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Future of biofuels and other alternative fuels in aviation

Modeling economic and environmental impacts of possible scenarios of biofuels and alternative fuels use in aviation

Steinbeis Advanced Risk
Technologies GmbH

EU-VRi

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Steinbeis-Edition

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Foreword

This report is the result of the task "T.3.2.1 - Ex-ante economic impact analysis: establishing of overall methodology" in the work package "WP3.2: Economical Evaluation" in the EU Project Alfa-Bird.

By establishing an original methodology and by providing a corresponding web-based assessment tool, described in this report, it becomes possible to analyze scenarios of future use of biofuels and other alternative fuels in a very clear way. Focused on the long term with a time-horizon up to the year 2030, this type of analysis is a requirement for any socio-economic analysis in the field of new energies.

Because of large uncertainties and numerous unknowns involved, it is essential to be able to perform a series of interactive "what - if" analyses, instead of focusing onto one scenario and one set of assumptions, no matter how carefully these might have been chosen/selected those types of approach got limitations and this model try to overcome them. This type of solution has been deemed necessary by virtually all of the stakeholders who participated in a survey performed during the project: 350+stakeholders and 40+ countries worldwide.

The methodology provides clear explanation of all steps for the assessment of environmental and health impacts, and a good definition and guidelines to measure "indicators" (qualitative, quantitative, semi-quantitative, monetization) needed for analyzing these impacts. The methodology, following largely ISO 14040, 14044 and SEA/REACH approaches, is based on the idea that the biofuels and other alternative fuel will have to "compete" at the market against established solutions/technologies and that in this type of competition, the life-cycle related factors can play an extremely important role.

Hence, a fuel-substitution model will not and cannot be a result of a single decision (e.g. a political decision), but will be a result of interaction of a number of factors like technology effectiveness, GHG emissions, land-use planning, production costs, annual savings, market prices, mitigation strategies, etc.

This report looks at those possibilities primarily from the point of view of three basic scenarios:

- "Business As Usual",
- "Low Environmental Incentives"
- "High Environmental Incentives"

Looking at three main indicators (Resource productivity, Resource specific impact and Eco-efficiency), and proposes, at the end, a multi-criteria decision making matrix in order to optimize and help any decision about the future strategy of implementation.

This model and associated report provides great insights to anyone who would like to address the extremely important topic of Biofuel market introduction. It has been one of the highlight of the FP7 Alfabird project and is recommended to all stakeholders in the aviation biofuel domain.

Y. ALLOUCHE

Airbus R&T program Engineer for alternative fuels and environment

Alfabird Technical coordination

Executive summary

Based on the aim to develop the use of alternative fuels in aeronautics of ALFA-BIRD project, the different tasks (Task 3.2.1, Task 3.2.2, and Task 3.2.3) within the WP3.2:Economical Evaluation contribute to reach the general goal of the project and also, go beyond the initial expectations specified in the DoW of the Grant Agreement No. ACP7-GA-2008-213266 of the project.

In order to address in an effective way the different tasks, the work performed in this report develops a methodology which is not based in "static" scenarios and assumptions but on dynamical ones. A web based tool based on a dynamical competition model for fuel substitution has been developed. Investment and market factor are modeled by the Lotka-Volterra dynamical system for the substitution of fossil by alternative fuels. This is a paradigmatic modeling approach for systems where multiple technologies with limited production capacities compete in a confined market. In this model projections for the demand of a candidate fuel (and, by that, its market penetration) are outcomes of a dynamical model taking the overall supply of competing options and their price into account.

The model was developed as an ASP.NET 4.0 Website. The user can specify target capacities for market shares of GtL (Gas-to-Liquid), BtL (Biomass-to-Liquid) and CtL (Coal-to-Liquid) fuels. The number of plants required to reach this market share is then calculated and used to compute the development of production capacities. An additional user input is a carbon tax, i.e. a monetary penalty on CO_2 emissions. These costs are calculated for the three model fuels and added to the price. Oil price scenarios are also selected by the user by specifying mean annual change rates over five year intervals. The model calculates the dynamics of Jet A1, GtL/CtL, and BtL market shares in time. In particular it is focused on the use of carbon capture sequestration for GtL/CtL and the indirect land use change (iLUC) for BtL. The fuel technology analyzed is marked by two main driven phases, the investment factor and the market factor. The candidate fuel reached market penetration which is economically viable given the fuel demand at a given production cost.

From these dynamics the S-curve is measured. From the market shares at each year the development of GHG emissions are displayed too. The Website allows comparing two runs with different settings (i.e. the "current" run to a "baseline" scenario). Detailed information on the price and capacity development projection is displayed as a data table and can be downloaded in standard formats for post-processing.

This report integrates the approach of the SEA methodology, the development of the stakeholders' basis (350+stakeholders and 40+ countries worldwide), the results of Life Cycle Assessment, Multi-criteria Decision Making (MCDM) tool and the decoupling indicators.

The integration of the decoupling indicators (resource efficiency indicators) aims to show how the overall economic growth is related to the overall environmental impact of resource use. In the consequence it informs whether and to which extent we can decouple growth from impact. Within this report it is being developed this indicators for the use of GtL and BtL, where the main input for these indicators relies on the fuel substitution model and the references used for its development.

The work performed in this report shows clearly that Economical modeling, SEA, LCA, MCDM and decoupling indicators are dependent on many input parameters and assumptions, which can lead to many different and very uncertain results. The dynamical approach developed, used and presented in this work shows that the transparent what-if analysis is possible.

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1 Introduction

1.1 Goals and objectives

WP 3.2 aims to provide a comprehensive analysis of economy related impacts of the alternative fuels for aircraft developed within Alfa-Bird project on all stakeholders in the value chain as well as onto the society in general.

The economic evaluation, together with results of environmental impact evaluation done in WP3.1: Environment balance, and technical syntheses done in WP3.3: Future alternative fuels strategy and implementation, is considered as the main result of the whole project - an innovative set of aircraft fuels implying reasonable ownership costs and guaranteeing sustainable aviation.

The economic analysis within WP3.2 has to provide an insight into the relationship between the selected alternative fuels and their cost parameters. In a first step, the direct costs to produce, distribute and use the alternative fuel candidates previously assessed are to be evaluated, including revenues from by-products, and compared to their equivalent data regarding conventional fuels. Additionally, the fuel availability aspect has to be assessed since it plays a major role in the viability of a world-wide transportation device such as aircraft. The consequences on air transport market have to be deduced from the whole set of data.

The evaluation is to be completed by a cost-effectiveness study that, for each alternative fuel candidate, relates the basic costs to the environmental impact. A qualitative approach will be performed first providing indications on the cost to reduce emissions. A further quantitative attempt will lead, via normalization methods, to a comparison between all the selected candidates.

Three tasks are set up to allow achievement of the overall goals:

Task 3.2.1 – Ex-ante economic impact analysis: establishing of overall methodology

Task 3.2.2 - Ex-ante economic impact analysis: establishing the stakeholder basis and application of the methodology

Task 3.2.3 – Application of the commonly accepted indices for CSR onto the Alfa-Bird technology

The objective of the Task 3.2.1 (Figure 1) is to establish an overall methodology for economic impacts analysis and develop corresponding tool for methodology implementation. The overall methodology has to include:

- setting up the Framework for Economic Impact Analysis including
  - measuring economic direct impacts: economic growth and competitiveness, economic welfare at regional, national or EU level, investments and market shares
  - Identifying and measuring anticipated socio-economic impacts micro, meso and macro levels, i.e. at the levels of partners, their parent organizations immediate target users and the society at large:
- the economical aspects of the scientific and technological impacts:
  - measuring innovation and technological breakthroughs, standards agreements, industrial and
  - technological leadership, lasting integration, knowledge transfer, infrastructure development, mobility of personnel;
- the economical aspects of the environmental impacts:
  - resource-use,
  - structural changes with impact on climate change, air, water and soil pollution, bio-diversity, safety and security
- the economical aspects of policy and regulation impacts:
  - standards formulation,

  - policy development, including relevance of the impacts to the overall EU policy goals
- the economical aspects of sustainability in terms of lasting value of the impacts
- the economical aspects of impacts of research activities on various sets of actors, such as the research teams and their organizations, the immediate users and the society at large.
- EU-VRi (its founding member Steinbeis R-Tech) will establish the methodology and produce the tool for its implementation
- INERIS, Airbus CE and IFP will provide the application with specific inputs, know-how, and contacts, review the methodology during its development and report about its respective applications.

Within Task 3.2.2 a stakeholder data base is established and proposed methodology applied, together with final assessment of methodology application results.

In Task 3.2.3, the application of the commonly accepted indices for CSR onto the Alfa-Bird technology is developed.

Compilation of results from the tasks is provided in this final report for the Work package 3.2. (Task 3.2.4).

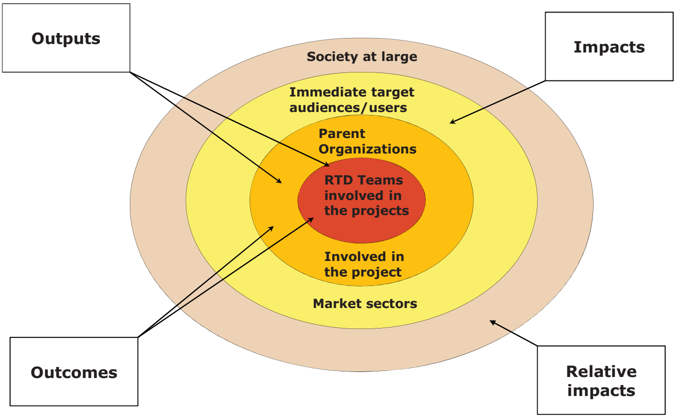

Figure 1: Ex-ante economic impact analysis: overall methodology

1.2 *Overall methodology*

In addition to scientific and technical activities related to the development, testing and validation of new fuel mixes for aircrafts, the ALFA-BIRD project relies on an environmental balance and an economical evaluation – both within SP3 and addressed in work packages WP3.1 and WP3.2 respectively.

