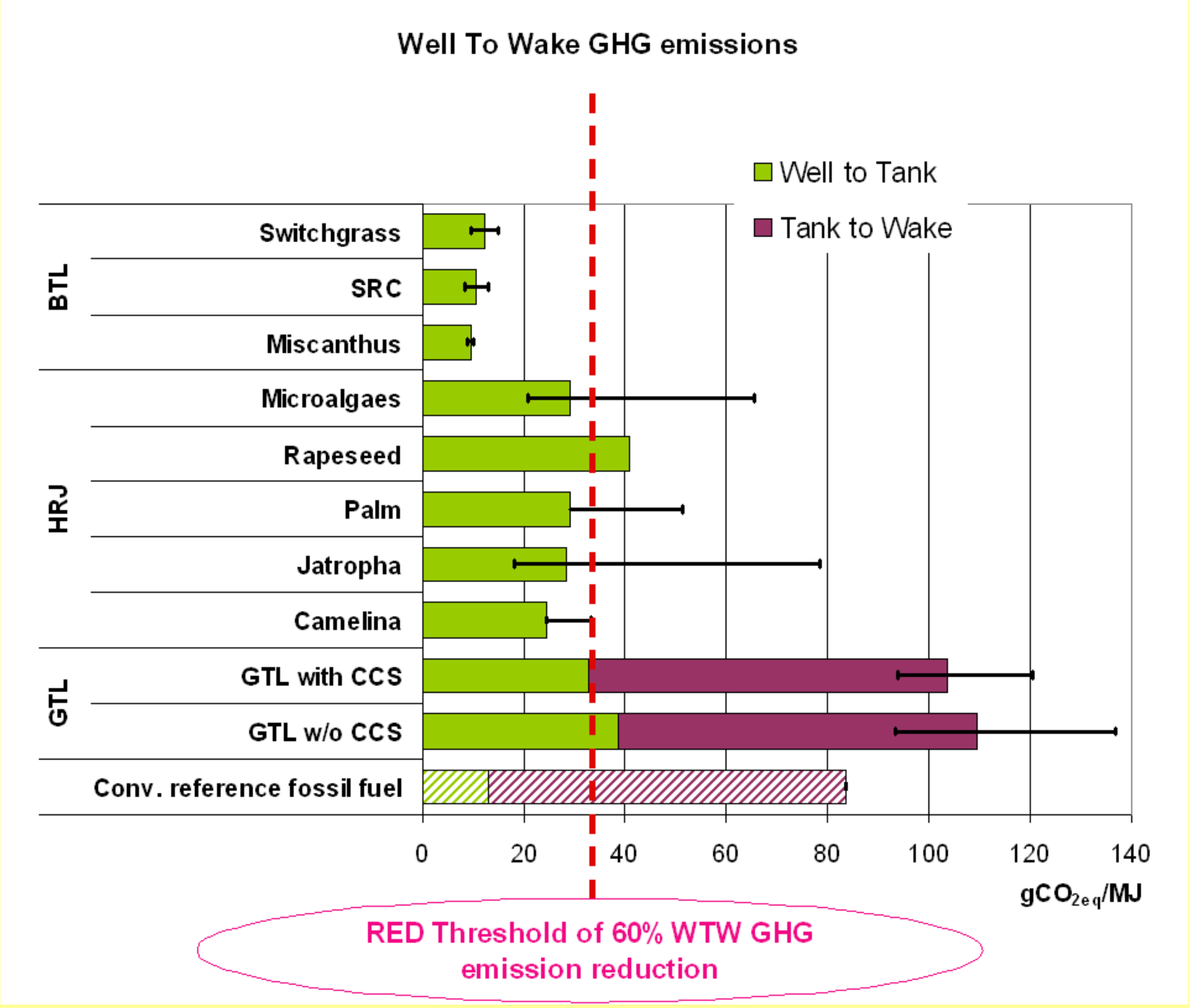
BtL pathways are able to reach the target and demonstrate significant emissions reductions, up to 90% in the case of myscanthus. BTL process nevertheless exhibits poor yields and a high energy demand which call for an optimisation.

HRJ are emitting more GHG than BtL, and their ability to reach the target depends on the feedstock and on the emissions associated to the cultivation step which has to be carefully optimised. For example, minimizing fertilizers inputs by the use of the crop co-products demonstrates significant life cycle emissions in case of jatropha.

For algae, the whole production chain of algae oil needs to be optimised, the best performances being obtained with a high integration with CO_2 and nutrients sources. Energy consumption is also to be carefully studied, the use of non renewable energy being potentially high.

All these potential benefits compared to kerosene can nevertheless only be achieved if no negative impact of land use change is associated to the feedstock production. Evaluation indeed shows that, either negative or positive, the land use change has a higher impact than the whole fuel production chain. Land use change is thus a primordial parameter for the selection of the crops and lands to be used for biofuel production. Cultivation of perennial crops on grassland or croplands can have a positive impact on GHG balance as the cultivated species may store more carbon than the considered lands.

Methodological assumptions used in LCA are often cited as a very sensitive parameter. Despite difference of methodology in some calculation, similar tendencies in the results can nevertheless be observed in other studies.



Note:

- The reference pathway considered for algae corresponds to autotrophic algae with average characteristics from literature data. Microalgae are grown in open raceways mixed with wheel paddles in a facility covering about 100 ha. Pounds are located near an electrical plant in order to recycle the flue gases with 15% mass of CO_2. A purification step of flue gases is required in order to extract CO_2 and to feed algae on it. To carry out photosynthesis, microalgae use sunlight energy, CO_2 and nutrients. These nutrients are supplied by sludge from waste water treatment plant considered as a waste.
- Reference processes data are from NextBTL for HRJ, RENEW for BTL and IFPEN and Shell for GTL
- Uncertainty bars correspond to sensitivity to the inputs data range found in literature.

SWAFEA results for green house gas life cycle emissions

Environmental and societal impacts

Indirect Land Use Change

Life cycle analysis emphasizes the utmost importance of a careful control of land use change for the limitation of green house emissions.

The difficulty arises from the fact that land use change can be induced indirectly by biofuels production and so may not be immediately visible. Indirect land use change (iLUC) results from the displacement of cultures because of the deployment of energy crops on areas that were used for other purposes and especially for food production.

ILUC is difficult to observe and to calculate because it is an indirect process, it has a global impact and it has a temporal shift. Induced land use change may also occur in a completely distinct geographic area. Understanding iLUC impacts requires knowing the various ways in which any increase in demand for biofuels will be met. There is no consensus yet on the methodology to address iLUC nor on the results.

Indirect land use change is also difficult to introduce in certifications scheme. Standard systems can only contain requirements that fall within the control of the companies (e.g. agricultural producers) and therefore within the control of the certification system.

Currently, for the RSB standard, the overall feeling is that ILUC factors should not currently be used in the GHG emissions calculations. The focus should be on reducing and minimising risks at the project level, promoting practices and feedstocks that lower the risks of indirect impacts or compensating for displacement.

Deforestation and biodiversity

Life cycle analysis clearly underlines the critical impact of deforestation on carbon emissions. Deforestation is also a major source of biodiversity loss. From both points of view, the worst impact occurs when destroying tropical forest where nevertheless the highest deforestation is currently taking place.

Deforestation is not necessarily associated to biofuels. The extension of food markets such as the one of edible oils may be an important driver when countries chose to use them as a tool for their development. Biofuels can only add to this pressure.

Biodiversity can also be endangered by over exploitation of forests without deforestation. Sustainable management of forest needs to be implemented with measure like leaving residues on ground. Sustainability criteria of the RED also stipulate that primary forest should not be used which, at word scale, potentially annihilates the potential production of energy biomass from forestry on the 2050 horizon.

Other environmental impacts

Water is clearly a critical issue with view to biofuels development. Many countries already present some water availability issues. Irrigation should be considered carefully and only when nutrients are available in sufficient quantities not to be the limiting factor.

Non irrigated crops such as short rotation coppices may nevertheless have significant impacts on local hydrology and their implementation has to be carefully considered in relation with local conditions. A difficulty may stem from the fact that there is no accepted definition of water scarcity.

The risk of proliferation of modified species with improved resistance and productivity is particularly raised by algae. The containment of the culture may be a major issue. This is also the case with view to the use of genetically modified crops. Sustainability frameworks like the RSB stipulate that invasive species or micro-organisms must be adequately contained and that technologies for GMO shall minimizes the risks for the environment. This may prevent the use of GMO at least in a first step for biofuels production.

Competition with food

Competition with food is probably the first fear associated with biofuels development.

According to FAO, the main effect of biofuels on food security will come from their impact on food product prices and on people incomes, especially in the poorest countries with high deficits of the agriculture trade. In the longer term, biofuels may have a potential positive effect if their production revitalizes agriculture in developing countries. Examples exist of countries where commercial production developed without negative impacts on food production. A major factor for such positive revitalisation is investment in agriculture and local infrastructure which is also required to obtain the high yields necessary to reach the biofuels production targets. The general feeling is nevertheless that at world scale the net effect on food security in the short term is likely to be negative.

Societal and economical impacts

Development of large commercial cultures implies reallocation of land and resources. This has serious impacts on rural societies the subsistence of which is closely linked to natural resources and access to land.

The combination of insufficient legal frameworks to protect small holders with plans to promote and develop market production may result in conflicts for land property. This is in particular the case in developing countries where vagueness or inconsistencies in the national laws don't always protect the rights of indigenious people which still regulate their affairs through customs.

A question is also the place of the small holders in the rapid development of this market agriculture which tends to favour concentration and large plantations benefiting from vertical integration and of a larger investment capability. No clear sustainability criteria states about concentration which is not only observed in developing countries' agriculture. For rural and social development, it may be nevertheless important to involve small holders which can be favoured by public investments in infrastructure, diffusion of techniques, legal or market institutions. Contractual agriculture is another mean.

Societal and economical implications of biofuels may also raise barriers to their development and this also in developed countries. This the case, for example, of infrastructures for forest exploitation or changes in the agricultural practices or equipment required for new crops (such as short rotation coppices). Perennial crops may also not be well perceived by farmers due to the loss of flexibility they imply. Specific measures such as long-term contracts with fuel producers could be required to promote their deployment.

Existence of policy measures and incentives or subsidies along with access to credit is also prerequisite which may induce bottlenecks in developing countries. The development however may be funded by foreign investors and be seen as contributing to the economical uptake of the country with nevertheless the potential drawbacks of large commercial agricultural production on local people.

A last question is the one of the priority for some developing countries which have the potential to be energy biomass supplier but at the same suffer from a limited access to energy. Question is to know whether the benefit would not be higher for the country to develop electrification rather than investing in biofuels.

Atmospheric impacts

The studies initiated in SWAFEA have been carried out considering Synthetic Paraffinic Kerosene (SPK) blends with Jet A-1 which are currently the main candidates for aviation alternative fuels.

From literature data and from the combustion tests performed in the frame of SWAAFEA, the most notable impact of SPK blends on engines emissions is a strong reduction of particulate matters, both soots and aerosols, due to the lower contain of these fuels in aromatics and sulphur. Available data indicate that soot initial concentration at the engine nozzle exit may be reduced by 30% to 90% at cruise conditions.

This reduction in particulates emissions is a positive factor for local air quality since soots are considered as an important source of severe respiratory affection and sulphur oxidation leads in particular to sulphuric acid formation. However a quantitative evaluation of the impact of the reduced soot emissions is currently not possible because no extensive database on aircraft soot emissions is available to perform simulations. The consequence of the reduced SO_2 emissions have been evaluated on the base case of Paris airports but the impact on local air quality turns out to be rather limited because aviation is not the main source of sulphate in France.

Particulate matters also influence the formation of contrails since they trigger the condensation of water vapour and induce the formation of induced cirrus clouds which modify the radiative forcing of the atmosphere. Detailed simulations of a turbulent wake performed in SWAFEA show that reducing the soot emission index reduces the diameter of the ice particles that form on soots and following decreases the optical depth of the contrails. This is likely to reduce the effect of the contrails on radiative forcing and thus on climate.

The impacts of SPK blends on other engines emissions, like CO, NOx or UHC, are much more limited. In particular, NOx are mainly dependant on the combustor configuration and for SPK fuel, the difference of fuel properties compared with Jet A-1 have only a second order effect. The impact may be positive or negative depending on the engine and thrust rate. Emissions variations are also induced by the consumption reduction due to the higher heating value of SPK.

A global simulation has been performed to assess the possible impact of these emissions change on ozone concentrations, using a traffic and fleet projection in 2026 and considering the use of a 50% SPK blend with Jet A-1. For the hypotheses used to estimate the emissions of NO_X, CO and UHC, a global reduction in NO_X emissions of 1.4% is obtained, when CO and HC emissions respectively increase of 0.16% and 11%. The simulation results clearly show an associated net decrease in ozone concentrations at mid latitudes. However, modelled ozone changes (~2%) remain below the ozone concentration natural variability. Therefore, with the strong assumptions and uncertainties from the modelling strategy and the emission inventories used, alternative fuels may not decrease much the ozone induced radiative forcing from aviation.

CONCLUSION: KEY MESSAGES AND RECOMMENDATIONS

Key Messages

- A significant amount of biomass may theoretically be available at world scale for energy application, mainly from agriculture, without endangering food security. It is however far from covering the projected world energy demand in 2050, evidencing a strong need for complementary energy sources.
- The biomass potential could support the objective for aviation to have a carbon neutral growth from 2030 at the emissions level of 2020, if it was accepted to process 52% of the available biomass in biofuel. This is already a high percentage which nevertheless leaves a significant amount of biomass for other uses than aviation and transportation. At contrary, reaching the 50% emissions reduction target appears as calling for an excessive ratio of the global biomass potential for aviation and transport.
- The analysis at European level shows that Europe is likely to be a net importer of either biofuels, either raw materials. In the neutral carbon growth scenario, it could provide up to 38% of the fuel uplifted in Europe from European biomass.
- Reaching the biomass production potential requires a significant effort and investment in agriculture, putting in cultivation large amount of lands that are not cultivated today, the availability of fertilizers and of manpower. If it seems feasible by 2050 from the yield increase technical point of view, it does not mean that the foreseen development of the production can be achieved in the next 40 years.
- From a life cycle point of view, only biofuels offer the promise of a significant reduction of the green house gas emissions. Alternative fuels derived from fossil feedstocks, CTL and GTL, have detrimental impacts on green house gas emission compared to traditional kerosene even in case of carbon capture and sequestration.
- From the GHG emissions point of view, BTL is the most promising option. It complies with the 60% thresholds of the RED on life cycle emissions reduction. Maximising lignocellulose production also leads to the highest primary energy potential from biomass.
- For HRJ, the ability to reach the target depends on the feedstock and on the emissions associated to the cultivation steps which have to be carefully optimised.
- Potential benefits compared to kerosene can only be achieved if no negative impact of land use change is associated to the feedstock production. Either negative or positive, the land use change has a higher impact than the whole fuel production chain. This highlights the importance of controlling indirect land use change (iLUC) that can results from culture displacement. However no methodology is today accepted to address iLUC.

- At world scale and in the short term, the net effect of biofuels on food security is likely to be negative, mainly due to the impact of biofuels production on food price. In the longer term, positive effects could be obtained if biofuels production contributed to the general development of agriculture, bringing technology and improved practices in developing countries that also benefit to food production.
- Environmental and societal impacts of biofuels are not specific to biofuels or to the crops used to produce them. They exist for traditional agriculture and are mostly relevant of agriculture management and of development policies of the interested countries. The fact is that biofuels development will put additional pressure on existing trends.
- Algae could provide answer to biomass availability and to some environmental impacts, thanks to high productivity and low requirements on land quality. It nevertheless calls for synergies with other production in order to fully benefit from the potential advantages. Research is required to better evaluate their potential and before deployment may take place.
- Environmental certification following sustainability frameworks is today the principal way to ensure the sustainability of biofuels production. Existing frameworks, such as the one of the RSB are quite comprehensive and detailed, capturing most of the sustainability issues, even though they currently have difficulties in handling indirect effects.
- Apart from impacts on life cycle green house gas emission, synthetic paraffinic kerosene (SPK), produced from either fossil resources or biomass through Fischer-Tropsch or hydroprocessing, leads to a strong reduction of particulates emissions of aircraft engines. This is due to their low aromatics and sulphur contents.
- While the reduction of soot emissions is likely to have significant positive effects on air quality around airport, no quantitative impact evaluation is currently possible because no extensive database on aircraft soot emissions is available. Conversely, evaluations show a negligible impact of sulphur emissions reduction for a city like Paris because aviation is not the main source of sulphate.
- Reduction of particulates emissions has also proved to reduce the optical depth of contrails formed by the condensation of water vapour on engines exhaust aerosols at cruise flight conditions. This is likely to reduce the effect of the contrails on radiative forcing and thus on climate.
- Impact of SPK fuels on ozone concentrations and radiative forcing through NO_x, CO and UHC emissions is limited and bellow the natural variability for the assumptions, modelling strategy and emission inventories used in SWAFEA.

Recommendations

- Present regulations in Europe should be harmonized to more efficiently enforce sustainability of aviation biofuels. Biofuels should match the RED requirements and be certified in order to account for zero emissions in the ETS.
- Inclusion of aviation in the RED should be more clearly stated and communicated.
- Similar measures are required at ICAO level for a worldwide application in accordance with ICAO's resolution on climate change.
- If bilateral agreements between the European Union and third countries are likely to be the relevant level to address political aspects of sustainability, it should not necessarily exclude certification of the producers.
- Methodological approaches and policy measures are required to address iLUC.
- Aviation fuel being a global commodity, harmonisation of sustainability regulations should be searched among the various world areas. In particular, there would be a strong benefit from an alignment on a global LCA methodology.
- Biomass production being a key issue, demonstration of energy crops performances under controlled agricultural practices ensuring sustainability should be initiated. Availability and impact of the fertilizers should be further analysed along with the impact of the projected use of grazing land from both an environmental and societal point of view.
- Researches on algae are an important axis to diversify sources of biomass and relax the pressure on agriculture. They should be oriented toward demonstrations at significant scale, to confirm yields and scalability of the production, and toward the study of integrated projects in order to maximise the potential benefit and minimize the life cycle impact on both emissions and energy.
- Deeper analysis of atmospheric impacts of alternative fuels is required to completely assess their global final effects. These fuels should be considered in the on-going or proposed research programs on aviation impact on atmosphere and following on climate.

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INTRODUCTION

The European Commission's Directorate General for Mobility and Transport has initiated the SWAFEA study in February 2009 to investigate the feasibility and the impact of the use of alternative fuels in aviation. The goal is to develop a comparative analysis of different fuel and energy options on the basis of the present knowledge and to propose a possible vision and roadmap for the future deployment of the most promising solutions.

Behind the introduction of alternative fuels in aviation, there is a strong concern in Europe about the environmental impacts of transportation and energy production, in particular with view to Green House Gas (GHG) emissions and climate change. This is expressed through the Renewable Energy Directive [1], issued in April 2009, which sets a binding target of 20% for renewable energy use in Europe by 2020 and further defines a specific target of 10% for transportation. As far as biofuels are concerned, these targets come with additional requirements on the CO_2 emissions on a life cycle basis that should be at least 35 % less than for conventional fuels, and at least 60 % lower from 2018.

Though aviation contribution to the world global emissions is today limited to about 2 or 2.5%, the continuous growth of air traffic promises a fuel consumption increase that technological progress will not compensate. This may significantly undermine the reductions of emissions made by the other sectors to combat climate change and leads to consider the introduction of aviation in the global 10% target of the Directive for renewable energy use in transport.

The willingness to include aviation in the general effort of green house gas emissions reduction is also marked by the decision to introduce aviation in the Emission Trading Scheme (ETS) in 2012. The consequence will be the ceiling of aviation emission at 97% (then 95% from 2013) of their level in 2005 and the necessity for airlines to buy 15% of their allowances through auctions. This will add to the direct cost of jet fuel for aircraft operators. Thus ETS may become a driver for introduction of new technologies on aircraft but also for the use of alternative fuels, with reduced carbon impact, such as biofuels.

Nevertheless, environmental impacts are not limited to green house gas emissions only. This is recognized by the Renewable Energy Directive that also defines sustainability criteria that biofuels should respect to be accounted for in the Directive application. Strictly speaking, sustainability encompasses all environmental, societal and economical potential impacts that should be under control for an activity to be run in the long term without damages for the society.

An entire work package of the SWAFEA study has thus been dedicated to the analysis of the sustainability of the introduction of alternative fuels in aviation.

This analysis has been divided in two parts:

- the assessment of environmental impacts and sustainability aspects of the fuel production and distribution, which is the "Well To Tank" part of the sustainability assessment, or rather the “Field to Tank” part in case of biofuels;

- the analysis of the specific atmospheric impacts of aviation, especially because of the particular altitude at which aviation's emissions take place, which is the “Tank to Wake” part of the sustainability assessment.

Biofuels are major candidate for alternative fuels, especially with view to greenhouse gas (GHG) emissions reduction. Therefore a first focus of the sustainability assessment has been put on the availability of the biomass required for their production. A proper analysis has been carried out to complement the available evaluations of the global biomass production capability in order to satisfy the energy demand.

The Life Cycle Analysis (LCA) of the different alternative fuels constitutes the second focus of the study. LCA is the relevant methodology to assess the total environmental impacts of alternative fuels from well or field to wake. It allows to evaluate not only GHG emissions but also other relevant potential environmental impacts such as the cumulated primary energy demand, for the different steps of the fuel production chain. The Life Cycle Analysis is thus a crucial part of the sustainability assessment and a very important tool for the pathways selection.

The last part of the analysis is related to general aspects of sustainability. Not all of these aspects can be captured at a global level and many of them are local such as the environmental impact of growing a given crop in a given place or the social impacts of developing new agriculture practices. Considering the variety of possible situations, it would probably not make sense to aim at providing a unique and general answer. The goal retained in the SWAFEA study is rather to highlight a variety of situations that could result from alternative fuels production on the basis of a number of "case studies".

The results of this assessment of production and distributions impacts of alternative fuels are presented in the first part of this report.

The second part is related to the potential consequences of alternative fuels on the atmospheric impacts of aviation.

Apart from noise pollution, the most directly visible effect of aviation for the public is the impact on local air quality around airports with the consequences on human health of the pollutants produced by the strong concentration of aircraft on airports, especially during taxi, take-off and landing phases. On the basis of the emissions data today available for the first aviation alternative fuels, an analysis has been carried out in the frame of SWAFEA to identify the potential differences with the classical Jet A-1 emissions.

A more indirect impact of aviation emissions is related to the high altitude at which these emissions are released. Particular physical and chemical phenomena take place that have an impact on atmospheric chemistry and on the radiative balance of the atmosphere. For example, contrails formed by condensation of water vapour onto exhaust aerosols and soot particles trigger the formation of cirrus clouds, which contribute to the greenhouse effect. Nitrogen oxides emissions perturb the natural chemical cycles and lead to ozone production or destruction depending on local air mass composition and insolation. These ozone perturbations along with the emissions of CO_2, water vapour, soot particles, sulphuric aerosols from combustion and ice particles formation give an additional contribution to the greenhouse effect. Again, on the basis of the available data for the first aviation alternative fuels, a preliminary evaluation has been carried out in the frame of SWAFEA of the potential consequences of these fuels on high altitude atmosphere chemistry and following on radiative forcing and green house effect.

PART 1: PRODUCTION AND DISTRIBUTION IMPACTS OF ALTERNATIVE FUELS

1 SCOPE OF THE STUDY

Two categories of alternative fuels enter in the scope of the SWAFEA study.

The first one includes fuels stemming from fossil resources other than crude oil (and its unconventional forms like tar sands or oil shale). It presently consists of the Fischer Tropsch synthetic fuels made from coal (CTL for Coal to Liquid) and gas (GTL for Gas to Liquid). These fuels give access to fossil feedstocks with larger identified reserves than crude oil and a different geographical distribution which can make them of particular interest for some countries like China or the United-States. Whilst they provide an improved security of supply, these fuels nevertheless don't bring any reduction of green house gas emission and may even induce an increase of these emissions due to the transformation process of the fossil feedstock [2].

The second category is the one of biofuels which, in addition to be renewable, is expected to bring significant green house gas emissions reduction since the carbon emitted through combustion is balanced by the carbon absorbed by the growth of the biomass used to manufacture the fuel.

In comparison with fossil based alternative fuels, biofuels nevertheless introduce the requirement to produce the feedstock and not only to extract it from existing resources. This enlarges significantly the scope for assessing their sustainability to new questions covering not only the feedstock transformation but also the sustainability of its production and the question of the associated GHG emissions that for these fuels become a major contributor.

Considering their potential for GHG emission saving and the current lower level of understanding of their impacts, most of the effort in SWAFEA has been dedicated to the assessment of the sustainability of biofuels.

As an introduction to this assessment of alternative fuels impacts, the first chapter presents some currently existing regulations and frameworks for biofuels sustainability with sustainability criteria against which assessing the pathways and various impacts.

The biofuels' feedstock needing to be produced from agriculture or other biomass sources, the question of the biomass potential availability has been addressed first. The answer is far from being straightforward because of its intrinsic complexity and also because of the multiple combination of feedstocks that can come into the system: forest resources, agricultural crops, waste (including urban waste) and finally new types of resources like algae or yeast that enter in completely different ways of production. These different resources are addressed separately in chapter 3.

The Life Cycle Analysis of the different fuel options and pathways is presented in chapter 4. The primary goal of the study is to evaluate the performance of the candidate pathways in terms of GHG emissions, energy consumption and water demand in order to select the most promising options and quantify their benefit with regard to traditional kerosene. Further the analysis aims at highlighting the driving parameters and the influence of the methodological issues that are still under discussion for LCA.

Last in chapter 5, other aspects of sustainability that cannot be addressed through LCA are presented. The focus is there more on local aspects of environmental and societal impacts that the development of alternative fuels may have. The analysis is based on literature review and a number of case studies. Case studies indeed allow a more thorough analysis of a given situation and the understanding of a complex issue on a concrete basis. These case studies have been selected in order to cover quite different kinds of products and of production conditions including both European and developing countries situations.

2 SUSTAINABILITY AND SUSTAINABILITY FRAMEWORK

The definition of sustainability and of an associated framework of assessment criteria is not part of the SWAFEA study. This is a challenging issue upon which a number of other interdisciplinary groups are already actively working. Not less than 67 initiatives are reported [3], all relevant for various part of the bio-energy value chain.

The main issue for SWAFEA was to get a global picture and to select a relevant set of criteria to assess the sustainability of alternative fuels for aviation.

2.1 The European Renewable Energy Directive (RED)

As already mentioned in the introduction, the primary purpose of the European Renewable Energy Directive (RED) [1] is to set binding targets at European level for the introduction of renewable energy by 2020:

- at least 20 % of the Community's gross final consumption of energy should come from renewable energies;
- the share of energy from renewable sources in all forms of transport should be at least 10 % of the final consumption of energy in transport.

No specific quota is defined for aviation but consumption of biofuels in aviation can contribute to the achievement of the 10% target.

The RED provides a first set of sustainability requirements for biomass based fuels. Three articles of the Directive are expressly dealing with sustainability criteria for biofuels:

- Article 17 about the "Sustainability criteria for biofuels and bioliquids";
- Article 18 about the "Verification of compliance with the sustainability criteria for biofuels and bioliquids";
- Article 19 about the "Calculation of the greenhouse gas impact of biofuels and bioliquids".

Article 17 focuses on five major aspects:

1. Greenhouse gas emission saving from the use of biofuels shall be at least 35% in 2010, 50% in 2017, and 60% from 2018 (paragraph 2);
2. Raw material shall not be obtained from land with high value: high biodiversity value (paragraph 3), high carbon stock (paragraph 4) or peatland (paragraph 5), apart from very few exceptions;
3. The European Commission has to report every two years about the national measures taken to respect sustainability criteria;

4. It has to report every two years about the societal impacts and in particular about the availability of food at an affordable price especially for people living in developing countries (paragraph 7).
5. It has to report about the implementation of major international conventions at members States and third countries level.

Article 18 (and also paragraph 7 of Article 17) mentions clearly the need for biofuel operators (producers, processors...) to monitor their compliance towards sustainability. These businesses have to prove that their operations are fulfilling the different criteria set up by the European Commission.

Article 19 provides guidelines for the calculation of GHG emissions in the Life Cycle Analysis.

In June 2010, the RED has been complemented by a Communication from the European Commission [4] stating that operators have to demonstrate to the Member States that the sustainability criteria are respected. For this purpose, they can use one the three proposed ways:

- by providing the relevant national authorities with data in compliance with requirements of the Member States;
- by using voluntary scheme recognized by the Commission;
- in accordance with the terms of bilateral or multilateral agreement concluded by the Union with third countries.

To demonstrate compliance with the GHG reduction thresholds, operators can also use default values provided by the RED for certain pathways. These default values are set at a conservative level to make it unlikely for economic operators to claim values that are better than their actual value. For example, the published default values for the biodiesel pathways from rapeseed and soybean do not pass the 35% minimum GHG saving and palm oil only passes with methane captured at the mill [5].

2.2 Round Table for Sustainable Biofuels (RSB)

Among the multiple groups involved in sustainability framework definition is the RSB (Roundtable for Sustainable Biofuels)[6] has the broadest coverage of key stakeholder groups in its membership: farmers and growers of biofuel feed-stocks, industrial biofuel producers, retailers, blenders, transporters, banks and investors, rights-based NGOs, rural development and food security organisations, environment and conservation organisations, climate change and policy organisations, trade unions, smallholder farmers organisations and indigenous people's organisations and intergovernmental organisations. In addition aviation organisations such as SAFUG (Sustainable Aviation Fuel Users Group)[7] and IATA are members of the RSB.

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[6] http://cgse.epfl.ch/page65660.html

[7] http://www.safug.org/

It should be noted however that Germany which was the first Member State to transpose the RED into its national laws, has selected the International Sustainability & Carbon Certification System (ISCC) and not the RSB in its recognised certification schemes [5].

The RSB presents a comprehensive and very detailed framework covering almost all relevant sustainability aspects [6]. It details not only key principles but also a complete set of instruments:

- the principles and criteria are commented in a guidance document;
- they are completed by a precise set of more than 250 indicators of compliance [7];
- several guidelines documents have been published in association with the 12 principles, providing a detailed approach to improve the sustainability of any biofuel.

The twelve RSB Principles & Criteria cover the following areas; 1) legality, 2) planning, monitoring & continuous improvement, 3) greenhouse gas emissions, 4) human & labour rights, 5) rural & social development, 6) food security, 7) conservation, 8) soil, 9) water, 10) air, 11) use of technologies, inputs & management of wastes, 12) land rights. These principles are detailed in Annex 1.

For many of its criteria, the RSB Principles & Criteria are referring to the Renewable Energy Directive published by the European Union, either in the definition of the sub-criteria or in the guidance documents for implementation. Further analysis shows that the sustainability criteria from the Directive are mostly covered by the RSB. A difference can be noticed for GHG reduction targets associated to biofuels which are not quantified in the first version of the RSB.

Given the broad endorsement of the RSB and coupled with the organisation’s aspiration to be the recognised “one-stop shop” for alternative fuel compliance by the European Union, it was decided to use the RSB Principles & Criteria as a basis for the sustainability criteria in SWAFEA with one exception: RSB uses a different GHG emissions LCA methodology than RED, which yields GHG reduction values that cannot be directly compared. The LCA calculations in this report are based on the RED methodology. In addition the RSB was supplemented in SWAFEA with quantitative requirements taken from the Renewable Energy Directive (in particular for GHG emissions reductions thresholds) and eventually with specific criteria from other frameworks when needed.

It should be underlined that most RSB criteria are local and address only the direct activities of farmers and producers. This goes with the fact that sustainability is essentially local since it strongly depends on local conditions both from the environmental and societal point of view. RSB nevertheless recognizes the existence of large-scale or macro impacts that are difficult to address at the local scale. Large scale impacts result in particular from macroeconomic interactions amongst food, fodder, fiber and fuel markets. Indirect land use change (iLUC) enters this category of indirect large scale impacts and so does probably competition with food through markets interaction and iLUC.

One should also note that the RSB standard setting is an evolving process. The RSB framework version 2 was under elaboration while the SWAFEA study was carried out and has been approved in

November 2010. The major evolution compared to the previous version is the introduction of a threshold for greenhouse gas emissions reduction which has been set to 50%. Considering the difficulty for many biofuels to pass this requirement, it has been proposed to enforce it at the "blender" level though the RSB certification is normally applied at the producer level. The threshold thus applies for final blends and not for their constituents. However, no single biofuel type with emissions greater than the corresponding fossil fuel reference value would be allowed. In that sense, the RSB is more permissive than the RED which requires the compliance with a mass balance system in which all the raw materials used to obtain the final product shall comply with the Directive sustainability criteria. Since the first RSB principle states that "*biofuels operation shall comply with all applicable laws and regulations of the country in which the operation occurs*", it should nevertheless not enter in contradiction with the RED in Europe. To avoid a violation of RSB’s Principle 1, all biofuel produced in the EU will have to meet the RED in addition. This concerns in particular the methodology for Life Cycle Analysis, which is not the same for RSB and for RED. Indeed RSB promote the allocation of the co-products on an economical basis when the RED stipulates an allocation on an energy basis. EU biofuels will thus have to undergo two different LCAs for RSB certification; RSB is currently developing a software tool intended to facilitate this task.

2.3 Relevant non-EU regulation: the Renewable Fuels Standards (RFS)

In the frame of the Energy Independence and Security Act of 2007 (EISA), the United States have also enforced regulation concerning biofuels [8] that we mention here because of its importance for the international market competitive situation. They have been defined by the U.S. Environmental Protection Agency (EPA) under the National Renewable Fuel Standard program, commonly referred as the RFS program.

The most noticeable provision of the recently revised RFS, known as RFS 2, is to fix quota for biofuels introduction in the U.S. These volume standards should rise from 12.95 billion gallons in 2010 to 36 billion in 2022, with also quotas per categories of biofuels (cellulosic biofuel, biomass based diesel and advanced biofuels) which is a unique feature. In addition EISA expanded the RFS program beyond gasoline to generally cover all transportation fuel[8]. There is nevertheless no specific mandate relative to renewable content in jet fuel.

In the frame of the RFS, EPA has promulgated a credit trading program, allowing obligated parties to generate or acquire credits to demonstrate compliance with their annual renewable fuel volume obligations. Credits can also be used by an obligated party to meet its requirements in the following year, or traded for use by another obligated party. RINs, Renewable Identification Numbers, form the basic currency for the RFS. A RIN must be generated for all renewable fuel produced or imported into

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[8] [8] states that :"EISA expanded the RFS program beyond gasoline to generally cover all transportation fuel. This now includes gasoline and diesel fuel intended for use in highway vehicles and engines, and nonroad, locomotive and marine engines".

the United States, and RINs must be acquired by obligated parties for use in demonstrating compliance with the RFS annual requirements. EPA’s program requires RINs to be transferred with renewable fuel until the point at which the renewable fuel is either: (a) purchased by an obligated party, or (b) blended into gasoline or diesel fuel by a blender. At such time, RINs are “separated” from the volumes. RINs have a monetary value and can then be traded on the market independently from the volume to which it had originally been assigned [9]. In order to generate RINs, the fuel must comply with the RFS2 definition of renewable fuel.

While there is no mandate for fuel suppliers to supply renewable jet fuel, they can receive RINs for each gallon of renewable jet fuel that is produced as long as it meets the requirement contained in the RFS2.

First RFS2 introduces threshold for greenhouse gas emissions reductions which also define the required performance to qualify for a category of biofuels:

- 20% is the minimum required reduction in lifecycle emission for any renewable fuel produced at new facilities;
- 50% is the threshold to qualify for biomass-based diesel or advanced biofuel,
- 60% is the threshold for cellulosic biofuel.

In addition, EISA changed the definition of renewable fuel to require that it be made from feedstocks that qualify as "renewable biomass". EISA's definition of the term "renewable biomass" limits the types of biomass as well as the types of land from which the biomass may be harvested.

To quote EISA, the term "renewable biomass" means each of the following [10]:

(i) Planted crops and crop residue harvested from agricultural land cleared or cultivated at any time prior to the enactment of this sentence that is either actively managed or fallow, and nonforested.

(ii) Planted trees and tree residues from actively managed tree plantations on non-federal land cleared at any time prior to enactment of this sentence, including land belonging to an Indian tribe or an Indian individual, that is held in trust by the United States or subject to a restriction against alienation imposed by the United States.

(iii) Animal waste material and animal byproducts.

(iv) Slash and pre-commercial thinnings that are from non-federal forestlands, including forestlands belonging to an Indian tribe …, but not forests or forestlands that are ecological communities with a global or State ranking of critically imperiled, imperiled, or rare pursuant to a State Natural Heritage Program, old growth forest, or late successional forest.

(v) Biomass obtained from the immediate vicinity of buildings and other areas regularly occupied by people, or of public infrastructure, at risk from wildfire.

(vi) Algae.

(vii) Separated yard waste or food waste, including recycled cooking and trap grease.

RFS2 places the same duties on foreign producers of renewable fuels as domestic ones including the registration with EPA and the possibility of independent inspection.

2.4 Selected framework

Combined with the classification of sustainability criteria established in the course of the SWAFEA study, the RSB framework leads to the criteria structure depicted on Figure 1.

One can notice some lacks, in particular for energy and economical aspects. Economical aspects are addressed separately in the business case chapter, while the energy use will be documented in the frame of SWAFEA.

Last, indirect impacts like indirect land use change (iLUC) and possible indirect effects on food security don't appear in this framework but were integrated in the analysis, in particular for the estimation of the biomass availability.