This document presents the final report for the Work package 3.2 (Task 3.2.4), where it is included the other tasks. The first task is the Task 3.2.1, entitled: Ex-ante economic impact analysis: establishing of overall methodology for what it is devoted the chapters: 4, 5, 6, 7 and 8, and the Task 3.2.2 entitled: Ex-ante economic analysis: establishing the stakeholder basis and application of the methodology, for what it is devoted the chapter 2 of this report.

The report provides elaborates methodology for the economic evaluation (Task 3.2.1) of the new alternative fuels. The methodology is based on four cornerstones, which will be analyzed in deep along the report:

1. The EU Socio-economic analysis (SEA) framework (Chapter 4)
2. Life Cycle Assessment (Chapter 5)
3. Fuel substitution model (Chapter 6)
4. EU-JRC - Decoupling Indicators (Chapter 7)

The purpose of a socio-economic analysis (SEA) is to evaluate what costs and benefits (e.g. the introduction of biofuels in jet fuel) will create for society. The SEA process compares this action with, for instance, a business as usual (BAU) scenario (e.g.: no change brought to aircraft fuel as it is today).

Life Cycle Assessment has been developed as a tool over recent decades. The main goal of this tool is to identify the resource flows and environmental impacts associated with the production of the alternative fuels: GtL (gas to liquid fuel), CtL (carbon to liquid) and BtL (biomass to liquid). International standards such as ISO 14040 and ISO 14044 assist in the specification, definition, methods and protocols associated with LCA studies.

Fuel substitution model has been carried out in a very compressive way for GtL and BtL technologies. In particular it is focused on the use of carbon capture sequestration for GtL and the indirect land use change (iLUC) for BtL. The fuel technology analyzed is marked by two main driven phases, the investment factor and the market factor. The candidate fuel reached market penetration which is economically viable given the fuel demand at a given production cost.

The integration of the decoupling indicators (resource efficiency indicators) aims to show how the overall economic growth is related to the overall environmental impact of resource use. In the consequence it informs whether and to which extent we can decouple growth from impact. Within this report it is being developed this indicators for the use of GtL and BtL, where the main input for this indicators relies on the fuel substitution model and the references used for its development.

2 Establishing Stakeholder Basis (Task 3.2.2)

Stakeholder's basis for biofuels has been established virtually within Task 3.2.2

The first survey to gather the stakeholders was sent in November, 2011. The survey used the R-Tech/EU-VRi management system database, which includes more than nine thousand contact information in different fields, e.g. industry, research, higher education.

The survey gather around 350 stakeholders for biofuels in 40 countries worldwide. Figure 2, illustrates the number of stakeholders distributed by country. It can be observed in the pie chart that the highest percentage corresponds to Germany, France, and Italy. Spain, Belgium, Austria, United Kingdom, have also an important participation.

In order to get a better overview of the participation in different countries, a threshold of 1% has been set off, which means that, under category "other" there are 37contact information which belongs to other 23 countries worldwide. In Figure 3, it can be observed the complete results for 40 worldwide.

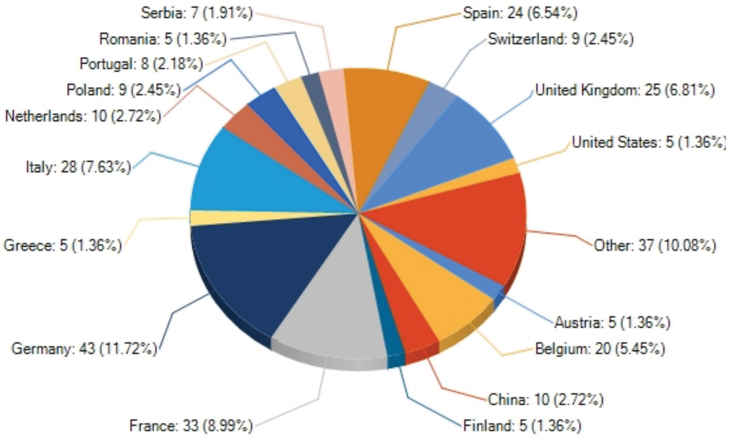

Figure 2: Stakeholder basis: 350 stakeholders, 40 countries (threshold of 1%)

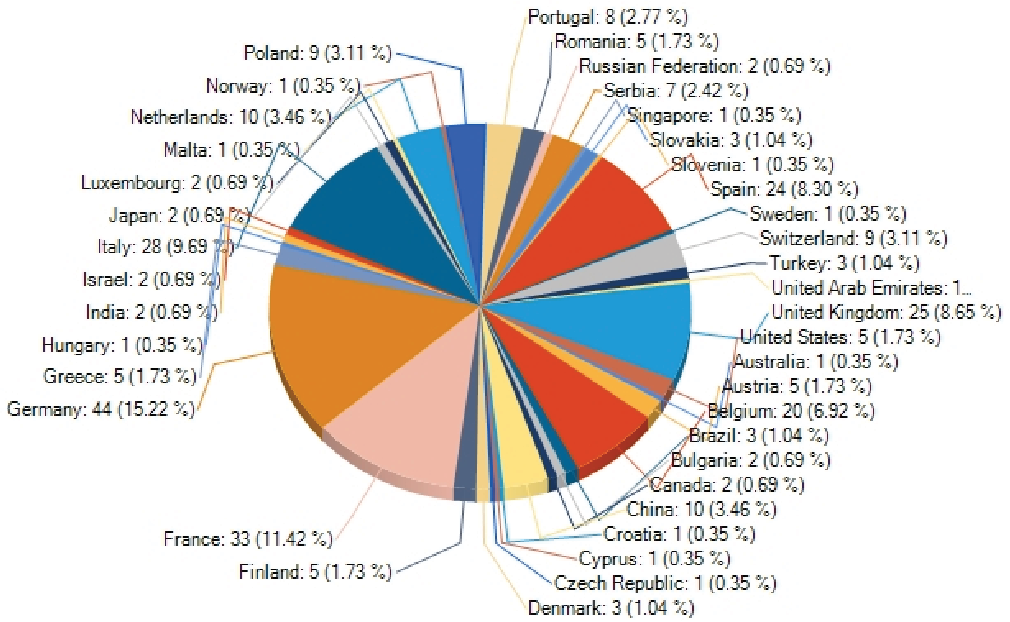

Figure 3: Stakeholder basis: 350 stakeholders, 40 countries

3 Proposed solution (Task 3.2.1)

Proposed solution of the methodology for economic evaluation of new alternative fuels is based on four cornerstones

- The EU Socio-economic analysis (SEA) framework.
- Life Cycle Assessment
- Fuel substitution model
- EU-JRC (Decoupling indicators)

3.1 The EU Socio-economic analysis (SEA) - Framework

SEA aims at assessing all relevant (positive or negative) impacts of an activity over its entire life-cycle. It sets a systematic and comprehensive framework for comparing different scenarios, thus making it possible to focus on differences in terms of impacts between different scenarios or activities. For the sake of ALFA-BIRD, scenarios for alternative fuels could be compared with a kerosene ‘business as usual’ scenario.

SEA also aims at assessing the distribution of the different impacts (costs and benefits) in a geographical sense and over different sectors or social or population groups.

SEA is rather a framework bringing together distinct assessment methods than an assessment method in itself (cf. Figure 4). It makes use of inputs from specific assessment methods, such as LCA and economic analyses, to which it adds further aspects not covered by these methods to arrive at a global analysis of all relevant impacts of a product alternative or activity.

It takes a cost-benefit view, covering the assessment of relevant private and social costs and benefits. In assessing externalities it draws on further available methods and data sources. Examples for these, as far as the environment and health are concerned, are outlined below.

SEA is a pragmatic approach. It foresees iterative assessment processes where the basic idea is to conduct assessments of which the efforts are proportional to the outcome. This implies also to quantify or monetize impacts only to the extent necessary to arrive at robust conclusions. Acknowledging furthermore limits to a quantification or monetization of certain impacts, SEA can be qualified as defining a cost-benefit type framework for assessing scenarios. SEA also puts emphasis on uncertainty assessments in order to assure robust conclusions.

In order to judge the overall performance of different scenarios against each other, specific assessment tools can be used, depending on the objective and the data available (cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis …).

3.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool for environmental management which has been developed during the past thirty years. LCA considers the entire life cycle of a product or service. It encompasses all processes in raw materials extraction, energy and materials production, product manufacturing, use and final disposal, reuse or recycling, and includes the transportation between these life cycles stages. The potential environmental impacts and resource consumptions are assessed based on the analysis of input (resource consumptions) and output (emissions to air, water and land).

The environmental LCA is developed according to the ISO LCA framework which consists in four major steps: Goal and scope definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation.

LCA is a powerful tool to help to the decision makers characterize the environmental trade-offs associated with product or process alternatives, and select the option which results less aggressive to the environment. Within this study SimaPro software is used to model the environmental impact to the different midpoints/endpoints analyzed by Intergovernmental Panel on Climate Change (IPCC) and Ecoindicator 99 methods.

3.3 Fuel Substitution Model

Investment and market factor are modeled in a quantitative way for the substitution of fossil by alternative fuels. The model combines features of market diffusion and competition dynamics, technological learning, experience curves and scenario modeling. Competition between different fuels on the market is modeled by the Lotka-Volterra dynamical system. This is a paradigmatic modeling approach for systems where multiple technologies with limited production capacities compete in a confined market. In this model projections for the demand of a candidate fuel (and, by that, its market penetration) are outcomes of a dynamical model taking the overall supply of competing options and their price into account. That is, it is assumed that each market participant buys the cheapest available fuel on the market (i.e. acts rational). Production capacities are adjusted to this market-generated demand level and economies of scale effects are estimated – the higher the demanded quantity, the more ambitious the aims for production capacities, the stronger the economies of scale effect. This is a positive feedback loop which ultimately leads to a lock in of a specific fuel.