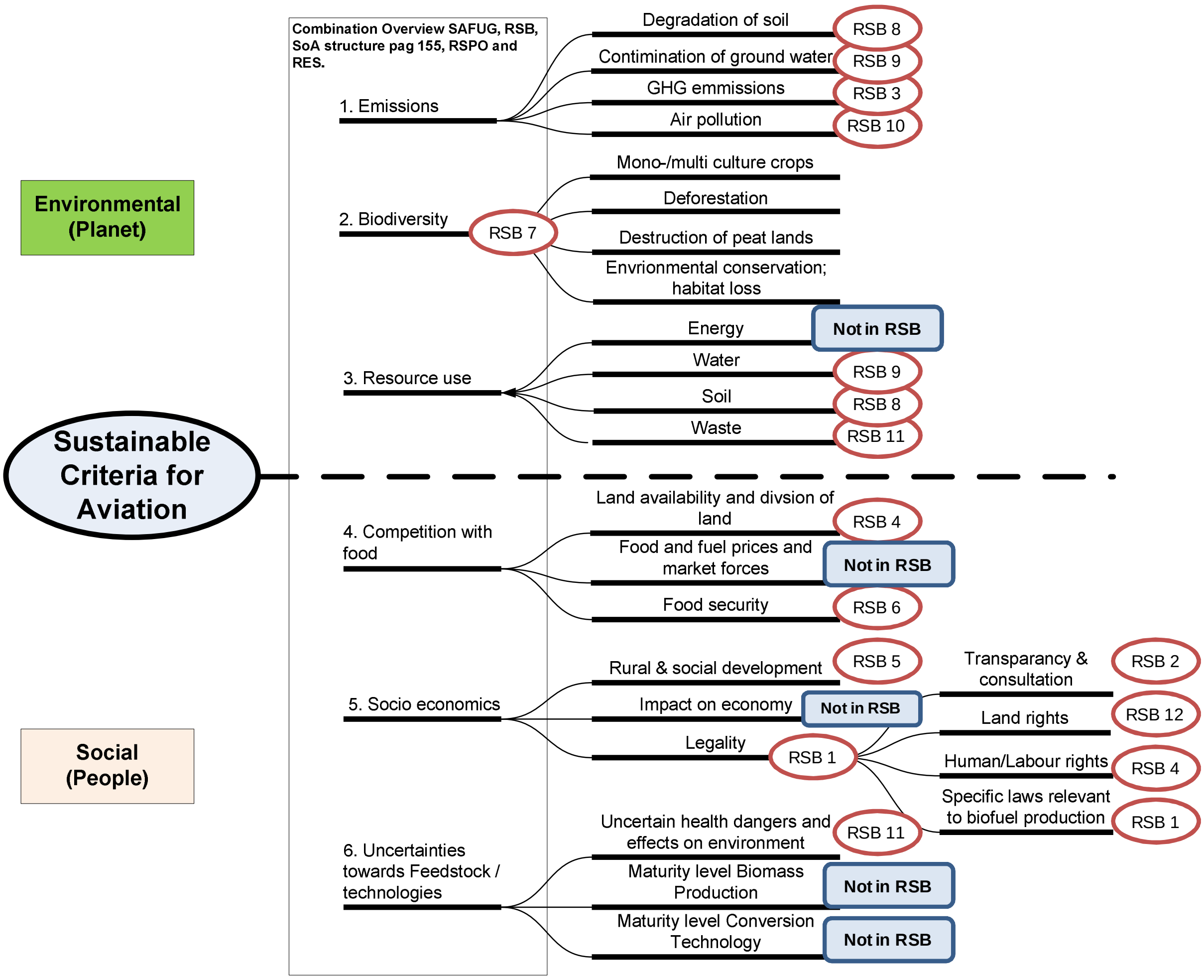

Figure 1: synthesis of RSB sustainability framework for SWAFEA

These sustainability principles and criteria have been applied at various levels of detail for the 3 steps of the sustainability assessment, depending also on the available information:

- for the feedstock selection and production scenario elaboration (general principle on the basis of available data);
- as an evaluation tool of the Life Cycle Analysis results (GHG emissions, energy & water consumption,…);
- in the case studies which are the most relevant situations to apply the sustainability framework.

3 AVAILABILITY OF BIOMASS FOR BIOFUEL PRODUCTION

3.1 Global demand for energy and bioenergy

Before entering the review of the biomass available for bio-energy production, it is worth setting some figures for the global energy demand that will serve as reference to assess biomass potential.

Reference figures for the study stem from the International Energy Agency (IEA) and its World Energy Outlook 2009 [11]. They are given for a reference scenario corresponding to no change in the current governments' policies, and for two voluntary scenarios aiming at containing or even reducing the greenhouse gas emissions: Scenario 450 and Blue Map scenario (Figure 2).

In the Scenario 450, Nations commit to a reduction goal of CO_2 emissions that allow to keep GHG concentration at 450 ppm of CO_2 equivalent in 2030, an objective IEA states to be progressively shared all over the world. Reaching this target requires the adoption of a structured framework of effective international policy mechanisms and their implementation. In IEA's vision, the largest contribution to this limitation of GHG emissions comes from energy efficiency (54%), renewable energy coming only in second position with 23% of the reductions.

The Blue Map scenario covers the 2050 horizon and is the most ambitious: it targets a 50% reduction of GHG emissions by 2050 compared to the current values. Such emission reductions require the rapid deployment of clean technology which involves a very high marginal cost of CO_2 about 200 USD/t. In this scenario, 36% of the reductions are obtained thanks to energy efficiency and 21% through the use of renewable energy.

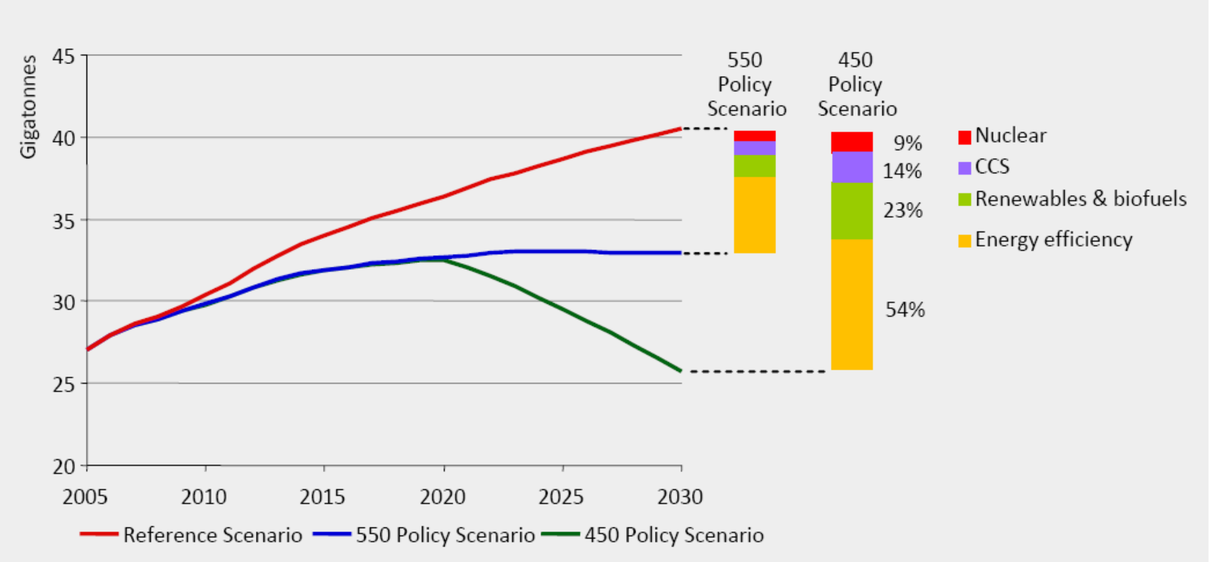

Figure 2: IEA's scenarios for GHG emissions (OECD/IEA 2008)

The corresponding energy consumptions are summarised in Table 1. In IEA's view, biofuels only represent 9.3% of the transport final energy consumption in 2030 and about 26% in 2050.

		Reference Scenario		Scenario 450	Blue Map Scenario
EJ/year	2009	2030	2050	2030	2050
Primary energy demand	502	705	977	604	750
Primary biomass demand	_51_*	67	90	82	150
Biomass share	10.2%	9.6%	9.2%	13.6%	20%
Final energy demand	347	482	664	427	443
Transport final energy demand	95	140	204	126	112
Biofuels demand in transport	2.2	5.6	4.5	11.7	29.1
Share of biofuels in transport	2.28%	4.00%	2.21%	9.29%	25.98%

Table 1: World energy consumption for IEA's future scenario [12]

(*: 2008 value from WEO 2010)

EJ/year	2010	2030	2050
Total final energy consumption	8.6	14.7	24.5
"IATA carbon neutral growth" from 2030			
Biojet consumption	0	3.7	13.5
Biojet share	0.0%	24.8%	55.1%
IATA 50% reduction target in 2050			
Biojet consumption	0	3.7	20.1
Biojet share	0.0%	24.8%	81.9%

Table 2: Energy demand for aviation

Table 2 provides the aviation demand for fuel following IATA's projection [2] and the biofuel demand for two different possible scenarios:

- a carbon neutral growth for aviation from 2030 at the emissions level of 2020
- a more ambitious scenario leading to a 50% reduction of CO_2 emissions from aviation in 2050 compared to the 2005 level.

The second scenario is based upon the high-level goals adopted by IATA in June 2009 and endorsed by the aviation industry[9] in the joint industry submission to ICAO in September 2009:

- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020;
- A cap on aviation CO2 emissions from 2020 (carbon-neutral growth);
- A reduction in CO2 emissions of 50% by 2050, relative to 2005 levels

The first two goals were included in ICAO's Resolution on Climate Change in October 2010.

Note that economic measures, such as emissions trading and carbon offsets, can be used to meet those goals, which will certainly be necessary in the first time after 2020. Therefore the SWAFEA scenario assumes reaching carbon-neutral growth with "technical" means only (fuel efficiency and biofuels) in 2030 (Figure 3).

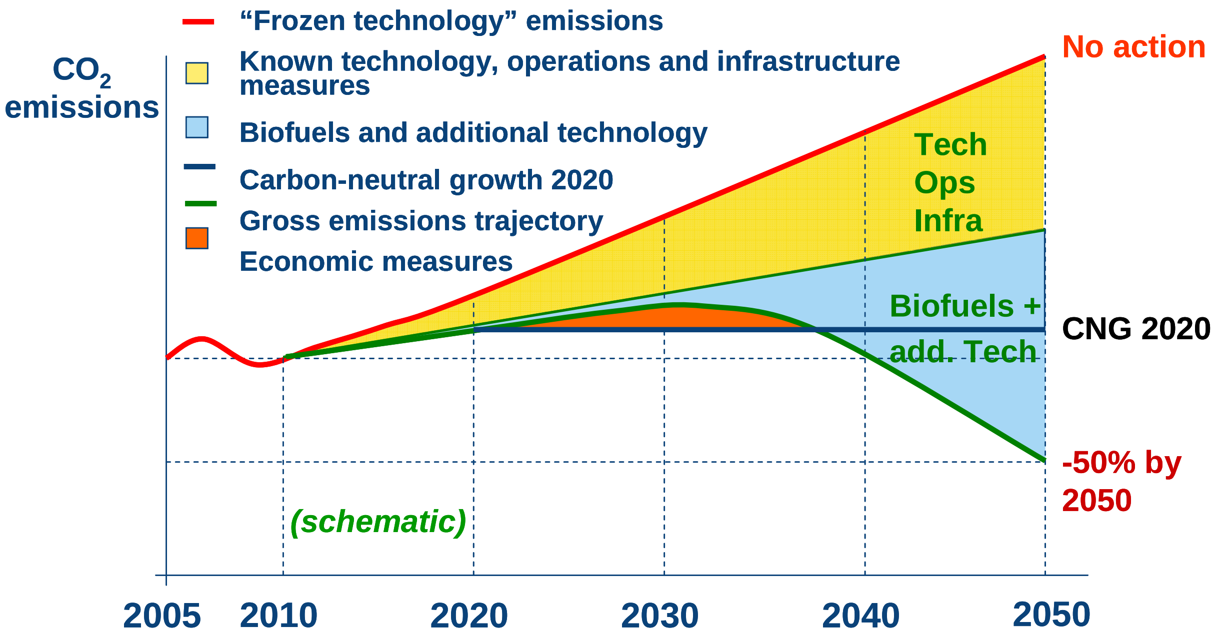

Figure 3: IATA emissions reduction roadmap

For the achievement of both scenarios, LCA emissions of the fuel are not taken into account and the biofuel is considered as "carbon neutral" however this is not the case from a full life cycle point of view.

Although this description is not fully correct from a cause-and-effect point of view, the same reasoning is used when describing CO2 emissions from fossil fuels in transport: Only the combustion emissions (e.g. 3.15 kg CO2 per kg of kerosene) are accounted for as transport emissions, while the "well-to-

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[9] represented by the world associations ACI (airports), CANSO (air navigation service providers), IATA (airlines) and ICCAIA (manufacturers)

tank" emissions from production are accounted for as energy industry emissions (e.g. from refineries). Similarly, one could consider biofuels as "carbon-neutral" in transport and count the "field-to-tank" emissions for biofuels as agricultural respectively energy industry emissions.

Considering the different LCA emissions of the various biofuel pathways would nevertheless make the evaluation complex. Following, the figures considered here for biofuel demand underestimate the volumes that would be required to actually match the life cycle emissions reductions objectives.

Both of these two scenarios are clearly very ambitious and would require strong political support. In particular limiting aviation emissions in 2030 to 2020 levels, implies a very strong ramp-up of biofuels production by 2030, in order to provide, for aviation only, the equivalent of 170% of the current worldwide production of all biofuels, which would also represent 31% of the biofuel production as seen by IEA in its Scenario 450. As a reference for comparison, the energy biomass production has globally doubled from 1971 to 2007 (IEA, 2010) but the biofuel production has increased from 9.52 Mtoe[10] in 2000 to 58.11 Mtoe in 2009 (IFP statistics) which represents an average increase of about 20 % per year over the period. As said above, the ICAO Assembly has included the carbon-neutral growth goal in its Resolution 17/2, resolving that "ICAO and its member States with relevant organizations will work together to strive to achieve a collective medium term global aspirational goal of keeping the global net carbon emissions from international aviation from 2020 at the same level". The challenge is real.

Table 3 finally gives the demand for fuel in Europe for the same scenarios.

EJ/year	2010	2030	2050
Total final energy consumption	2.26	3.18	4.35
"IATA carbon neutral growth" from 2030			
Biojet consumption	0	0.5	1.7
Biojet share	0.0%	17.0%	39.3%
IATA 50% reduction target in 2050			
Biojet consumption	0	0.5	3.2
Biojet share	0.0%	17.0%	73.3%

Table 3: European energy demand for aviation

3.2 Global biomass resources

This chapter analyses the potential availability of what could be called the "traditional" biomass which includes biomass from agriculture, forestry and waste, and in fact corresponds to the already existing

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[10] Million tons of oil equivalent – 1 toe = 41.88 GJ

streams of biomass. New streams, in particular algae, are appearing nowadays; they will be addressed in a following chapter.

Potential availability should be understood at the total amount of biomass that could be produced on earth under given assumptions, mainly technical and ecological. The analysis doesn't constitute a prediction of the biomass production that is likely to be seen at the 2050 horizon, but an estimate of the possible production from a "technical" point of view. In particular the assessment doesn't include any coupling with any kind of economical equilibrium model aiming at simulating the developments of the production under different economical scenarios. Thus the result should be understood as a "maximum" biomass production capability assuming that the conditions for production are achieved but also under given sustainability constraints that are enforced in the evaluation. The evaluation finally gives the conditions that are required to reach this potential.

A proper analysis has been carried out in the frame of SWAFEA for the agriculture biomass production based on a simulation of the world agriculture production capability. For forestry and residues, a literature review was carried out.

3.2.1 Agricultural resources

For the estimation of available agricultural resources for biofuel production now and in the future, a logical framework or methodology was applied that takes into account the available resources of cropland and grazing land in the world, their climate and soils, and projections on how much of these would be required for food security and the preservation of biodiversity. The methodology is described in 6 logical steps.

The first step in the methodology consisted of an analysis of FAOStat national agricultural production data on the UN region level. Thirty years (1980-2009) agricultural data of all 22 UN regions in the world (Figure 4) were analysed to extrapolate productivity increase of selected cereal and oil seed crops to the year 2050 on the regional level. The cereal crops comprised wheat, maize and sorghum and the oil seed crops comprised rapeseed soybean and sunflower. Table 4 summarizes the results on the continent level. Sub-regional values applied in the methodology can be found in Annex 1.

Figure 4: 22 UN regions

	Africa	Asia	Europe	South America	Northern America	Australia & New Z.	Oceania
Cereals	1.57	2.63	0.84	1.00	1.28	1.53	0.56
Oil seeds	1.20	2.26	0.91	1.13	1.45	1.30	0.89

Table 4: Average productivity increase rates (% year^{-1})

Cereals and oilseed crops between 1980 and 2009 (FAOStat).

(sub-regional values applied in the methodology are available in Annex 1).

Based on differences in harvestable fractions, root/shoot ratios, dry matter fractions, seed oil contents and lignocellulose fractions of selected crops (Annex 2), the oil and lignocellulose productivity of alternative crops was derived. This enabled the assessment of productivity of those crops that are of particular interest for biofuel production, but which are not present in FAOStat at the moment. The productivity values of the year 2000 (average values between 1997 and 2003) were used as baseline values (Annex 3). The crops included specific temperate and tropical species (and comprised species that used the C3- and the C4-photosynthetic pathway), annual and perennial species, including those for short coppice rotation (Table 5).

Biomass component	Annual		Perennial	
	C3	C4	C3	C4
Lignocellulose	**Italian rye grass** (Lolium multiflorum)	**Sweet sorghum** (Sorghum saccharatum)	**Reed canary grass** (Phalaris arundinacea) **Common reed** (Phragmites australis) **Perennial rye grass** (Lolium perenne)	**Miscanthus** (Miscanthus spp.) **Switch grass** (Panicum virgatum)
Lignocellulose SRC			**Eucalyptus** (Eucalyptus spp.) **Poplar** (Populus spp.) **Willow** (Salix spp.)	
Sugar	**Sugar beet** (Beta vulgaris)			**Sugar cane** (Saccharum officinarum)
Starch	**Wheat** (Triticum aestivum)	**Maize** (Zea mays)	**Cassava** (Manihot esculenta)	
Oil	**Camelina** (Camelina sativa) **Oilseed rape** (Brassica napus) **Soy** (Glycine max) **Sunflower** (Helianthus annuus)		**Jatropha** (Jatropha curcas) **Oil palm** (Elaeis guineensis)	

Table 5: Crops that were considered for biofuel production in the different regions

The second step in the methodology included the application of dynamic simulation modelling [13] linked to spatial databases with detailed information on soil properties, climate conditions and land use in order to simulate biophysical productivity potentials of cereals (maize and wheat) and perennial species (eucalyptus, poplar and willow) on current cropland and grazing land in the 22 UN regions.

The ratio between actual productivity (derived from FAOStat) and potential productivity (derived from dynamic simulation) was introduced as 'Development Index', to illustrate the success rate of regional agricultural practices to efficiently use the available natural resources climate, soils and water (Figure 5).

The Development Index or success rate depends on how socio-economic and cultural qualities are able to deal with biophysical challenges in a region. Factors like knowledge transfer, the availability and costs of inputs and the risk of their application play an important role here. The difference between potential and actual productivity is introduced as the 'yield gap' that must be closed to reach biophysical maximums. The timespan required to overcome the yield gap reveals the required productivity increase rates.

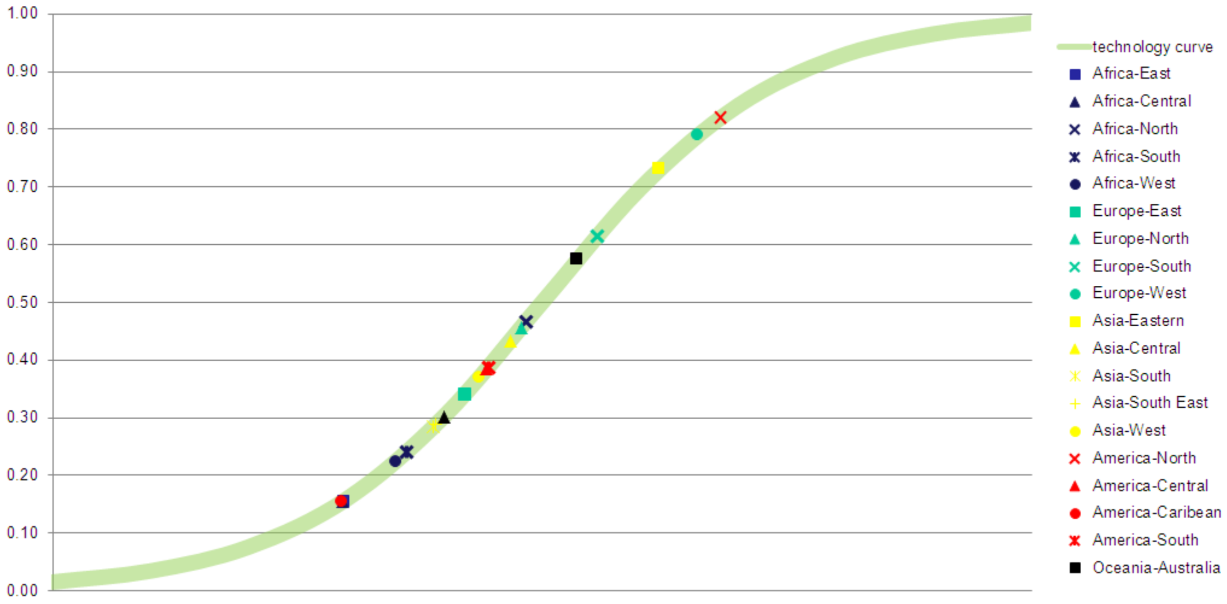

Figure 5: Development Index

Expressed as ratio between actual productivity and biophysical maximum productivity levels for the 22 UN sub-regions.

As can be observed from Figure 5, Northern America and Western Europe with all their implemented technologies display the highest Development Index. In the applied methodology, the North American value of 0.82 was set as a maximum attainable value for all other regions, implying that some regions have better productivity increase potentials than others. This technology option is indicated as '**T**' in the subsequent figures and tables. In any case the biophysical maximum values for biomass production were never exceeded, as 18% of available resources of soils and climate were not used.

The third step of the methodology consisted of the identification of annual and perennial species that maximally produced oil or lignocellulose as the feedstock for biofuel production in the 22 regions (See Table 5 and Annex 2). Crop harvestable fractions, root/shoot ratios, dry matter fractions, seed oil fractions and lignocellulose fractions were used to derive the final oil or lignocellulose productivity on a hectare base.

The fourth step in the methodology concerned the identification of available land (Mha) that may be used for the production of biofuels (Figure 6). Current oil palm and sugar cane areas were excluded.

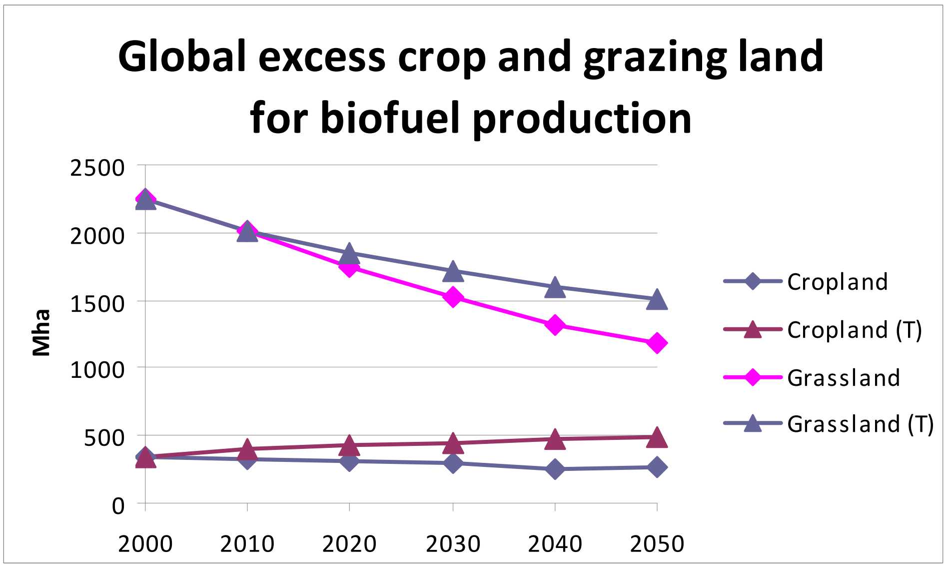

Figure 6: Excess cropland and grazing land

After securing food supply and preserving biodiversity at current productivity increase rates and for a technology scenario (T) in which the same Development Index value (0.82) of North America is reached in all regions before or in the year 2050.

The ambition to produce biofuel feedstock in a sustainable way was implemented by respecting the European rules in the Renewable Energy Directive (RED) and abide by the principles set by the Round Table on Sustainable Biomass (RSB). As a result, food security was set as a first priority for the use of cropland and grazing land. Therefore, regional expectations for developments in population growth, diet change and productivity of crops and grazing land were projected to the year 2050 (see Annex 4). A global share of 50% cereals and 20% oilseed crops in human diets was used to calculate the land requirements for food security with the productivity increase rates from Table 4.

The fifth step concerned the application of additional sustainability criteria on land use. As a rule, only annual biofuel crops were selected on possible remaining cropland to retain flexibility for instantly returning to food crops when required. To preserve biodiversity, remaining grazing land after securing food supply was only partially used for biofuel production. Following other authors [14], 30% was set aside for biodiversity motives. On grazing land, only perennial biofuel species were selected, in order to minimize the negative impact of greenhouse gas emissions by land use change. In the methodology, the use of forest land and high carbon stock grazing land as well as protected areas was excluded for biofuel production. As an additional rule, the annual oil and lignocellulose crops were grown in a 2:1 and 1:2 rotation to prevent soil and plant health problems related to the growth of the same crop year after year. For perennial species the same ratio was applied.

In the applied methodology, the sub-optimal growth conditions for crops grown on grazing lands were also acknowledged. Sub-optimal growth conditions for crops on grazing land may result from reduced soil fertility of grazing lands, adverse soil chemical properties and by slopes. In the methodology, crop productivity was reduced by 25% if grown on grazing land.

As the sixth and last step, the production of oil or lignocellulose volumes were calculated for different scenarios of crop rotations and land use and converted to primary energy by lower heating values (LHV) of 17.8 GJ ton^{-1} for lignocellulose and 38.0 GJ ton^{-1} for vegetable oil. In the scenarios the final volumes of oil or lignocellulose were set as a priority. The technology scenarios (T) that were applied point to the situation where productivity increase rates lead to a Development Index value of 0.82 before or in the year 2050. All scenario options are summarized in Table 6. Results are displayed in Figure 7 and Figure 8 and the final results in 2050 are summarized in Table 7.

		Cropland					Grazing land					
Scenario	Name	Landuse	Annual	Perennial	Oil	Ligno	Landuse	Crop prod.	Annual	Perennial	Oil	Ligno
1a	Max oil	100.0%	100.0%	-	66.7%	33.3%	70.0%	75.0%	-	100.0%	100.0%	*
1b	Max oil, no grazing land	100.0%	100.0%	-	66.7%	33.3%	-	-	-	-	-	-
2a	Max ligno	100.0%	100.0%	-	33.3%	66.7%	70.0%	75.0%	-	100.0%	-	100%
2b	Max ligno, no grazing land	100.0%	100.0%	-	33.3%	66.7%	-	-	-	-	-	-
1aT	Max oil (T)	100.0%	100.0%	-	66.7%	33.3%	70.0%	75.0%	-	100.0%	100.0%	*
1bT	Max oil, no grazing land (T)	100.0%	100.0%	-	66.7%	33.3%	-	-	-	-	-	-
2aT	Max ligno (T)	100.0%	100.0%	-	33.3%	66.7%	70.0%	75.0%	-	100.0%	-	100%
2bT	Max ligno, no grazing land (T)	100.0%	100.0%	-	33.3%	66.7%	-	-	-	-	-	-

[1] In case no perennial oilseed species was available for excess grazing land, a perennial lignocellulose species was selected

Table 6: Scenario settings for calculating global primary energy production on excess cropland and grazing land after securing food supply and preserving biodiversity**.**

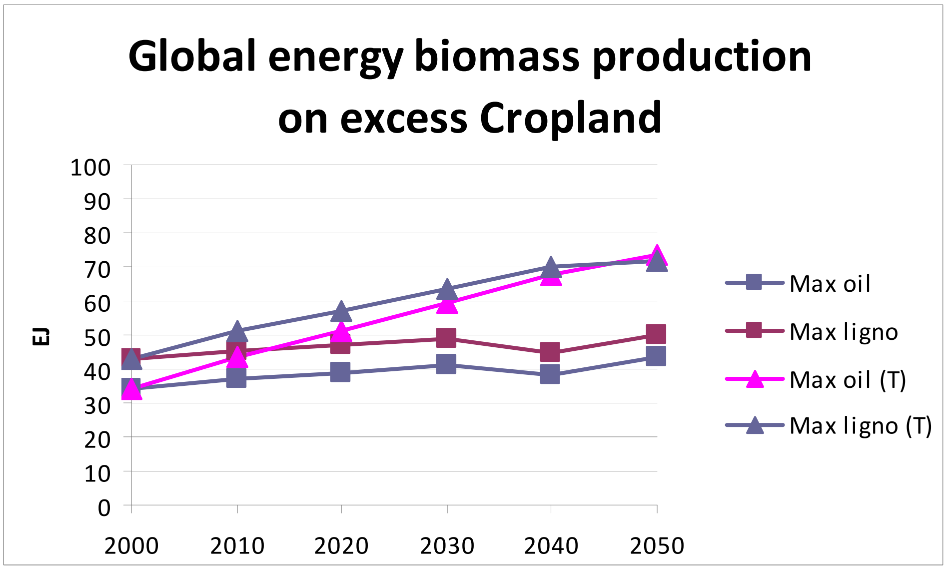

Figure 7: Energy biomass production (EJ) on excess cropland

After securing food supply and preserving biodiversity at current productivity increase rates and for a technology scenario (T) in which the same Development Index value (0.82) of North America is reached in all regions before or in the year 2050.

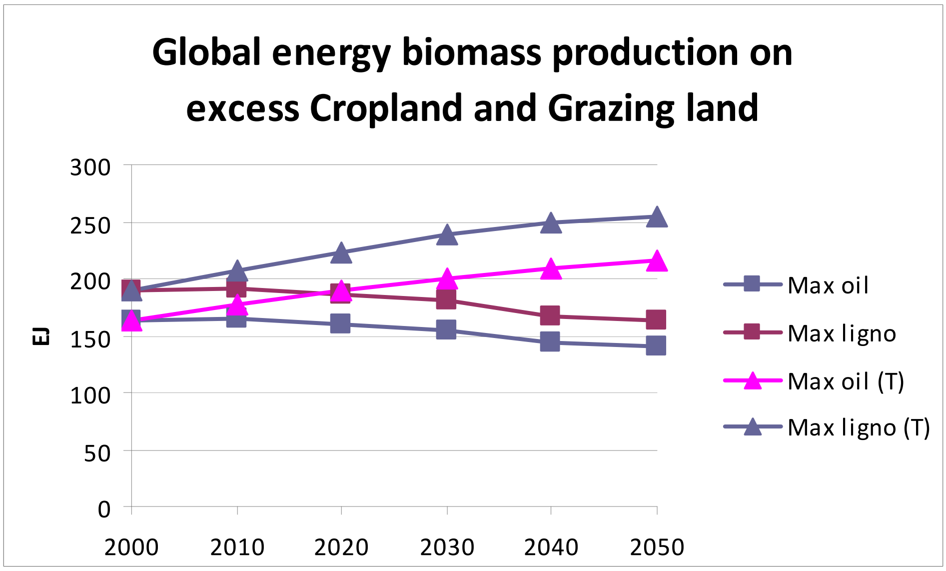

Figure 8: Energy biomass production (EJ) on excess cropland and grazing land
After securing food supply and preserving biodiversity at current productivity increase rates and for a technology scenario (T) in which the same Development Index value (0.82) of North America is reached in all regions before or in the year 2050.

Table 7: Global primary energy production results for different scenarios at current productivity rate scenario and for a technology scenario (T) in which a Development Index value of 0.82 is reached in all regions before or in the year 2050.

Result 2050 Global	Current Productivity Scenario (Extrapolate 1980-2009 values to 2050 [1])							
Scenario	Oil		Ligno		Sugar[3]		Total	
	(Mha)	(EJ)	(Mha)	(EJ)	(Mha)	(EJ)	(Mha)	(EJ)
1a Max oil	365	49.5	748	89.6	20	1.2	1133	140.4
1b Max oil, no grazing land	192	23.4	96	18.7	20	1.2	308	43.3
2a Max ligno	96	11.7	1017	150.9	20	1.2	1133	163.8
2b Max ligno, no grazing land	96	11.7	192	37.4	20	1.2	308	50.3

Result 2050 Global	Technology Scenario (Solving 82% of the yield gap in 2050 [1, 2])							
Scenario	Oil		Ligno		Sugar [3]		Total	
	(Mha)	(EJ)	(Mha)	(EJ)	(Mha)	(EJ)	(Mha)	(EJ)
1aT Max oil	547	70.6	996	143.5	20	1.2	1563	215.3
1bT Max oil, no grazing land	322	37.0	161	35.1	20	1.2	503	73.3
2aT Max ligno	161	18.5	1382	235.1	20	1.2	1563	254.8
2bT Max ligno, no grazing land	161	18.5	322	52.3	20	1.2	503	72.0

[1] No extrapolation beyond 82% of yield gap, the average year 2000 level of Northern America

[2] May occur before 2050

[3] Not analysed, only provided as illustration

Finally, the results of potential biomass production from agriculture, translated in fuel production, are given on Table 8 and Table 9 for the more conservative "current productivity increase" scenario[11]. Fist table gives the potential production from jet fuel when the hydroprocessing of oils is optimised for jet fuel production (then the kerosene yield is about 70% of the total hydroprocessed products) and the second one the respective production when the process is oriented toward diesel.

Scenario "max Kero", EJ/y		Grazing land			No grazing land		
		Oil	Ligno	Total	Oil	Ligno	Total
Max oil	Feedstock	41	90	131	19	19	38
	Kerosene	28	14	**41**	13	3	**16**
	Other fuels	12	41	53	5	9	14
Max ligno	Feedstock	10	152	161	10	38	48
	Kerosene	6	23	**29**	6	6	**12**
	Other fuels	3	69	71	3	17	20

Table 8: Agricultural biomass potential at world level in 2050

Simulation for current productivity increase scenario and optimisation of hydroprocessing for jet fuel production.

Scenario "max diesel", EJ/y		Grazing land			No grazing land		
		Oil	Ligno	Total	Oil	Ligno	Total
Max oil	Feedstock	41	90	131	19	19	38
	Kerosene	12	14	**25**	5	3	**8**
	Other fuels	28	41	68	13	9	21
Max ligno	Feedstock	10	152	161	10	38	48
	Kerosene	3	23	**26**	3	6	**8**
	Other fuels	6	69	75	6	17	24

Table 9: Agricultural biomass potential at world level in 2050

Simulation for current productivity increase scenario and optimisation of hydroprocessing for diesel production.

The second case is often considered as more likely to happen due to a higher interest for producer to make diesel fuel. Even in the less favourable case, one can see that a significant amount of jet fuel can be produced compared to the demand of the most requiring IATA target, providing in addition a significant amount of co-product fuels. This is the case when energy crops are produced using both

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[11] A 85% in mass for the final products is assumed fro hydroprocessing, and a yield of 25% in mass for BTL.

For BTL the ratio of kerosene is assumed to be 25%, for hydroprocessing it can be either 30% or 70% depending on the optimisation of the process.

croplands and grazing lands. When production is restricted to croplands, the potential decreases drastically and no longer matches the aviation demand, even for the less demanding "carbon neutral growth" target.

From the point of view of jet fuel production, favouring oil seeds crops provides an advantage in terms of volume of fuel produced only if hydroprocessing plants are optimised for jet fuel production. In the other case, higher results are obtained by favouring lignocellulose crops. From a global point of view, considering the total final energy produced, the "max ligno" scenario always provide higher results and is probably to be preferred[12].

These results are nevertheless theoretical results which assume that the increase of yields is achieved and that all the lands are put in production. This means that fertilizers are available in sufficient quantities and also equipment, infrastructures and manpower.

Table 10 provides the geographic distribution of the production. The highest potential is located in America, both Northern and Southern, while Africa has the lowest production capability in 2050.

Europe has a significant potential, the largest part, about 81%, of this production originating from Eastern Europe[13].

Figure 9 also shows that except for Europe and Oceania, the potential decreases over time, especially for Africa and Northern America.

Geographic area	Oil	Ligno	Kerosene	Other fuels	Total biofuels
Africa	0.2	8.5	1.3	4.0	5.3
Asia	1.3	8.7	1.7	4.8	6.5
Europe	3.7	15.9	3.5	9.7	13.2
Latin America	0.7	43.2	6.7	20.0	26.8
Northern America	3.2	45.7	7.8	22.9	30.7
Oceania	0.4	29.5	4.6	13.6	18.2

Table 10: Potential biofuels production per geographic area (in EJ/y)

Scenario "Max lingo" and "Max diesel", energy crop on both croplands and grasslands

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[12] One could nevertheless object that we have here the results of a global choice of type of crops to be favoured and not an optimisation region per region of the choice between oleaginous and lignocellulose.