3.4 EU-JRC (Decoupling indicators)

The decoupling indicators method (resource efficiency indicators) aims to show how the overall economic growth is related to the overall environmental impact of resource use. In the consequence it informs whether and to which extent we can decouple growth from impact. This addresses the question of weighing “economic goods/bads” against “environmental bad/goods”. For each technology a specific set of indicators is composed, which quantify this trade-off.

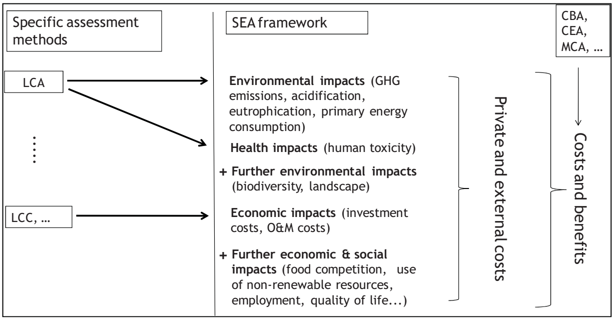

Figure 4: SEA - a framework bringing together complementary assessment methods [1]

4 Socio Economic Analysis (SEA) – Framework

4.1 Introduction

SEA is compounds by five different stages [2], with possible iterations, for example to adjust the boundaries or to collect further information if necessary to reach robust results (See Figure 5 and the Tables: Table 1, Table 2 Table 3, Table 4)

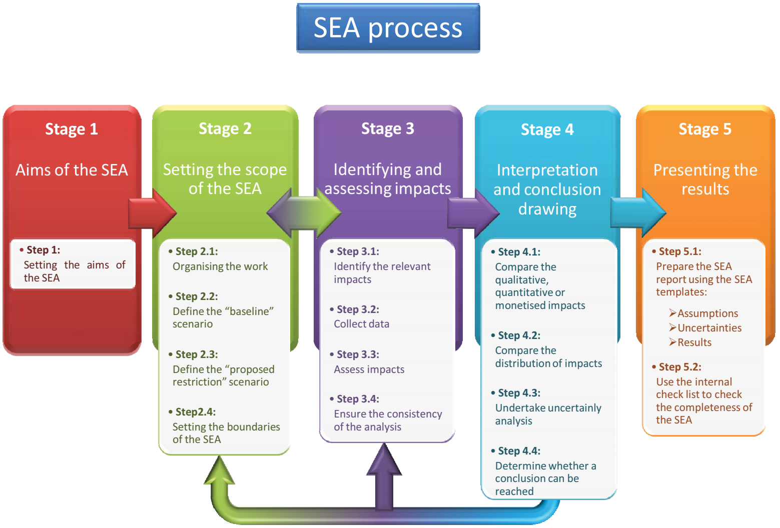

Figure 5: Socio-Economic-analysis process

Table 1: Stage 1: Aim of the SEA

STAGE 1: AIMS OF SEA	IMPLEMENTATION ALFA-BIRD	OUTPUT
Setting the Aim of the SEA	Based on the Dow establish the purpose of the study.	Explaining in the final report the aim and the context.

Table 2: Stage 2: Setting the scope of the SEA

STAGE 2: SETTING THE SCOPE OF THE SEA	IMPLEMENTATION ALFA-BIRD	OUTPUT
Organize the work	Define the work plan according to the results of SWAFEA project.	Explanation in the report the method and the different assumptions. Chapter 6
Define the base scenario	Business as usual (BAU)	Detail explanation in the report the business as usual scenario. Chapter 6
Define the proposed scenarios	Low Environmental Incentives, High Environmental Incentives.	Detail explanation in the report the two scenarios. Chapter 6
Setting the boundaries of the SEA	Time frame up to 2030, for the substitution of JetA1 for BtL and GtL.	Detail explanation in the report the two scenarios. Chapter 6

Table 3: Stage 3: Identifying and assessing the impacts of the SEA

STAGE 3: IDENTIFYING AND ASSESSING THE IMPACTS	IMPLEMENTATION ALFA-BIRD	OUTPUT
1. Identify the main impacts		
a. Create a list of impacts	- Create the list of economic impacts	Chapter 6
b. Screen the impacts (only consider the major impacts)	- Define the criteria of selection of major impacts.	Chapter 6
2. Collect Data	- Identify possible sources (Alfa-Bird partners, industry, associations, experts, journals, Statistic databases, WEF, etc)	Sources and validation of information: ALTRAN, IATA,IFP, AIRBUS
3. Assess Economics Impacts	- Build the calculation model	Web based calculation model – developed as an ASP.NET 4.0 Website Annex 2
4. Ensure the consistency of the analysis	General comparisons with other available studies and support from partners involved.	Comparisons with SWAFEA studies and benchmark with AIRBUS, and IATA.

In the third stage of an SEA all important impacts need to be identified and assessed. This assessment may be iterative, starting from readily available data and subsequently including more detail and further qualitative, quantitative and monetized data. Checks of consistency are recommended to avoid over- or underestimation of impacts and double-counting.

Table 4: Stage 4: Interpretation and conclusion drawing of the SEA

STAGE 4: INTERPRETATION AND CONCLUSION DRAWING	**IMPLEMENTATION ALFA-BIRD**	**OUTPUT**
5. Compare the qualitative, quantitative results	Additional use of the Multi Criteria Decision Making tool (MCDM)	Analysis from the application of the MCDM tool to the different criteria for fuels analyzed along the project. Chapter 8
6. Compare the distribution of impacts	Use the Multi Criteria Decision Making tool (MCDM)	Analysis from the application of the MCDM tool to the different criteria analyzed along the project. Chapter 8

In the fourth stage is where the use of appropriate SEA tools, such as cost-benefit analysis or multi-criteria analysis, may be necessary to compare the overall performance of the different scenarios. Furthermore, the distribution of impacts is to be analyzed. Appropriate consideration should be given to uncertainty analysis.

The Stage 5 of the SEA: Presentation of the Results, SEA guides underline the importance of transparency with respect to assumptions, reasons for including or excluding specific impacts, and results (presentation not only in aggregated form but also individually) ...

4.2 Potentially relevant environmental and health impacts

The analysis covers all effects relevant to health and the environment that may arise over the complete life-cycle chain of biofuels production and use. These may refer, for example, to:

Emissions (GHG, air pollutants, emissions to water and soil) that might arise in the production Stage (extraction or cultivation and collection of raw materials), in the processing Stage (transformation to (bio-)fuel), during transport of raw, semi-finished and finished materials (transport for supply of production site, transport between production site and processing plant, transport on production and processing sites, transport for distribution of fuel), during storage of raw, semi-finished and finished materials, in the use phase of the fuel, or owing to waste treatment.

Such emissions may for example be due to energy consumption, to burning for cultivation or otherwise preparing land for biomass production, as impact of changes in land use on carbon stock and GHG emissions, e.g. due to changes to above ground (vegetation) or underground (soil) carbon sinks, from (agro-) chemicals use and from other products used in extraction or cultivation and from production of (agro-) chemicals used, from (farm) machinery used or from waste and leakage.

The quantity of *resource uses (energy, water, land)* and impacts on *resource quantity or quality (e.g. water, soil)*, may also be relevant. Further impacts on *biodiversity* may for example result from agro-chemicals, emissions or resource use.

For biofuels potential human health and environmental impacts may, for example, consist in:

a) Human health
    - morbidity (acute & chronic effects) – respiratory organics/inorganics
    - mortality (premature death) – respiratory organics/inorganics
    - economic impacts to society, e.g. health care services caused by human health effects
b) Environment
    - Ecological impairment, e.g. biodiversity, habitat, ecosystems structure and functions
    - water, air, soil quality impairment (Europhication, acidification, eco-toxicity ...)
    - Climate change
    - Waste generation
    - Ozone layer depletion

4.2.1 Approaches to an assessment of environmental and health impacts

Here we zoom into stage 3 of an SEA and give examples of how environmental and health impacts are assessed using economic approaches [2], [3], [4].

Air pollution

Health impacts:

- where available, use of concentration-response functions to quantify morbidity and mortality
- monetization approaches exist for some pollutants; indicators used are frequently ‘Value of statistical life’ (VSL) and ‘Value of life year lost’ (VOLY); monetization is based on willingness to pay (WTP) analyses, the assessment of health-care costs,
- where no concentration-response functions exist, qualitative assessment can for example focus on the severity of the effect or on exposure characteristics (dose, frequency, duration ...)

Environmental impacts:

- estimates about external costs exist for several air pollutants, alternatively, abatement or removal costs may be used
- semi-quantitative assessment uses critical loads data for eutrophication and acidification, and indicators linking concentrations or fluxes of ozone to vegetation impacts
- qualitative description of the likely magnitude and extent of an impact to a given environmental compartment or the risk for an impact on particular populations or species

GHG emissions

- Use of market prices (for CO_2), often relying on the predicted quota prices under the Emission Trading System (ETS)

Pollution to water

- for waste water, abatement or removal cost estimates do not yet exists but should be developed in the framework of the EU Waste Water Framework Directive
- qualitative assessment can for example focus on the severity of the effect of emissions to water on water quality or on exposure characteristics (dose, frequency, duration ...)

Pollution to soil

- whether information on removal or restoration costs exist should be assessed
- qualitative assessment can for example focus on the severity of the effect of emissions to soil on soil quality or on exposure characteristics (dose, frequency, duration ...)