[13] In the 22 UN regions considered here, Eastern Europe comprises: Belarus, Bulgaria, Czech Republic, Hungary, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Ukraine

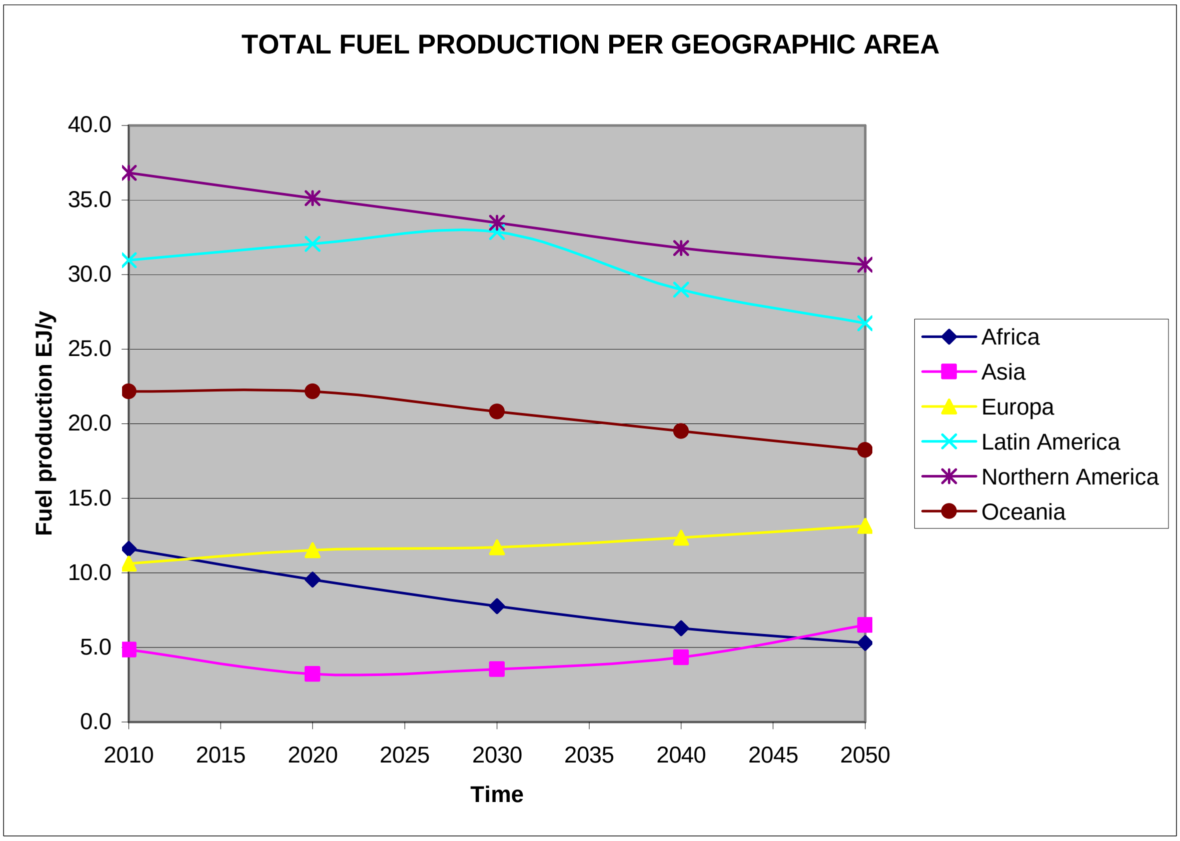

Figure 9: Evolution over time of total fuel potential production per geographic area

3.2.2 Forest resources

No proper evaluation of forest resources was carried out in the frame of the SWAFEA study. Data have been extracted from literature review. In forest we don't include short rotation forestry which was included in agriculture resources.

A detailed analysis of the potential of forestry for bioenergy in 2050 has been carried out and published by Smeets and Faaij [15] in 2006. It includes all kind of woody biomass from forestry, defined as all the aboveground woody biomass of trees, including all products made from woody biomass. The projection was performed by comparing the future demand with the future supply of wood on the basis of a review of existing databases, scenarios and outlook studies (in particular from FAO). Results are provided at world and regional (FAO) levels and distinguish between roundwood and wood residues and wastes.

Different scenarios were considered in the study to provide a range of evaluations. It combines 3 demand levels (low, medium, high) coming directly from the compilation of literature data about roundwood and woodfuel demands in 2050. Three origins of wood are considered: trees outside forests (TOF, which are trees growing in orchards, meadows, gardens, alongside roads etc.), plantations (for which three levels of production were also considered depending on the extension of plantations) and natural forests. The wood available for bioenergy is the difference between wood supply and demand, priority being given to other uses than bioenergy for sustainability reasons.

The bioenergy potential of forests is limited to surplus forest growth, meaning forest growth not used for roundwood and woodfuel when assuming that TOF and plantations are not used for bioenergy. It is based on the yearly increment that means the maximum of wood that can be annually harvested from forests without deforestation or reducing the standing stocks. Protected area are excluded (a minimum of 10% of protected forest is assumed at national level) and also inaccessible areas or areas that cannot be harvested with classical logging technologies. Deforestation is excluded in the results we present (results with a continuous deforestation trend are available). The considered yields nevertheless imply a much higher average intensity in global harvesting compared to the present ones, which is recognised by the authors as a potential danger for biodiversity. Also technology improvements are considered resulting in a 16% decrease of the wood demand (this percentage corresponds to the present possible gain if best technologies were applied).

A particular feature of the study is to consider that trade of wood is possible when a given region has a deficit of wood to satisfy its priority demand for industrial roundwood and woodfuel. However the authors recognise that long distance trade of traditional woodfuel is rather unlikely. Also the study doesn't take into account that demand and supply are normally in balance through price fluctuations.

The results from Smeet & Faaij are summarised for roundwood only (without residues) in Table 11. The figures exlude leaves, twigs, needles, etc. They are expressed in EJ on the basis of a Higher Heating Value of 20 GJ/ton[14]. Four levels of biomass availability are estimated:

- The technical potential which is the maximum potential including technical barriers;
- The economical potential which is the technical potential that can be produced at economically profitable levels;
- The ecological-economical potential that includes in the economical potential additional ecological criterion such as restriction of exploitation to already disturbed forests in order to preserve biodiversity;
- The ecological potential which only includes ecological criterion to the technical potential.

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[14] Usually for biofuels production, the Lower Heating Value is considered, which is about 18 GJ/ton for woody biomass.

The higher heating value (HHV) is determined by bringing all the products of combustion back to the original pre-combustion temperature, and in particular condensing any vapor produced. The lower heating value (LHV) is determined by subtracting the heat of vaporization of the water vapor from the higher heating value.

				Bioenergy potential	
Primary energy based on HHV - EJ/y		2002	2050	Range	medium demand / medium plantation
Demand	Roundwood & woodfuel	38	42 - 66		
Supply	Trees outside forests	13	13		
	Plantations	6 (1995)	9 - 23		
	Forest technical potential		103	59 - 97	70
	Forest economical potential		45	1 - 39	15
	Ecological - Economical potential		23	0 - 17	0
	Ecological potential		42	0 - 36	8

Table 11: Forest potential for bioenergy – Smeets & Faaij

The first comment about these results is clearly the very large range of the evaluation, from 0 to 97 EJ/y of forestry biomass at the world scale. The two main parameters behind this range are the uncertainty on the demand for roundwood and woodfuel (which varies by 50% depending on the scenario), and the contributions of the plantations to the total wood supply (variation by a factor 2.5 depending on the scenario). The authors also mention as key factors the area for harvesting and the yield. They indicate a poor quality of the data and the uncertainty related to future developments. In particular economical and future ecological considerations have a large influence on the future harvest intensity.

Logging residues (bark, branches, etc.) can be to this roundwood forestry resources. Their potential was also assessed by Smeets together with processing residues (woodchips, sawdust, black liquor) together with wood wastes (waste paper, discarded furniture, demolition wood, etc.). Due to a large number of parameters involved and to a lack of detailed data, the estimate is nevertheless not as detailed as for roundwood. The potential of forestry residues was computed to be between 21 and 35 EJ/y, the medium demand, medium plantation scenario leading to 28 EJ/y (39% from processing residues, 39% from waste and 22% from logging). Applying the same ratio to the lower and upper bounds of the variation range give an amount of logging residues between 4.6 and 12 EJ/y.

Results show that from a technical point of view, the demand for roundwood and woodfuel can be met without further deforestation and woody biomass can contribute significantly to energy production. Even in the worse case, there is a significant potential compared to the world primary biomass demand as seen by IEA's Blue Map scenario. Assuming a BTL transformation, the lower forestry biomass potential leads to about 34 EJ/y of fuel[15], which covers the whole biofuel demand seen by IEA. Considering that 25% of this fuel could be jet fuel, forestry biomass could lead to the production

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[15] Assuming a 0.25 yield in mass for the BTL transformation and a LHV of 43 GJ/ton for the fuel.

of 8.5 EJ of jet fuel per year, more than half of the required volume for the "carbon neutral growth" scenario. Achieving this potential means to significantly increase the level of harvesting and thus requires important infrastructure development and also manpower.

However economical and environmental criteria both considered separately or together, may strongly limit the supply of wood from the forests, leading to insufficient supply with regard to wood demand.

To estimate the economical potential, Smeet uses the Growing Annual Increment (GAI) of the commercial growing stock in 1995[16] as a proxy. Nevertheless, we can consider that such criteria are closely linked to the present view and the present energy context. In a world with a much higher pressure on energy, it could be assumed that the evolution of energy price would lead to different trade off between the various uses of wood and to different economical conditions for which the exploitation of forest is considered as viable. In this case, the economical potential of wood for bio-energy could be closer to the technical potential than assumed in the study of Smeet et al.

The technical figures of Smeet already include sustainability criteria: preservation of the stock and a minimum of 10% of protected forest. But authors recognize possible impact on biodiversity due to increased intensity of forest use (such exploitation also induces societal aspect meaning that "all forest" are exploited with consequences on recreational use or local use). Their ecological potential thus introduces a higher level of environmental protection by limiting the exploitation to already disturbed forests and taking into account soil erosion. This raises the question of the required level of preservation from a sustainability point of view including biodiversity.

Following the RED (article 17, paragraph 3), primary forest should not be used to provide feedstock for biofuels. The ecological criteria from Smeet should thus be used for the assessment which means that in a conservative approach, forestry potential is limited to logging residues and 4.6 EJ/y, while the "optimistic" potential is about 48 EJ/y (primary energy).

3.2.3 Residues and waste potential

Evaluations of residues and waste availability can be found in Hoogwijk(2003) [16] and Smeet(2007) at world level and in EEA(2006) and Fischer(2007) [18] for Europe.

In residues and wastes, we include:

- Agriculture harvesting residues (straw, stalk, leaves…);
- Process residues (or secondary residues) from crops and wood processing (oilcakes, hulls, shells, sawdust, wood chips…);
- Animal Manure;

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[16] The commercial growing stock is the part of the growing stock that consists of species considered as actually or potentially commercial under 1995 market conditions (following FAO Global Fiber Supply Model). Smeet recognizes it may be an underestimation of the economical potential of bioenergy.

- Waste (tertiary residues) including foodstuff unsuitable for human consumption, wood waste (paper waste or demolition wood) and municipal waste.

When aggregating or comparing the published data, attention should be paid to the way forest logging residues are accounted for because they are some time part of forest resources, some time of residues.

Hoogwijk(2003) results come from a literature review and cover all kind of residues and wastes.

Smeet(2007) results are associated to a global assessment of bioenergy potential at worldscale. It relies on agriculture scenarios that all assume a high degree of productivity because the authors' investigations came to the conclusion that food demand could only be achieved at this condition. Agricultural residues evaluations are directly associated with these levels of agriculture production and take into account the demand for feed.

Both analyses rely on the assumption that 25% of the residues can realistically be recovered because of their scattered production, their high moisture content and also their other uses such as organic fertilizers.

Results are summarised in Table 12.

	Agriculture residues	Wood residues[17]	Animal manure	Urban waste	Total
Hoogwijk(2003)	10 - 32 EJ/y[18]	10 - 16 EJ/y	9 - 25 EJ/y	1 - 3 EJ/y[19]	30 - 76 EJ/y
Smeets(2007)	46 - 66 EJ/y	21 - 35 EJ/y	na	-	76 - 96 EJ/y

Table 12 : Residues and waste potential (based on a Higher Heating Value of 19 GJ/ton)

From this figures, residues and waste appear as a significant source of biomass, with an energy potential similar to the one of forest resources. The largest contribution to this potential comes from agricultural residues (mainly primary) while urban waste appears as a marginal contributor in both cases[20].

With view to these evaluations, some limitations should probably be introduced.

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[17] In this table, wood residues include both wood harvesting and wood processing residues, detail being not known for Hoogwijk. For Hoogwijk, the assumption for recovery ratios range from 25% to 50% for harvesting residues, and 33% to 42% for sawmill residues.

[18] Taking only into account bagasse as secondary residues.

[19] based on a recovery assumption of 75% of municipal organic waste, and a range of 0.1 to 0.3 t of refuse per capita depending on the level of development

[20] It can be noted that IEA [17] provides much higher estimations for forest residues with a range from 30 EJ/y to 159 EJ/y depending on the standards for forestry material removal and technical potential.

First, animal manures don't seem to be actual candidate for biofuels production.

Also not all wood residues and waste are to be considered. If we refer to developed countries, almost all of the processing residues of wood are used (95% in France[21]). This could also be a trend for other areas along with development. Use of waste wood should also be considered carefully since these wastes are not necessarily suitable for biofuels due to contamination. We have thus chosen not to include wood residues in our assessment (logging residues being included in forest residues).

In addition, IEA [12] indicates that the analysis they carried out on a number of emerging and developing countries shows that a recovery ratio of 25% for the residues seems too optimistic since existing uses often reduce the availability of residues. IEA thus also considers in its evaluation of biomass availability a ratio of only 10%.

Finally, keeping in mind that the highest evaluation of Smeets are associated to very high technology level in agriculture, the lower bound of the evaluation range for agriculture residues is probably a more conservative value. Applying a range of recovery ratio from 10% to 25% leads to a range for agricultural residues between 16.6 and 46 EJ/y.

Assuming a 0.25 yield in mass for the BTL transformation, a LHV of 43 GJ/ton for the fuel[22], this would lead to about 8.9 to 24.7 EJ/y.

3.3 Synthesis of biomass availability

Finally, assembling the previous results for the different sources of biomass leads to the figures in Table 13 for the total primary energy:

EJ/y	Agriculture	Forestry	Residues	Total
Primary energy	162.2	4.6 - 48	16.6 - 46	183.4 – 256.4

Table 13 : Total primary energy potential in 2050

In this table, in a conservative approach, we have chosen the lower technology hypothesis and following the conclusion of chapter 3.2.1, we have considered the agricultural scenario maximising the production of lignocellulose biomass. In a same conservative way, we will only take into account the lower bound in the continuation.

Compared to the primary energy demand from Table 1, the biomass potential represents 18.8%of the total demand in the reference scenario, and 24.5% of the aggressive "Blue Map" scenario. This is a

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[21] FCBA

[22] Which leads to a conversion factor of about 0.56

significant percentage which nevertheless evidences the strong need for other energy sources. In the same time the biomass contribution to global energy mix projected in the IEA's Blue Map scenario is not so far from the assessed biomass potential.

If fully converted in biofuel, assuming BTL process and oils hydroprocesssing, this biomass can produce about 112 EJ/y of final energy[23], which represents 16.9% of the final energy total demand of the reference scenario, and 25% of the one of the Blue Map. This potential biofuel production covers the total transport final energy demand of this second scenario, and is significantly higher than the contribution of 29 EJ/y projected by IEA for biofuel in transport.

From the 112 EJ/y of biofuels, about 29 EJ/y can be jet fuel if biofuel production is dominated by diesel production and 32 EJ/y if jet fuel is targeted in priority in oils hydroprocessing. These figures have to be compared with the jet fuel demand ranging from 13.5 EJ/y for the carbon neutral growth scenario, and 20.1 EJ/y for the 50% emissions reduction target, keeping in mind that these two figures are underestimations since actual LCA emissions of the fuel are neglected. Assuming a 80% "carbon intensity" for biofuels[24], which is already an aggressive value with view to the results presented in chapter 4.1, would require 16.7 EJ/y of biofuel for carbon neutral growth and 24.4 EJ/y (fuel kerosene substitution[25]) for the 50% emissions reduction target in 2050.

Finally with this 80% biofuels "carbon intensity" assumption, reaching the 50% emissions reduction in 2050 would mean to use about 76% of the total biomass potential to make biofuels. Aviation would then use 21.8% of the total biomass primary energy potential.

In such a scheme, 24.4 EJ/y of jet fuel would lead to the production of 61 EJ/y of co-produced biofuels. This last value corresponds to a much higher contribution of biofuels in other modes of transport than projected in the IEA's Blue Map scenario which accounts for 29.1 EJ/y corresponding to a biofuel share of 26% in transport. More generally, using the BTL conversion ratio, the Blue Map scenario projects only the use of 54 EJ/y, i.e. 36%, of biomass primary energy for biofuels, meaning that 96 EJ/y, 64%, of the primary biomass demand is dedicated to other uses. When 76% of our assessed biomass is used for biofuels, only 43 EJ/y are left for other uses. **Reaching the IATA 50% reduction target thus means to displace a significant part of the other world biomass demands toward other sources of energy**.

From this point of view, the carbon neutral growth scenario is probably more realistic whilst still very demanding. With 16.7 EJ/y of jet fuel, it requires 52% of the biomass to be processed into biofuels which is still higher than IEA's projection. This scenario would lead to 41.6 EJ/y of

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[23] Sugar from sugar cane has been neglected in this figure.

[24] Emissions from biofuel = 20% of kerosene emissions

[25] Fuel complete substitution is in fact insufficient to reach the 50% reduction target if the biofuel carbon efficiency is 20%.

co-produced biofuels, a global share of biofuel in transport final energy demand of 52% and would let 88 EJ/y for other uses.

However, it should be underlined again that this potential corresponds to a theoretical potential associated to strong uncertainties, even if the most conservative values have been selected at each step of the assessment. **Achieving this potential requires a significant effort and development of the agriculture production, meaning high investments in infrastructure, education and also the availability of manpower. If some "realistic" figures have been retained in the potential yields increases, it does not ensure that the agriculture production can ramp-up following the time schedule considered in this assessment.**

Finally, one can remark that from chapter 3.2.1 that the availability of biomass from agriculture, which is by far the major contributor to our estimate of the total biomass potential, is decreasing with time. At the same time, the projections for air transport see a continuous growth of the traffic and fuel demand. In the long term, the two evolutions are therefore not compatible, showing the need for either a revolution in aircraft efficiency and energy sources or the identification of additional sources of biomass.

3.4 European biomass potential

3.4.1 Agricultural resources

If the global methodology of chapter 3.2.1 is applied to the EU27 countries[26] to evaluate its role in the global picture, several input variables change. The productivity increase of cereal crops (maize and wheat) and oilseed crops (soybean, sunflower, and rapeseed) is quite different for the countries in the UN region and EU27 countries (Table 14).

	Eastern Europe		Northern Europe		Southern Europe		Western Europe	
	UN	EU27	UN	EU27	UN	EU27	UN	EU27
Cereals	1.07%	1.92%	-0.30%	-0.19%	1.39%	5.34%	1.21%	10.23%
Oil seeds	0.86%	1.22%	0.72%	0.36%	1.14%	0.58%	0.90%	1.27%

Table 14: Average productivity increase rates (% year^{-1}) for cereals and oilseed crops in Europe UN regions and in EU27 countries between 1980 and 2009 (FAOStat).

Also for the statistics on cropland and grazing land around the year 2000 differ considerably (Table 15).

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[26] EU27 comprises Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom

	Eastern Europe		Northern Europe		Southern Europe		Western Europe	
	UN	EU27	UN	EU27	UN	EU27	UN	EU27
Cropland	204.6	26.4	15.4	19.8	42.1	24.9	31.5	34.8
Grazing land	116.5	13.3	23.3	34.6	28.3	22.5	25.3	29.5

Table 15: Cropland and grazing land (Mha) for the year 2000 (average 1997-2003) in Europe UN regions and in EU27 countries (FAOStat).

Figure 10 displays the development between the year 2000 and 2050 of EU27 excess crop and grazing land that may be available for biofuel production after securing food supply and preserving biodiversity, thereby taking into account the projected changes in population size, diet change and productivity increase of the crops.

The EU27 biofuel production (EJ) between 2000 and 2050 on excess cropland is given on Figure 11 and on excess cropland and grazing land on Figure 12. The 2050 distribution of cropland and grazing land over lignocellulose and oilseed crops with their energy production can be found in Table 16.

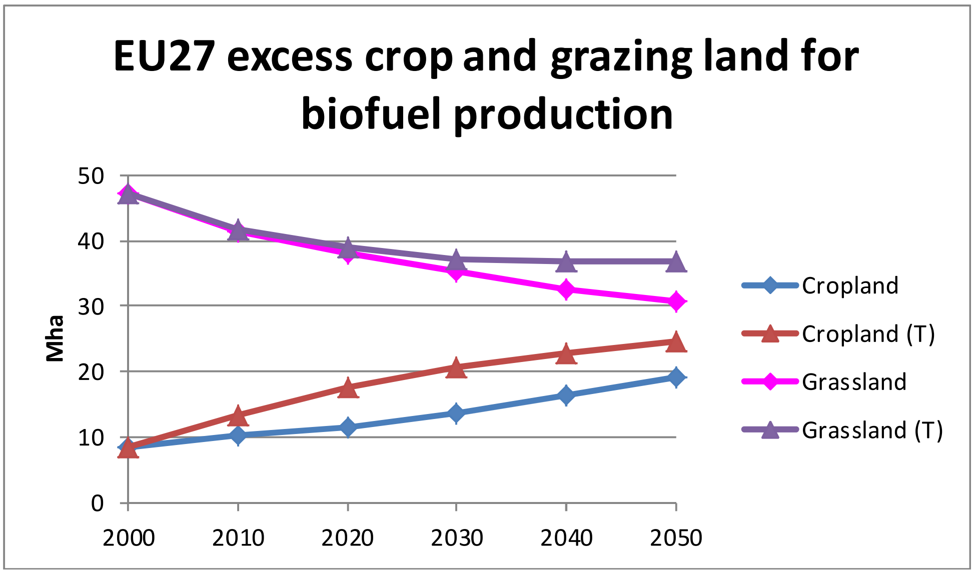

Figure 10: Excess cropland and grazing land in EU27 countries after securing food supply and preserving biodiversity at current productivity increase rates and for a technology scenario (T) in which the same Development Index value (0.82) of Northern America is reached in all regions before or in the year 2050.

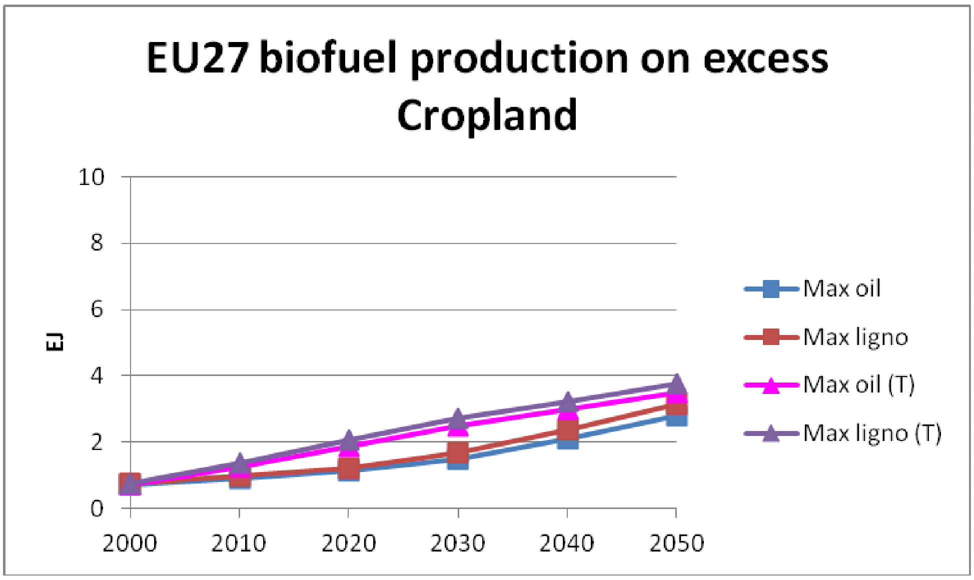

Figure 11: EU27 biomass production (EJ) on excess cropland after securing food supply and preserving biodiversity at current productivity increase rates and for a technology scenario (T) in which a Development Index value of 0.82 is reached in all regions before or in the year 2050.

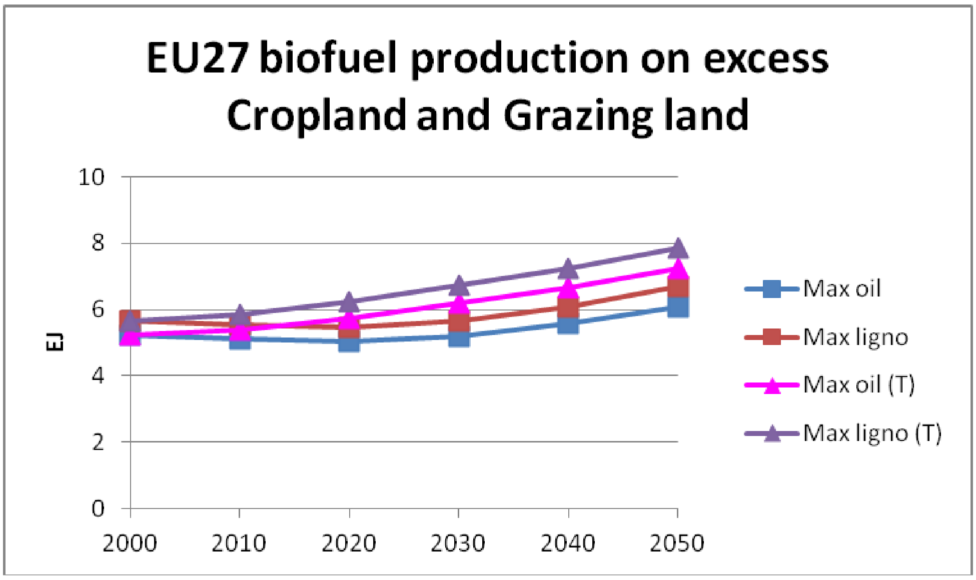

Figure 12: EU27 biomass production (EJ) on excess cropland and grazing land after securing food supply and preserving biodiversity at current productivity increase rates and for a technology scenario (T) in which a Development Index value of 0.82 is reached in all regions before or in the year 2050.

Result 2050	Current Productivity Scenario							
EU27	(Extrapolate 1980-2009 values to 2050 [1])							
Scenario	Oil		Ligno		Sugar[3]		Total	
	(Mha)	(EJ)	(Mha)	(EJ)	(Mha)	(EJ)	(Mha)	(EJ)
1a Max oil	13	1.7	28	4.4	0	0.0	41	6.1
1b Max oil, no grazing land	13	1.7	6	1.2	0	0.0	19	2.8
2a Max ligno	6	0.8	34	5.9	0	0.0	41	6.7
2b Max ligno, no grazing land	6	0.8	13	2.3	0	0.0	19	3.1

Result 2050	Technology Scenario							
EU27	(Solving 82% of the yield gap in 2050 [1, 2])							
Scenario	Oil		Ligno		Sugar [3]		Total	
	(Mha)	(EJ)	(Mha)	(EJ)	(Mha)	(EJ)	(Mha)	(EJ)
1aT Max oil	16	2.1	34	5.1	0	0.0	51	7.3
1bT Max oil, no grazing land	16	2.1	8	1.4	0	0.0	25	3.5
2aT Max ligno	8	1.1	42	6.8	0	0.0	51	7.9
2bT Max ligno, no grazing land	8	1.1	16	2.7	0	0.0	25	3.8

[1] No extrapolation beyond 82% of yield gap, the average year 2000 level of Northern America

[2] May occur before 2050

[3] Not analysed, only provided as illustration

Table 16: EU27 primary energy production results for different scenarios at current productivity rate scenario and for a technology scenario (T) in which a Development Index value of 0.82 is reached in all regions before or in the year 2050.

Following the same assumption than in chapter 3.4.1 (conservative technology hypothesis, selection of the "max lingo" scenario and use of both croplands and grazing lands), the potential biomass available in EU-27 amounts to 6.7 EJ/y, 5.9 EJ/y coming from lignocellulose and 0.8 from oil.

The total conversion of this biomass in biofuels would produce 4.3 EJ/y of fuel including 1.43 EJ/y of kerosene.

3.4.2 Forest resources

At European scale, the European Environment Agency [19] has carried out a detailed analysis of the forest potential for bioenergy in the frame of a very strict sustainability framework insuring a resources use compatible with the environment.

The study evaluates the potential for the 25 European countries before last European Union extension, for the year 2030[27]. The evaluation includes the amount of unused forest residues and of complementary fellings[28] which is available when environmental guidelines are applied to the

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[27] Greece, Luxembourg, Cyprus and Malta were not included because of a lack of inventory

[28] Forestry biomass in this study comprises residues from harvest operations that are normally left in the forest after stem wood removal, such as stem top and stump, branches, foliage and roots.

increased use of forestry biomass. Among these guidelines are preservation of biodiversity, of soil fertility, soil erosion or water protection. The main criteria are:

- No intensification of use on protected forest areas;
- Foliage and roots are always left on the site;
- The extraction rate for residues from stem and branches is limited according to the suitability of the site (75% on highly suitable site and 15% to 50% on moderately to marginally suitable sites).

The environmentally compatible bioenergy potential from forestry residues is estimated to be around 15 Mtoe and could increase to 16.3 Mtoe in 2030. An additional 28 Mtoe in 2010, and approximately 23 Mtoe in 2030 could be provided by complementary fellings and their residues. The increase in forest residues from regular fellings is the result of a rising demand for traditional forest products, which at the same time implies a reduction of complementary fellings due to higher harvesting for traditional products.

The EEA notes that if fossil energy prize rises, a substantial amount of wood biomass could be diverted from competing industries toward bioenergy, mostly at the expense of pulp and paper production. Then energy potential would increase from about 2 Mtoe in 2020 to 16 Mtoe in 2030. It should be noted that the EEA's study was carried out with the rather low hypothesis concerning crude oil price of 35 € per barrel (~ 50 $/bbl).

The EEA's results are summarized in EJ/y in Table 17 together with Smeet's results for Europe when medium demand and medium plantation hypothesis are considered. Smeet's results however are for 2050 and Europe includes a larger area than EU-25 with in particular Norway and Eastern Europe including Bulgaria, Romania and the Balkan's Republics[29] (Eastern Europe as a whole representing a lower contribution than Western Europe to woody biomass: 40% for roundwood from a technical point of view, 14% for logging residues). It should also be kept in mind that in its most pessimistic scenario (high demand, low plantation), Smeet globally sees at world level a shortage of wood when economical or ecological constraints are considered.

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[29] Eastern Europe covers: Balkan's republics (except Turkey), Czech Republic, Hungary, Poland, Romania, Bulgaria, Slovakia, Slovenia.

		Roundwood	Wood logging residues	Total
2010: EEA, EU 25		1.17 EJ/y	0.63 EJ/y	1.80 EJ/y
2030: EEA, EU 25		0.96 EJ/y	0.68 EJ/y	1.64 Ej/y (+0.67*)
2050: Smeets, Europe	Tech. potential	2.8 EJ/y	0.8 EJ/y	3.6 EJ/y
	Economical potential	1.4 EJ/y	0.8 EJ/y	2.2 EJ/y
	Econ.-ecol. potential	0	1.0 EJ/Y	1.0 EJ/y
	Ecol. Potential	1.6 EJ/y	1.0 EJ/Y	2.6 EJ/y

Table 17: Forestry biomass for Europe

(*: additional amount for high crude oil price assumption)

Note that Smeets' results are expressed in Higher Heating Value, EEA's results in Lower Heating value

The main potential for complementary fellings is located in central Europe, Italy, France, and the United Kingdom. Spain also presents a potential because it currently uses a small part of forest increment. In Northern Europe, which has a high proportion of forest area, the biomass increment is almost already used today. For forest residues, the highest resources densities are located in central Europe and the United Kingdom.

Improved forest management practices could further improve the productivity of the forests. EEA however considers the potential as limited because of the already high management level in Europe. This is not necessarily shared by all experts who see some potential through plant breeding and new species. This has nevertheless to be evaluated with view to sustainability criteria and has also to take into account the various uses of wood that should remain possible when modifying species characteristics.

With view to the developments of this potential, some barriers have to be taken into account.

Viable exploitation of forest resources requires a minimum surface. In a country like France, 74% of the forest is shared by a multitude of private owners (FCBA [20]) which on the hand side complicates access to the parcels and on the other hand reduces their surface. FCBA estimates that the profitable threshold for smallholders is around 4ha and considers that unless a surge in cooperative creation, there will be low incentive for these owners to exploit their forest [21]. It can thus be expected that only medium to large exploitation will benefit from the development of the energy wood supply chain. Situation is nevertheless different in countries like Germany, Austria or Scandinavia. In Scandinavia, the owners of the forest are also the foresters.

The infrastructure required to access the wood resources also constitute a difficulty for the development of the production with potential societal acceptance issues. The availability of qualified manpower is also a difficulty because of the hardness of the work.

3.4.3 Waste potential

EEA (2006) provides an in-depth evaluation at European level for all kinds of residues and wastes (excluding logging residues which are classified as forest resources). The study considers the following principles:

- Waste minimisation;
- No energy recovery from waste currently going to recycling or reuse
- Household waste currently landfilled are made available for energy production;
- More extensive practice of agriculture (encouraged for sustainability) influence the availability of agricultural residues).

The availability of biowaste resources for the 25 European countries is seen to be almost constant from to 2010 to 2030 with a variation from 4.14 EJ/y (99 Mtoe) to 4 EJ/y. The reduction is associated to a decrease of household waste due to minimisation practice and a reduction in the wood processing residues due to a reduced demand for wood products and paper.

The contribution of the various residues and waste streams is given in Figure 13. Municipal wastes exhibit a significantly higher share than in the previously mentioned studies. They nevertheless do not represent more than 15% of the total waste and residues potential.

EEA mentions as main sources of uncertainties of the assessment: the uncertainties on historic statistics on waste, wood processing residues, the decrease of household wastes generation and the competing uses of waste. With energy price increase they suggest that a higher share of waste could be diverted to energy.

By comparison, Smeet gives a range from 6 to 7 EJ/y for residues and waste potential for Western plus Eastern Europe.

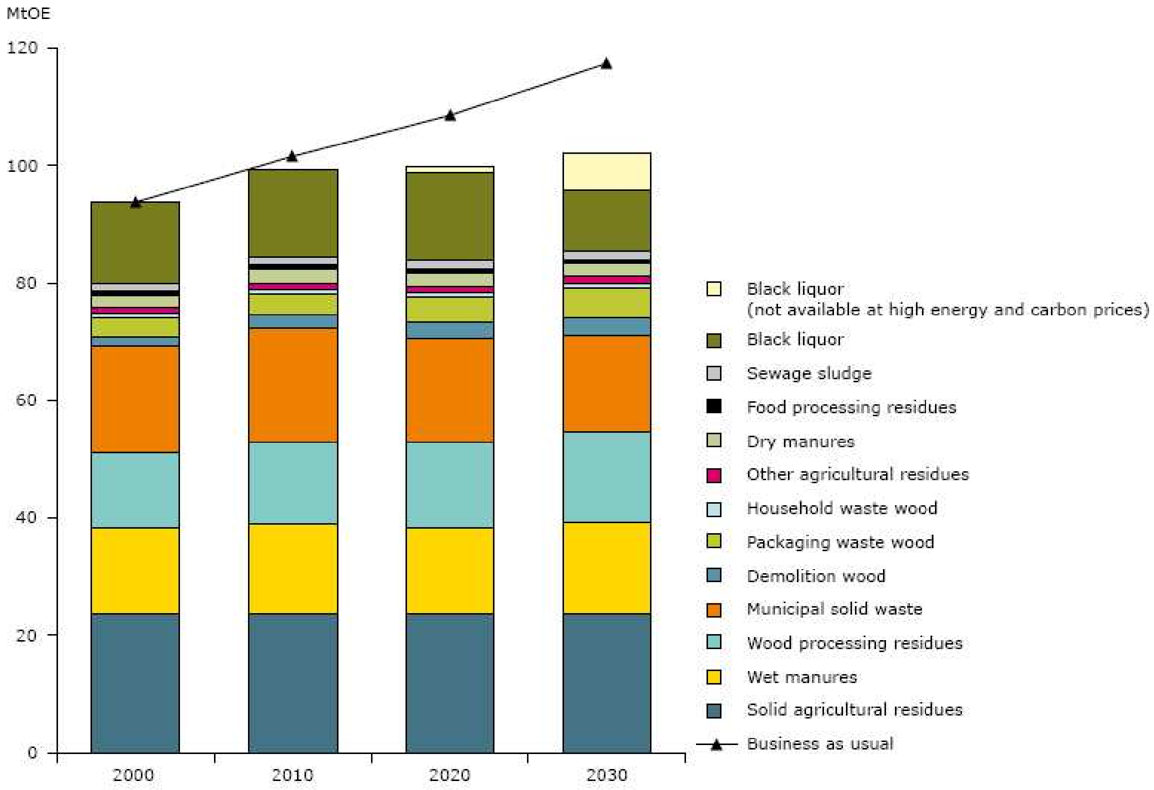

Figure 13: Environmentally-compatible biowaste energy potential in Europe-25 (EEA 2006)

Applying the same restriction than for global waste potential estimation leads to retain only agricultural waste, i.e about 22% or the total which represents 0.88 EJ/y. Adding urban wastes would lead to a potential of 1.48 EJ/y. Nevertheless urban waste may already be used for other application like heating which also induce less technical problems than conversion in biofuels.

3.4.4 Synthesis for Europe

Table 18 summarises the potential of the different sources of biomass for Europe in 2050 (for waste the value in 2030 as simply extrapolated).

Resources	Primary energy	Biofuel	Jet fuel
Agriculture	6.7	4.3	1.4
Forest	0.7 - 2.2	0.4 - 1.3	0.1 - 0.3
Waste	0.9	0.5	0.1
Total	8.2 - 9.7	5.2 – 6.1	1.6 - 1.8

Table 18: EU-27 biomass potential in 2050 (EJ/Y)

For biofuel potential, this table assumes a total conversion of European biomass in fuel. For forest a range of value is given: the lower bound corresponds to the global assessment of chapter 3.2.2 where a world shortage of wood is anticipated in the worse case.

The total amount of fuel uplifted from Europe was projected to be 1.7 EJ/y for the carbon neutral growth and 3.2 EJ/y for the 50% emission reduction target.

Considering a 80% carbon intensity for biofuels like in the global evaluation, the demand for jet fuel from Europe becomes respectively 2.12 EJ/y and 4 EJ/y.

This shows that Europe is not likely to be self sufficient for none of the two scenarios and has to import some biofuels or raw materials. For the carbon neutral growth scenario, if we make the same assumption as for the global biomass availability that 52% of the available biomass is converted in biofuels, Europe can provide about 38% of its fuel needs for aviation, which is nevertheless a lower dependency situation than with petrol. But the agriculture potential estimation was done considering Europe self sufficiency for food which may correspond to significant changes compared to the present trade situation.

3.5 New sources of feedstocks

The limitation on lands available for agriculture together with the concern about land use competition push for the search of feedstock which could provide very high yields or not enter in competition with traditional production for land usage. From their laboratory characteristics and performances, algae seem to promise both, with the additional advantage not to require fresh water. Thus algae have received over the recent years a large interest and communication success.

Theoretical and laboratory yields of algae are actually very high with a combination of a rapid growth and rich oil content. Depending on the species, oil contents between 20 and 77% are presented along with yields reaching 58 m^3/ha/y to 136 m^3/ha/y, which is about ten times the yield of oil palm [22].

Algae considered for biofuel application are mainly autotrophic microalgae. To grow, autotrophic algae need inorganic sources of carbon, such as CO_2, ammonia or nitrates as a source of nitrogen and photosynthetic energy to synthesize organic compounds. A second family of algae consists of heterotrophic algae which grow on natural carbon source such as sugar and for which solar energy is not necessary (heterotrophic algae are produced in fermenters). In that case however large quantities of sugar have to be produced that ultimately stem from crop plants, and algae can be seen as a way to process the sugar in lipids to further make fuel rather than a way to produce feedstock. Though it seems to concentrate less effort, this way was used for the first algal-derived aviation fuel (SolaDiesel RDTM produced by Solazyme Inc. from september 2008). Yeats can also be used in a similar way to produce lipids.

Currently algae production for energy use is at the preliminary development stage and no example of commercial energy production from algae exists. There is no experience on large scale cultivation (hundreds or thousands of hectares) ad processing [23]. The two main challenges for such a production are to confirm at large scale the high performances obtained in laboratory or pilots, and to reach competitive production costs for energy production. Indeed fuel produced from algae will have to compare with fossil fuel prices where prices of algae products may reach hundreds or thousands of dollars on other markets like health care products [24].

Intense activity is currently deployed in the field to address the various technical challenge of algae fuel production. It's also a highly competitive domain with intellectual property and patents issues that prevent scientists and entrepreneurs from sharing their system performance figures.

Technical challenge first concern the way to produce the algae. Two approaches are today competing, the open systems, mainly raceway ponds (Figure 14), and the photobioreactor which are closed systems. Raceway ponds have the advantage of a lower capital and operation costs but their productivity is lower [25]. There are in particular issues with temperature control, water evaporation, loss of CO_2 and possible contamination of the algae. Only a limited amount of species is dominant enough to maintain itself in an open system [24] [23]. Most of these drawbacks are solve by photobioreactors whose design is nevertheless complex. In addition to higher biomass production yields, photobioreactors also present the advantage of a high biomass concentration which significantly lowers the cost of harvesting [22].

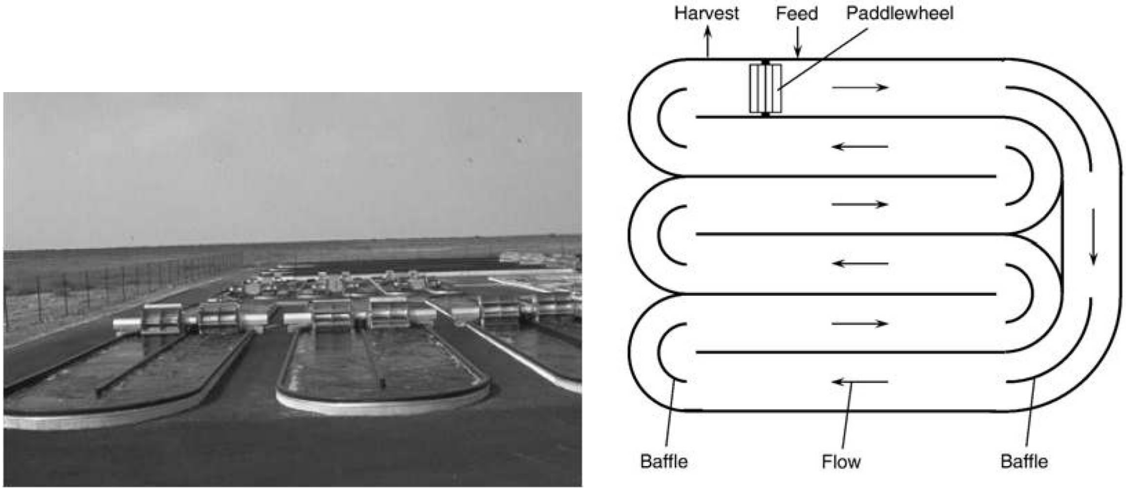

Figure 14: Raceway pond [22]

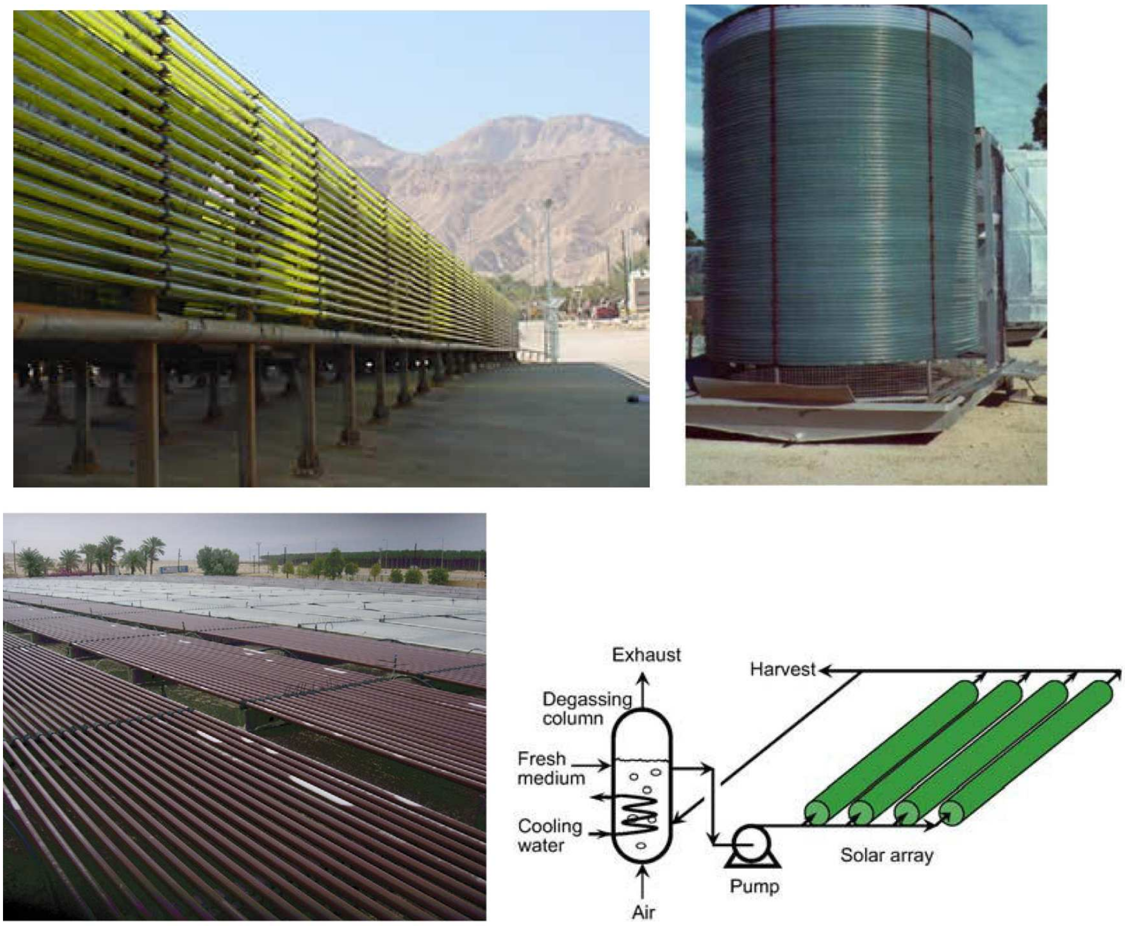

Figure 15: Photobioreactor [22]

R. Rodriguez [25] provides some comparative average figures for biomass production costs for the different systems. They range from 4100 $ per ton in open ponds to 9800 $/ton in photobiorectors (heterotrophic algae production in fermenters is comparatively cheaper with 2000 $ per ton) but the author points out some possible large variations. The University of Wageningen reports similar cost from a flat panel photobioreactor: 7.9 € per kilogram for a one hectare test. Figures provides for final oil range between from 2.1 $/l to 8.4 $/l for open ponds, and from 3.2 $/l to 9.1 $/l for photobioreactors.

Following Rodriguez, algae cultivation represents a limited part, about 17%, of producing algal oil. Largest contributors to final cost are harvesting and dewatering, 36%, and oil extraction, 40%. Photobiorector could thus compensate their higher capital and operating cost by their advantage from the harvesting point of view (Chisty provide lower biomass production costs for photobioreactor than for open ponds). Efficient harvesting techniques are thus required for an economically viable production of algae and a number of techniques (centrifugation, foam fractionation, flocculation, etc.) are currently investigated at laboratory or small scale production site. The same considerations apply for oil extraction.

From a general point of view, improving the economical viability of algae requires both technological improvements at each steps of the production process but also a high integration of the process and the development of synergy with other application and co-products.

Producing 1 kg of algae demands about 1.8 kg of carbon and achieving significant yields require bubbling CO_2 in the culture media. A source of CO_2 is thus needed, an ideal solution being to dispose of flue gases, for example from an electrical plant which could also provide heat for algae drying. Also a source of nutrients is required. They can be supplied in the form of agricultural fertilizers which are easily available but can be a significant cost factor. Use of wastewater from fishery or other animals farming are often suggested. These parameters also significantly influence the life cycle of the production both from the point of view of the energy balance and the green house gas emissions.

On other hand, developing algae production for the only purpose of biojet production doesn't seem feasible from an economical perspective and most algae start-ups are currently pursuing supplementing markets for their products. The co-production of high value biomass is essential to support the commercialization of algae based fuels. SBAE industry for example sees the production of oil for biofuels as a co-product of a main biomass production dedicated to fisheries [27]. Analysis of patent applications described by Sapphire Energy, Solazyme and Synthetic Genomics show a majority of non fuel application [25].

The requirement to think about algae production as an integrated system adds to the development complexity and may also limit the available production sites. A preliminary estimation of algae production capability in Europe has been carried out by Skarka [28] taking into account the constraint of the availability of both suitable land and carbon source. To ensure the availability of CO_2 for reasonable costs, it was assumed that an algal production facility has to be located within 2 km of a CO_2 source. In such a radius, only lands with sparse vegetation were selected. Protected areas were also excluded. Using yields from the literature and a lower heating value of 20 GJ/ton, Skarka estimates the overall production potential from microalgae in Europe and the Union of the

Mediterranean[30] to 0.35 EJ/y. Main production sites are in Spain, France and Italy. Germany also has a significant potential thanks to a large number of CO_2 sources. At the contrary, in North Africa, CO_2 sources are not sufficient. Wastewater availability was not taken into account in this preliminary study, neither solar irradiation. In those conditions, the author concludes that the potential of algae seems to be limited in Europe, which is confirmed when compared to the previous figures for other biomass.

As a conclusion, considering the early stage of algae production, drawing conclusion about their future potential and contribution to biofuel production seems premature. Research and demonstration at significant scale are still required and emergence of commercial large scale production may take time. However, their potential advantages clearly justify the continuation and the development of research in the field.

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[30] Union of the Mediterranean includes: Algeria, Armenia, Egypt, Israel, Jordan, Lebanon, Libya, Morocco, Tunisia, Turkey

4 LIFE CYCLE ANALYSIS

Based on the methodological guidelines set by the European Directive on the promotion and use on renewable energy (2009/28/CE) [1], assessments have been made within the SWAFEA study on greenhouse gases (GHG) emitted for the production and use of alternative fuels and on energy consumption associated to the various fuel chains. Those assessments were made following the Life Cycle Analysis principles. A detailed description of the methodology and of various assumptions made for calculations is available in the SWAFEA Life Cycle Analysis Report [30], but the main parameters and methodological choices are reminded below.

- Geographic and time relevance of the calculation: fuel chains evaluated are supposed to be relevant for the European Union in the middle term (~2020-2030). Depending on the chain assessed, some operations may occur outside the European Union, in particular biomass cultivation in the case of tropical species (e.g. Jatropha, Palm oil), primary resources extraction and treatment (e.g. natural gas, crude oil), conversion into final fuel in the case of Gas-to-Liquids plants (supposed to be build near gas fields).
- System boundaries: all steps from the raw material extraction and treatment (renewable or non renewable) to the final use of fuel are included. Impacts associated to infrastructure construction and dismantling are neglected, as well as the impact of the aircraft itself (those steps are either considered to be negligible in the final assessment or not relevant for the comparison of various alternative fuels – because the impact is the same in all cases).
- Accounting for co-products: in case of co-production (i.e. when a given step produces several outputs, including the product of interest), impacts are allocated to coproducts on the basis of their energy content (on a Low Heating Value basis). An exception to this is for electricity coproduced by cogeneration from a resource that is not a coproduct of the step: in this case, a credit is given to the step, equal to the amount of GHG emissions or energy consumption that would have been generated if a same amount of electricity had been produced from the same fuel with a standard power plant.

Alternative fuels for aviation produced from fossil feedstock and biomass feedstock have been assessed in this study. Fossil-based pathways assessed are Conventional Jet fuel and FT fuel from natural gas (GtL) from Qatar, Nigeria and Algeria. Biomass-based pathways studied cover:

- Hydrotreated Renewable Jet (HRJ) fuel from Rapeseed, Camelina, Palm, Jatropha and Algae;
- FT fuel from lignocellulosic biomass (BtL) including Miscanthus, Switchgrass and wood from Short Rotation Coppice (SRC).

4.1 GHG emissions

Figure 16 provides an overview of the results for different pathways investigated for the selected conversion processes. It corresponds to the value of specific processes (Renew for BTL and NexBTL for HRJ), knowing that sensitivity has been assessed for different processes and are given on Figure 17 (detailed results are presented in [30]).

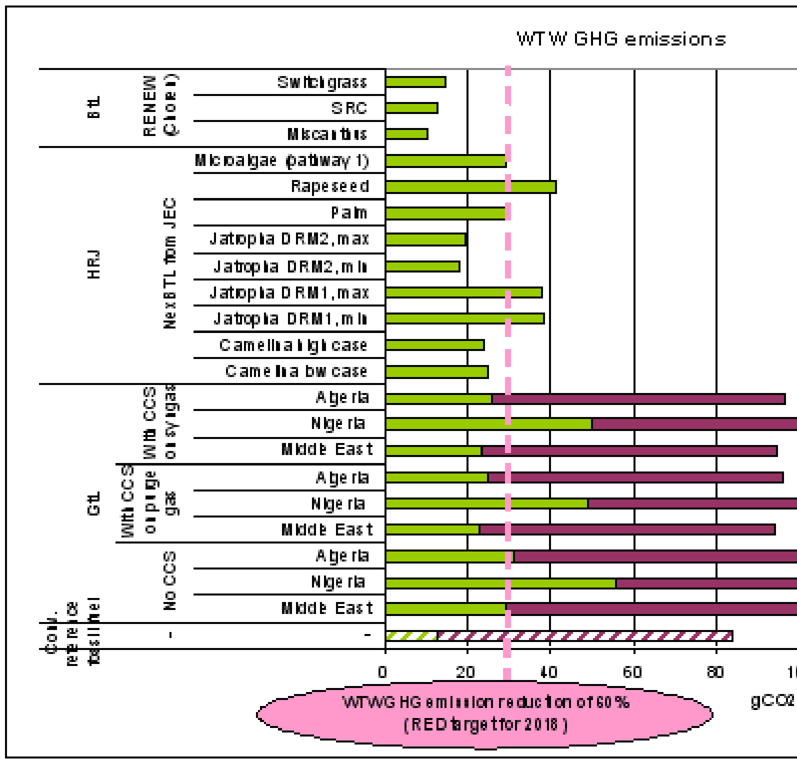
Concerning bio-based fuels in the European context, a minimum level is set by the RED for GHG emissions reduction associated to biofuels. From 2018 on, biofuels produced from conversion plants build after 2013 will have to reach a minimum of 60% GHG emissions reduction compared to the reference fossil fuel. All BtL considered in this study reaches this 60% reduction threshold. However, regarding HRJ, only some feedstock can achieve the 60% GHG emission reduction.

Generally speaking, as presented in Figure 17 & Figure 18, the highest contribution to GHG emission for biomass-based fuel is the cultivation step. This is due to the use of agrochemical inputs, such as nitrogen and associated upstream and downstream GHG emissions (in particular N_2O). HRJ chains may not reach the 60% emissions reduction when emissions during the cultivation step are particularly high. This is in particular the case for camelina when the scenario with the highest inputs is considered. By the way, camelina presents better results than rapeseed because of the lower level of nutrients (and also reduced consumption of diesel when culture without tillage is considered). Also for Jatropha, the better results are obtained when residues are returned to the land rather than using nutrients (DRM2 scheme). Hence for minimizing GHG emissions for bio-based fuel pathway, cultivation step has to be optimized.

One can also notice on that the different data used for the process lead to differences between the results but don't change the final tendencies.

Concerning the alternative fuels from fossil feedstock assessed in this study, GtL do not allow any possibility for reducing GHG emissions or energy consumption compared to reference fossil fuel, even in case carbon capture and sequestration (CCS) is used. This conclusion also applies for CTL (Coal to Liquid) which was not studied in the frame of SWAFEA but for which many results are available.

WTW GHG emissions for selected pathways ar



- The reference pathway considered for algae corresponds to autotrophic algae with average characteristics from literature data. ha. Pounds are located near an electrical plant in order to recycle the flue gases with 15% mass of CO_2. A purification step of microalgae use sunlight energy, CO2 and nutrients. These nutrients are supplied by sludge from waste water treatment plant co
- For jatropha, two different scenarios are presented. The first one, DRM1, considers that all fruits and seeds are removed. I methodology set by the RED. For the DRM2 case, coproducts of jatropha oil are supposed to return to soil. In this case, no agricultural inputs are lower because of the coproducts recycling. A sensitivity to the crop yields is also presented (with a minimu
- For camelina, two cultivation scenarios are compared: a first one with a lower fertilizer input and the absence of tillage, a second

Figure 16: SWAFEA assessment of WTW GHG emissions

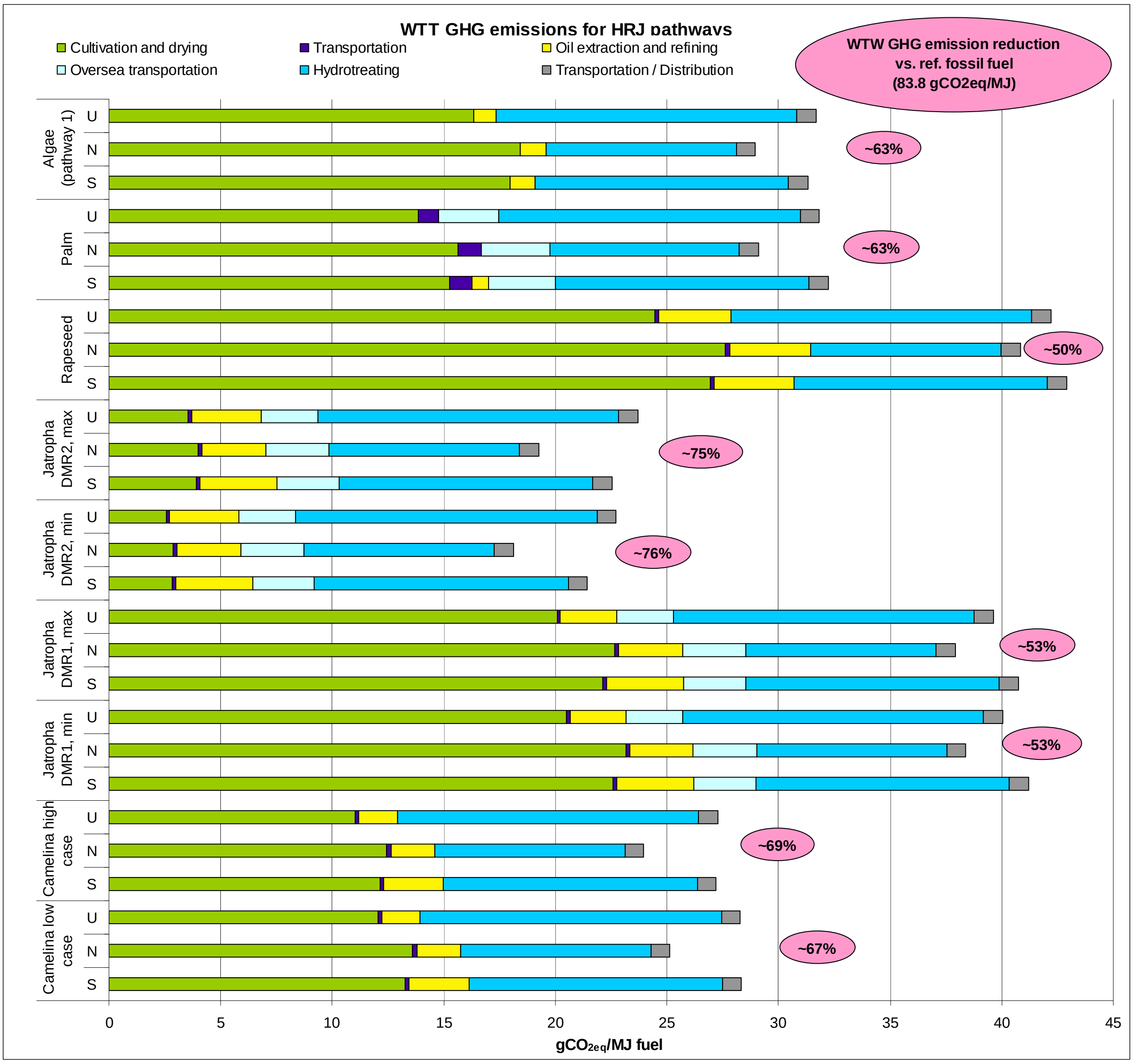


Figure 17: Contribution of well to tank GHG emissions for HRJ pathways

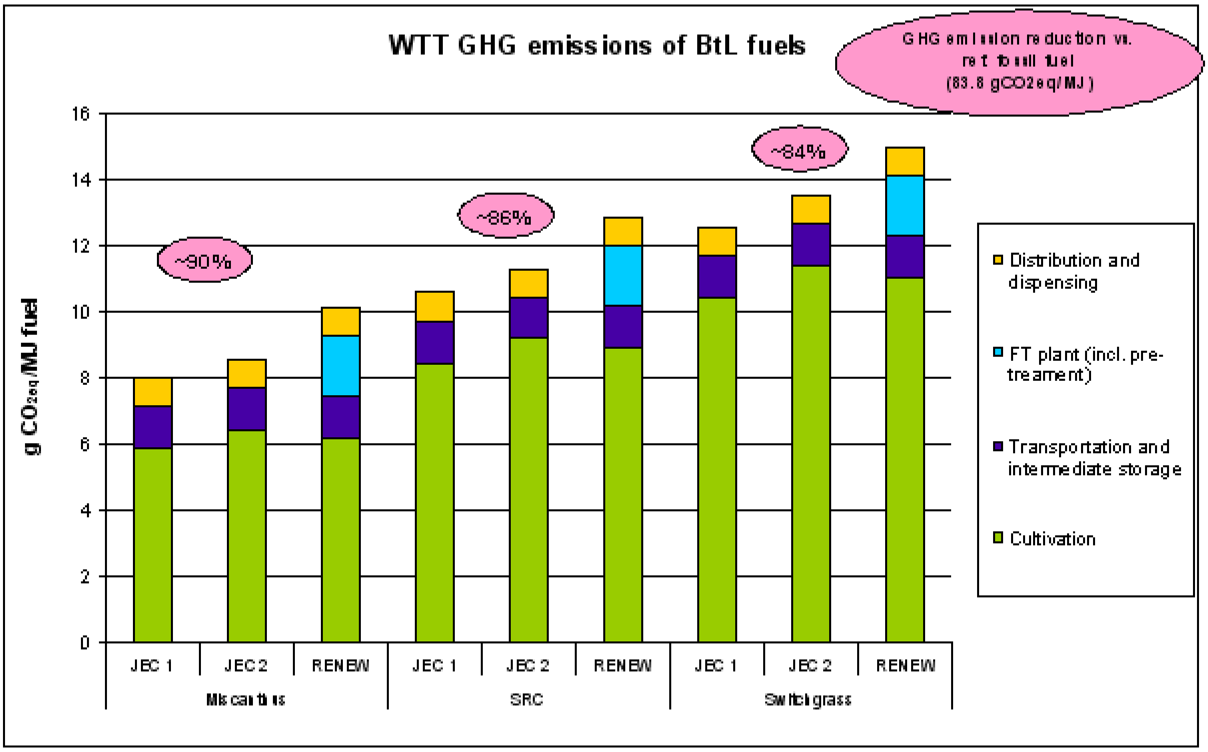


Figure 18: Contribution of well to tank GHG emissions for BTL pathways

(JEC1, JEC2 and RENEW correspond to the three different sources for process data)

An analysis of the sensitivity of the results to the input data is presented on Figure 19 which gives the variation range of GHG emissions for each pathway when some specific parameters are varied. Those parameters are:

- Nutrients inputs level and tilling for camelina;
- Recovery level of methane emissions from the fruit residues in case of palm oil;
- Diesel consumption for jatropha which in the literature shows high variation (knowing that in the reference scheme, harvesting is done manually);
- Energy efficiency of the plant for GTL synthetic fuel.

In case of algae, the influence of a number of parameters has been studies, including: origin of nutrients (recycling or chemical instead of sludge), harvesting and drying process, and extraction process (Figure 20).

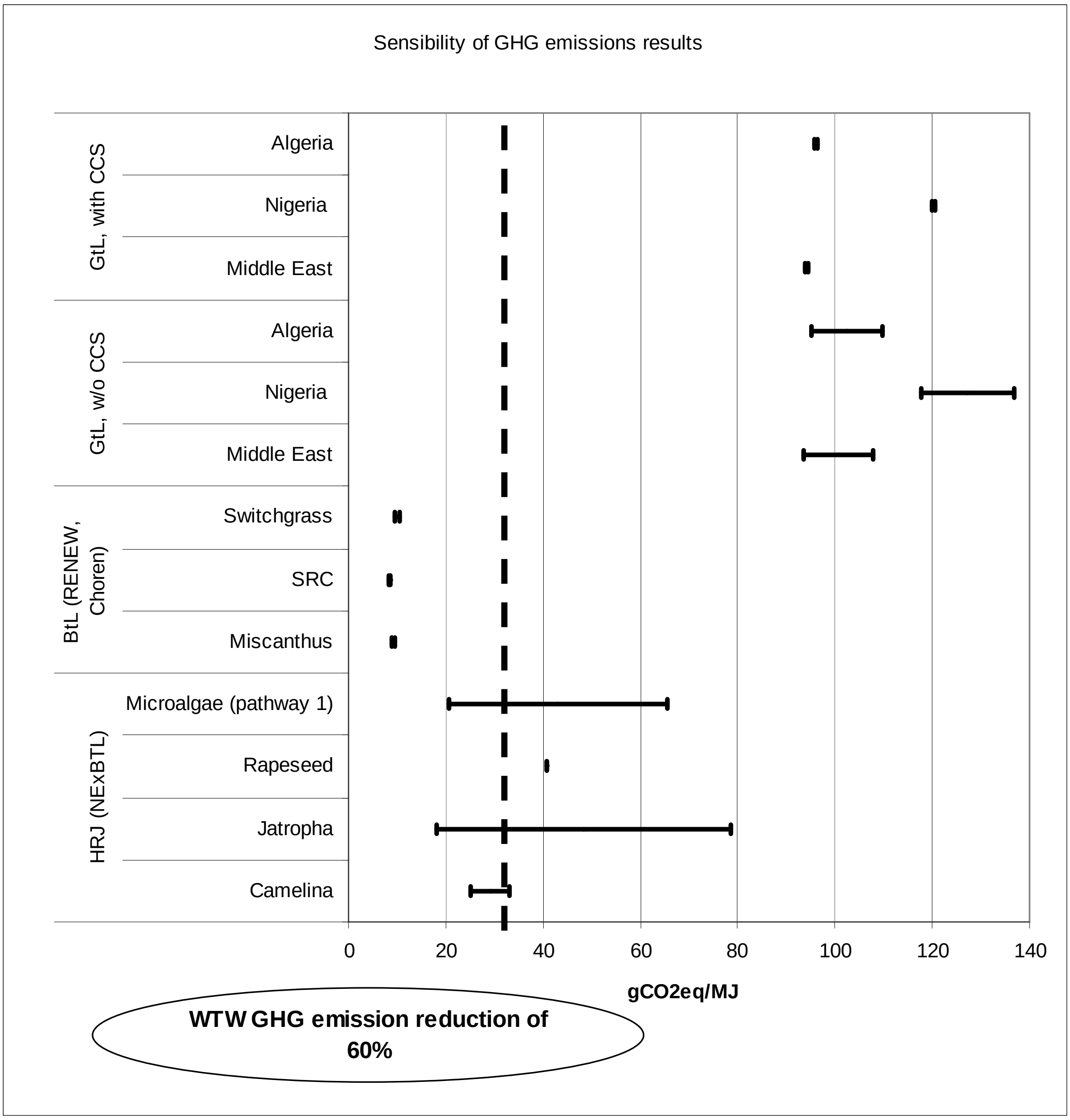


Figure 19: sensitivity analysis results on WTW GHG emissions for all pathways studied for chosen process conversion

As depicted on Figure 19 and Figure 20, especially for Algae, Jatropha, Camelina and GtL without CCS, results are very sensitive to the input data. Moreover, depending on the data considered a fuel can comply or not with the 60% GHG emission reduction target defined by the RED.

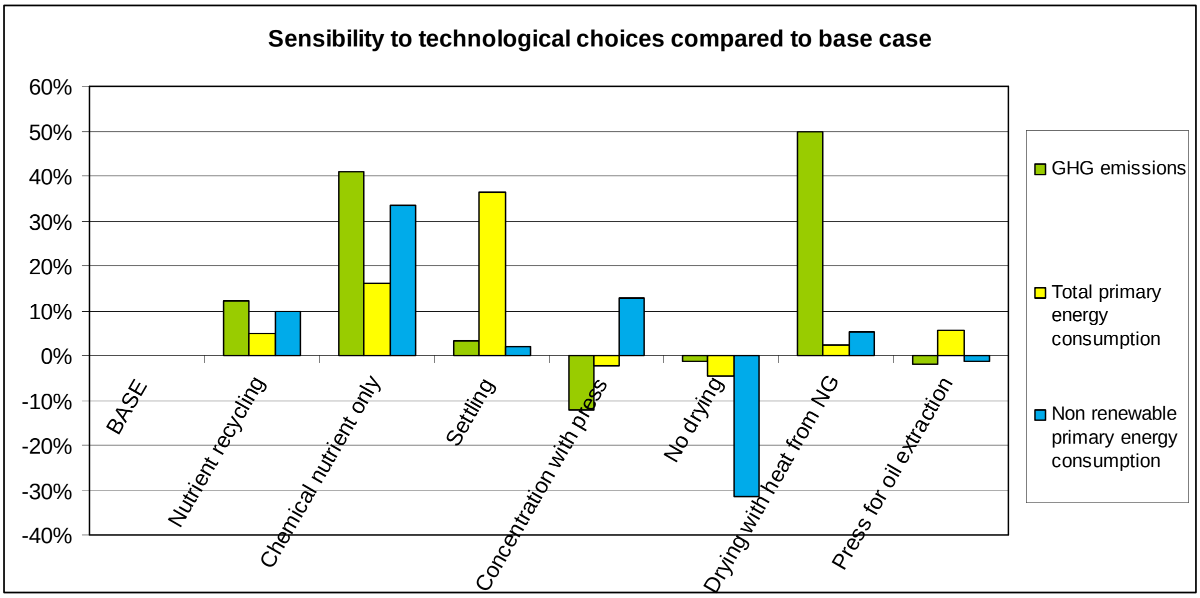


Figure 20: sensitivity to technological choices for algae WTT emissions

Methodological assumptions used in LCA are often cited as a very sensitive parameter and during the past 2 or 3 years, various initiatives have been launched (certification schemes, regulation) in order to give guidelines for GHG emissions assessments of biofuels. Despite difference of methodology in some calculation, the same tendencies in the results can be observed [32]. Specific assumptions are discussed today from a methodological point of view: ILUC, N_2O, carbon stocks… These assumptions are very site specific and can change the GHG balance in a positive or negative manner.

By the way, the analysis has shown a specific sensitivity of algae LCA to methodological assumptions and in particular to way of accounting for the co-product. This is due to the high energy content of the biomass residues after oil extraction which strongly reduces the emissions allocated to the oil production when an energetic allocation is used instead of an avoided impact methodology.

4.2 Expended Energy

GHG emission is not the only indicator that has to be taken into account in the present context. Increased scarcity of fossil energy and energy resources management are real issues that have to be handled in parallel with climate change issues. Energy use indicators such as total and non renewable primary energy consumption quantify the potential contribution for alternative fuels to these impacts. Results for energy indicators show that even if BtL is the best in terms of GHG emissions, it is the worst pathway in terms of total energy consumption. Indeed BtL process yields are poor (2MJ of feedstock for 1MJ of product) and should be optimized. In the same way HRJ from algae energy consumption has to be lowered by optimizing technologies and yields or by using renewable energy sources for covering energy requirements.

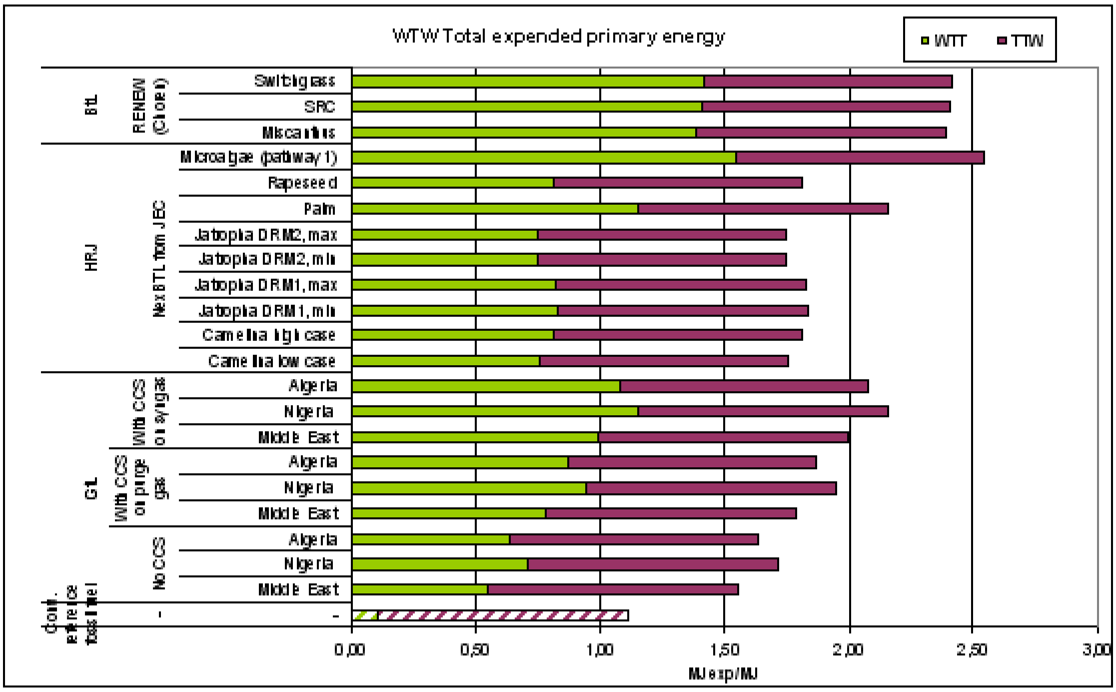


Figure 21: WTW total expended primary energy for all pathways studied for chosen process conversion

Compared to the total expended energy, for HRJ and BtL the non renewable energy consumption is smaller (Figure 22). For BtL, it corresponds to the biomass production step (fertilizers and diesel consumption). Regarding HRJ a half of this energy is consumed during the cultivation steps (fertilizers and diesel) but, hydrotreatment through the natural gas consumed for the production of hydrogen contributes for 15% to 40%. For algae, the main contribution to the consumption of non renewable energy is due to the heat required for the drying[31]. GtL with CCS on syngas consumes more non renewable energy than GtL with CCS on purge gas and also compared to GtL without CCS. For GtL, the consumption of the fuel itself contributes the most, followed by the energy required in the GtL plant.

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[31] In the present evaluation, the heat comes from the power plant. It nevertheless comes from non renewable energy and is accounted for in the indicator.