Resource use

Fossil fuel energy carriers:

- quantification of the use as % of resource available
- qualitative information on impact on energy source availability

Land use:

- quantification of area converted for bio-fuel production with information on initial land (use) type
- quantification of the use as % of resource available
- qualitative information on impact on soil availability for other purposes, on risk for soil erosion, …

Water use:

- quantification of the use as % of resource available
- type of water resource consumed as proxy for impact

Biodiversity

- qualitative information on conversion of intact ecosystems or areas with high biodiversity values
- qualitative information on exposure of ecosystems to emissions, on changes in water quality and quantity of the water system of ecosystems, on changes in land use and soil quality

- monetization approaches to assess impacts from air pollution and land use changes have been suggested, their acceptability needs to be evaluated

Further ecosystems effects

- monetization using information on the generation of income (from crops, fisheries, …), cost estimates for damage prevention or cleaning/restoration costs, and WTP for recreational or non-use values

Waste generation

- qualitative information about types of waste created
- waste treatment costs

It is foreseeable that a full quantification and monetization of all relevant environmental and health effects of biofuels production and use will not be feasible. The results of the study are likely to consist in a mixture of qualitative, quantitative and monetized assessments.

Quantification and monetization methods are in constant evolution, and the number of studies assessing specific ecosystems effects is constantly growing. For the purpose of the ALFA-BIRD WP 3.2 study, available data and specific methods, tools and values are used in order to overcome whit the large numbered of uncertainties and numerous unknowns involved in such a complex environment.

5 Life Cycle Assessment (Task 3.2.1)

5.1 Introduction

Analyzing environmental impacts of new technologies and products during its life cycle is becoming an ever increasing factor of sustainable success. This is also applied to new process and materials being developed in many EU FP7 projects. Within the task 3.2.1 of Alfa Bird project denominated Ex-ante economic impact analysis: establishing of overall methodology, a life cycle analysis is developed with the aim to determine the environmental impact over the life cycle of selected alternative fuels.

Life Cycle Assessment encompasses all processes, environmental releases and resources consumption beginning with the extraction of raw materials, design, manufacturing, distribution, use and final deposition of the product (See Figure 6). In consequence LCA can help to the decision makers to characterize the environmental trade-offs associated with product or process alternatives, and select the one which results in the less aggressive to the environment.

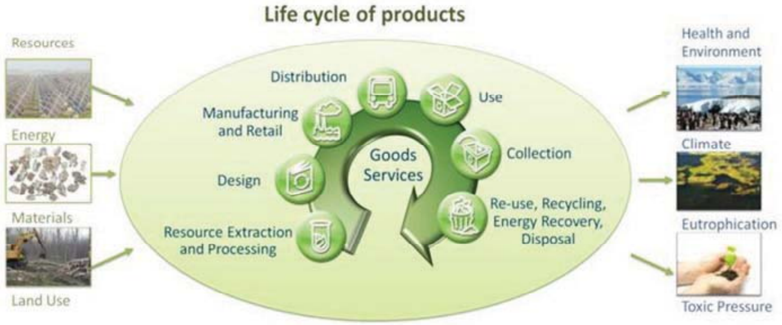

Figure 6: Life Cycle of products good and services [5]

Life Cycle Assessment has been developed as a tool over recent decades. The main goal of this tool is to identify the resource flows and environmental impacts associated with the provision of products and services. International standards assist in the specification, definition, methods and protocols associated with LCA studies. ISO 14040 [6] describes the principles and framework for life cycle assessment and ISO 14044 [7] provides specific requirements and guidelines for conducting an LCA. The framework structured in the ISO 14040 standard breaks down the LCA methodology into four distinct phases (See Figure 7)

1. *Goal and scope definition*: This first phase establishes the aim of the study, including the system boundaries, functional unit, the reference flow, and the product systems. It is also in this phase where it is determined the depth and the breath of the LCA study.

2. *Life Cycle Inventory (LCI)*: In the second phase of a LCA the inputs and outputs data of the product system(s) throughout its lifecycle are collected and quantified (e.g., energy and raw materials requirement, atmospheric emissions, waterborne emissions, solid wastes, waste water discharges, and other releases for the entire life cycle of a product, process or activity). ISO 14044:2006 define the following steps for Life Cycle Inventory: collecting data, calculating data and allocation.

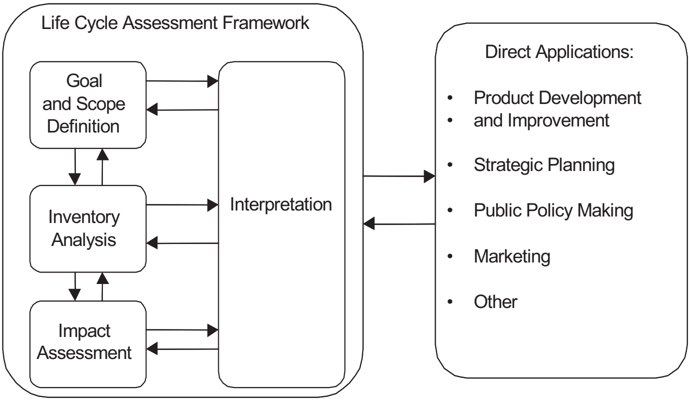

Figure 7: LCA methodology according to ISO 14040/14044

3. Life Cycle Impact Assessment (LCIA): The third phase of an LCA provides additional information to better understand the magnitude and significance of the potential environmental impacts of the product system (s) under study. This phase assesses the human and ecological effect of the energy, water, resources usage, and environmental releases identified in the inventory analysis. The LCIA attempts to establish a link between the product or process and its potential environmental impacts. The results of LCIA allow comparing each option being assessed and show the relative differences in potential impacts to the environment.

   The basic structure of the impact assessment methods includes the following elements:

   - Characterization: One of the mandatory elements from ISO 14044:2006 is the calculation of category indicator results, which involves the conversion of LCI results to common units and the aggregation of these results to the common impact category. Once LCI results are assigned to impact categories previously defined, it is necessary to define characterization factors. These factors reflect the relative contribution of the life cycle inventory results to each impact category. Following ISO standard the impact category indicators are between the inventory results and the endpoint. Furthermore, indicators that are chosen close to the inventory results (midpoint level) have a lower uncertainty, while indicators near to the endpoints can have significant uncertainties (endpoint level). For example CML method is a midpoint method, the unit of global warming is Kg CO_2 equivalence. In the other hand, Ecoindicator 99 method is a endpoint method, the indicator for climate change is expressed in Disability Adjusted Life Years (DALY) [8]

     Additionally, it is stated in ISO 14044.2006 the optional elements of the LCIA, which can be used depending of the goal and scope of the LCA, these elements are normalization, grouping, and weighting.

   - Damage Assessment: The main purpose of this step is to combine a number of impact category indicators that refers to the same endpoint into a defined unit. These means that the indicator results are presented as three or more indicators endpoints or damage categories (also called area of protection).

     For instance in the Eco-indicator 99, there are three endpoints: *resources, ecosystem quality* and *human health*. In the case of human health all the impact categories are expressed in DALY (disability adjusted years). As a result it is allowed to add to the human health impact category DALYs caused by carcinogenic, ozone depletion layer, respiratory effect, etc. The same case applies for ecosystem quality and resources with the impact categories expressed as PDF (Potentially Disappeared Fraction) and MJ Surplus energy respectively.

The most used impact categories in LCIA are: global warming (expressed in CO_2 equivalents), ozone layer depletion (CFC-11 eq.), acidification (SO_2 eq.), Europhication (PO_4 eq.), human toxicity (1,4-DCB eq.)

- Normalization: This step shows in what extend the impact category has a significant contribution to the overall environmental problem. This means, the impact category is divided by the reference. A used reference is the average yearly environmental load in a continent or country and then, divided by the number of inhabitants. In the normalization step all the impact category indicators get the same units, which makes easier to compare them, for instance European reference.
- Weighting: This step is the most controversial step within life cycle impact assessment. It consists in the use of a panel of expertise that proposes default weights for the impact categories. This means that the impact category indicators are multiplied by this weight factors.

It is of a high importance the selection of the impact categories (endpoints) because they define the issues of the environmental concern, such as respiratory diseases, extinction of species, drying forest, reduced resource, etc. (See Figure 8) [8].

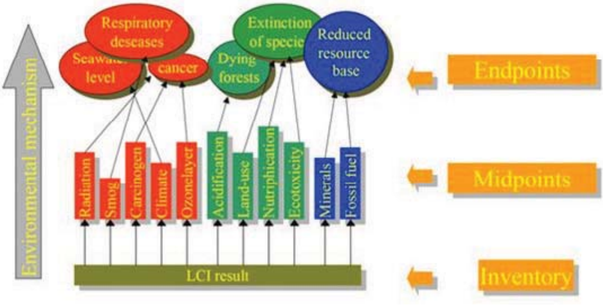

Figure 8: Overview of the impact assessment method

Additionally, herein lies the differences of the impact assessment methods, they do not cover all the same impact categories. It is essential for each LCA study to select the right method which addresses the most relevant categories. For instance CML 92 method does not include the impact categories noise, land use and fine particulates.

4. Interpretation: This is the final phase of the LCA procedure, in which the results of the inventory analysis and/or impact assessment are interpreted and discussed taking into account the goal and scope definition. The principal goal of this stage is to check the consistency of the assumptions, to analyze the results in order to set down conclusions and recommendations for the decision making process.

   ISO standards have defined the following elements for the life cycle interpretation phase, as follow:
   - Identification of significant issues based on the result of LCI and LCIA. Conclude implications of the methods used, assumptions made, allocation rules, cut-off decisions, impact categories, category indicators and models.
   - Evaluation through sensitivity analysis, consistency checks and completeness.
   - Set down conclusions, limitations and recommendations.

Nowadays the concept of life cycle thinking has become an ever increasing factor for the development of new products. Consumers are more interested to know the environmental history behind products and Life cycle Assessment is the key to give answers related to the environmental impact of the whole product from cradle to grave.

Within this specific chapter dedicated to LCA, three alternative fuels called the "second generation" or synthetic biofuels are being compared with the traditional aviation fuel Jet A1. Characteristics of these fuels are the use of non-conventional sources such as natural gas, coal and biomass. Analysis includes well to wake approach, where some preliminary results from tank to wake from the WP 3.1.1 have been included.

5.2 Goal and Scope of the analysis

The goal of the current LCA is to compare different production routes for alternative fuels in aeronautics from an environmental point of view. The assessment includes all process stages from well to wake.

The alternative fuels being compared are synthetic fuels which are produced from the feedstock (biomass, gas, coal) through a process denominated Fischer-Tropsch (FT) synthesis. Therefore the fuels considered are:

- CtL: Coal to Liquid
- GtL: Gas to Liquid
- BtL: Biomass to Liquid

The synthetic fuels will be analyzed from a cradle to grave approach. The functional unit used to express results is 1 MJ of energy.

The first part of the evaluation is related to well-to-tank (WTT) where it is includes the steps related to the extraction of the resources, conversion at the FT plant and delivery of the fuel to the tank. The second part, tank-to-wake(TTW) corresponds to the combustions of the fuel during the operation at the aircraft.

5.2.1 Assumptions for BtL

Based on Renewable Energy Directive [9], it was assumed on this analysis that the *"Emissions from the fuel in use, shall be taken to be zero for biofuels and bioliquids",* as a result the combustion of the BtL fuel is considered carbon-neutral, due to the CO_2 emissions from the combustion of the fuel are supposed to be compensates by the CO_2 uptake during the plant growth. This assumption is consistent with previous studies [10] and [11]. However we would like refer herewith to the land use change (LUC), which has a strong impact in any LCA results for Biofuels.

Direct and Indirect Land Use Change: Greenhouses gases due to land use change has been identified as a potentially significant contributor to the environmental profile of biofuels. The term direct land-use change (dLUC) refers to the changes connected to the field where the cultivation of the biofuels is taking place. Indirect land-use change (iLUC) refers to the situation where forests or grassland are cleared to compensate for land taken to grow fuel crops. Due to international trading of crops, these lands are displaced to other parts of the world, thus increasing net carbon dioxide, competing with local production of food and commodity prices. iLUC is absolutely crucial, and it can have an important impact on GHG emissions, as well as in biodiversity, water and other natural resources. Land use can affect drastically any type of results, either positive or negative therefore it needs to be evaluated locally.

For the BtL case presented in this report, data from Renew project is taken into account. Inventory data for land occupation (m^2 a) and transformation from pasture (m^2) used is based on the inventory indicators developed by Ecoinvent. However, this additional information in the inventory does not lead to any increase in CO_2 emissions due to the lack of a proper and internationally accepted methodology for assessing all the aspects of land use.

Later in this report is presented a comparison of different studies available. It can be observed how the LUC can drive drastically the overall GHGs emissions to positive or to very negative way. Comprehensive and well implemented international methodology from European Consensus is absolutely vital in order to ensure the promising "green energy" of biofuels.

5.3 Life Cycle Inventories

Data for the evaluation WTT have been gathered form deliverables of the project, from databases such as JRC, Ecoinvent, and from reports publicly available [12], [13], [14] and [20]

CO_2 emissions data for TTW have been gathered from literature [38] for Jet A1 and from the information showed by DLR during the third Alfa-Bird meeting (g/Kg fuel). The following table shows the data gathered so far for CtL, GtL and Jet A1. As it was mention before the combustion of BtL is no considered (Table 5).

Table 5: CO_2 emissions from the combustion of alternative fuels

Combustion[1]	**CtL**	**GtL**	**Jet A1**
CO_2 [g/MJ fuel]	72,8	71,4	73,9
Source of the data	DLR WP3.1.1	DLR WP3.1.1	[38]

[1] LHV for Fischer-Tropsch diesel: 43,247 MJ/kg

5.3.1 Kerosene (Jet A1)

Data set for Kerosene was gathered from the LCA services provided by the Join Research Centre of the European Commission. The data set provided represents a cradle to gate inventory for the Kerosene and it covers all relevant processes, steps/technologies over the supply chain with a good overall data quality. The data set also considers the exploration over crude oil extraction to transport to the refinery. The data inventory is partly based on primary industry data, partly on secondary literature data.

The reference in the database is kerosene at refinery; 700 ppm sulphur – 1 kg (Mass) and the allocation for all products of the refinery is applied by mass and net calorific value. More details about LCI for kerosene can be found in the public webpage of the Join Research Center for Life Cycle Inventories. The transportation from the refinery to the service station has been assumed to be around 1000 km.

In addition, secondary data related to the upstream and downstream processes have been gathered from Ecoinvent database version 2.2, which is the most up to date and complete data base with around 4224 processes.

5.3.2 Coal-to-Liquid fuel

Extraction: As it is shown in Figure 9, the process for Coal to Liquid fuel production starts with the extraction of coal at the field. The data set used for this process was gathered from Ecoinvent database. The modules for coal extraction from Ecoinvent includes coal mining and preparation, coal processing and coal storage and transportation.

Conversion at the Fischer-Tropsch plant: It is assumed that the conversion step occurs close to the feedstock extraction and remote form end-user markets, therefore, it is not considered transportation from the field of extraction to the CtL plant. Data for the conversion step was collected based on the public report prepared for the U.S. Department of Energy and Environmental Solutions, LLC [12](See Table 6). This report involves the development of GHG inventories and also it includes the development of preliminary estimates for criteria pollutant emissions during the conversion step. The design of the FT processes in the reference [12] is for plant with nominal capacities of 50,000 bpd.

The conversion process of coal to liquid fuel can be broken down into three main plat areas: the syngas generation area, the Fischer-Tropsch conversion area and the product upgrading area. The syngas generation area, involves the coal preparation step, air separation (99,5% pure oxygen), and gasification (CO_2 is used as a carrier gas for the feed coal) [12]. In the Fischer-Tropsch conversions area, the syngas is converted into hydrocarbons using slurry bubble-column reactors. In this area is also included the facilities for the use of the iron catalyst and the CO_2 removal step, where a portion of CO_2 stream is sent to the gasification plant and the remainder is directly vented to the atmosphere. Finally, the Fischer-Tropsch product upgrading area includes the hydrotreating of naphtha and distillate, and also, the hydrocracking stage which cracks the Fisher-Tropsch wax stream and produce additional naphtha and distillate.

The emissions evaluated during the conversion of the fuel in the Fischer-Tropsch plant are associated with the burning of fuels generated within the plant (See Table 6). The fuels are generated in the Fischer-Tropsch conversion area (purged recycle gas) and in the product upgrading area (off gas) to be used in fire heaters and in boilers. However the major sources of the GHG emissions come from the area of carbon dioxide removal, is in this stage where carbon capture sequestration can be implemented to reduce the amount of GHG emissions vented to the atmosphere. In addition, in the syngas generation area, it is included a sulfur recovery plat, and based on this, SOx emissions have also been estimated as it is shown in Table 6.

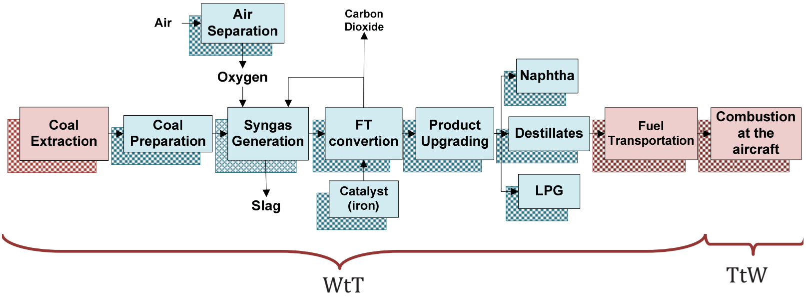

Figure 9: Flow Diagram for WtW CtL-pathway fuel

Table 6: Inventory data per bbl of FT-CtL Liquid Products [12]

Raw Materials	
Coal (MF ton)	0,3675
Butanes (bbl)	0,062
Catalysts & Chemicals (lb)	13,52
Water Make-Up (gal)	286
Electric Power (kWh)	25,79
Products	
C3/C4 LPG (ton)	0,003
Gasoline/Naphtha (ton)	0,060
Distillates (ton)	0,066
Slag (ton)	0,044
Emissions	
CO_2 (g)	534311
CH_4 (g)	58,55
N_2O (g)	2,16
SOx (g)	197,64

NOx (g)	89,08
CO (g)	15,66
VOC (g)	61,40
PM (g)	50,40
Thermal Efficiency (LHV)	50,4%
Carbon Efficiency	40,1%

Transportation & Combustion at the aircraft: Data for transportation from the plant to the service station was taken from Ecoinvent Database and the distance considered was 1000 km. Data related to the products of combustion at the aircraft was taken from the data shown by DLR during the Third Alfa-Bird meeting as it was shown in Table 5.

5.3.3 Gas-to-Liquid fuel

Extraction: As it is illustrated in Figure 10, the process for GtL fuel production starts with the oil and gas production for natural gas. The dataset used to describe this process was based in onshore production in Nigeria from Ecoinvent database. Allocation for the co-products crude oil and natural gas is based on heating value.

Conversion: Data for the conversion of gas to a synthetic fuel is collected from the reference [12](See Table 7). The main areas of GtL plant are similar to the main areas of CtL plant: syngas generation area, conversion area and product upgrading area. The syngas generation area is mainly composed by the air separation which provides 99, 5% of oxygen and by the partial oxidation (POx) which partially oxidizes natural gas to syngas. The Fisher-Tropsch conversion area includes the syngas conversion, the facilities for the use of the cobalt catalyst and the carbon dioxide removal. The upgrading area is composing as well by the hydrotreating of naphtha and distillate and the hydrocracking processes.