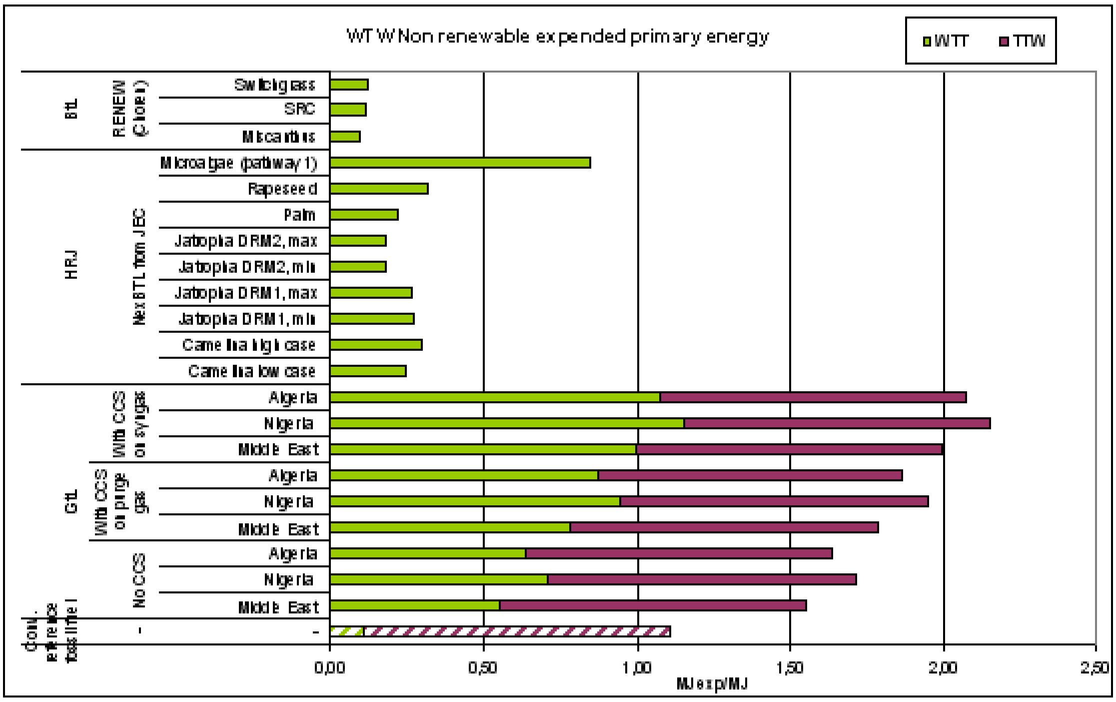

Figure 22: WTW non renewable expended primary energy for all pathways studied for chosen process conversion

4.3 Land issues

Land use change has not been included in the baseline calculation. However, this may have an important impact on GHG assessments. A lot of recent studies have shown that the contribution of land use changes may offset all benefits from a given alternative fuel if the biomass used for biofuel production is grown on a land formerly covered by vegetation with high carbon stocks (such as forests). In our study, the conversion of forests into cropland has not been taken into account, as it is excluded by the RED for the production of biofuels. However, some changes in the use of land have been evaluated (Table 19), in connexion with the hypothesis selected for the estimation of the biomass availability presented in chapter 3.2.1. Those changes include the conversion of grassland for the cultivation of perennial crop or the cultivation of perennial species on cropland. The results of those calculations are positive on the GHG balance, as the actual species cultivated stores more carbon than the reference land considered. On the contrary, cultivating annual crops could lead to carbon destocking. Either negative or positive, it should be mentioned than the land use change has a higher impact on LCA than the whole fuel production chain.

Reference land use considered		Grassland		Cropland		Grassland	
Climate region ***Soil type***		**Warm temperate, dry** ***High activity clay soils***	**Cold temperate, moist** ***High activity clay soils***	**Warm temperate, dry** ***High activity clay soils***	**Cold temperate, moist** ***High activity clay soils***	**Tropical Dry** ***Sandy soil***	**Tropical moist** ***High activity clay soils***
Annual crops	Camelina low case	79,7	277,2	-	-	-	-
	Camelina high case	63,0	192,9	-	-	-	-
	Rapeseed	40,0	122,4	-	-	-	-
Perennial crops	Miscanthus	-11,8	-7,9	-28,3	-63,7	-	-
	SRC	-17,3	-11,5	-41,5	-93,4	-	-
	Switchgrass	-16,6	-11,0	-39,8	-89,6	-	-
	Jatropha	-	-	-	-	-254,7	-328,6

(CO_2 emissions from LUC have been distributed over 20 years)

Table 19: Carbon stock evolution in soils expressed in CO2eq per MJ of Fuel (positive values means that soil destocks carbon, negative values means that soil stores carbon)

Other criteria are relevant for selecting promising bio-based pathways. Land occupation of the cultivation is an important one. As presented in Table 20, from a land occupation point of view, algae, palm and myscanthus are of particular interest for producing biofuels.

Feedstock	Biomass productivity in t/(ha*year)	oil content for HRJ feedstock (% weight basis)	Jet Productivity in GJ/(ha*year)
Rapeseed	3.3	40.5%	43
Camelina	2.2	40%	28
Palm oil	19 (FFB)	22.5%	149
Jatropha	0.5 – 1.5 (Dry seeds)	35%	6 - 19
Algae	75.6	34%	808
Miscanthus	15	-	118
SRC	10.5	-	81
Swictgrass	12	-	85

Table 20: Biomass indicative productivity per hectare

Water needs for cultivation must also be kept in mind to assess a bio-based fuel. Nevertheless no consensus exists for taking into account these issues. Indicators and dedicated methodologies for water issues assessment have to be further investigated.

4.4 Conclusions about life cycle analysis

The results of the assessment carried out within SWAFEA have first confirmed the previous results from the state of the art [2] about GTL pathways GHG emissions. GTL leads to an increase of GHG emissions even in case carbon capture and sequestration is applied. If GTL can have significant effect on the fuel security of supply for aviation by giving access to extended fossil resources, there is no hope that it could provide environmental benefit from the greenhouse gas effect point of view. Its deployment would even have detrimental impacts compared to traditional kerosene.

At the contrary, all the biofuels pathways considered in the study demonstrate a potential for GHG emissions reduction. Nevertheless, their ability to reach the RED's targets in terms of emissions thresholds depends strongly on the process and on the parameters and the optimisation of the pathway.

BtL pathways are able to reach this target and demonstrate significant emissions reductions, up to 90% in the case of myscanthus. A weakness of the BTL process is its poor yields, which translate in a high primary energy demand. Efficiency of BTL process calls all for an optimisation.

HRJ are emitting more GHG than BtL, and their ability to reach the target depends on the feedstock and on the emissions associated to the cultivation steps which have to be carefully optimised. Jatropha proved to offer the best performances of the studied crop for the cultivation conditions under consideration. Nevertheless its productivity is rather lower than for the other pathways considered here which in return would call for a larger amount of land.

For algae also, the whole production chain of algae oil needs to be optimised, the best performances being obtained with a high integration with CO_2 and nutrients sources. For the studied case, energy balance is worse for algae than for other biofuels, all the more that it is non renewable energy consumption. Energy is thus a point to be more precisely considered for algae.

All these potential benefits compared to kerosene can nevertheless only be achieved if no negative impact of land use change is associated to the feedstock production. Evaluation indeed shows that, either negative or positive, the land use change has a higher impact than the whole fuel production chain. Land use change is thus a primordial parameter for the selection of the crops and lands to be used for biofuel production. In a production scenario like the one considered in chapter 3, attempt was done to minimise land use change impact with eventually positive effect thanks to the selection of perennial crops for to grazing lands[32].

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[32] This scenario nevertheless doesn't guaranty that no indirect land use change can happen. Indeed, food requirement being satisfied first by conversion of grazing lands in croplands, and then imports if land is still not sufficient, land use can happen that would not happen is food from croplands was imported in priority.

5 ENVIRONMENTAL AND SOCIETAL IMPACTS

The previous chapters about sustainability frameworks, biomass availability and life cycle analysis have already pointed out a number of sustainability issues potentially associated to the development of alternative fuels and in particular of biofuels.

A first concern is directly related to one of the intrinsic motivations for going to biofuels which is the reduction of GHG emissions. Chapter 4 has clearly demonstrated the major contribution of land use change (LUC) to the life cycle emissions of any biofuel pathways based on agricultural feedstocks. Such dominating influence is also evidenced in other studies like the one carried out in the frame of PARTNER [31]. Beyond the direct control of the surfaces on which bioenergy cultures are developed, the issue is complicated by the indirect effects that biofuels production may have and in particular the indirect land use change (iLUC) which is today a sensitive issue.

Directly connected to the question of the availability of energy biomass but also to land use change issues is the question of the competition between energy and other use of biomass, with at first rank the competition with food.

A third global aspect is the preservation of natural resources like forests and biodiversity.

Then biofuel development has more local aspects covering local environmental impacts, such as water use or local pollution, and also societal impacts.

The purpose of this chapter is to provide a quick overview of these different impacts that should be taken into account in any biofuel development, for aviation as for the other energy use of biomass. In complement to the literature review, a number of case studies have been carried out in the frame of SWAFEA to illustrate various aspects of these environmental and societal impacts. They covered oil palm plantation in Indonesia, jatropha in Tanzania and Mozambique, wood in France and camelina in North America.

5.1 Direct and indirect land use change

Direct land use change is a straightforward issue the potential impact of which, in terms of green house gas emissions, leads to the requirement of a careful and strict control of the lands that are used for any settlement of energy biomass.

A much more difficult question is the indirect land use change resulting from displacement of cultures because of the deployment of energy crops on areas that were used for other purposes and especially for food production. An indirect land use change impact is initially triggered when an increase in the demand for a crop-based biofuel begins to drive up prices for the necessary feedstock crop. This price increase causes farmers to use a larger proportion of their cultivated acreage to grow this distinctive feedstock crop. The offset of this lack of food land leads to the use of land not previously used for agriculture[33]. The result of this process is deforestation which can have negative impact on the environment and climate. Culture may also be displaced on grazing lands with also potential negative impacts.

Various scenarios can lead to iLUC as illustrated by the following examples:

- Substituting normal crop production for energy crops or modifying the crop rotation to include energy crops cause a drop in supply of the original crop, which lead to land use change to restore the level of supply;
- Co-products of energy crops may increase the supply of animal feed, potentially causing farmers to shift their production activities to more profitable ones, potentially incurring emissions from land use change;
- Increased crop prices (potentially caused by energy crops being substituted for normal crops) will create incentives for crop importing nations to increase land use to reduce the amount imported, and encourage crop exporting nations to increase land use in order to increase sales. Within the EU, increased energy crops are expected to come from idle land, while in developing countries it is expected to come from expanded land use [33].

ILUC is difficult to observe and to calculate because it is an indirect process, it has a global impact and it has a temporal shift. Induced land use change may also occur in a completely distinct geographic area in case of trade modifications following energy crops introduction. Understanding ILUC impacts requires knowing the various ways in which any increase in demand for biofuels will be met (Figure 23).

The impact magnitude of ILUC is very uncertain and depends for instance on the area and type of land brought into agricultural production, the carbon stock as well as biodiversity and other characteristics of the converted land, the potential for improved crop yields on existing and new land and finally the future use of co-products. There is no consensus yet on the methodology to address iLUC nor on the results.

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[33] R. Bailis – SWAFEA Stakeholders Meeting, Munich, July 2010

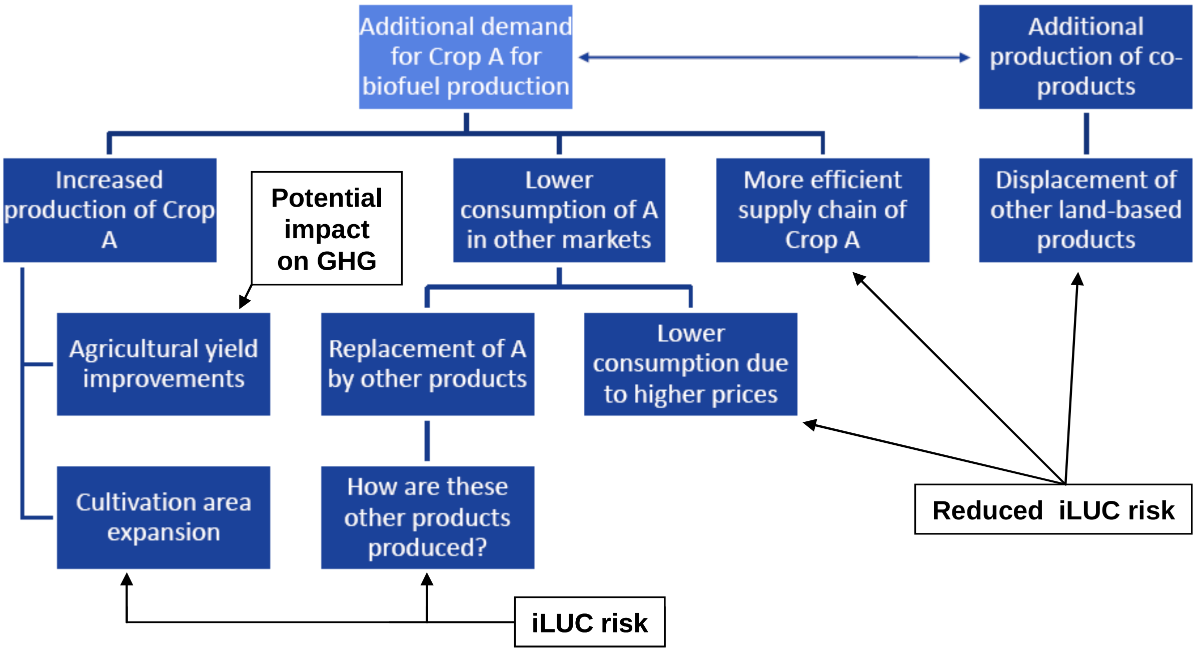

Figure 23: possible way to answer increased demand in biofuels[34]

ILUC is still in debate in Europe and has not yet been introduced in European standards.

RSB is also at its initial stages of defining how indirect impacts should be addressed in the RSB standard (a working group has been created in January 2010 on Indirect Impact). Standard systems can only contain requirements that fall within the control of the companies (e.g. agricultural producers) and therefore within the control of the certification system. Auditing outside the control of the company and standard system is not possible, and the company does not have any influence on activities outside their operations. Therefore standard systems concentrate on controlling micro-level issues such as direct land use change[35]. Currently, for the RSB standard, the overall feeling is that ILUC factors should not be used in the GHG emissions calculations. The focus should be on reducing and minimising risks at the project level, promoting practices and feedstocks that lower the risks of indirect impacts or compensating for displacement.

In the US, the state of California recognized that a strong development of biofuels in the U.S. will cause conversion of lands not only in the U.S but also in the countries having agricultural trade with the U.S. California has recently proposed the Low Carbon Fuel Standard that considers CO_2 emissions from indirect land use change[36]. A similar proposal has been announced by the U.S. Environmental Protection Agency which proposed different values to include iLUC in the lifecycle

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[34] K. Vad – E4Tech – SWAFEA Stakeholders Meeting – Munich, July 2010.

[35] M. Gaebler – SWAFEA Stakeholeders Meeting, Munich July 2010.

[36] California Environmental Protection Agency, 2009

analysis of biofuels for the Renewable Fuels Standard. Due to the complexity of the topic and the absence of an accepted methodology, the proposed values will continue to be reviewed before a new standard is fully adopted [12].

R. Bailis reports evaluation of iLUC that have been carried out in the U.S. for corn ethanol and sugar cane ethanol over a period of 30 years using the different models defined in the LCFS (California, State level), RFS1 and RFS2 (EPA, federal level). The difference in numbers for the various methodologies is currently causing some serious issues. For example, corn derived ethanol meets the Federal EPA ILUC requirements but fails to meet the Californian LCFS iLUC requirements.[37]

The situation confirms the current lack of consensus in ILUC science generally.

iLUC risk minimisation is a priori an argument in favour of feedstock like waste, residues or algae for which the risk seems to be lower, provided that residues collection is done in a controlled manner not to impact fertility or require synthetic fertilizer.

5.2 Deforestation and biodiversity

Considering the dominant impact of land use change in life cycle emissions of biofuels production and also the conservation principles of the RED or the RSB framework, the assessment of the potential biomass availability presented in chapter 3 was based on the rule that no deforestation should be considered in the frame of energy biomass development. The rule was applied in an absolute manner by freezing forest surfaces so that neither direct nor indirect land use change could reduce them.

Reality could nevertheless be quite different under the pressure of market forces.

Indonesia is a good example of deforestation induced by the development of commercial agricultural production of oil palm. This development is not primarily linked to biofuels since palm oil is mainly consumed as edible oil and the world market of edible oil is in strong growth (word primary oilseed crops production has increased by 40% between 2001 and 2009[38]). Since the nineties, demand for palm oil has exploded in India, China, Pakistan and Middle East as these countries adopt western consumerist lifestyles. Demand is expected to double by 2020, with an annual increased of 4% per year [37]. Use for biofuels has also developed and palm oil represented 10% of biodiesel production in 2008[39].

Palm oil production has increased in Indonesia by 400% between 1994 and 2004, and the plantation areas saw increases of up to 500 000 ha per year at the end of the nineties ([34], [35]). Indonesia has

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[37] R. Bailis – SWAFEA Stakeholders Meeting, Münich July 2010.

[38] FAOSTAT.

[39] Commercial production of biodiesel started in Indonesia in 2006 and reached 600 Ml in 2007. Thanks to the national production of palm oil, Indonesia is expected to become the second world producer of biodiesel in 2017 with 3 Gl [39]

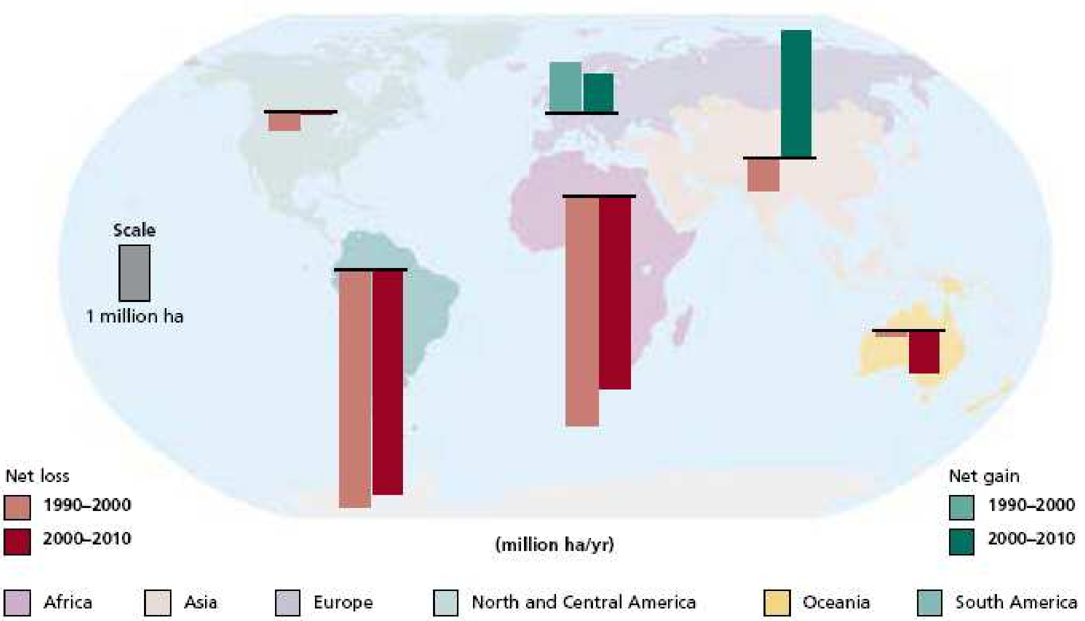
now about 6 Mha of land under oil palm. Palm oil has been estimated to be responsible for 29% of the deforestation of Sumatra, one of the four major islands of the country which has lost 65% of its forest cover from 1982 to 2007. In the same time, the development of timber plantations contributed for 24% [36]. Forest Peoples Programme and Sawit Watch, an Indonesian NGO, report that existing regional plan have already allotted a further 20 Mha for oil palm plantation. "*Although the Forestry Department has called for a moratorium on further conversion of forests this has been done through the weakest of all possible regulations, symptomatic of a long-term tussle between different Ministries seeking to control Indonesian land*" [37].

Considering that Indonesia has 10% of the world’s remaining tropical forests which are home to over 20,000 plant species – accounting for 10% of the planet’s total –, 12% of the world's mammal species and 17% of bird species, many of which are unique, conservation principles are clearly not respected by such a development of oil palm. Stratton also assessed the life cycle emission for the palm oil conversion to HRJ to be between 1.75 and 2.21 times those of conventional jet fuel in case of conversion of tropical rain forest [31] (land use change emissions were allocated over 30 years). Indonesian palm oil is thus not likely to comply with the target of CO_2 emissions reduction.

Indonesia is an example, but FAO indicates that most of the deforestation occurs through transformation of tropical forest in agricultural lands, even if there is a deceleration over the last decade (Figure 24).

Obviously deforestation induces high risk for biodiversity through loss of habitat and destruction of natural area with unique species. In particular primary forests (36% of total forest area), especially tropical moist forests, include the most species-rich, diverse terrestrial ecosystems. A good point is that FAO's observations show an increase of the area of forest designated for the conservation of biological diversity (they represent 12% of the world's forest) or included in protected area. However, the area of primary forest continues to decline.

Annual change in forest area by region, 1990–2010



Annual change in forest area by country, 2005–2010

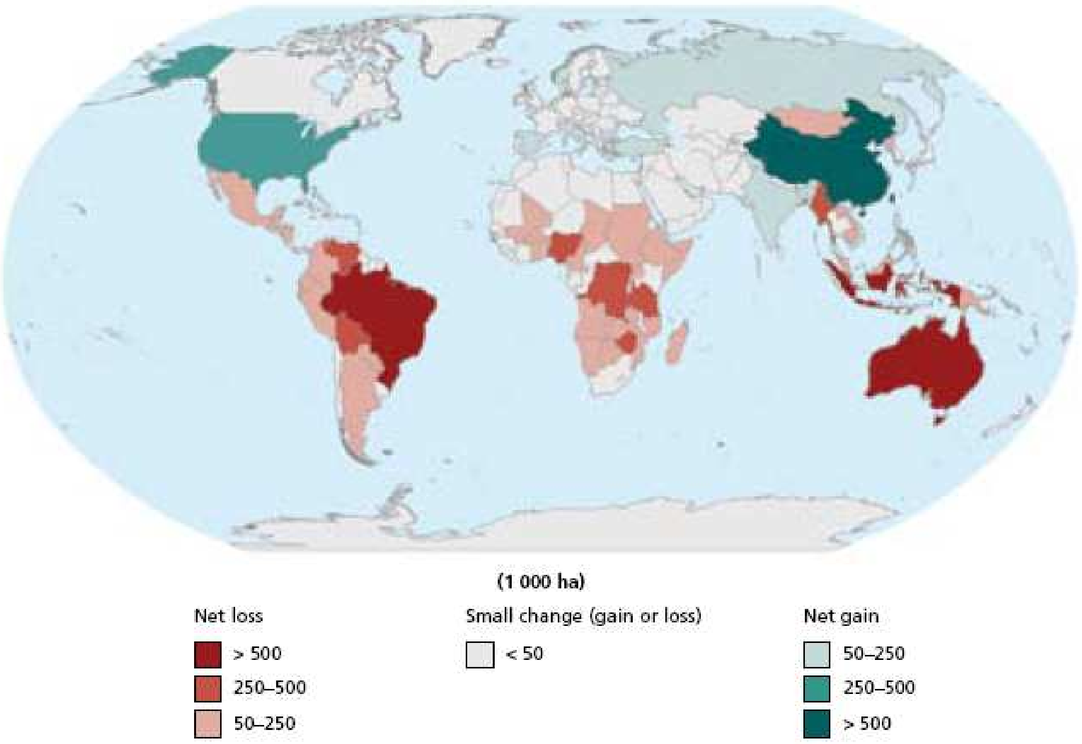


Figure 24: Annual change in forest (FAO, [38])

But lost of biodiversity can also occur through forest resources exploitation, without deforestation.

According to European Environment Agency, a lower intensity use of a significant share of the forest, together with a moderate utilisation in relation with the annual increment, have created positive conditions for biological diversity in Europe and increased the share of deadwood. A certain amount of deadwood is recognised as an important factor for biodiversity. Increased extraction of forest residues and complementary fellings may result in an intensification which can compromise the nature conservation value of such forests. Residues extraction affects the composition of flora and fauna through habitat homogenisation and more intense soil disturbance. When extracting forest residues or complementary fellings it is thus important to leave behind a proportion of residues, deadwood and old trees not to increase the pressure on biodiversity[40].

It seems nevertheless that no clear quantification exists for biodiversity requirements. In addition in the sustainability criteria from the RED, the criteria and ranges for highly biodiverse grasslands are not well defined [5].

To conclude about biodiversity, it should also be noted that biodiversity issues may also exist for agricultural energy crops. An aspect of loss of biodiversity is related to agriculture biodiversity and the diversity of the used crops. FAO points out the fact that most of the plantations for biofuels feedstock rely on a unique specie. The low genetic variety induces a higher vulnerability to pest and disease and is said to be worrying.

5.3 Other environmental impacts

Intensification of agriculture to match both an increased food demand and the production of biofuels is likely to have other consequences on the environment than deforestation of green house gas emissions.

Water use is an important factor for the production of biomass.

In a country like the United States, more than 80% of the fresh water is already consumed for agriculture (70% a world scale, FAO [39]) and there are growing limitations on fresh surface and ground water availability[41]. Many major ground aquifers see reduction in water quality and yields. Most state water manager expect shortages over the next decade under average conditions. Sandia estimates that irrigation of even a small percentage of biofuel acreage could increase water consumption by 3 to 5 Bgal per day over a total consumption of 100 Bgal/day.

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[40] However, in some man made forest presently not exploited due to economical low attractiveness, thinning for biomass uses can provide the opportunity to open very dense coniferous forest plantations and thereby improve biodiversity.

[41] Mike Hightower, Sandia Laboratories, CAAFI environmental panel, August 2010.

Even with no irrigation, attention is to be paid to water use in relation with local situation. Some short rotation coppices for example, like poplar or eucalyptus, may have strong impact on local hydrology. Other lignocellulose crops like myscanthus or switchgrass seems to be less demanding.

Water is in addition also consumed for feedstock processing and biofuels production, but the quantities is limited compared to those incorporated in the feedstock are low (1 L per liter of biodiesel from soy) [40] [41].

Water availability appears not to impose a constraint on bioenergy production in countries such as Canada, Brazil, Russia and Indonesia. However, South Africa, China, and India are already facing a situation of water scarcity, which is projected to become increasingly difficult even if large-scale bioenergy production does not materialize. Finally some countries, such as the USA and Argentina, are projected to join the group of countries that withdraw more than 25 percent of available water [42]. In any case, an important point is that irrigation should be considered only when nutrients are also available in sufficient quantities.

In Europe, water use is a concern in the Southern parts where water availability is low and varies from year to year. In general there has been a significant increase in competition for water between agricultural production, urban land uses, tourism and nature conservation in drier region of Europe. The share of agricultural in total water use stands between about 7% and 50% in Northern and Southern countries of the 15 Western European countries. A report from UNEP on water indicators for biomass sustainability standards indicates, that although the RED requires biofuel producer to provide information on measures taken for water protection and the avoidance of excessive water consumption, in areas where water is scarce, there is no globally accepted definition of water scarcity [43].

Water pollution is another issue of intense agricultural production which can be also increased in case of biofuels because of the processing. Streaming of excess nutrients or pesticides in surface water and infiltration in ground water is a known impact of the increase of fertilizers. Concerning feedstock processing and transformation, existing techniques are normally efficient to control pollution when they are deployed [39].

Concerning the impacts on soils quality, it depends mainly on agricultural practises and management as for any culture. Main concern could come for an increased use of residues that would not let on ground enough material for soil replenishment.

5.4 Competition with food

Competition with food is probably the fear most commonly associated with biofuels development. This issue may have various manifestations, from a potential pressure of biofuel production on food market price to a deficit of food production with regard to the population needs.

A first aspect is related to the fact that in developing countries subsistence economy based on agriculture and natural resources often represent a significant part of the economy. FAO gives the example of Tanzania, which is a candidate for the development of energy crops like sugar cane, oil palm and jatropha and where food security depends on access to the land for numerous households [39]. Development of industrial production of energy crops pushes for the mobilisation of large contiguous areas and may lead to small holders' expropriation, inducing a risk for food security. A similar example can be given for palm oil production in Indonesia where companies aim at gaining access to contiguous lands. Competition with food here occurs through the societal impacts of bioenergy agriculture developments.

According to FAO, the main effect of biofuels on food security will come from their impact on food product prices and on people incomes. Impact is potentially higher for less developed countries which have seen the deficit of their agriculture trade strongly increases over the last 20 years. Impact exists even for rural population because many households don't possess enough land to be net producers. Only the net sellers would benefit from an increase of their income thanks to the price increase. Indonesia illustrates the consequence of palm oil on food market. The number of rice producers is lowering and rice production doesn't increase enough to meet the demand which means higher imports and a higher price for the population [44].

In the short term, FAO remarks that the increases of international food price don't necessarily translate to local market, especially if local policies exist to isolate the national economy like in India or in The Philippines where restrictions to international trades exist. Theses policies require funds. In the longer term they may reduce the answer of the offer to the demand increase. In the longer term also, the poor households that do not possess land could benefit from the increase of food prices through the increase of demand and salary for manpower but it seems that the relation between food price increase and salary in agriculture is not established. The general feeling is that at world scale the net effect on food security in the short term is likely to be negative.

However, FAO sees a potential positive effect if biofuel production revitalizes agriculture in developing countries, a number of which amongst the poorest have conditions to be large biomass producers. Examples exist where the development of commercial production by small farmers didn't happen at the expense of food products. This has been the case in Mali with cotton where food crops have benefited from the technology and practices improvements brought by this new culture. Farmers which benefit of these progresses for cotton have higher yields than less equipped producers. This was obtained thanks to investments in agriculture.

Tanzania, where the transport network is a key structural weakness, is also an example of potential impact of lack of infrastructure. In seasons with adequate rainfall, it can produce enough food to cover its domestic demand but food insecurity results from an inefficient distribution network from surplus regions to deficit regions [39] (over the last years, however recurring drought has worsened the situation and forced the increase of imports).

This last question of infrastructure and agriculture practices brings back to the previous evaluation of biomass availability for energy use. In the long term, an intense use of biomass to substitute fossil resources and contribute to the decarbonisation of the society calls for a high productivity level all over the available surfaces and so implies strong investment in agriculture and infrastructure in developing countries.

In the RSB sustainability framework, Principle 6 defines measures to improve local food security in relation with biofuels development. This consists of an assessment of the risk to food security, with if required the implementation of a mitigation plan, and of specific measures like "*setting aside land for food growing, increasing yields, providing opportunities for workers to carry out household-level food production, sponsoring agricultural support programs and activities, and/or making value-added food byproducts available to the local market"*.

5.5 Societal and economical impacts

Societal and economical impacts of the development of alternative fuels are obviously multiple and strongly dependant on the kind of country under consideration.

Many impacts are identified for developing countries which present a higher vulnerability both for political, administrative and technical reasons.

Rural society, access to land and land rights

A first societal impact is linked with the structure and organisation of the society in developing countries which has already been mentioned for food insecurity.

Coming back to Indonesia example, between 60 and 90 million people make a livehood from areas classified "State Forest Areas" which represent some 70% of the national land area. A large proportion of the rural people regulate their affairs through custom (referred as "indigenous people" in international law) [37]. Oil palm expansion has major consequences for these rural populations since it implies major reallocation of land and resources.

The Indonesian Constitution respects the existence of customary law communities and recognizes their customary rights in land. But, according to Sawit Watch, other laws or inconsistencies in the laws provide only weak recognition and ambiguously, procedures for titling such lands are absent, defective or rarely applied. Although the 1945 Constitution of Indonesia recognizes the existence of traditional political entities based on the heritage of indigenous peoples, some laws enacted retain the ‘domain’ principle which affects the rights of indigenous peoples. In particular the Constitution and laws recognise the right of the State to control and allocate natural resources for the benefit of the Indonesian people. The laws allow the reallocation of lands for State purposes and for private sector uses in accordance with national development plans. For Sawit Watch, this too often leads to reallocation of lands at the detriment of indigenous people. As a result, the plantation business is the most conflict-prone land based sector in Indonesia [46].

IEA reports similar problem with land ownership for agriculture in Tanzania [12]. There is not yet any commercial production of biofuels in Tanazania but there are plans to develop them on the basis of sugar cane, jatropha and oil palm. If agriculture is dominated in Tanzania by badly equipped smallholders, there is a shift from subsistence to market oriented production and the number of large-scale farm increases. Although land is abundant and a process exists for their allocation[42], agriculture suffers from disputes over land ownership. Inconsistencies and vagueness concerning land occupation and land ownership render the distribution of land a difficult task. As a result, "land grabbing" occurs, which excludes local farmers and favours large privatised plantations. Rural population claims that decisions are taken without consideration of alternatives and without their participation.

These examples show a combination of insufficient legal frameworks to protect small holders with a still high dependence of rural population to local subsistence agriculture and plans to develop market production and commercial activities in the country. A rapidly increasing demand for biofuels on top of higher agricultural demands or objectives can only increase the pressure on the transition these countries are presently experiencing.

In a sustainability framework like the RSB, the potential impact of the development of biofuels we have described through the example of Indonesia and Tanzania is mainly tackled through the principle 12 related to land rights and in some way through the principle 5 about rural and social development. The RED also demands that social impacts be reported every two years. When the problem stems from an unclear definition of land property, the principle application may nevertheless be difficult to demonstrate.

Beyond lands right, the issue illustrated here is related to the transition from a rural society to a more industrial and commercial one with concentration effects. There is not a clear principle about these concentration effects. By the way, concentration effects don't affect developing countries only. The development in the United States of "giant" farm for milk production is a striking example of such concentration and there is a project now also in the United Kingdom[43]. FAO however considers that it is of importance to involve small holders in the cultivation of raw materials for biofuels and that small farm may present some advantages in term of supervision and flexibility. The example of Thailand shows that small exploitation may be efficient: already in the early nineties, Thailand was exporting more rubber and pineapples than Indonesia and Philippines where production was mainly done in plantations. Nevertheless, when transformation and commercialisation become more complex, plantations answer to the need of vertical integration. They are also better adapted when large

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[42] From FAO [39], all lands in Tanzania are classified either village or national lands. The process to rent a land is complex and long. It requires the agreement of the village, of the district, of the region and of the Ministry, and even the President for large surfaces. At the end of the process, the village is classified national land and belongs to the Tanzanian Investment Center that rents the land for a period of 99 years.

[43] cf. Courrier International, n°1048, 2 December 201 0, article from The Ecologist.

investments are required and, with view to sustainability, certification is also a heavier burden for small farmers. Involvement of small holders may be encouraged by public investments in infrastructure, diffusion of techniques, legal systems and market institutions. Contractual agriculture may also be a mean for biofuel investors to create the feedstock market while preserving food production and social improvement. Concerning environmental certification, a framework like RSPO (Round Table for Sustainable Palm Oil[44]) stipulates that palm oil mills are to ensure that all smallholders and out-growers which form part of their supply chain meet the certification standard within 3 years.

Societal and economical barriers

In developed countries, societal aspects of the development of biofuels are obviously of different nature but may also raise barriers.

In chapter 3.4.1 related to forest resources in Europe, some economical barriers to wood exploitation have already been pointed out such as the division of forest in France among a large number of small proprietary which have low incentive to exploit their parcels. The infrastructure required to get access to the wood and its transportation is also a difficulty. Its improvement may in addition induce problems of acceptance. Also the question of the manpower availability has been mentioned[45]. Professionals point out that there is a significant gap between the available amount of wood and the volume that can actually be extracted [21]. The economical price of energy wood is determining in filling the gap. Professionals also raise the question of the impacts on landscape and on the relation between the society and the forests that have to be integrated in the development of forest harvesting.

Development of new type of crops may also raise specific difficulties. In the production scenario presented in chapter 3, lignocellulose perennial crops were considered. In particular for sustainability reason, only perennial crops were selected on grassland for energy use. Perennial crops nevertheless induce a loss of flexibility for farmers with view to market fluctuations. There is thus a reticence to this kind of crops (the reason why they were not introduced on cropland in the production simulation). In addition, in case of short rotation coppices, the cultivation techniques substantially differ from agriculture practises and require specific machinery for harvesting. The development of perennial crops may thus require pluriannual contracts with fuel producer to secure the farmer's position.

The economical attractiveness of the crop is also an important point to consider. Presently in a country like France, without subsidies, the income is hardly attractive for farmers in case of short rotation coppices which are even in competition with wind mill for land use[46].

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[44] www.rspo.org

[45] FCBA reports that in France, in spite of wages that are not so low, there is difficulty to attract manpower in the wood sector because of the hardness of the work and the long absence from household it implies.

[46] Nicolas N'guyen The, FCBA, SWAFEA Stakeholders Meeting, Munich, July 2010.

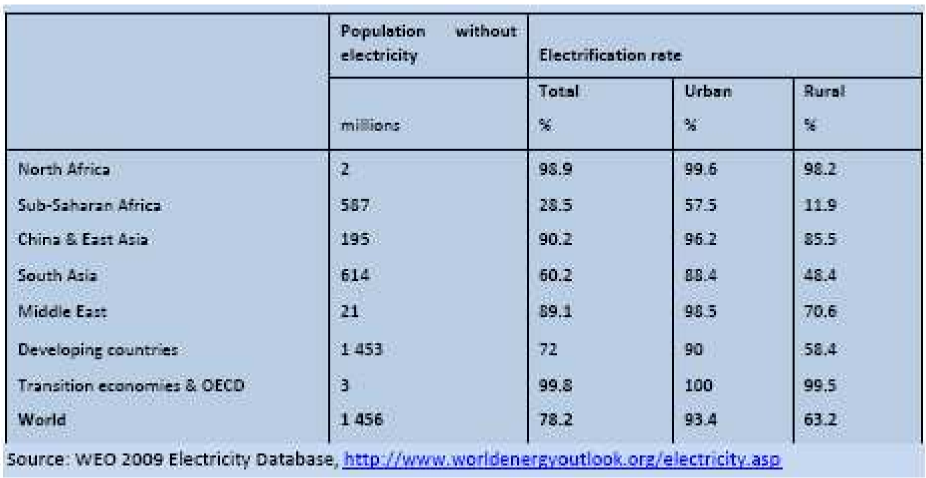
In their context, comparable barriers exist in developing countries. The 3 to 5 years for a jatropha to enter in full production is for example a difficulty for farmers with limited resources who don't have the capital to invest in projects where the potential revenues are several years away. Specific support would be need for them and more generally for the development of the agricultural tool as already mentioned about food security issue.

To support the production and consumption of biofuels, policy measures are usually required which may include direct subsidies per output of biomass, reduction of infrastructure costs (subsidised loans, capital grants), guaranteed price of biofuels, quota or tax exemptions. However subsidies are very low in developing countries and even in emerging countries subsidies are much lower than in OECD countries.

Need for subsidies is also true for end users due to the higher production cost of biofuels. The Indonesian government for example is pushing for the development of biofuels. It has reduced then suppressed in 2005 the subsidies on fossil fuels, allowing the biofuels industry to become viable [39]. The absence of subsidies has nevertheless caused a 126% increase in fuel price and subsequently has increased inflation to 18% [44] in a country where more than half of the population lives with less 2 USD a day [47]. Such example can obviously not be extrapolated directly for aviation due to a quite different consumer profile, but aviation fuels are likely to be part of a global biofuels development. On the other side, aviation by providing an additional world based market can contribute to the viability of biofuels production.

The next economical aspect of the development of biofuels is related to investment capacity, especially for biofuels like BTL for which the capital cost is expected to be up to ten times higher than for first generation biofuels [12]. If it is not necessarily a difficulty in emerging countries like China or Brazil, it is considered as one of the bottleneck for developing countries. There, investment will mainly depend on foreign investors for which administrative or governance problems may be a restraint. Lack of qualified man power and background in such industry in developing countries (there is for example no refinery in Tanzania) is also a difficulty. Because second generation biofuels are also more expensive to produce, these countries may not be user of these fuels but rather exporters or producers of feedstocks.

A final question to consider for the contribution to aviation fuel of the biomass from developing countries where a significant part of the production capability is located, is the priority use of the biomass these countries should do. Indeed, in developing countries, access to energy is often an issue and rural electrification is of greater priority than substituting biofuels to fossil fuels (Table 21). From the point of view of domestic use, IEA for example considers in its study on second generation biofuel (BTL and cellulosic ethanol) that in a country like Tanzania, the technical and economic effort required to develop such fuels would be too high considering the energy priorities that could be satisfied with less effort. Such a consideration could also apply for the development of aviation fuels. In that context, biofuel production for aviation could be driven like automotive fuels by exportation with capital expenditure covered by foreign investors, which would contribute to the development of the country. Actually, discussions are going on in Tanzania regarding whether biofuels should be used domestically or exported but there are not yet any mechanism that could ensure one or the other. The second option nevertheless brings back to the examples of the development of large commercial agricultural productions with their potential impacts on rural society: eviction of local farmers in favour of foreign large plantations, deforestation and so on.



	Population without electricity	Electrification rate		
		Total	Urban	Rural
	millions	%	%	%
North Africa	2	98.9	99.6	98.2
Sub-Saharan Africa	587	28.5	57.5	11.9
China & East Asia	195	90.2	96.2	85.5
South Asia	614	60.2	88.4	48.4
Middle East	21	89.1	98.5	70.6
Developing countries	1 453	72	90	58.4
Transition economies & OECD	3	99.8	100	99.5
World	1 456	78.2	93.4	63.2

Source: WEO 2009 Electricity Database, http://www.worldenergyoutlook.org/electricity.asp

Table 21: Access to electricity in different developing regions in 2008

5.6 The specific case of algae

Algae are expected to bring significant advantages from the sustainability point of view. First of all, algae should be the mean to decouple biofuel production from land use competition with food. Algae can also allow to make an increased use of fossil CO_2 by growing biomass thanks to fossil fuels combustion gases. This is not carbon sequestration but for a same amount of CO_2 released in the atmosphere, this increases the energy production. Algae biomass could also provide fertilizers. Nevertheless, as pointed out by FAO [24], integrating the full potential of these benefits influences other choice in the algae production concept. For example, using algae residues as nutrients for their gross reduce the potential of valorisation as co-product that may be an important factor of the global economical viability of the production. Choosing the most environmentally, economically and socially sustainable concept is thus very complex.

Land use

In case of algae, there is no quality requirement for land which can be unfertile, arid or desert. There are large amount of such land which often overlaps area with high sunlight intensity. FAO report indicates that 15% of these undeveloped lands would have sufficient access to the sea on the basis of a maximal distance of 100 km and that some desert areas also have saline ground water. That's for example the case for New Mexico in the United-States.

One can nevertheless object that such resources are also not unlimited and that their use is not without impacts:

- salt and fresh water aquifers are often connected, and the extraction of the salt water will impact the integrity of the fresh water, posing problems to agriculture and drinking water sources;
- aquifers are interconnected underground and can stretch under multiple states, which poses complex sovereignty and ownership laws and restricts the extraction of water.

Another aspect of saline water use is that due to evaporation, salt is deposing in the ponds requiring desalting to maintain a proper concentration for algae.

These water issues with algae have to be analysed on a case by case basis depending on the project parameters.

Even if algae production has low requirements for land quality, problems may arise when considering very large facilities up to 1000 ha. Plots of this size with low current economic and ecologic value can be scarce [24]. It was also seen the importance of integrating algae production with CO_2 and nutrients sources that put an additional constraint. A deeper analysis of facility size and location (like the one initiated by Skarka [28]) is thus needed.

Environmental impacts

Large open facilities size may also induce additional problems such as fog blankets and other local climatic changes. During heavy rain, closed systems built on hard surface may result in water disposal problems [29] and in open systems this may lead to high nutrient, high biomass excess water.

An associated environmental risk is linked with the research currently on-going in many companies in order to improve the productivity of algae, eventually using genetics engineering. These new algae have different, mostly better resistance to external contamination and climates. Spilling of these algae in the environment may have disastrous effects on local eco-systems. Spilling resistant algae into lakes can result in rapid growth of the algae and overgrowing local lake flora by blocking all incoming light and killing all food for fauna as well.

This question of potential proliferation is probably a critical point to study in case of algae. This may be an argument in favour of closed systems like photobioreactors which are likely to allow a better control. This is in any case a criterion from the RSB that biofuels operation shall prevent invasive species from invading outside the operation site (principle 7) and that micro-organism used in biofuels operation which may present a risk to the environment shall be adequately contained to prevent release into the environment (principle 11). This last principle applies also for genetically modified organism (GMO) which could be developed not only for algae but also for all kinds of energy crops. It states that "*The technologies used in biofuel operations including genetically modified: plants, micro-organisms, and algae, shall minimize the risk of damages to environment and people, and improve environmental and/or social performance over the long term*". This principle may prevent the use of GMO at least in a first step for biofuels production.

The requirements of algae for nutrients may present either opportunities or risks from the environmental point of view. Indeed, it is often expected that algae may use manures from livestocks farming, a point which nevertheless requires confirmation considering potential pollution by pathogens, heavy metals, medicines or other pollutants. FAO report [24] indicates that due to the fact that algae produce oxygen during the day, they are likely to produce less GHG emission from the use of manure than agriculture. Risks may stem from the wastewaters from algae production. Ideally these waters are recycled at least partially, which may require additional treatment and energy input. Possible problems are the accumulation of unwanted compounds and proliferation of micro-organisms feeding on the organics in the recycled water. Non-recycled water should be disposed of properly, which can be more difficult due to the high salt content.

6 SYNTHESIS

Considering a set of sustainability criteria in line with the European Reusable Energy Directive (RED), an assessment of the amount of biomass potentially available in 2050 for energy use and production of biofuels has been achieved.

The outcome is that a significant amount of biomass may theoretically be available, mainly from agriculture, whilst considering conservative choices at each step of the assessment. It is far from covering the projected world energy demand in 2050, evidencing a strong need for complementary energy sources. Nevertheless it could support the objective for aviation to have a carbon neutral growth from 2030 at the emissions level of 2020, if it was accepted to process 52% of the available biomass in biofuel. This is already a high percentage which nevertheless leaves a significant amount of biomass for other uses than aviation and transportation[47]. At contrary, reaching the 50% emissions reduction target appears as calling for an excessive ratio of the global biomass potential for aviation and transport.

However the assessed biomass production is theoretical, meaning that the land is there to produce the amount of biomass with "reasonable" technology assumptions (yields) in agriculture. This does not mean that achieving this level of production is easy. It implies to push the technology development in all the geographic areas and to put in cultivation large amounts of lands that are not cultivated today. This requires investment in agriculture, education of the farmers and also the involvement of the required manpower. The assessed production also requires that the fertilizers are there. Last, if the yearly increase in yields considered in the study seems to be realistic considering the evolution over the last 30 years, it does not mean that the foreseen development of the production can be achieved in the next 40 years. Experience over the last decades, in Africa for example, has some time proven disappointments in the effort to ramp up agriculture production. In such technology development scenario, it is also possible that the diet developments change more rapidly than projected, thereby consuming part of the achieved increase in biomass production for food products.

In the longer term however, the analysis shows that there is a need for either a revolution in aircraft efficiency and energy sources or the identification of additional sources of biomass. Indeed the biomass availability is projected to decrease over time, while in 2050 the current projections do not see any stabilisation of air traffic and fuel demand.

Some aspects of the assessment would benefit from further investigation. In particular, it would be worth evaluating what the production means in terms of fertilizers availability and production. Also the production scenarios have been built in order to ensure global food security and to induce no negative

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[47] It should be noted that in the performed assessment, woodfuel had already been deduced from the available biomass

land use change for biofuel productions. The possibility of indirect effects in such scenario should nevertheless be further analysed. Last the consequences of using the projected amount of grazing land would benefit from further analysis both from an environmental and societal point of view (about 10% only of the grazing lands are not dedicated to food or energy biomass production).

In connexion with the biomass production scenarios, the life cycle emissions of the considered pathways for fuel production have been estimated. The analysis confirms the actual potential of biofuels to reduce green house gas emissions, while other fossil based alternative fuels like GTL don't provide any benefit even when using carbon capture and sequestration.

For biofuels however, the feedstock cultivation step is the dominant contribution to life cycle emissions because of the use of fertilizers. If BTL succeeds in reaching the RED thresholds of 60% reduction of green house gas emissions, matching this target with HRJ requires a careful optimisation of the cultivation steps, which is also the case for algae. Best results are nevertheless obtained with BTL while favouring the production of lignocellulose feedstock has also demonstrated to lead to the highest potential of biomass primary energy. For an environmental point of view, BTL thus appears a better choice[48].

Over all, both for BTL and HRJ, the targeted reduction in green house gas emissions can only be achieved if no detrimental effects of land use change are associated to the production of biofuels. This is in all cases the dominant effect. Land use for biofuel production should thus be carefully controlled. However the difficulty stems from the possibility of indirect land use change (iLUC) triggered by the displacement of cultures following the deployment of energy crops. There is today no methodology to deal with iLUC and it can hardly be addressed through certification schemes.

If the different methodological approaches used for the LCA don't change the general tendencies of the results, they nevertheless impact the quantitative results which can be a concern with view to the application of environmental regulations and the sustainability certification of the fuel. A fuel may comply with the emissions reduction thresholds under certain regulation frameworks only. The existing differences also lead to the requirement for multiple assessments depending on the place where the fuel will be used (RSB is currently implementing different methodology in its LCA tool). Since aviation fuel is a global commodity, there would be a strong benefit from an alignment on a global LCA methodology.

Considering the other potential environmental and societal impacts of biofuels production, they don't appear to be intrinsic features of either biofuels or crops used to produce them, if we except competition with food. Oil palm is for example not intrinsically a bad crop (from the productivity point of

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[48] Oil seeds are nevertheless not to ban especially when considering the possibility of crop rotation on croplands. In addition, theoretically, in the oil from oil seeds only C, H and O is removed from the field, thereby possibly contributing more to sustainability then other crops in which nutrients and organic matter is harvested for biofuels.

view it is even the ideal crop). Deforestation, water use, risks of pollution or societal impacts exist for traditional agriculture and are mostly relevant of agriculture management and development policy of the interested countries. The fact is that biofuels development will put additional pressure on existing trends.

Concerning the competition with food, the simulation of the potential biomass production tends to show that biofuel production is possible while preserving the priority for food. Currently 250 Mha of cropland is not harvested, although in some regions (in Africa for instance) diets hardly reach healthy intake values. This simulation was of course done in a theoretical manner assuming the existence of a high level control on the repartition of crops production between energy and food crops. The reality may of course be different depending on the market forces that will drive the priority development of one or the other sector. Considering the multiple interactions that exist on food market and its global dimension, it is not clear that the food security issue may be tackled only through the certification schemes. FAO opinion is that, at world scale, the net effect on food security in the short term is likely to be negative, mainly due to the impact of biofuels production on food price. In the longer term, positive effects could be obtained if biofuels production contributed to the general development of agriculture, bringing technology and improved practices in developing countries that also benefit to food production. In any case, such progresses in agriculture are definitely requested in order to reach the biomass production potential required to satisfy biofuels needs.

Algae could be an answer since it enters in a quite different way of production and release a priori much of the quality requirement on lands. It nevertheless calls for synergies with other production and some water needs that may limit the suitable area for their production. Containment of high efficient optimised species is also a difficulty. Researches are still required before deployment may take place.

Existing sustainability frameworks such as the RSB catch most of the sustainability issues and are quite comprehensive. Questions could be raised about their applicability in countries where weakness exists in local laws and administration, or about the requested demonstration effort compared to the actual demonstration possibility. However, RSB indicates that 20 pilot projects have been carried out over the world and that there was no feedback saying that the process was too complex[49].

If efficiently and rigorously applied, these certification schemes should provide guardrails for the potential impacts of the development of biofuels, in aviation as in the other sectors. In any cases, there is currently no clear alternative to such certification schemes.

In Europe, some improvements could be applied to the current regulations in order better enforce the sustainability of aviation biofuel.

Though the RED doesn't exclude aviation from the 10% target of renewable energy in all forms of transport, many actors of the sector encountered in the course of the SWAFEA study didn't believed aviation was included in the RED. A better communication should thus be organised and the text could

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[49] RSB, SWAFEA International Conference, Toulouse, 9-10 February 2010.

be clarified. Indeed the directive states that the target applies to the final energy consumption of the Member States. In the case of aviation, this may be something ambiguous since most of the aviation consumption is done on international roads by airlines from different countries. The directive may be thus understood as applying only to domestic flight which is not the view of the European Commission.

On the other side, there is no sustainability criteria associated to the use of biofuels in the Emissions Trading Scheme. Fuels originating from biomass account for zero emissions, whatever their life cycle emissions or actual sustainability are. This is not the case for the RFS in the United States where the fuels have to meet requirements in order to qualify for RINs and so be tradable. These requirements include both emissions reductions thresholds and constraints on the biomass used for their production. To enforce sustainability criteria on the fuel used in aviation, such an approach should probably be applied for the European ETS which could require for example that the fuel should be certified in order to account for zero emissions in the ETS.

However deployment of alternative fuels in aviation is foreseen at a much wider scale than Europe (or flights to or from Europe) through the ICAO's resolution on climate change of October 2010. Similar mechanisms should thus be considered at ICAO level to ensure that the development of biofuels in aviation globally follows a sustainable way.

One of the practical aspects of the global dimension of aviation is the burden that environmental certification may represent for both the airlines and the fuel producers if independent regulations emerge in the different world areas with globally similar sustainability principles but differences in their detailed implementation. The case of the LCA methodology which is not the same for the RED and the RSB or the RFS is an illustration of the coming difficulties which will require multiple certifications of the fuels. Harmonisation would undoubtedly help but may be difficult to reach at international level.

To demonstrate compliance with the sustainability criteria, the Communication from the European Commission in June 2010 also proposes the reference to bilateral or multilateral agreements concluded by the European Union with third countries. The review of potential environmental and societal impacts of the developments of biofuels has highlighted the interactions between those impacts and the development policies or economical choices made at the political level in the involved countries. Bilateral agreement between EU and third countries may thus be the relevant level to debate some of the sustainability issues induced by biofuels developments. But due to the local character of sustainability, it is questionable whether it could fully replace a certification of the producers.

PART 2: ATMOSPHERIC IMPACTS

1 INTRODUCTION

Aviation emissions have an impact on atmospheric chemistry and on the radiative balance of the atmosphere. For example, contrails formed by condensation of water vapour onto exhaust aerosols, including soot particles, may trigger the formation of induced cirrus clouds. Emissions of nitrogen oxides perturb the natural chemical cycles, lead to ozone production or destruction depending on latitude and altitude, and modify methane time of residence in the atmosphere ([48]). Along with sulphate aerosols formed in aircraft plumes, these indirect effects from burning fuel at cruise altitude provide further contributions to the greenhouse effect in addition to CO_2 emissions. The most recent evaluations of these in-flight effects point out that the overall radiative forcing is 2 to 3 times higher when all emissions and induced effects are taken into account than it could be from CO_2 emissions ([49]).

Given the forecast of the air traffic increase (e.g. [50]), it is anticipated that air traffic may double in the next twenty years compared to the present situation. Air traffic contribution to climate change may therefore increase.

The overall radiative forcing (RF) corresponding to the current aviation, shipping and ground transportation traffic has recently been evaluated within the framework of the QUANTIFY European project[50]. Figure 25 shows the relative radiative forcing contribution induced by the direct and indirect effects of air transport emissions in operation (until 2005).

As can be seen, aircraft NO_x emissions lead to direct ozone production in the upper troposphere, but also to methane reductions, which is also a greenhouse gas. The total net radiative effect is about half of the CO_2 radiative forcing.

The additional cloud cover due to contrails and contrail-induced cirrus has a RF magnitude comparable to the one due to the emissions of CO_2 alone. The available evaluations are nevertheless very uncertain and need to be refined.

Indeed, either for the RF due to nebulosity change (high clouds for aviation) as well as for the perturbation in chemistry (O_3, CH_4), the effects are indirect and non-linear, have regional characteristics due to the location of the major routes, and have much shorter lifetimes than the one due to the sole accumulation of CO_2. There magnitude is therefore more difficult to estimate.

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[50] http://www.pa.op.dlr.de/quantify/

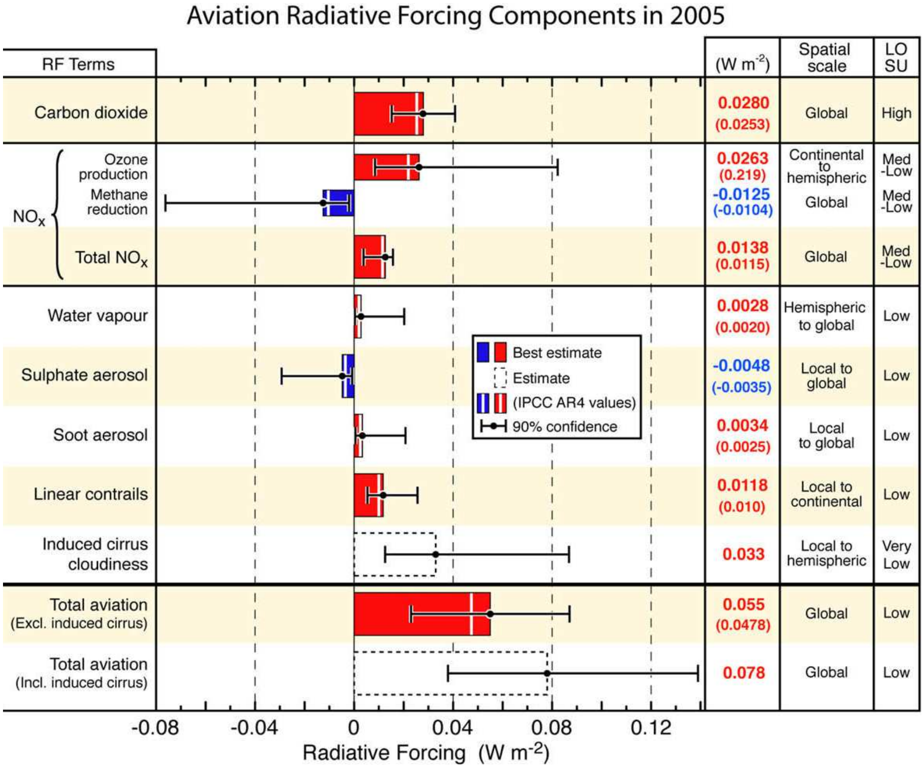

Figure 25: Comparison of the various factors contributing to the radiative forcing due to aviation emissions until 2005 ([49])

Alternative fuels can change the overall balance of the radiative forcing because of the possible change in CO_2 , NO_X, aerosols, soot and other compounds emissions.

In addition to large scale and global effects, aircraft emissions also have a local impact on air quality in and around airport areas. The issue is directly related to the impact of aircraft engine combustion products on population health and on ecosystems, especially during taxi, take-off and landing phases. As air quality concerns in large cities are continuously growing, the impact of a new fuel for aviation is of major interest as some significant improvements could be expected.

Some measurements of engine emissions from biofuel operations have been done in conjunction with the biofuel test flights carried out in 2008 and 2009 [51]. However, no thorough evaluation of these possible effects is available so far.

2 AIRCRAFT ENGINE EMISSIONS

Combustion products, due to the combustion of a fuel composed of carbon and hydrogen with atmospheric air can be divided into three parts:

- main main fuel combustion products, namely carbon dioxide (CO_2) and water (H_2O), which are generated in fixed amounts according to stoichiometric rules – 1 kg of jet fuel generates 3.15 kg of CO_2 and 1.24 kg of H_2O
- products related to combustion efficiency such as carbon monoxide (CO), unburned hydrocarbons (UHC) or soot (associated to smoke);
- products related to the air composition, such as nitrogen oxides (NO and NO_2 also called NO_x);
- products related to the fuel composition such as sulphur oxides (SO_2 and SO_3).

Even if the type of combustor and its design optimisation play an important role in the emission process, the concentration levels of these pollutants in gas turbine exhausts can be related directly to the temperature, the time of residence, and the concentrations history in the combustor. The concentrations of carbon monoxide and unburned hydrocarbons (incomplete combustion products) are highest at low power conditions, and decrease with increasing power. On the other hand, nitrogen oxides and smoke are fairly insignificant at lower power settings and attain maximum values at the highest power conditions.

There are very few public data on the impact of alternative fuels on aircraft emissions. However, it is possible to make some assumptions as far as drop-in alternative fuels are considered. Indeed, alternative fuels with synthetic components produced in accordance with Specification D7566 meet the requirements of D1655. Specification D7566 does not yet include all fuels from non-conventional sources. Fischer-Tropsch (FT) or Hydroprocessed Renewable Jet (HRJ) in semi synthetic blend (up to 50% with Jet A-1 according to the current D7566 specification, respectively its extension to HRJ blends expected for early 2011), or fully synthetic (D7566 expected evolutions) have chemical compositions very close to natural kerosene derived from crude oil. Simple analysis, supported by the few experimental results available, can help in evaluating their impact on current aircraft engine emissions. However, the lack of data on advanced engine configurations, such as lean staged injection combustors, makes very difficult the extrapolation towards the evaluation of alternative fuels impact on the emissions of engines like the General Electric GENx.

2.1 Carbon dioxide and water (CO_2, H_2O)

These are the major exhaust gases of jet fuel-air combustion. The global amount of CO_2 and H_2O generated only depends on the fuel consumption and its composition. The two first order parameters are the energy content (expressed in MJ/kg) and the C/H ratio.

Generally, the proposed SPK (F-T or HRJ) have specific energy contents in the upper range of Jet A-1 specifications[51] which could induce a potential fuel consumption reduction and therefore a CO_2 and H_2O emissions reduction too. This point has to be confirmed by the global air traffic analysis scheduled in the study.

In the same way, the C/H ratio in the composition plays a part in the amount of CO_2 and H_2O produced per kg of fuel. For conventional kerosene, it can be expressed through the emission indexes:

- EI CO_2 = 3155 g/kg,
- EI H_2O = 1237 g/kg.

There is no hydrogen content item in the D1655 specification, but the global trend for SPK is to have higher hydrogen content (C/H≈5.7 vs. C/H ≈6.1 for Jet A-1) which is mainly caused by near-zero aromatic hydrocarbon content (with a high C/H ratio) in SPKs. This trend will lead to a lower value of EI CO_2 and a higher value of EI H_2O.

From the tank-to wake point of view, the intrinsic features of SPK should induce a reduction of CO_2 emission.

2.2 Carbon monoxide and unburned hydrocarbons (CO, UHC)

CO and UHC emissions are generated by incomplete combustion. In an engine aircraft, their amount depends mainly on:

- fuel air ratio (FAR),
- air temperature and pressure at the combustor inlet station,
- fuel injection and mixing in the combustor primary zone,
- the engine rating - production is lowest during take-off and climb, increases during cruise and is highest at idle.

Carbon monoxide production is directly related to the combustion efficiency. No significant change is expected with the use of alternative drop-in fuels.

Unburned hydrocarbons include fuel that emerges at the combustor exit in the form of droplets or vapour, and also the products of thermal degradation of the parent fuel into species of lower molecular weight, such as methane or acetylene. They are normally associated with poor atomization, inadequate burning rates, chilling effects of film cooling air, or any combinations of these. The expected impact of alternative fuel on UHC, although limited, can be higher than on CO. However, the

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[51] ASTM D1655 : not less than 42.6 MJ/kg – Experimental results from HRJ or F-T SPK : close to or above 44 MJ/kg

UHC emission will depend on the fuel chemical properties and on the combustor configuration. It seems difficult to forecast the behaviour which could certainly be positive or negative depending on the engine types.

2.3 Nitrogen Oxides

Nitrogen oxides (NO and NO_2) are produced by the oxidation of atmospheric nitrogen in high-temperature regions of the flame. The process is endothermic and proceeds at a significant rate only at temperature above around 1800 K. Thus in contrast to CO and UHC, NO_x arises mainly in the hot central region of the combustor, and levels are higher at full power settings, corresponding to take-off and climb.

Therefore, for a given engine cycle, the combustor configuration is the key parameter in NO_x production. As far as drop-in fuels are concerned, fuel property discrepancies between Jet A-1 and alternative fuels play a second order part in this process, with a positive or negative impact depending on the engine and on the thrust rate.

2.4 Particulate matter (PM)

The properties of HRJ and FT jet fuels are similar: near-zero sulfur and near-zero aromatic content, leading to a major difference with respect to Jet A-1 for smoke and particulate emissions. Indeed, these ultra low sulphur jet fuels would virtually eliminate secondary particulate matter due to sulfur-oxide emissions while also reducing primary particulate emissions due to aromatics.

This trend is clearly pointed out by engine test measurement both in terms of ICAO Smoke Number (Figure 26 and Figure 27), and on small particle distribution (Figure 29).

Engine emissions and performance measurements have been made on different aircraft engines with 100% pure and blended alternative “drop-in” fuels:

- CFM56-7B engine test (General Electric) - Figure 26 and Figure 29;
- Pratt and Whitney Canada small turbofan engine - Figure 27: ;
- full annular combustor rig tests on AE3007 (Rolls-Royce) - Figure 28.

While having little impact on engine performance and gaseous emissions, alternative fuels use leads to large reduction in particulate matter emissions.

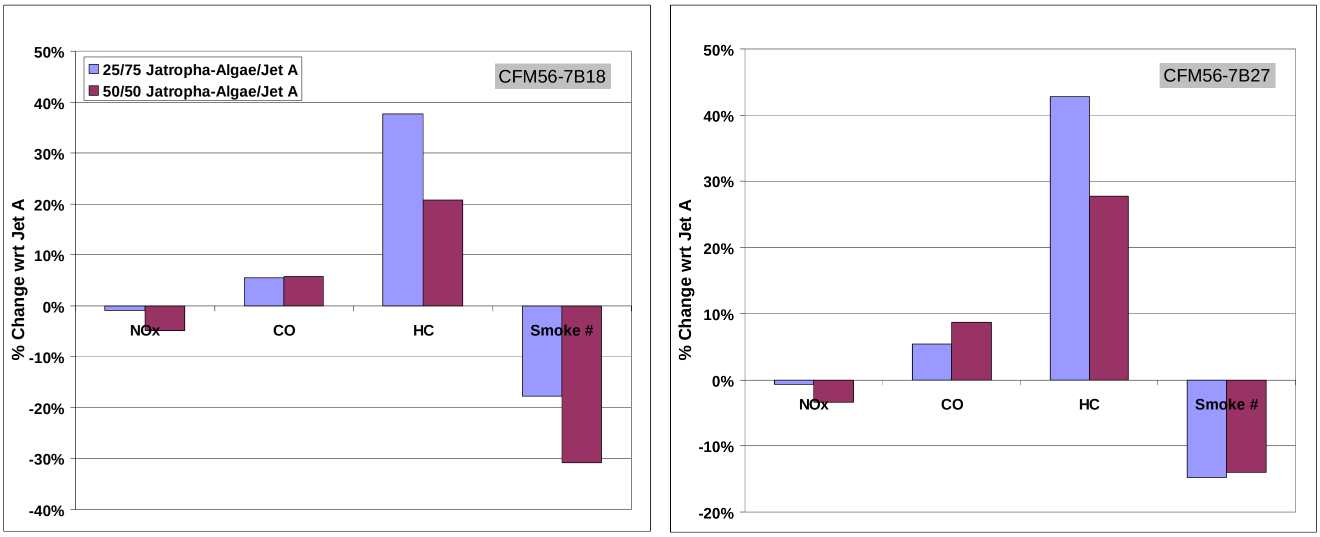

Figure 26: LTO emissions and maximum smoke number for test blends as % difference from Jet A for lowest (18K) and highest (27K) CFM56-7B engine ratings **([52])**

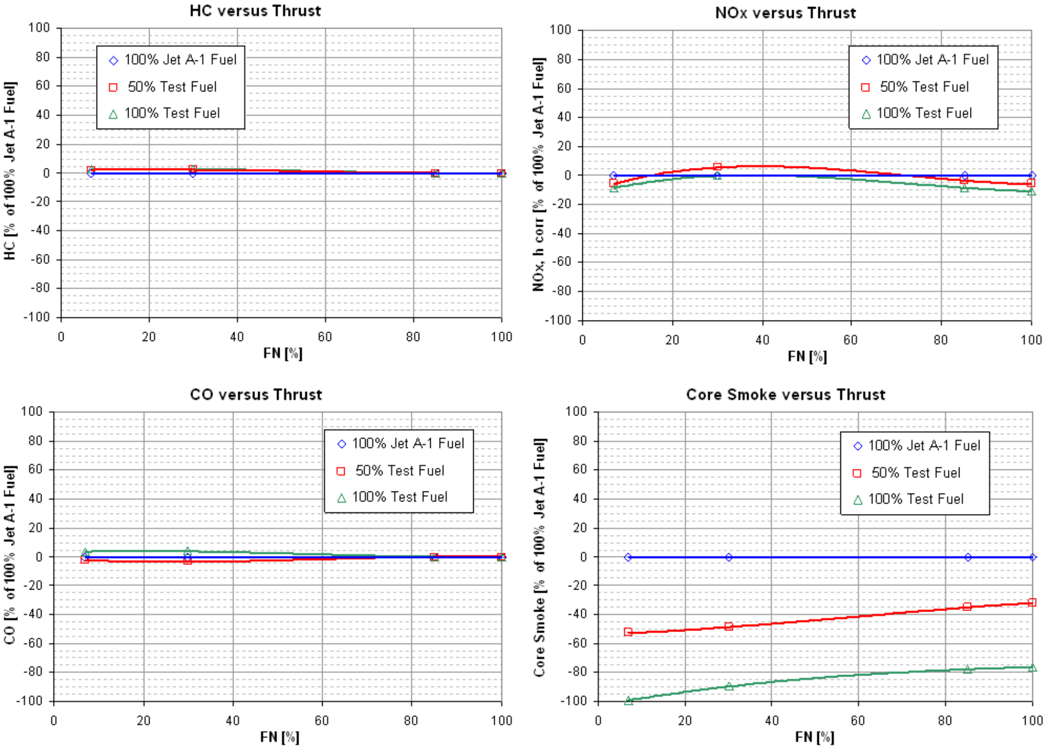

Figure 27: Emission data collected for Jet A-1, blend of 50% Jet A-1 and 50% Neste Oil and 100% Neste Oil in a Pratt and Whitney Canada small turbofan engine ([52])

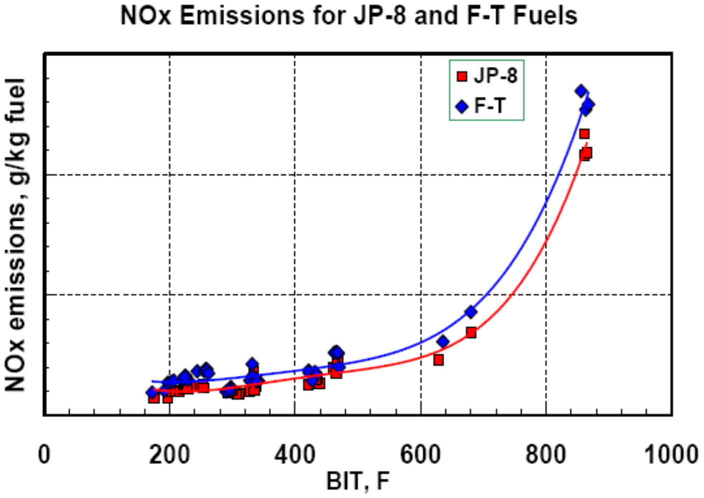

Figure 28: AE3007 full annular tests ([53])

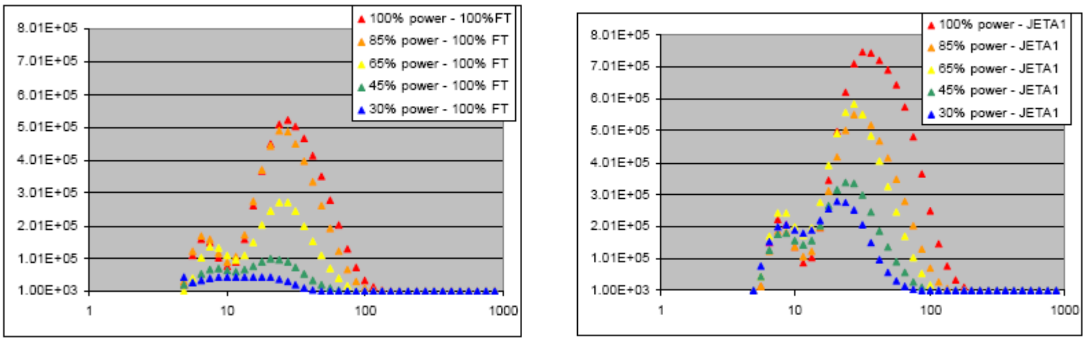

Figure 29: CFM56-7B engine Test ([54])

3 INFLUENCE OF ALTERNATIVE FUELS ON NEW PARTICLE FORMATION AND CONTRAIL PROPERTIES

3.1 Role of emitted material

3.1.1 Soot particles

Jet-fuel combustion increases ambient particulate matter concentration by releasing primary particles or by indirectly promoting the formation of secondary particles. Primary particles (mainly carbonaceous particles or soot) are emitted in large amounts and their emission index varies from 10^{13} to 10^{15} particles per kg of fuel burnt depending on the type of engine used (e.g.[55]). Modern engines tend to emit much less soot particles than older versions. Soot particles behave differently whether they are emitted at ground level or at cruise altitude and they subsequently induce different kind of impacts on the atmosphere.

The first one is related to local air quality. Due to their small size (30-40 nm average equivalent diameter, see for instance [56]), soot particles can be inhaled and are considered as an important source of severe respiratory affection. They can also serve as sites for chemical reactions to take place and therefore contribute to air quality change.

The second type of impact induced by soot particle emissions is related to their fate in the upper troposphere and lower stratosphere at typical flight levels. As they are mainly formed of carbon, they absorb incoming sun radiations and cause therefore a direct positive radiative forcing. From the most recent evaluations, this effect is real but remains limited. The main contribution of soot particles to the Earth's radiative balance perturbation is due to their propensity to act as condensation nuclei, once they get chemically activated (e.g.[57]). Being initially hydrophobic, soot particles become hydrophilic in the aircraft plume (although this point is still discussed). As the aircraft plume cools down by entrainment of cold ambient air, emitted water vapour condenses on the cores provided by the primary particles and freezes if the atmospheric flight conditions are suitable. Ice crystals are thus created and form a condensation trail. As the aircraft plume keeps diluting in the atmosphere, conditions may change as they adjust to ambient values. The newly formed contrail can either evaporate (short-lived contrail) or persist a few minutes or even several hours or days and spread over a large distance (persisting contrail). Ice crystals interact with the Earth's outgoing infrared radiation, being relatively transparent to the sun incoming radiations. A positive greenhouse effect is then produced.

The evolutions of the local and the plume thermodynamic conditions are critical to determine contrail onset. However soot particles provide the necessary cores to promote ice formation, especially due to the current high emission indices.

3.1.2 Sulphur

The fuel sulphur content (FSC) in jet-A1 is normalised and must not exceed 3000 ppm by mass (3 g/kg fuel). Typical values are comprised between 300 and 800 ppm but can differ as a function of the area. Oxidation processes take place in the engine and in the plume and lead to the formation of sulphur dioxide (SO_2) which is thus converted into sulphur trioxide (SO_3) and sulphuric acid (H_2SO_4). This conversion factor is comprised between approximately 0.5 and 5% and depends partly on the engine and the combustor type and settings.

While emitted at ground level, these compounds alter local air quality and contribute to the formation of acid rainfalls. When emitted in flight, they trigger the formation of new particles (volatile aerosols) promoted by the thermodynamic properties of the sulphuric acid and water binary mixture and the presence in large amount of chemi ions[52]. The concentration of volatile particles is very high in the fresh plume and the apparent emission index (number concentration in the plume converted into an equivalent emission index at the engine exit) is close to 10^{17} particles per kg of fuel burnt. Once formed, volatile particles quickly grow due to coagulation and condensation processes and form nanometer size droplets (~10nm, see Figure 30).