GtL generates a small amount of power, which is sold to the electric grid. Resources, products or emissions are allocated by energy to fuels products (97, 4%). Life cycle inventory per bbl of FT-GtL liquid product is presented in Table 7.

As it was explained in CtL section, the emissions are associated to the burning of fuels within the plant. One of the differences in the design of the GtL plant is the production of electricity; in this case the fuel gas from the conversion area is also used in fire heaters in the gas turbine to generate the electric power.

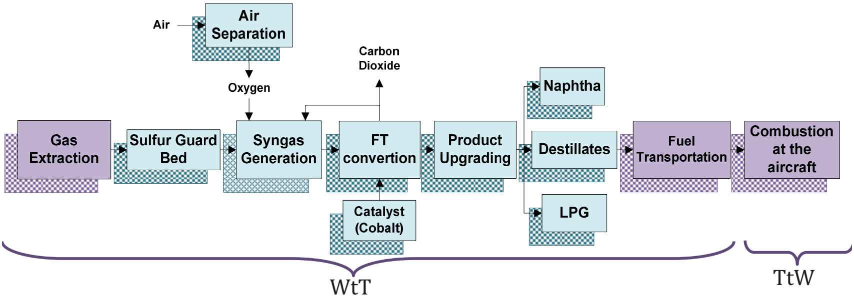

Figure 10: Flow Diagram for WtW GtL-pathway fuel

Table 7: Inventory data per bbl of FT-GtL Liquid Products

Raw Materials	
Natural Gas (Mscf)	8927
Butanes (bbl)	0,008
Catalysts & Chemicals (lb)	0,13
Water Make-Up (gal)	455
Electric Power (kWh)	-13,2
Products	
C3/C4 LPG (ton)	0,003
Gasoline/Naphtha (ton)	0,048
Distillates (ton)	0,079
Emissions	
CO_2 (g)	119687
CH_4 (g)	8,45
N_2O (g)	1,60
SOx (g)	0,06
NOx (g)	51,93
CO (g)	12,61
VOC (g)	3,77
PM (g)	1,14
Thermal Efficiency (LHV)	59,1%
Carbon Efficiency	57,0%

Transportation & Combustion at the aircraft: After the conversion, the transportation step is included from the location of the GtL plant (Nigeria) to the service stations in the EU market (Germany). Data for transportation was used from Ecoinvent database assuming transport by ship. Data related to the products of combustion at the aircraft was taken from the data showed by DLR during the Third Alfa-Bird meeting as it was shown in Table 5.

5.3.4 Biomass-to-Liquid fuel

The dataset for the evaluation of BtL fuels production has been investigated in a European research project RENEW. Within the RENEW project [13], three types of biomass were studied for the conversion to BtL-fuels. These are short rotation wood (willow-salix or poplar), miscanthus and wheat straw. The life cycle inventories are public available and are based on regional information investigated for Northern, Eastern, Southern and Western Europe and technical modeling of different conversion plants.

The well to wake analysis of the BtL fuel involves the biomass cultivation, the conversion at the plant, the transport to the service station and finally the combustion at the aircraft (See Figure 11). Within this report the analysis is focus in short rotation wood scenario with cEF-D8 (Centralized Entrained Flow Gasification) process at the conversion plant [13].

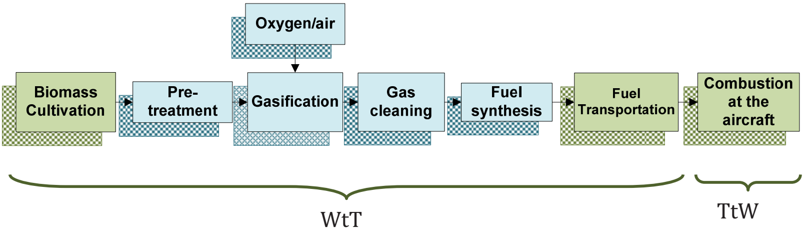

Figure 11: Flow diagram for WtW BtL-pathway fuel

Cultivation: The inventory of the biomass production includes the process of soil cultivation, sowing, weed control, fertilization, pest and pathogen control, and harvesting and bailing. Inputs for fertilizers, pesticides and planting stocks are also included, as well as their transports to the farm [14]. The key figures per kg of dry matter short rotation wood are showed in the following table; however the complete inventories used for this analysis are public available at the reference [14].

Table 8: Key data per kg of dry matter short rotation wood [14]

Raw Materials	
Biomass: Bundles, short-rotation wood (kg)	1
N-fertilizer [g/kg DS]	0,0052
P2O5-fertilizer [g/kg DS]	0,0040
K2O-fertilizer [g/kg DS]	0,0065
Lime [g/kg DS]	0,005
Diesel use [g/kg DS]	0,0051
Energy content of biomass [MJ/kg DS]	0,00004
Yield, bioenergy resource [kg DS/ha/a]	10537
Losses during storage	7%

Conversion: Prior the gasification a pre-treatment for the biomass is necessary. The biomass is transported, stored and processed (e.g. dried) before it is delivered as a biofuel to the conversion plant. Life cycle inventory for this stage, including assumptions for transport and storage facilities are shown in detail in [14].

The conversion process is based in an optimal technology, and the concepts investigated at [14] are based on a scale of 500 MW biomass input. The conversion from biomass to BtL was followed the Centralized Entrained Flow Gasification (cEF -D) process. The cEF-D is divided in three steps: auto thermal pyrolytic decomposition (LTV reactor), oxidation of the carbonization gas and gasification of char in the production of Fischer-Tropsch fuel. Some of the key figures of the inventory at conversion plant are shown in Table 9, however the completes inventories used in this analysis are public available at the reference. [14].

Table 9: Key data of LCI for conversion of Biomass to BtL

Process: Centralized Entrained Flow Gasification		
Product 1 [Kg]	BtL fuel	
Conversion rate(biomass to all liquids)	energy	53%
Capacity biomass input [MW]	power	499
All liquid products (diesel, naphtha, DME) [toe/h]	toe/h	22,5
Carbon dioxide	kg	450
Particulates, > 10 um	kg	5

Transportation & Combustion at the aircraft: After the conversion to Fischer-Tropsch fuel, it is assumed an average distance of 150 km with lorry 28t from the plant to the service station. As it was assumed in [9], the combustion of the BtL fuel is considered carbon-neutral, due to the CO_2 emissions from the combustion of the fuel are compensated by the CO_2 uptake during the plant growth.

5.4 Life Cycle Impact Assessment

As it was mention previously, in this stage of the life cycle assessment, the inventory results are transformed by means of scientific models into impact category results. This transformation is made by specific impact assessment methods such as IPCC (Intergovernmental Panel for Climate Change) and Ecoindicator 99 method [15]

5.4.1 IPCC 2001 (Climate Change)

One of the most widely used life cycle assessment is the characterization of gaseous emissions according to their global warming potential. This method is a problem oriented approach due to it focuses solely on GHG emissions. The time horizon used in this study is 100 years. Table 10 shows the results of the application of IPCC method to the Life Cycle Inventory of alternative fuels.

In Figure 12, it can be observed that CtL and GtL have 58% and 33% respectively more emissions of the CO_2eq to the atmosphere than JetA1. In the other hand BtL generates 73% less CO_2eq emissions than Jet A1.

Table 10: Results from the application of IPCC method

Fuel	**Extraction/Cultivation [Kg CO2 eq./MJ]**	**Conversion [Kg CO2 eq./MJ]**	**Transportation [Kg CO2 eq./MJ]**	**Combustion [Kg CO2 eq./MJ]**
Jet A1	**0.00862**		**0.00448**	**0.0739**
BtL	**0,00785**	**0,00735**	**0,0008**	**--**
GtL	**0,0214**	**0,0326**	**0,0058**	**0,0714**
CtL	**0,0108**	**0,1202**	**0,004**	**0,0728**

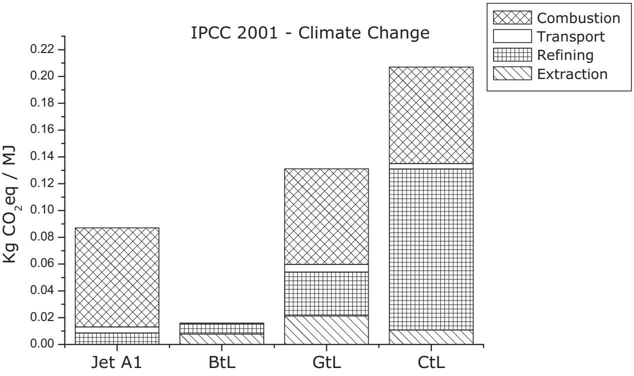

Figure 12: Application of the IPCC 2001 method - WtW

5.4.2 Eco - indicator 99

Eco-Indicator method is a "damage oriented method" which looks at both direct and indirect resources to analyze environmental impacts on human health, ecosystem quality and resources. Damage to Human Health is expresses as the number of year lost and the number of years lived disable; these are combined as Disability Adjusted Life Years (DALYs). As a result it is allowed to add to the human health impact category DALYs caused by carcinogenic, by ozone depletion layer, by respiratory effect, etc. The same case applies for Ecosystem Quality where the impact categories are expressed as PDF (Potentially Disappeared Fraction). PDF is related to the loss of species over a certain area, during a certain time due to emission of variety of substances, the impact categories are e.g. ecotoxicity, ozone layer depletion, land use, etc. Finally the damage category Resources depletion is expressed as "surplus energy" which means the extra energy of future generations to extract the remaining resources, due to the best resources has been already extracted. All impact categories addressed by Ecoindicator 99 are the following:

- Carcinogens: carcinogenic effects due to emissions of carcinogenic substances to air, water and soil. Damage is expressed in Disability Adjusted Life Years (DALY) / kg emission).
- Respiratory Organics: respiratory effects resulting from summer smog, due to emissions of organic substances to air (DALY/Kg emission).

- Respiratory Inorganics: respiratory effects resulting from winter smog caused by emissions of dust, sulphur and nitrogen oxides to air (DALY/Kg emission).
- Climate Change: damage resulting from an increase of diseases and death caused by climate change (DALY/Kg emission).
- Radiation: damage resulting from radioactive radiation (DALY/Kg)
- Ozone Layer: damage due to increased UV radiation, due to the emissions of substances to air which causes ozone depletion layer (DALY/Kg)
- Ecotoxicity: damage to ecosystem quality, due to the emission of ecotoxic substances to air, water and soil. Damage is expressed in Potentially Affected Fraction (PAF)*m2year/kg of emission.
- Acidification/Europhication: damage to ecosystem quality due to emissions of acidifying substances to air. Expressed in Potentially Affected Fraction (PAF)*m2year/kg of emission.
- Land Use: damage resulting from the conversion of land or occupation of land. Expressed in Potentially Disappeared Fraction (PDF)*m2*year/m2.
- Minerals: Surplus of energy per kg mineral, as a result of decreasing of resources.
- Fossil fuel: Surplus energy per extracted MJ, kg or m3 fossil fuel.

5.4.2.1 Characterization

Characterization factors in this method are calculated at end-point level (damage).

The results from Ecoindicator99 (See Figure 13) applied through the use of SimaPro software give a clear picture of the environmental impacts associated to the four fuels studied.

The impact category (endpoint in ISO terminology) climate change is related to the data from greenhouse gases – i.e. CO_2, CH_4, N_2O, CFCs- emitted during the extraction, production, distribution and combustion of the fuels. Carbon dioxide (50%-70%) and dinitrogen monoxide (20%-40%) are the major elementary flows with respect to Climate Change. As it is illustrated in the figure the mayor contribution to this category is CtL fuel.

Acidification and Europhication are caused mainly by ammonia, sulphur dioxide and nitrogen oxides in about equal shares. GtL shows the highest impact to this category due to the comparable quantities of nitrogen oxides during the extraction of natural gas. BtL has also an important contribution to this impact category due to emissions of acidifying substances attributed to the biomass production and the operation of transport devices and tractors. In addition more the 50% of the release of Eutrophication emissions can be attributed directly to the agricultural production process (ammonia, nitrates, phosphates and nitrogen oxides).

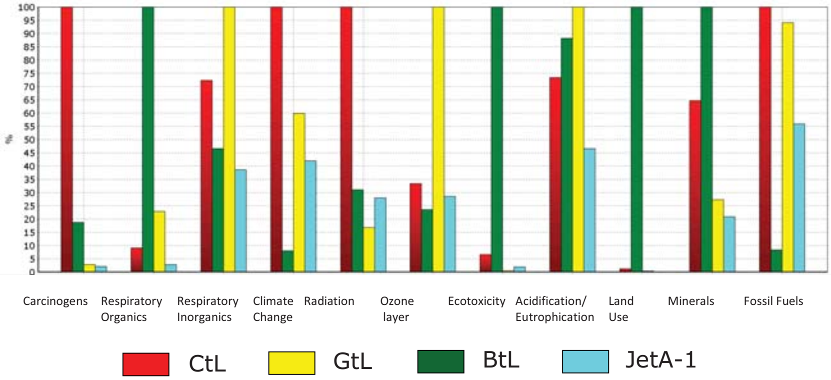

Figure 13: Comparison Jet A1 vs. GtL, CtL, BtL fuels - Characterization/Impact categories – WtW

The highest impact in carcinogens is due to CtL fuels, in which the long life cycle shows more quantity of arsenic (ion), cadmium and particulates< 2.5 um released to the air and water. Respiratory effects from environmental pollution are caused mainly by particulate matter PM$_{10}$ and PM$_{2.5,}$ nitrate and sulphate, SO$_3$, O$_3$, CO and NOx. In Figure 13

Figure 13: Comparison Jet A1 vs. GtL, CtL, BtL fuels - Characterization/Impact categories – WtW, it is illustrated that the respiratory inorganic category is highly impacted by GtL and respiratory organic is highly impacted by BtL. For the case of GtL, the extraction of natural gas releases more nitric oxide, sulphur dioxides, nitrogen oxides in compare with other fuels. In the case of BtL there are significant isoprene emissions which impact respiratory organics category due to the production of the biomass.

CtL has an important contribution to the radiation impact category, due to the extraction of carbon involves mainly the emission to the air of Radon-222. Radon is a naturally occurring radioactive gas found in soils and rock.

The ozone depletion layer is highly affected by GtL fuel due to highest impact is represented by the emission to the air of methane from the natural gas extraction process.

BtL shows the highest impact to the impact categories: ecotoxicity, land use and minerals. Ecotoxicity is due to the comparable level of chromium released during the biomass production. Land use is related to the transformation to pasture and occupation of the land. Minerals are mainly due to the use of nickel along the life cycle of the BtL fuel in comparison with the other fuels (production).

Finally in regards to fossil fuel, CtL and GtL show the highest impact which is related mainly to extraction of coal and natural gas.

The change of land use (direct or indirect has an important impact on GHG emissions) in some cases land use induces more GHG emissions for BtL fuels than conventional fuels. In this study is addressed the occupation of land and the transformation from pasture as it was done in the source of data used for BtL [13]

5.4.2.2 Damage Assessment

The results of the impact categories previously showed in Figure 13

Figure 13: Comparison Jet A1 vs. GtL, CtL, BtL fuels - Characterization/Impact categories – WtW are now aggregated into three damage categories (See Figure 14). These damage categories are: human health, ecosystem quality and resources. As it can be illustrated, CtL has the highest impact in the categories human health (carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer) and resources (minerals, fossil fuels), while BtL has more impact in ecosystem quality (ecotoxicity, acidification, eutrophication and land use).

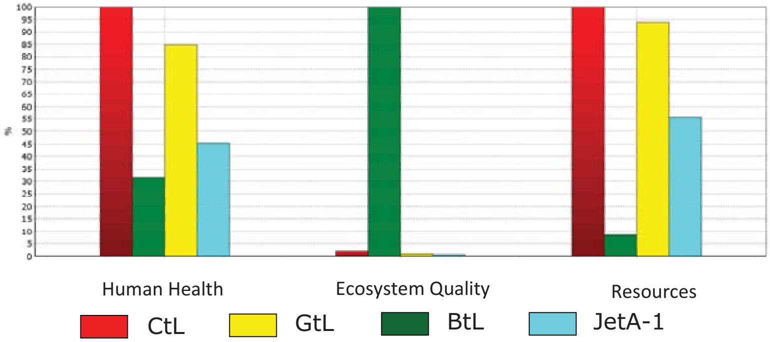

Figure 14: Comparison Jet A1 vs BtL, CtL and GtL fuels - Damage Assessment / Damage Categories - WtW

5.4.2.3 Normalization

The normalization results (See Figure 15) calculated with Ecoindicator 99 method shows that within the European context the damage on ecosystem quality and the resources is more significant than the damage on human health.

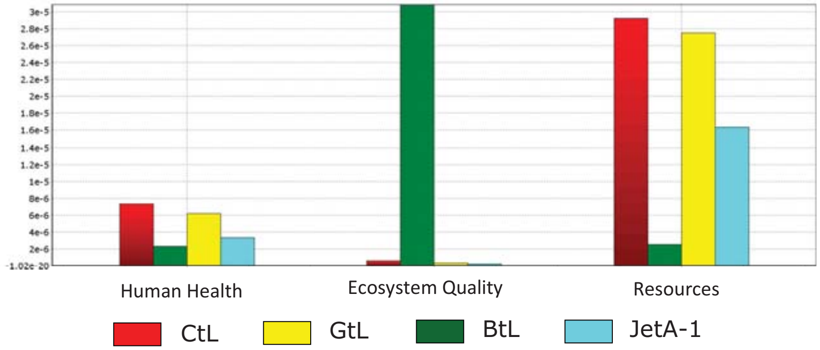

Figure 15: Comparison Jet A1 vs. GtL, CtL and BtL fuels - Normalization/ Impact Categories - WtW

5.5 Life Cycle Interpretation

In this step the results are analyzed through a sensitivity analysis where it is introduced carbon capture sequestration (CCS) for CtL and GtL. In addition, it is included GtL fuel with extraction of gas natural in Russia [16] and the production of BtL fuel from miscanthus.

CCS data has been found in [17], [18], and [19] where the CCS energy requirement directly determines the increases in plant-level resource consumption and environmental burden associated with producing a unit of useful product while capturing $CO_{2.}$ The process reported in [19]captures 1.055 $MtCO_2$/year with a considerable energy demand of 60 MW in the capture unit. The pipeline transport requires additional energy for recompression (275 kW). The mass flow rate of CO_2 is given as 36,6 kg/s over 500 km. The LCI data for pipeline is taken from Ecoinvent database and the additional energy required for injection (reservoir of 20 bar) is 77 kW [19].

The results for the calculation are shown in the following sections below.

5.5.1 Carbon Capture Sequestration CtL (WtT)

The results presented on Figure 16and data in Table 11, show that CCS reduces the amount of CO2eq./MJ released to the atmosphere in around 57%. The transportation and extraction of coal are not affected by this implementation.

5.5.2 Carbon Capture Sequestration GtL (WtT)

It the GtL analysis it has been included the case where the location of the extraction of natural gas is in Russia. The results using the data from Ecoinvent database shows less GHG emissions in the gas natural extraction in Russia in compare with Nigeria. CCS is also included in both cases and they are illustrated in Figure 16 and the data are shown in Table 11. As it is considered the same type of plant, the reduction in CO_2 emissions due to CCS is in the same proportion. However considering the overall reduction well to tank, it can be observed that implementing CCS to the GtL plants generates 47% and 31% less CO_2 emissions for GtL plant from Russian and Nigerian coal respectively.