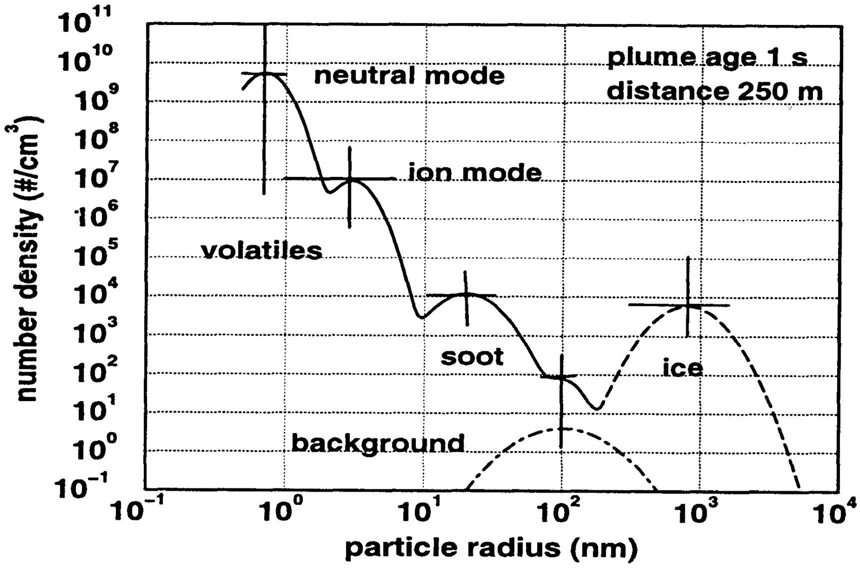

Figure 30: Typical size distribution of the different types of particles in an aircraft plume (from [58])

Sulphate aerosols are naturally produced in the atmosphere, for example from volcanic eruption or from ocean emitted DMS (Di Methyl Sulfide). In the upper troposphere, they induce a negative

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[52] Ions produced at high temperature in the combustion chamber.

radiative forcing (cooling effect) by reflecting the sun's incoming radiation. They can enhance the natural Junge's stratospheric aerosol layer.

But they also contribute to a positive radiative forcing by participating to contrail formation (see diagram in Figure 31). In a first step, sulphuric acid promotes soot particles activation and enhances their condensation properties by forming a total or partial liquid coating. In a second step, freshly nucleated aerosols interact also with soot particles and activate soot particles growth. Finally volatile aerosols may freeze (homogeneously, without any soot core) and therefore may contribute to ice crystals formation.

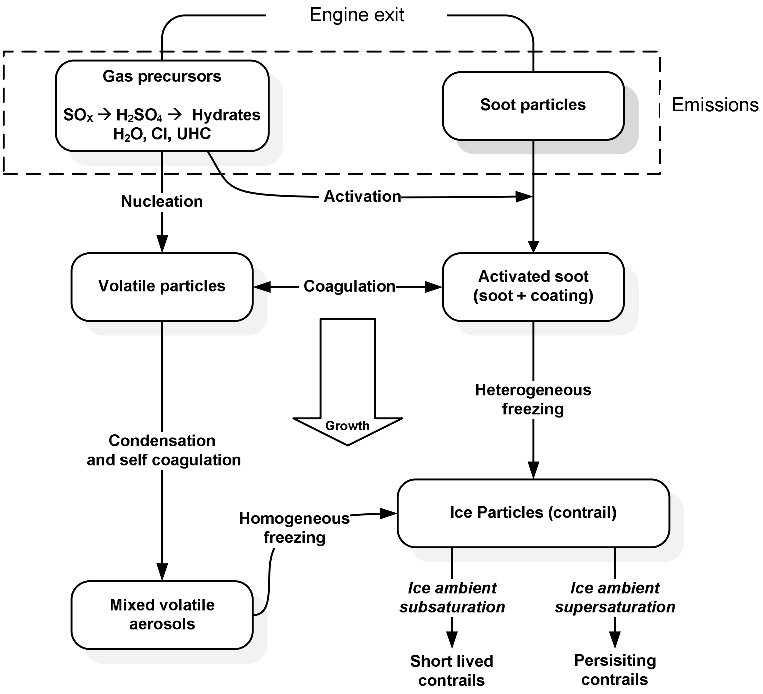

Figure 31: Diagram of the different plume microphysical processes leading to contrail formation (from [59])

3.2 Evaluation of alternative fuels emissions impact

3.2.1 *Formation of volatile particles*

The properties of combustion aerosols and atmospheric particles formed in the plume strongly depend on the exhaust composition. Alternative fuels contain much less sulphur compounds than typical jet-A1. Classical values for the FSC generally range from 300 to 800 ppm. But new fuels are likely to contain values close to 15 ppm or even less. Therefore, alternative fuels, whether they are used in a blend or not, should lead to significantly reduced number of particles formed from sulphate.

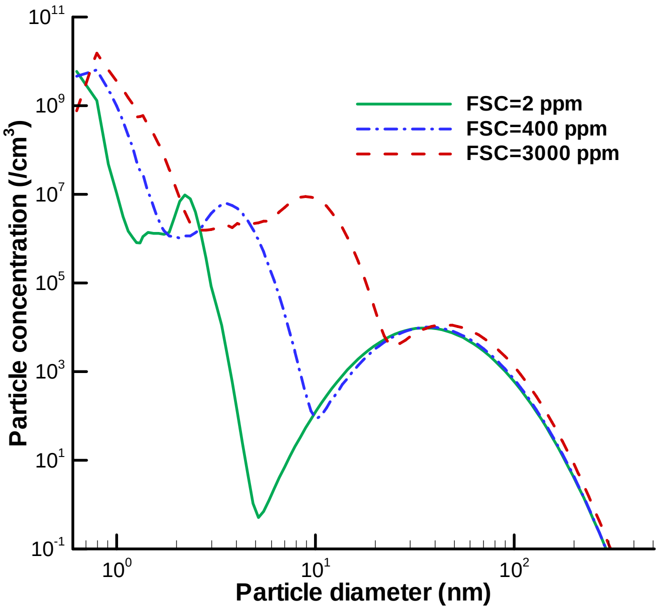

Figure 32: Impact of the FSC on volatile and soot particles size distribution (no contrail) after 0.5s

This is illustrated in Figure 32, showing the volatile and soot particles size distribution, 0.5 s past the aircraft in the plume. This simulation, done for flight conditions where no contrail formed, points out the influence of the fuel sulphur content on the size of the particles. Three cases have been selected:

- 3000 ppm, maximum admitted FSC
- 400 ppm average value for jet-A1
- 2 ppm, very low sulphur case which corresponds to the FSC of some alternative fuels tested in SWAFEA

The number concentration of volatile particles clearly increases with increasing FSC, which is an expected feature ([55]; [58]; [60];). For an aircraft burning a fuel with a 2 ppm, 400 ppm and 3000 ppm FSC, respectively, larger volatile droplets can reach a size of 5 nm, 12 nm and 35 nm at a concentration of 1/cm^3. Therefore, lowering the FSC leads to a decrease of volatile particles overall concentration but also of their size.

The effect on the atmosphere is difficult to evaluate. Undoubtedly positive for air quality concerns, reducing the FSC would lead at cruise altitude to opposite effects. On one hand, increasing sulphate aerosols concentration and size would lead to a negative radiative forcing (i.e a cooling effect) which would tend to reduce aviation overall impact on global warming (e.g.[61]). But on the other hand producing more and larger aerosols provides potentially more cloud condensation nuclei, more available reactive surface areas for chemical reactions.

It should also be noted that sulphuric acid is not the only condensable species which is available in the plume. Apart from water vapour, nitric acid is also present, although its properties make it relatively inefficient for particles growth. The question of the role of organic compounds (unburnt hydrocarbons, combustion products) particles growth is much more uncertain. Cumulated levels of organics concentration at the nozzle range between 20 and 100 ppm for jet-A1 but are currently not well known for alternative fuels. As organics contribute to particles growth ([62]), they tend to limit the effect of reducing sulphur contents by condensing on formed aerosols. Their possible role on ice nucleation is discussed later.

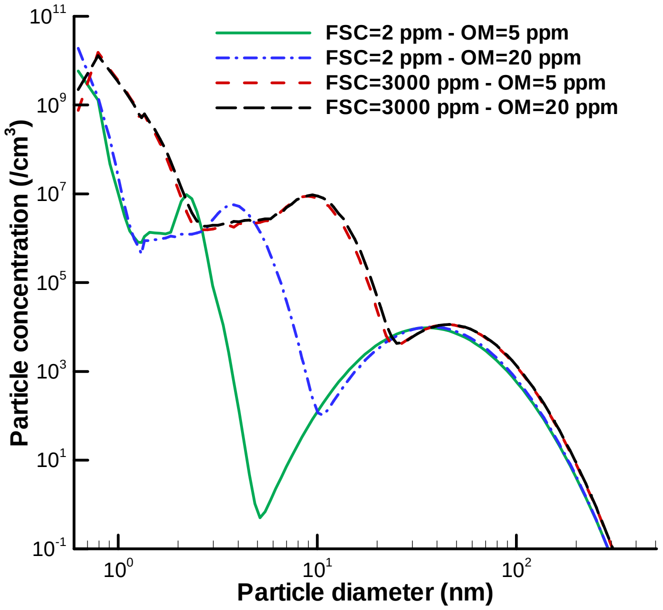

Figure 33: Role of OM in particles concentration and growth at 0.5s in an aircraft plume

This can be seen in Figure 33 where the volatile and soot particle distribution are plotted 0.5s past the aircraft, in the plume. When a very low FSC and a low organic matter (OM) emission index are used, particulate matter final sizes remain small. However, when increasing the amount of OM, the volatile particles size distribution gets broader, as if a larger FSC was used. This effect is only visible for low FSC. For larger FSC (3000 ppm in the figure), sulphate aerosol dominate and the initial amount of organics has only a limited effect on particles growth.

As a conclusion, using alternative fuels on large scales will limit new particle formation thanks to reduced fuel sulphur contents. It should therefore limit the formation of Cloud Condensation Nuclei, but not linearly, but also reduce the cooling effect associated to the production of high altitude sulphate aerosols. However the emission indices of other significant condensable species, such as hydrocarbons, are critical as their effect can be similar to H_2SO_4 regarding particles growth. Current candidates such as formaldehyde are currently under investigation to determine their effect. The question of the emission of large amounts of chemi-ions ([63]) is also an important point that needs to be addressed as they promote volatile particles formation and growth (e.g. [64]; [65]) Determining their emission index, their nature and reactivity is beyond the scope of SWAFEA, as for OM, but should be extensively studied like it has been done for standard jet-A1.

3.2.2 *Formation of ice particles*

Contrail formation depends on many different parameters:

- Ambient conditions (temperature, relative humidity)
- Rate of plume dilution in ambient air
- Initial number of cores (ice nuclei)
- Engine settings (propulsion efficiency)

Ice nucleation occurs from homogeneous or heterogeneous freezing processes but heterogeneous freezing generally dominates. As it can be seen from the diagram in Figure 31, contrail formation is related to different microphysical mechanisms, involving volatile and soot particles.

Alternative fuels analyses and emission measurements point out low aromatics content and as a matter of fact reduced smoke numbers and reduced soot particle number concentration. As a function of the type of fuel used, the blend, the type of engine and combustor technologies and the power settings, soot emission index can be significantly reduced. Available measurements from SWAFEA and other research program indicate that soot initial number concentration at the nozzle exit may be reduced by 30% to 90% at cruise conditions. Two effects can be expected from this change regarding standard jet A1 emissions. A decrease in soot emissions leads to a decrease of their direct impact on global warming if their properties remain unchanged. It is also likely to reduce the number of ice nuclei available in aircraft plumes and this may change contrail properties. But this has to be more carefully investigated, especially as recent studies suggest that if soot were eliminated some other aerosols may potentially promote contrail formation anyway ([66]). But this remains to be checked.

Two different but complementary approaches have been used in order to study contrail properties changes when alternative fuels are used. The first one is based on detailed microphysical calculations on a simplified aircraft plume, including all types of particles and microphysical processes, like it has been done for volatile particles. The second method is based on a detailed simulation of the turbulent wake of a more realistic aircraft plume, where ice spontaneously forms on soot particles.

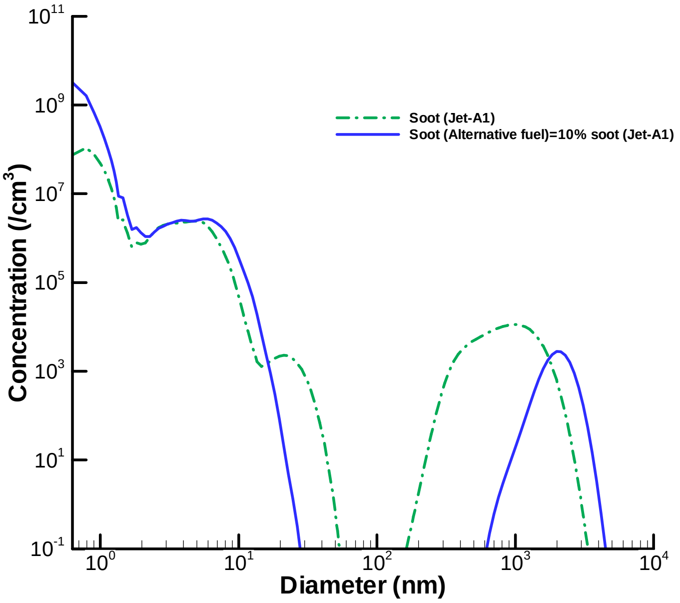

Figure 34: Size distribution of volatile, soot and ice particles in the plume of an aircraft (0.5s after engine exit) for a fuel with reduced aromatics contents and hence reduced soot initial concentrations

From detailed microphysical calculations, based on heterogeneous freezing mechanisms (soot act as ice condensation nuclei), reducing soot emission indices by a factor 10 does modify volatile, soot and ice particles properties. Figure 34 shows the size distribution of the different types of particles 0.5s after the nozzle exit, in the plume. For initial soot concentration which are typical for jet-A1 (although soot initial concentrations are very sensitive to the type of combustor/engine), ice crystals grow to an equilibrium size by water uptake. This size is close to 1 micrometer, which is representative of fresh contrails. All soot particles do not freeze, since a remaining mode is visible close to 30 nm.

When the soot particles emission index is decreased by 90%, several differences can be noticed:

- all the soot particles are converted into ice droplets contrarily to the first case
- ice particles grow to larger sizes (> 2 micrometer against 1)
- volatile droplets grow to slightly larger sizes

These changes are respectively due to the rate of ice nucleation, which is not efficient enough for a large initial number concentration of soot particles to be converted into ice; to the distribution of available water vapour, which leads to less but larger particles; to the coagulation process between volatile particles and soot, whose intensity is reduced when decreasing the soot concentration; Growth of volatile particles by self coagulation and condensation is then preferred.

The results on ice properties are qualitatively reproduced using complex wake dynamics simulations and simplified ice microphysics, as shown in Figure 35.

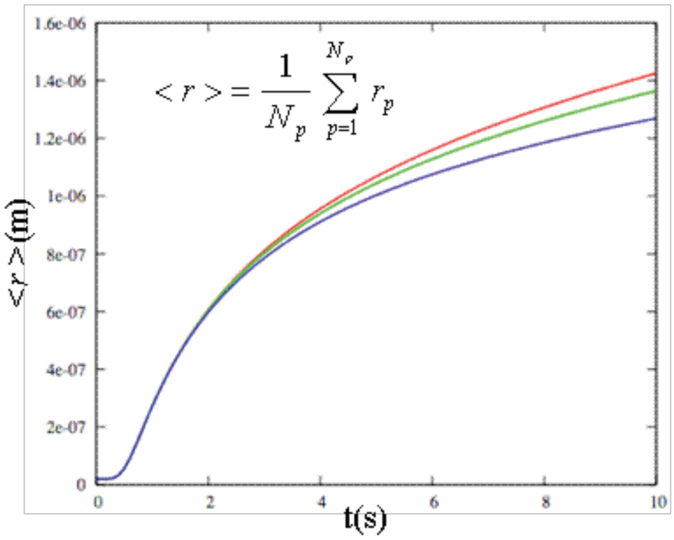

Figure 35: Ice crystals mean radius as a function of time in the aircraft plume. Blue: Initial soot concentration; Green: 50% reduction in soot; Red: 75% reduction in soot.

Reducing the soot emission index by a factor 2 and a factor 4 tends to decrease ice particles mean radius. One the most important parameter concerning contrail environmental impact is the optical depth which depends on ice crystals concentration and radius.

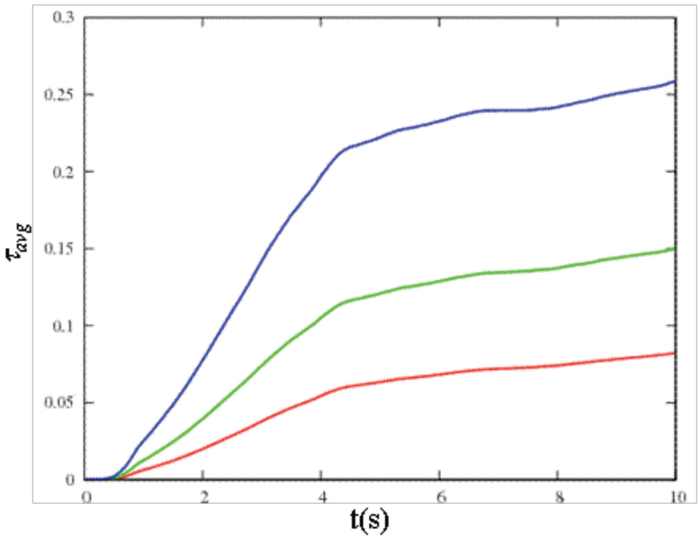

Figure 36: Contrail optical depth in an aircraft plume. Blue: Initial soot concentration; Green: 50% reduction in soot; Red: 75% reduction in soot.

Results for a single aircraft plume clearly indicate that contrails optical depths decrease with decreasing initial soot number concentration. The mean value is indeed divided by a factor 2 after 10s. As a result, using alternative fuels may lead to reduced contrail formation resulting in reduced climate impact, provided that other mechanisms but heterogeneous freezing are not involved in ice crystals formation. This point remains to be addressed as homogeneous freezing processes are not still well understood, in particular about the role that condensable material like organics may play.

The radiative global forcing for contrails (formed by heterogeneous freezing of all emitted soot particles) just after their formation is evaluated to be about 12 mW/m^2 for the present day fleet compared to a forcing of 28 mW/m^2 due to CO_2 aircraft emissions ([67]). According to our results the forcing due to young contrails would be reduced to 7,2 mW/m^2 for identical air traffic conditions if blended fuels are adopted. However, our calculations have been performed for young linear contrails a few seconds after engine emissions. It remains to be seen how the optical depth would evolve for older contrails,when the water vapor used for ice crystal growth comes from the atmosphere rather than from the engine exhausts.

4 AIRCRAFT EMISSIONS REGIONAL AND GLOBAL IMPACT

4.1 Fleet scenarios

The specific effects of aviation emissions on radiative forcing, and following on Greenhouse effect, have been detailed in the introduction. In addition to the analysis of the impact of using alternative fuels on contrails formation, two additional proper studies have been performed within SWAFEA to evaluate the impact on the global ozone budget and on the air quality around airports, knowing that if Green House effect is a crucial challenge, little compromise is today foreseen for the direct consequences of airports on their neighborhood.

Both studies rely on the simulation of aviation emissions impacts for a reference case, corresponding to conventional Jet A-1, and for the use of an alternative fuel.

For local air quality and impact on global ozone budget, simulations are global and rely on a scenario for both air traffic and aircraft fleet. This scenario is based on a traffic forecast from AIRBUS and is used to build a global three-dimensional emissions map over the globe as an input for the atmospheric impacts simulations. Year 2026 has been selected as a good compromise between the available forecast and a time horizon at which alternative fuels may have reached a significant deployment. The global process is illustrated on Figure 37

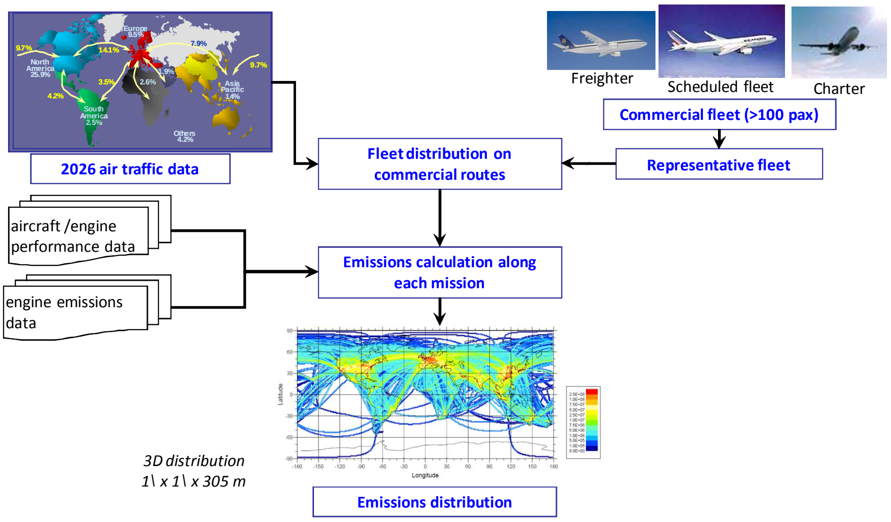

Figure 37: Process for production of scenario fleet emissions with the ELISA tool (AIRBUS)

Considering the current development in alternative fuels for aviation, it has been chosen to carry out these simulations for a 50% blend of SPK with Jet A-1. These fuels are presently the most probable alternative fuels for near term application, either being produced from Fischer-Tropsch or from lipids hydroprocessing. In both cases, their chemical compositions are close to each other. In addition, some emissions data are now available in the literature and some additional tests were performed in the frame of SWAFEA to complement this data base in particular by results for new generation combustion chambers. The simulation scenario in which 50% of aviation fuel comes from SPK (with a homogenous distribution of this alternative fuel in the world), represents a possible situation in 2026, although the actual penetration of alternative fuels at that time depends on many unknowns which are difficult to forecast.

The preliminary steps to perform are thus to build the fleet and air traffic scenario and to rebuild aircraft emissions for all the engines represented in the fleet, for the various flight conditions along aircraft trajectories.

The reference scenario has been built and is presented here after.

4.1.1 Reference fleet emissions scenario

Scenario of global air traffic emissions can be defined as an inventory or a plausible forecast of emissions produced by the aircraft that compose the fleet in operation (from gate-to-gate) along all listed routes in a given region (world, country, airport area, etc.), and for a specific date or duration (year, month, day, etc.).

The potential benefit of alternative fuel use is given by looking the difference between “reference case” and “new or alternative case”. So, two scenarios have to be performed: one reference scenario in which the fleet uses only conventional fuel (Jet A-1), and one alternative scenario in which the same fleet uses an alternative fuel (50/50 SPK/Jet A-1).

As the scenario’s results are used to perform environmental impact evaluations (local air quality and global impact), fleet emissions were produced for one year and at worldwide level, with data extraction for local air quality evaluation done for the example case of Paris, with its two major airports Roissy Charles-de-Gaulle and Orly.

Several steps were successively realised to obtain world fleet emissions scenarios. The methodology defined for the SWAFEA study as well as some hypotheses common to both scenarios are summarised hereunder. They have non-negligible impacts on the final result.

- Airbus Market Forecast was used to evaluate the air traffic demand for the year 2026 on each route operated by current commercial fleet able to transport at least 100 passengers (or equivalent freight). Such traffic is very similar to the one developed in the frame of ICAO/FESG studies.
- Due to the high number of potential in-service aircraft at this date, a limited list of 37 existing or in-development aircraft was selected to represent this commercial fleet. Each aircraft is associated to a specific engine/combustor couple for which emissions when using Jet A-1 fuel are certified or given by engine manufacturers. Based on previous research projects, this commercial fleet should represent ~85% of total fuel burned by aviation in 2026, last part being made by smaller commercial aircraft (<100 pax), business aviation, general aviation and military fleet.

- Representative aircraft were distributed on commercial routes they can operate, and the number of missions made by each of them was quantified in response to air traffic demand for the year 2026.
- Fuel burn and emissions were calculated along each mission by using industrial aircraft performance data, emission indices EIs and Boeing Fuel Flow 2 method. Each mission length is defined by the great circle distance, which corresponds to the smallest distance between departure and arrival airports.
- Finally, each mission being defined in the space by its trajectory whose geographical position is known, emissions were distributed into each elementary volume crossed by this trajectory (elementary atmospheric volume is represented by a bottom surface of 1° in latitude and longitude, and a height of 1000 feet or ~305m).

Methodology and hypotheses previously given were applied to perform the reference commercial fleet emissions scenario. Engine emissions data with conventional fuel come from the ICAO engine emissions certification databank. Total fuel burnt by this fleet for the year 2026 and associated emissions are given hereafter in Table 22.

Fuel burn	CO_2 emissions	H_2O emissions	SO_2 emissions	NO_X emissions	CO emissions	HC emissions
(Tg)	(Tg)	(Tg)	(Tg)	(Tg)	(Tg)	(Tg)
326.72	1030.81	404.16	0.196	5.307	0.871	0.034

Table 22: Total fuel burnt and associated emissions for the reference scenario (year 2026)

Geographical and vertical distributions are respectively given for fuel burn and NO_X emissions in figures 5.5 and 5.6. They underline strong spatial variability, which has strong effects on local chemical processes, and so on environmental impacts.

These results are in agreement with fleet emissions scenarios made in other recent studies (AERO2K, QUANTIFY, etc.).

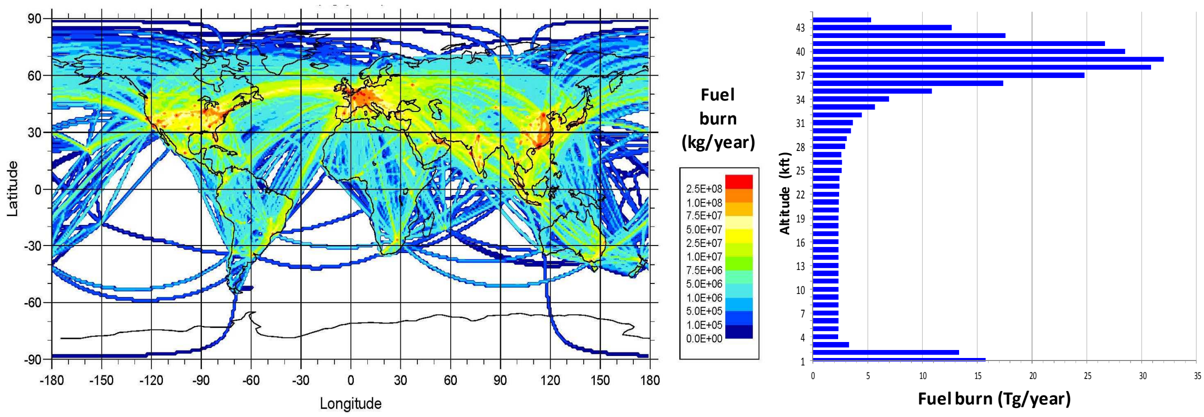

Figure 38: Modelling of geographical and vertical distributions of fuel burned by the commercial fleet in 2026.

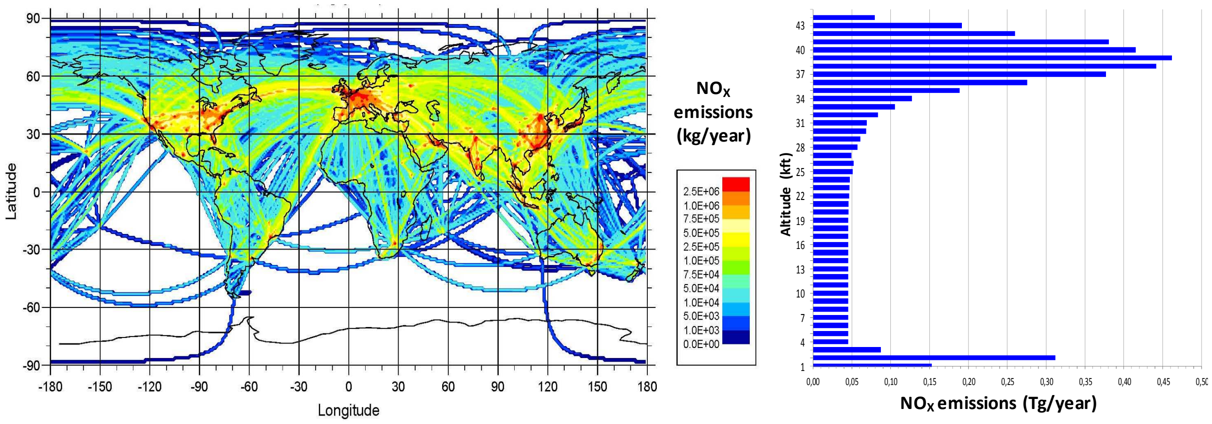

Figure 39: Modelling of geographical and vertical distributions of NO_X emissions produced by the commercial fleet in 2026.

4.1.2 Alternative fleet emissions scenario

Same air traffic demand, fleet composition and aircraft distribution on each route have been used to perform the alternative fleet emissions scenario. As very few data on emissions produced by engines using alternative fuels are available, several additional hypotheses have also been used to evaluate the new fuel consumption and emissions when a 50/50 SPK/Jet A-1 fuel is used.

- Fuel energy content has been used to calculate the fuel consumption evolution. Based on values used as reference for each fuel as given in the Table 23 a reduction of 1.1% has been applied on the fuel burned by each engine. New take-off weights have been calculated for each aircraft on each mission, as result of the balance between the lower alternative fuel mass and the higher volume of fuel required to perform the mission. These modifications have an influence on the vertical profile of emissions released by the aircraft.
- New emissions indices have been calculated for CO_2 and H_2O by using the H/C ratio given in the Table 23. As synthetic fuel is foreseen do not have S content, the emission index SO_2 of has been reduced of half.
- For NO_X, CO and HC pollutants, factors have been estimated and applied only to certified engines for each emission index and for each certified thrust rates. These factors vary strongly with the engine type and the rate of thrust, as explained bellow (positive or null factors have been applied for CO and HC emissions, positive or negative factors have been applied for NO_X emissions).

	100% Jet A-1	**50/50 SPK/Jet A-1**
Net heat of combustion mass	43.2 MJ/kg	43.7 MJ/kg
Net heat of combustion volume	34761 MJ/m^3	34086 MJ/m^3
Fuel density	804.3 kg/m^3	780.0 kg/m^3
H/C ratio	1.916	2.019
EI(CO_2)	3155 g/kg fuel	3138 g/kg fuel
EI(H_2O)	1237 g/kg fuel	1297 g/kg fuel
EI(SO_2)	0.6 g/kg fuel	0.3 g/kg fuel

Table 23: Reference values used for conventional and alternative fuels

Data used for Emissions Index (EI) evaluations come from the literature (see chapters 2.1 to 2.4) edited by the engine manufacturers.

It is difficult to forecast the gaseous emissions with a 50/50 SPK/Jet A fuel because they depend on the engine types. According to available data from publications, engine emissions assumptions are given for 3 engines types:

- GE certified engine: there was a slight reduction in NOx (~5%), and an increase in the CO (~4%) and UHC emissions (~20%) (see Table 24 based on [52]).
- Rolls-Royce certified engine: there was a slight increase in NOx (~5%), and a null factor in the CO and UHC emissions (see Table 25, based on [54]).
- Other engines (future engines, not yet certified), an additional hypothesis is made with a null factor in the NOx, CO and UHC emissions.

	EINOx	**EICO**	**EIHC**	**Fuel Flow**
Idle **7% Take-off Thrust**	0	+4%	+20%	-1.1%
Approach **30% Take-off Thrust**	-3%	+3%	+10%	-1.1%
Climb **85% Take-off Thrust**	-2%	0	0	-1.1%
Take-off **100% Take-off Thrust**	-5%	0	0	-1.1%

Table 24: Gaseous emissions variations with a 50/50 SPK/Jet A fuel on GE certified engines

	EINOx	EICO	EIHC	Fuel Flow
Idle **7% Take-off Thrust**	+5%	0%	0%	-1.1%
Approach **30% Take-off Thrust**	+5%	0%	0%	-1.1%
Climb **85% Take-off Thrust**	+5%	0%	0%	-1.1%
Take-off **100% Take-off Thrust**	+5%	0%	0%	-1.1%

Table 25: Gaseous emissions variations with a 50/50 SPK/Jet A fuel on Rolls-Royce certified engines

Significant lower smoke emissions are attended due to the reduction in the aromatic content. However, no smoke emissions assumption is estimated, because they are not introduced in the fleet scenarios.

Table 26 gives a synthesis of global emissions calculated for reference and alternative scenarios. For the commercial fleet of aircraft with 100 passengers and more operating in 2026, this should represent a global reduction of 3.7 Mt or 1.13% in fuel consumption. The fleet CO_2 emissions using such fuel should reduce of 17.2 Mt or 1.67%, when the H_2O emissions should increase of 3.66%. Strong reduction in SO_X emissions is also expected due to the low sulphur content of this alternative fuel associated to the reduction in fuel consumption; for the commercial fleet studied in SWAFEA, this should represent a global reduction of 0.1 Mt or 50.6%.

	Fuel (Mt)	CO_2 (Mt)	H_2O (Mt)	SO_X (Mt)	NO_X (Mt)	CO (Mt)	HC (Mt)
Reference scenario	326.7	1030.8	404.2	0.196	5.307	0.871	0.034
Alternative scenario	323.0	1013.6	419.0	0.097	5.232	0.872	0.038
Difference [alt-ref]	-3.70	-17.18	14.80	-0.10	-0.075	0.001	0.004
Difference [(alt-ref)/ref]	-1.13%	-1.67%	3.66%	-50.6%	-1.41%	0.16%	11.0%

Table 26: Global fuel consumption and emissions calculated for 2026 commercial fleet when using reference Jet A-1 or 50/50 SPK/Jet A-1 fuel

Due to hypotheses used in this study, the result obtained for gaseous pollutants depends strongly on engines selected to constitute the representative fleet. In this case small NO_X emissions reduction has been calculated for the commercial fleet using this alternative fuel. Significant increase has been obtained for HC emissions, when CO emissions show negligible increase.

The vertical distributions of the fuel consumption, H_2O and NO_X emissions are given in figure 38; they show that emissions are produced at higher altitude, as a result of the changes in the vertical profile that the aircraft makes on each mission. Such variations could have some impacts on the occurrence rate of persistent contrails and on the local ozone concentrations due to NO_X emissions.

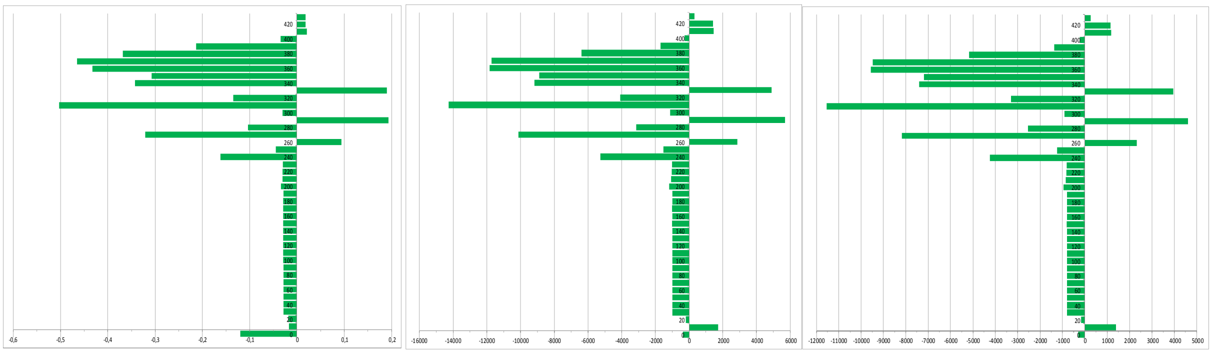

Figure 40: Change in the vertical distributions of fuel consumption (left), H2O emissions (centre) and NO_X emissions (right) when using 50/50 SPK/Jet A-1 fuel.

4.2 Aircraft emission impact on local air quality

4.2.1 Model description

For the study of the impact of alternative fuels on local air quality, the application case of Paris has been chosen. A simulation domain covering Western Europe, typically from 14°W to 24°E in longitude and from 35°N to 58°N in latitude, has been used to gether with a nested domain over Paris and its two airports Orly and Roissy-Charles De Gaulle to study the impact of aircraft emissions changes on air quality (see Figure 41).

Given a set of NO_x, SO_x, NH_3, PM, VOCs and CO emissions, the concentrations of 44 gas-phase and aerosol species have been computed using the CHIMERE model. Aerosols have also been simulated and distributed in different types: sulfate, nitrate, ammonium, secondary organic aerosol (SOA), sea salts (considered as inert here) and natural dust (from deserts and local erosion). The results have been used to evaluate air quality indicators as defined in the Directives (Air quality Directive, Directive on National Emission Ceilings). At the European scale, anthropogenic gas emissions have been taken from various available inventories such as EMEP[53] or GlobCover. The meteorological fields uses the WRF model (mesoscale meteorological model).

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[53] www.emep.int

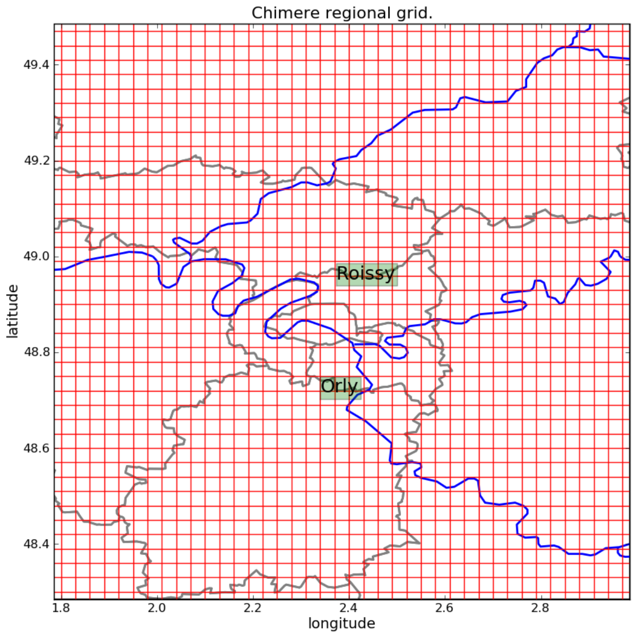

Figure 41: CHIMERE grid used for SWAFEA calculations

A first simulation has been done for the reference scenario with Jet A-1. It has been completed with the alternative fuel scenario provided by Airbus (see 4.1).

The CHIMERE model has been driven on an hourly base by the meteorological model MM5 for the dynamical parameters (wind, temperature, humidity, pressure, etc...), for 32 levels ranging from surface to 10hPa. The horizontal resolution was 54km over a domain encompassing the european CHIMERE domain. For the nested domain a 5 km resolution has been used to generate the meteorological fields which have been horizontally interpolated to fit with the CHIMERE domains. The year 2009 has been selected to perform the simulations.

Several data emission sources have been used and using the Airbus data on CHIMERE's grid was challenging. The Airbus data were provided on a 1° x 1° grid extracted over a domain encompassing the simulation domain. Since this resolution was coarse, complementary sets of data have been obtained from the DGAC[54] maps of airports and from the French National Inventory (for aircraft emissions).

AIRBUS provided emission data and fuel consumption at different levels for the reference and scenario cases (levels, NO_X, CO, CH_4, fuel consumption, emission ratio for CO_2 and SO_2). Data for particulate matter (PM10 and PM2.5) emissions were added from the French National inventory (INS).

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[54] French Civil Aviation Authority

It is important to mention that aircraft soot particles emission indices have not been taken into account, despite the benefit expected from using alternative fuels. Indeed:

- particulate matter emission data mainly rest on smoke numbers data collected during certification procedures; no general agreement has ever been found on a relation between smoke number and soot particles size distribution or mass; therefore, no data can be used from certification measurements;
- In flight measurements or ground level measurements have already been done on soot particles but no extensive sets of data are available for different engines, operating conditions, fuel flows etc. and remains difficult to apply on a general basis.

4.2.2 Simulations

Two simulations have been performed, one as the **base case** using reference emissions (called reference 2026) and an **alternative scenario** using alternative fuel emissions data.

The simulation results for the first six months of 2009 are depicted in Figure 42 and Figure 43. The footprint of the Paris urban network can be clearly identified. Moreover, the footprint of the airports is identified with higher PM10 and NO_2 concentrations and a lower O_3 concentration due to a titration effect.

As shown in Figure 43, the difference between the base case and the scenario is negligible, up to 3 ppt close to the CDG airport. This difference is very weak and consequently, the impact is negligible on O_3 concentrations (not shown here), less than 0.1 %. It is not necessary to plot usual indicators as SOM35[55] or AOT40[56] for ozone, the impact is nil on these indicators.

The impact on PM10 concentrations is slightly higher but remains less than 0.5 %. The higher decrease is observed around the CDG airport.

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[55] Sum of Ozone Means Over 35 ppb, indicator for health impact

[56] Accumulated Ozone over Threshold 40ppb, indicator for ecosystem impact

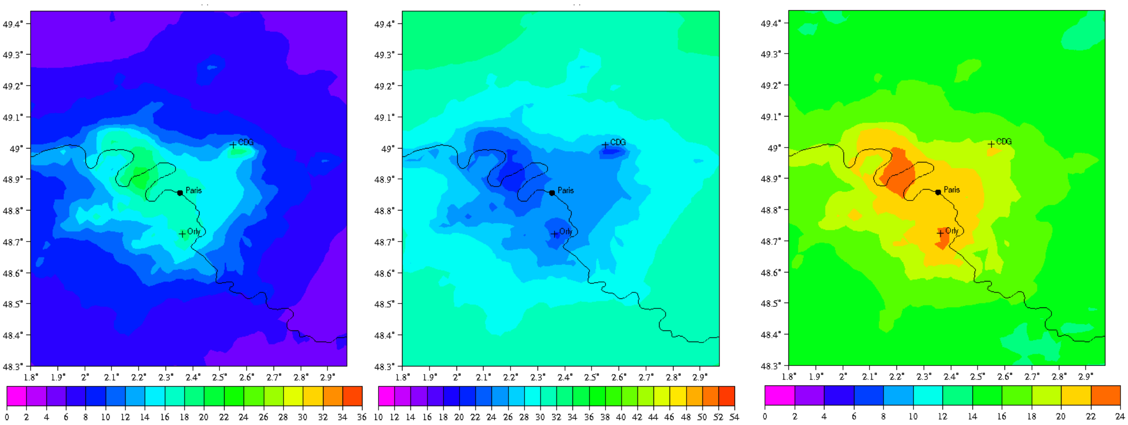

Figure 42 : Mean NO2 (ppb), O3 (ppb) and PM10 (µg.m^{-3}) concentrations from left to right for the 1st January – 15 June period

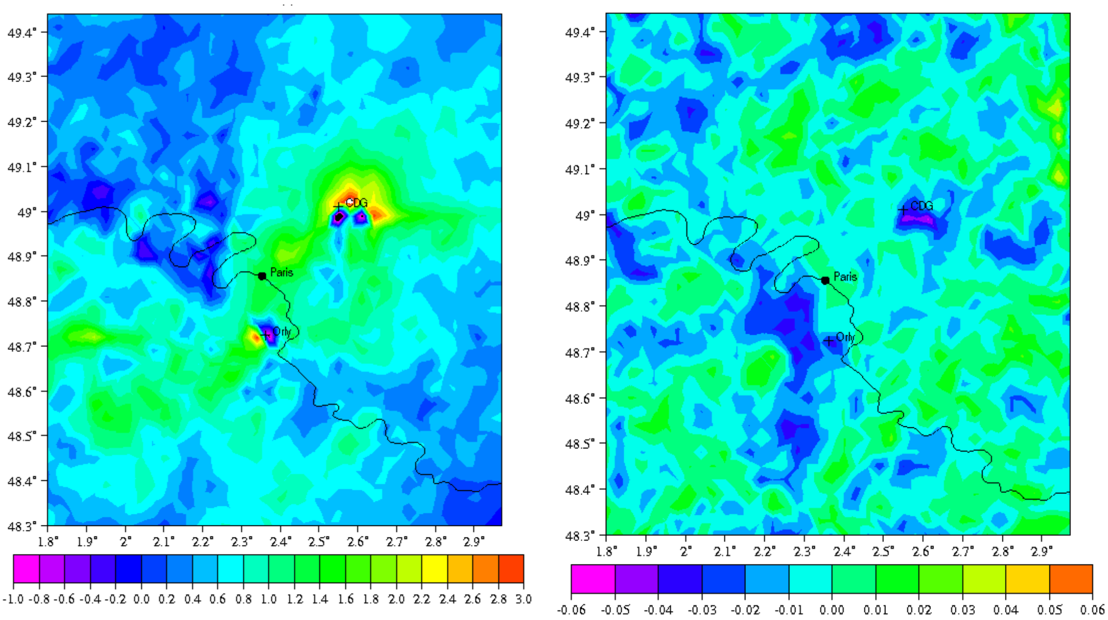

Figure 43 : Differences for NO2 (in ppt) and PM10 (in µg.m^{-3}) concentrations (from left to right) between the alternative scenario and the base case for the 1st January – 15 June period

4.2.3 Conclusion

Local air quality simulations have been performed with a chemistry transport model in Paris area. The results show that the impact of a new emission dataset for aircraft emissions that reflects the change in alternative fuels use does not give any visible impact on local air quality for O_3 and PM10 concentrations.

The SO_2 aircraft emissions decrease is significant but its impact is limited on sulphate concentrations since the SO_2 contribution of aircraft represents only 2 to 3 % of the total SO_2 emissions. In France, sulfate concentrations have mainly a regional or continental origin and a local measure on a low emitter has a negligible impact on local air quality. It should finally be noted that the expected benefit on soot particles emissions reduction cannot be assessed since no extensive database is available for such a variable compound.

4.3 Aircraft emissions global impact

Aircraft emissions global impact has been evaluated by considering ozone concentrations changes. Tropospheric ozone is indeed a gas with a significant contribution to the greenhouse forcing, and is an oxidant that can hamper living species and human health at high concentrations. Ozone is formed in the troposphere via several chemical cycles involving methane, NMHC and VOC species and the nitrogen oxides.

Emissions of nitrogen oxides tend to increase ozone formation. As such the aircraft NOx, CO and NMHC emissions contribute to the ozone production, especially at cruise altitude near the tropopause in the northern hemisphere. Current evaluations ([68], [69]) report that about 7% of the ozone at the tropopause in the North Atlantic corridor is due to the NOx injection by the current commercial fleet.

The possible impact of the use of alternative fuels on ozone formation has been investigated using a 2D photochemical model ([70]) using emissions scenarios at the horizon 2026 constructed by AIRBUS (Marizy, private communication, 2010). This scenario was based on gas emissions compiled by SAFRAN for current and alternate jet fuels.

4.3.1 Definition of scenarios for the aircraft traffic

The 2D model needs as input the global aircraft emissions as a function of altitude and latitude. For the present day traffic, this data is obtained from the inventory compiled within the framework of the QUANTIFY EU project (http://www.pa.op.dlr.de/quantify/). This “current” scenario is constructed for the year 2002. For the future traffic AIRBUS has derived a future scenario for the fleet composition and use and tabulated the emissions accordingly. A database is first derived with the assumption of using conventional jet fuel for the 2026 time horizon. Table 27 gives the global emissions considered by the 2D model for this scenario, referred as “reference” scenario. Figure 44 gives an example of input that is used by the 2D model after interpolation of the emissions on its horizontal and vertical grid.

From the latter scenario the emissions are recalculated assuming the use of alternate fuel (50% jetA1, 50% agro fuel). The new scenario obtained, referred as “alternative” scenario, give new emission data for the 2D model use. Table 27 summarizes the global emissions used within the 2D model for the various scenarios. For each scenario the 2D model is integrated until study state is reached, and the ozone evolutions from one scenario to the other allow the evaluation of the sensitivity of the system to the use of alternative fuels.

	Emissions in MT/year		
Scenario	NOx	HC	CO
Current 2002	2,06	0,013	0,338
Reference 2026	5,31	0,034	0,871
Alternate 2026	5,23	0,038	0,872

Table 27: Global emissions used for each scenario

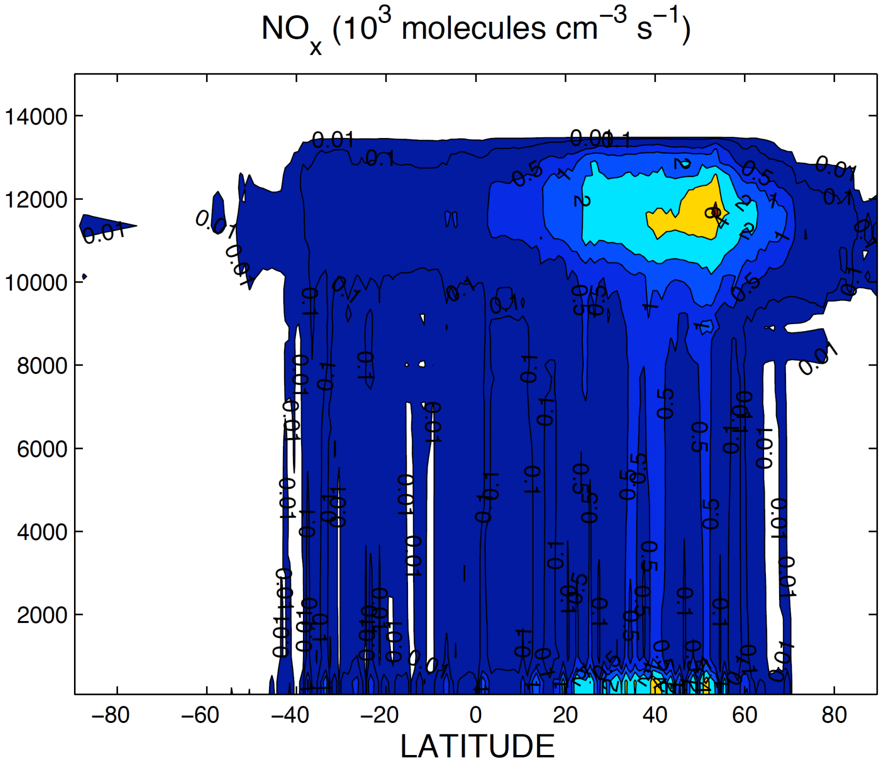

Figure 44: Distribution of the NOx injection rate as a function of latitude and latitude used by the 2D model (reference scenario for year 2026)

4.3.2 2D Model simulation of the ozone response

Figure 45 shows total ozone column variations between the “reference” and “current” scenarios. Those variations correspond to the ozone increase expected by the increase of the traffic between year 2026 and 2002 using present day standard jet fuel. As expected the ozone increase is only significant in the Northern Hemisphere with an increase in the range of 1% at mid-latitudes.

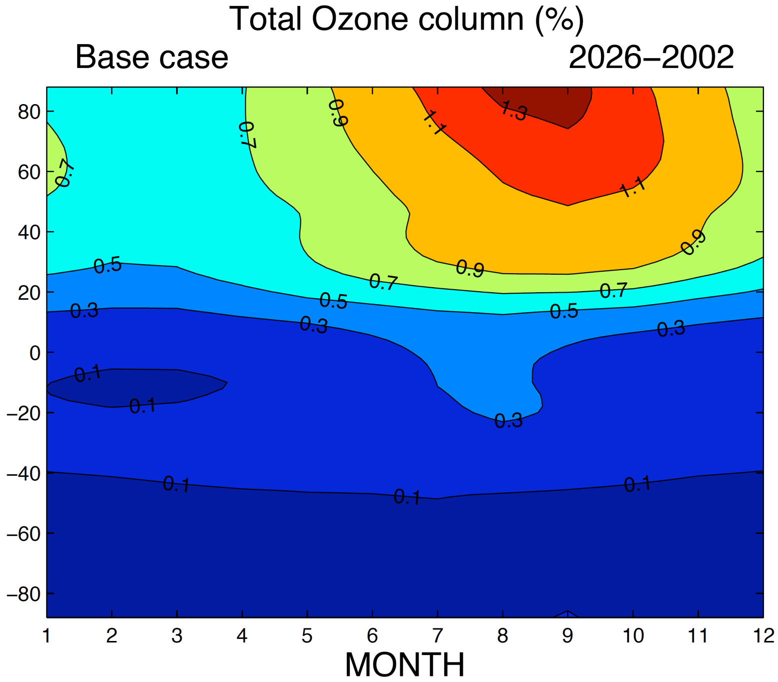

Figure 45: Ozone relative variation between 2026 and 2002 with the use of conventional fuel ((reference-curent)/current, total ozone column).

The impact of using alternate fuels is first seen on the NOx atmospheric content (Figure 46 left panel). At the 2026 horizon the NOx content would decrease by about 2% at cruise altitude in the NH. Consequently less ozone would be produced by the NOx aircraft emissions. In relative terms the ozone production would decrease by about 2.4% (quantity (alternate-reference)/(reference-current)), with little seasonal and latitudinal variations (Figure 46 right panel).

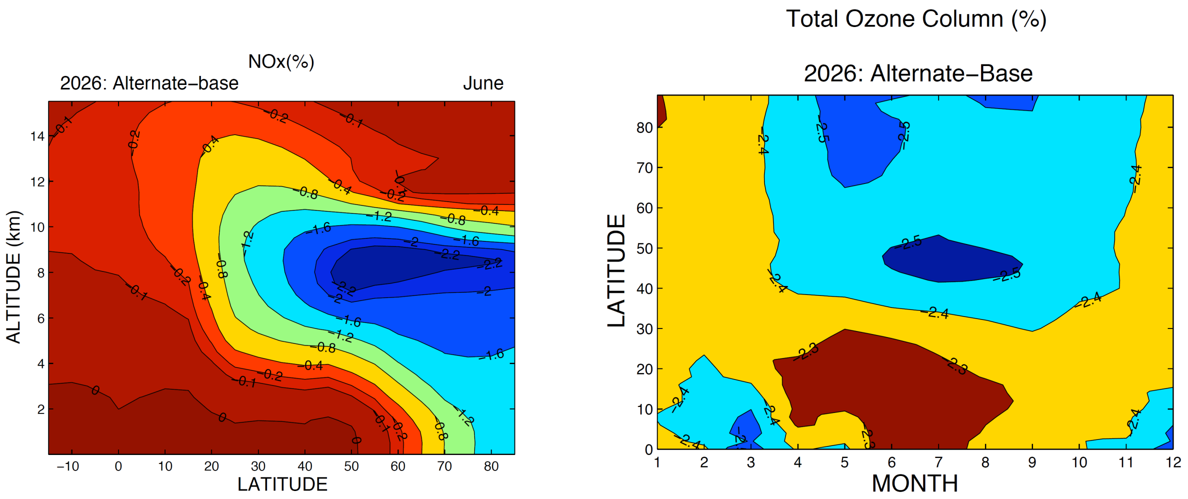

Figure 46: NO_X and O_3 variations due to the use of alternate fuels at the 2026 horizon.

4.3.3 Conclusion on global impact

We evaluate that the used of alternate fuel should have a very modest impact on the ozone atmospheric content. According to our model calculation, the ozone production at the 2026 time horizon would decrease by about 2.4 % when alternate fuel is used. This is a very small number that is at least one order of magnitude lower that variations due to natural variability or change that are expected to follow the decrease in the stratospheric chlorine loading. In addition, this result is quite uncertain because the NOx index of emission for alternate fuel appears to be very variable from one engine type to another, and also according to the power regime used. Thus the NOx emission reduction is result of a delicate balance directly related to the details of the fleet scenario. Most of the NOx decrease seems however to be related to the lowest fuel consumption in the alternate scenario compared to the reference one.

5 SYNTHESIS OF ATMOSPHERIC IMPACTS

The studies initiated in SWAFEA have been carried out considering Synthetic Paraffinic Kerosene (SPK) blends with Jet A-1 which are currently the main candidates for aviation alternative fuels.

From literature data and from the combustion tests performed in the frame of SWAFEA, the most notable impact of SPK blends on engines emissions is a strong reduction of particulate matters, both primary particles (soot) and aerosols formed in the plume, due to the lower content of these fuels in aromatics and sulphur. Available data indicate that soot initial concentration at the engine nozzle exit may be reduced by 30% to 90% at cruise conditions.

This reduction in particulates emissions is a positive factor for local air quality since soot particles are considered as an important source of severe respiratory affection and sulphur oxidation leads in particular to sulphuric acid formation. However a quantitative evaluation of the impact of the reduced soot emissions is currently not possible because no extensive database on aircraft soot emissions is available to perform simulations. The consequence of the reduced SO_2 emissions have been evaluated on the base case of Paris airports but the impact on local air quality turns out to be rather limited because aviation is not the main source of sulphate in France.

Particulate matters also influence the formation of contrails since they trigger the condensation of water vapour and lead to the formation of induced-cirrus-clouds which modify the radiative forcing of the atmosphere. Detailed simulations performed in SWAFEA show that reducing the soot emission index reduces the diameter of the ice particles that form on soots and following decreases the optical depth of the contrails. This is likely to reduce the effect of contrails on aviation radiative forcing and thus on climate.

The impacts of SPK blends on other engines emissions, like CO, NOx or UHC, are much more limited. In particular, NO_X are mainly dependant on the combustor configuration and for SPK fuel, the difference of fuel properties compared with Jet A-1 have only a second order effect. The impact may be positive or negative depending on the engine and thrust rate.

The use of 50/50 SPK/Jet A-1 fuel conducts to a reduction of the fuel consumption for each mission. For the commercial fleet operating in 2026 (SWAFEA scenario), this should represent a global reduction of 3.7 Mt or ~1.1% in fuel consumption and a reduction of 17.2 Mt or ~1.7% in CO_2 emissions, when the H_2O emissions should increase of 3.7%. Strong reduction in SO_X emissions is also expected due to the low sulphur content of this alternative fuel associated to the reduction in fuel consumption.

The reduction of the fuel consumption conducts also to a change in the aircraft take-off weight, and so in the vertical profile that the aircraft makes along each mission. As consequence, more emissions are produced at higher cruise altitudes. Such variations could have some impacts that need to be quantified on the occurrence rate of persistent contrails.

For the hypotheses used to estimate the emissions of NO_X, CO and HC of the scenario fleet when 50/50 SPK/Jet A1 fuel is used, a global reduction in NO_X emissions of 1.4% is obtained, when CO and HC emissions respectively increase of 0.16% and 11%. The results clearly show an associated net decrease in ozone concentrations at mid latitudes. However, modelled ozone changes (~2%) remain below the ozone concentration natural variability. Therefore, with the strong assumptions and uncertainties from the modelling strategy and the emission inventories used, alternative fuels may not decrease much the ozone induced radiative forcing from aviation.

CONCLUSION

Key Messages

- A significant amount of biomass may theoretically be available at world scale for energy application, mainly from agriculture, without endangering food security. It is however far from covering the projected world energy demand in 2050, evidencing a strong need for complementary energy sources.
- The biomass potential could support the objective for aviation to have a carbon neutral growth from 2030 at the emissions level of 2020, if it was accepted to process 52% of the available biomass in biofuel. This is already a high percentage which nevertheless leaves a significant amount of biomass for other uses than aviation and transportation. At contrary, reaching the 50% emissions reduction target appears as calling for an excessive ratio of the global biomass potential for aviation and transport.
- The analysis at European level shows that Europe is likely to be a net importer of either biofuels, either raw materials. In the neutral carbon growth scenario, it could provide up to 39% of the fuel uplifted in Europe from European biomass.
- Reaching the biomass production potential requires a significant effort and investment in agriculture, putting in cultivation large amount of lands that are not cultivated today, the availability of fertilizers and of manpower. If it seems feasible by 2050 from the yield increase technical point of view, it does not mean that the foreseen development of the production can be achieved in the next 40 years.
- From a life cycle point of view, only biofuels offer the promise of a significant reduction of the green house gas emissions. Alternative fuels derived from fossil feedstocks, CTL and GTL, have detrimental impacts on green house gas emission compared to traditional kerosene even in case of carbon capture and sequestration.
- From the GHG emissions point of view, BTL is the most promising option. It complies with the 60% thresholds of the RED on life cycle emissions reduction. Maximising lignocellulose production also leads to the highest primary energy potential from biomass.
- For HRJ, the ability to reach the target depends on the feedstock and on the emissions associated to the cultivation steps which have to be carefully optimised.
- Potential benefits compared to kerosene can only be achieved if no negative impact of land use change is associated to the feedstock production. Either negative or positive, the land use change has a higher impact than the whole fuel production chain. This highlights the importance of controlling indirect land use change (iLUC) that can results from culture displacement. However no methodology is today accepted to address iLUC.

- At world scale and in the short term, the net effect of biofuels on food security is likely to be negative, mainly due to the impact of biofuels production on food price. In the longer term, positive effects could be obtained if biofuels production contributed to the general development of agriculture, bringing technology and improved practices in developing countries that also benefit to food production.
- Environmental and societal impacts of biofuels are not specific to biofuels or to the crops used to produce them. They exist for traditional agriculture and are mostly relevant of agriculture management and of development policies of the interested countries. The fact is that biofuels development will put additional pressure on existing trends.
- Algae could provide answer to biomass availability and to some environmental impacts, thanks to high productivity and low requirements on land quality. It nevertheless calls for synergies with other production in order to fully benefit from the potential advantages. Research is required to better evaluate their potential and before deployment may take place.
- Environmental certification following sustainability frameworks is today the principal way to ensure the sustainability of biofuels production. Existing frameworks, such as the one of the RSB are quite comprehensive and detailed, capturing most of the sustainability issues, even though they currently have difficulties in handling indirect effects.
- Apart from impacts on life cycle green house gas emission, synthetic paraffinic kerosene (SPK), produced from either fossil resources or biomass through Fischer-Tropsch or hydroprocessing, leads to a strong reduction of particulates emissions of aircraft engines. This is due to their low aromatics and sulphur contents.
- While the reduction of soot emissions is likely to have significant positive effects on air quality around airport, no quantitative impact evaluation is currently possible because no extensive database on aircraft soot emissions is available. Conversely, evaluations show a negligible impact of sulphur emissions reduction for a city like Paris because aviation is not the main source of sulphate.
- Reduction of particulates emissions has also proved to reduce the optical depth of contrails formed by the condensation of water vapour on engines exhaust aerosols at cruise flight conditions. This is likely to reduce the effect of the contrails on radiative forcing and thus on climate.
- Impact of SPK fuels on ozone concentrations and radiative forcing through NO_x, CO and UHC emissions is limited and bellow the natural variability for the assumptions, modelling strategy and emission inventories used in SWAFEA.

Recommendations

- Present regulations in Europe should be harmonized to more efficiently enforce sustainability of aviation biofuels. Biofuels should match the RED requirements and be certified in order to account for zero emissions in the ETS.
- Inclusion of aviation in the RED should be more clearly stated and communicated.
- Similar measures are required at ICAO level for a worldwide application in accordance with ICAO's resolution on climate change.
- If bilateral agreements between the European Union and third countries are likely to be the relevant level to address political aspects of sustainability, it should not necessarily exclude certification of the producers.
- Methodological approaches and policy measures are required to address iLUC.
- Aviation fuel being a global commodity, harmonisation of sustainability regulations should be searched among the various world areas. In particular, there would be a strong benefit from an alignment on a global LCA methodology.
- Biomass production being a key issue, demonstration of energy crops performances under controlled agricultural practices ensuring sustainability should be initiated. Availability and impact of the fertilizers should be further analysed along with the impact of the projected use of grazing land from both an environmental and societal point of view.
- Researches on algae are an important axis to diversify sources of biomass and relax the pressure on agriculture. They should be oriented toward demonstrations at significant scale, to confirm yields and scalability of the production, and toward the study of integrated projects in order to maximise the potential benefit and minimize the life cycle impact on both emissions and energy.
- Deeper analysis of atmospheric impacts of alternative fuels is required to completely assess their global final effects. These fuels should be considered in the on-going or proposed research programs on aviation impact on atmosphere and following on climate.

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ANNEX 1: RSB SUSTAINABILITY FRAMEWORK

The 12 principles set by the RSB (version 1) for the sustainable assessment of biofuels are summarized here after.

Principle 1: Legality

Criterion	**Sub-criteria**
Biofuel operations shall follow all applicable laws and regulations.	Biofuel operations shall comply with all applicable laws and regulations of the country in which the operation occurs and with relevant international laws and agreements.

Implications for the biofuel sector: The guidance document is extremely explicit on the required compliance to national laws and regulations but also international regulations, such as the ILO's core labor conventions or the Universal Declaration of Human Rights. This should be demonstrated by the biofuel operators (producers and processors).

Principle 2: Planning, Monitoring and Continuous Improvement

Criterion	**Sub-criteria**
Sustainable biofuel operations shall be planned, implemented, and continuously improved through an open, transparent, and consultative Environmental and Social Impact Assessment (ESIA) and an economic viability analysis.	Biofuel operations shall undertake an Environmental and Social Impact Assessment (ESIA) to assess impacts and risks and ensure sustainability through the development of effective and efficient implementation, mitigation, monitoring and evaluation plans.
	Free, Prior & Informed Consent (FPIC) shall form the basis for the process to be followed during all stakeholder consultation, which shall be gender sensitive and result in consensus-driven negotiated agreements.
	Biofuel operators shall implement a business plan that reflects a commitment to long-term economic viability.

Implications for the biofuel sector: According to this principle, a sustainable production of biofuel requires a throughout planning process, backed by an important impact assessment, which is linked to several other RSB principles (6, 9 and 12 among others). Several guidance documents give great details of the way the ESIA should be constructed by the different actors of the biofuel supply chain.

The last sub-criterion requires a long term commitment from the different operators to the biofuel industry, a key element of the economic sphere of sustainability.

Principle 3: Greenhouse gas emissions

Criterion	**Sub-criteria**
Biofuels shall contribute to climate change mitigation by significantly reducing lifecycle GHG emissions as compared to fossil fuels.	In geographic areas with legislative biofuel policy or regulations in force, in which biofuel must meet GHG reduction requirements across its lifecycle to comply with such policy or regulations and/or to qualify for certain incentives, biofuel operations subject to such policy or regulations shall comply with such policy and regulations and/or qualify for the applicable incentives.
	Lifecycle GHG emissions of biofuel shall be calculated using the RSB lifecycle GHG emission calculation methodology.
	Biofuel shall have lower lifecycle GHG emissions than the fossil fuel baseline and shall contribute to the minimization of overall GHG emissions.

Implications for the biofuel sector: Any biofuel production should reduce the GHG emission over its lifecycle compared to fossil fuels, reduction which should be assessed according to a specific methodology.

In countries or regions where more stringent regulations apply, the RSB will be aligned on these rules: in the European context, the RSB will encompass the minimum 35% reduction defined by the European Parliament and the Council of the European Union[57] for biofuels produced and/or used in Europe. For biofuel produced and used outside Europe, there isn't any reduction threshold imposed by RSB. For comparison, the threshold currently discussed in the USA is 20%.

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[57] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

Principle 4: Human and labour rights

Criterion	**Sub-criteria**
Biofuel operations shall not violate human rights or labor rights, and shall promote decent work and the well-being of workers	Workers shall enjoy freedom of association, the right to organize, and the right to collectively bargain.
	No slave labor or forced labor shall occur.
	No child labor shall occur, except on family farms and then only when work does not interfere with the child's schooling and does not put his or her health at risk
	Workers shall be free of discrimination of any kind, whether in employment or opportunity, with respect to gender, wages, working conditions, and social benefits
	Workers' wages and working conditions shall respect all applicable laws and international conventions, as well as all relevant collective agreements. Where a government regulated minimum wage is in place in a given country, this shall be observed. Where a minimum wage is absent, the wage paid for a particular activity shall be negotiated and agreed on an annual basis with the worker. Men and women shall receive equal remuneration for work of equal value.
	Conditions of occupational safety and health for workers shall follow internationally-recognized standards.
	Operators shall implement a mechanism to ensure the human rights and labor rights outlined in this principle apply equally when labor is contracted through third parties

Implications for the biofuel sector: This principle is a reinforcement of the Principle 1: Legality. Apart the fact that slave labor and forced labor shall not occur, this principle essentially imposes minimum standards regarding child labor, minimum wages and freedom of representation and association.

Principle 5: Rural and social development

Criterion	**Sub-criteria**
In regions of poverty, biofuel operations shall contribute to the social and economic development of local, rural and indigenous people and communities.	In regions of poverty, the socioeconomic status of local stakeholders impacted by biofuel operations shall be improved
	In regions of poverty, special measures that benefit and encourage the participation of women, youth, indigenous communities and the vulnerable in biofuel operations shall be designed and implemented

Implications for the biofuel sector: In region of poverty, biofuel operators have to demonstrate the improvement of the welfare of communities involved and affected by biofuel operations.

Principle 6: Local Food Security

Criterion	Sub-criteria
Biofuel operations shall ensure the human right to adequate food and improve food security in food insecure regions	Biofuel operations shall assess risks to food security in the region and locality and shall mitigate any negative impacts that result from biofuel operations
	In food insecure regions, biofuel operations shall enhance the local food security of the directly affected stakeholders

Implications for the biofuel sector: The RSB acknowledges the possibility of a competition between food crops and fuel crops and defines several safeguards to avoid the degradation of food security by biofuels operations. The RSB framework defines specific actions for the operators, in order to improve the situation of local communities involved in the biofuel production and threatened by food insecurity. This may be in contradiction with the SAFUG pledge which states that “Jet fuel plant sources should be developed in a manner which is non-competitive with food and where biodiversity impacts are minimized”.

Principle 7: Conservation

Criterion	Sub-criteria
Biofuel operations shall avoid negative impacts on biodiversity, ecosystems, and other conservation values	Conservation values within the potential or existing area of operations shall be identified through a land-use planning process. Conservation values of local, regional or global importance within the potential or existing area of operation shall be maintained or enhanced
	Ecosystem functions and services that are directly affected by biofuel operations shall be maintained or enhanced
	Biofuel operations shall protect, restore or create buffer zones
	Ecological corridors shall be protected, restored or created to minimize fragmentation of habitats
	Biofuel operations shall prevent invasive species from invading areas outside the operation site.

Implications for the biofuel sector: Biofuel operations may not have negative impacts on ecosystems and biodiversity: operations have to be designed to at least maintain or improve the ecosystem in which they take place. This will have an impact on feedstock choice, but also on the definition of local cultural practices. To fulfil these criteria, large-scale monocultures will be avoided, which might have an impact on production costs.

This criterion might be considered less stringent than the one defined in the Renewable Energy Directive[58] which states that “Biofuels and bioliquids [...] shall not be made from raw material obtained from land with high biodiversity value, namely land that had one of the following statuses in or after January 2008, whether or not the land continues to have that status” (Article 17.3).

The RSB specifically mentions that conservation values and ecosystem functions shall be maintained or enhanced, which de facto forbids the exploitation of forest as defined in the article 17 paragraph 3.a of the Directive and is aligned with the exceptions presented in the article 17 paragraph 3.b.

The invasive prevention might limit the use of some crops in regions where they have not been historically cultivated at a large scale, which might limit the feedstock choice.

Principle 8: Soil

Criterion	**Sub-criteria**
Biofuel operations shall implement practices that seek to reverse soil degradation and/or maintain soil health	Operators shall implement a soil management plan designed to maintain or enhance soil physical, chemical, and biological conditions

Implications for the biofuel sector: the comments made for principle 7 also apply for principle 8: any biofuel production should maintain or enhance soil conditions. This principle will influence the feedstock selection but also the agronomic practices, thus being a key determinant of the potential yield. This might have a great influence on the economic viability of the production scenario.

The European directive insists on the fact that “Biofuels and bioliquids [...] shall not be made from raw material obtained from land with high carbon stock” (Article 17.4), which is also taken into account in the RSB, as mentioned in one of its guidelines documents[59]:

> “The Renewable Energy Directive (RED) is intended to promote the use of renewable energy in Europe, and stipulates that Biofuel production should be environmentally sustainable and meet certain targets laid down in the directive. Furthermore, it states that if land with high stocks of carbon in its soil or vegetation need to be converted for the production of raw materials for Biofuels and other bioliquids, some of the stored carbon will be released into the atmosphere leading to the formation of carbon dioxide. This could offset the benefits of biofuels through greenhouse gas emissions, and consequently the full carbon effects of such

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[58] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources.

[59] Annex to the Guidelines for environmental and social impact assessment, stakeholder mapping and community consultation specific to the biofuels sector – Ecosystem and Conservation Specialist Guidelines, RSB v1.

conversions must be accounted for in calculating the greenhouse gas savings of any biofuels project. **The RSB has similar guidelines and standards**."

Principle 9: Water

Criterion	**Sub-criteria**
Biofuel operations shall maintain or enhance the quality and quantity of surface and ground water resources, and respect prior formal or customary water rights	Biofuel operations shall respect the existing water rights of local and indigenous communities.
	Biofuel operations shall include a water management plan which aims to use water efficiently and to maintain or enhance the quality of the water resources that are used for biofuel operations
	Biofuel operations shall not contribute to the depletion of surface or groundwater resources beyond replenishment capacities
	Biofuel operations shall contribute to the enhancement or maintaining of the quality of the surface and groundwater resources

Implications for the biofuel sector: According to this principle, biofuel production cannot impose a tremendous pressure on water resources. Overall operations should maintain water quality (pollution minimisation) while maintaining available quantities at reasonable levels. This will have an impact on the whole production process: selection of "sober" feedstocks, design of water efficient process, and need of water treatment facilities. Overall this will impact the cost structure of the biofuel production.

Principle 10: Air

Criterion	**Sub-criteria**
Air pollution from biofuel operations shall be minimized along the supply chain	Air pollution emission sources from biofuel operations shall be identified, and air pollutant emissions minimized through an air management plan.
	Biofuel operations shall avoid and, where possible, eliminate open-air burning of residues, wastes or by-products

Implications for the biofuel sector: Air pollution from biofuel operations will have to be planned, monitored and minimised. This will have an implication on the process design and ultimately on production costs.

Principle 11: Use of Technology, Inputs, and Management of Waste

Criterion	**Sub-criteria**
The use of technologies in biofuel operations shall seek to maximize production efficiency and social and environmental performance, and minimize the risk of damages to the environment and people.	Information on the use of technologies in biofuel operations shall be fully available, unless limited by national law or international agreements on intellectual property
	The technologies used in biofuel operations including genetically modified: plants, micro-organisms, and algae, shall minimize the risk of damages to environment and people, and improve environmental and/or social performance over the long term.
	Micro-organisms used in biofuel operations which may represent a risk to the environment or people shall be adequately contained to prevent release into the environment
	Good practices shall be implemented for the storage, handling, use, and disposal of biofuels and chemicals
	Residues, wastes and byproducts from feedstock processing and biofuel production units shall be managed such that soil, water and air physical, chemical, and biological conditions are not damaged

Implications for the biofuel sector: This principle fosters the development of a risk assessment for the use of specific technologies in biofuel operations, which will certainly be tailored at the business level. However, this will have implications at the sector level: production costs will be altered when taking into account the cost for managing the risk (good practices, safety barriers...).

Principle 12: Land rights

Criterion	**Sub-criteria**
Biofuel operations shall respect land rights and land use rights	Existing land rights and land use rights, both formal and informal, shall be assessed, documented, and established. The right to use land for biofuel operations shall be established only when these rights are determined
	Free, Prior, and Informed Consent shall form the basis for all negotiated agreements for any compensation, acquisition, or voluntary relinquishment of rights by land users or owners for biofuel operations

Implications for the biofuel sector: This principle can be considered as an extension of principle 1, as it is mandatory for biofuel operations to operate legally. Complying with this principle might be problematic in countries where property rights on land are unclear, especially if the feedstock production takes place on marginal lands. This issue is mainly local and might not be generalised at the sector or the production scenario level.

ANNEX 2: CEREAL AND OIL SEED PRODUCTIVITY INCREASE RATES 1980-2009 (FAOSTAT)

	Africa					Asia					Europe				America				Oceania			
	Eastern	Middle	Northern	Southern	Western	Eastern	Central	Southern	Southeastern	Western	Eastern	Northern	Southern	Western	Caribbean	Central	South	Northern	Australia & NZ	Melanesia	Micronesia	Polynesia
Cereal	0.54	1.65	2.59	2.67	0.43	1.95	4.52	2.00	2.26	2.42	1.07	-0.30	1.39	1.21	0.48	0.98	1.54	1.28	1.53	1.84	-0.09	-0.09
Oil seeds	0.57	-0.42	0.08	0.93	4.86	1.24	4.75	1.75	0.82	2.73	0.86	0.72	1.14	0.90	0.89	0.89	1.61	1.45	1.30	0.89	0.89	0.89

	Africa	Asia	Europe	S-America	N-America	Australia/NZ	Oceania
Cereals	1.57	2.63	0.84	1.00	1.28	1.53	0.56
Oil seeds	1.20	2.26	0.91	1.13	1.45	1.30	0.89