5.5.3 Miscanthus vs Short Rotation Wood in BtL fuels

In Figure 16 is illustrated the GHG emissions for BtL from two different pathways. The production of Miscanthus shows 6% less GHG emissions released to the atmosphere than Short Rotation Wood. This difference is mainly due to short rotation wood use more fertilizer and to N_2O emissions to the field. The plant from CHOREN was used for the two analyses [13], [14].

Table 11: Data for GHG emissions of CtL production on a WtT basis

	Extraction/Cultivation [Kg CO2 eq/MJ]	**Conversion [Kg CO2 eq/MJ]**	**Transportation [Kg CO2 eq/MJ]**
CtL w/o CCS	0,0108	0,1202	0,004
CtL with CCS	0,0108	0,043	0,004
GtL Nigeria w/o CCS	0,0214	0,0326	0,0058
GtL Nigeria with CCS	0,0214	0,0143	0,0058
GtL Russia w/o CCS	0,00632	0,0326	0,006
GtL Russia with CCS	0,00632	0,01118	0,006
BtL-SRW	0,00785	0,00735	0,0008
BtL-MCT	0,0074	0,0071	0,0058

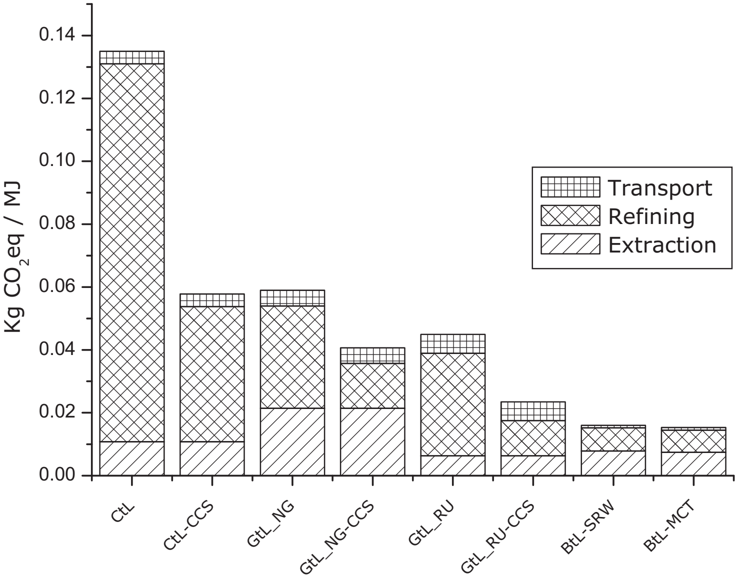

Figure 16: GHG emissions CtL, GtL and BtL production on a WtT basis.

5.5.4 WTW results: IPCC and Ecoindicator 99

Figure 17 illustrates the GHG emissions for the alternative fuels studied in comparison with Jet A1. The overall results show that fossil based alternative fuels even with CCS implementation emit more GHG emissions than Jet A1. Fuels from biomass show a reduction of 79% (MCT) and 78 %(SRW) compare to Jet A1

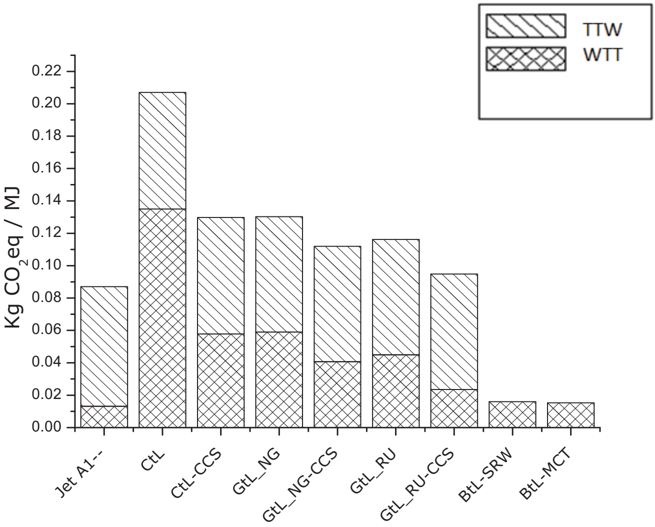

Figure 17: GHG emissions for alternative fuels on a WtW basis (IPCC)

The application of Ecoindicator 99 has been done through the use of SimaPro software. The WtW analysis is illustrated in the following figures. Figure 18, illustrates the relative contribution of the environmental impact to each impact category, where it can be observed the application of CCS in each of the fuels. If we compare CtL without CCS (green light color) with CtL with CCS, it can be observed that CtL with CCS indicates lower impact in the climate change impact category, because of the reduction on GHG emissions. The same can be observed with GtL without CCS and with CCS (from Nigeria or from Russia).

The impact category acidification/Eutrophication is highly impacted by GtL with the extraction of the natural gas in Nigeria. The extraction of natural gas in Russia shows 27% lower emissions related to acidifying substances such as nitrogen oxide and sulfur dioxide. In addition the extraction of gas natural from Russia generates 58% less of methane than the gas natural from Nigeria; this effect can be seen in the impact category for Ozone Layer.

BtL fuels have strong impact to the category respiratory inorganics, ecotoxicity, land use and minerals which is strongly related to the production of biomass. The difference of the use of miscanthus and short rotation wood is expressed also in these categories. The impact in all categories is higher for short rotation wood due mainly that this biomass requires more pesticides, land use, and the quantity of the emissions is higher than miscanthus.

In the other hand Jet A1, shows less environmental impact in comparison with fuels from fossil feedst fossil feedstock.

Figure 19, illustrates this fact more clearly, showing that Jet A1 has less impact in the damage categories from Resources and Human Health in compare with fossil based fuels. BtL shows the lowest impact in human health and the use of resources but it has an strong impact in Ecosystem Quality due mainly to the production stage which involves the release of organics like isoprene, chromium which promotes the ecotoxicity and land use.

Figure 20 illustrates in what extend the impact category has a significant contribution to the overall environmental problem (using Europe as a reference). It can be easily observed that the impact category related to resources is the most impacted in compare to human health, and the impact of biofuels to the ecosystem quality is remarkable due mainly, as mention before, to land use and ecotoxicity. In human health category can be observed the reduction of the impact when it is adapted CCS to the CtL and GtL plants.

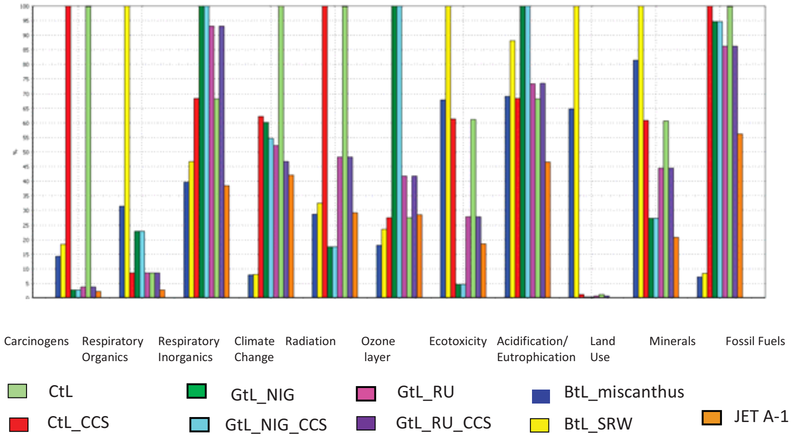

Figure 18: WtW results from Ecoindicator 99: Characterization/Impact categories

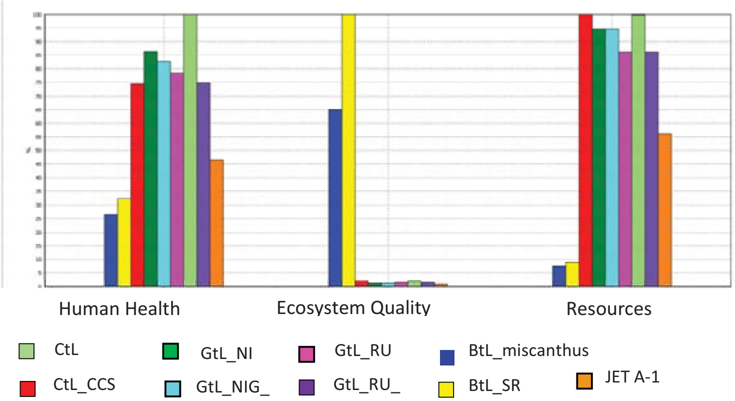

Figure 19: WtW results from Ecoindicator 99: Damage Assessment

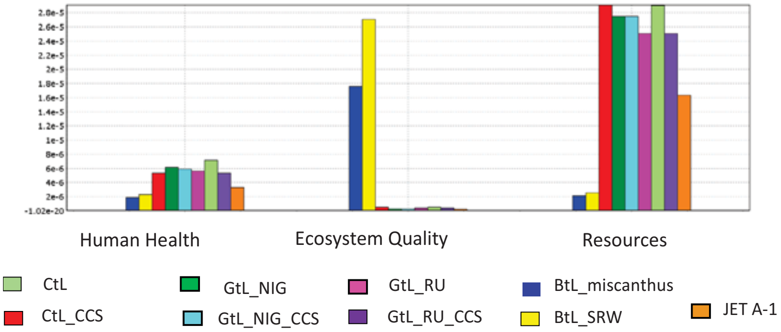

Figure 20: WtW results from Ecoindicator 99: Normalization

5.6 Results from other studies and general comparisons

5.6.1 HEFA/HRJ (hydroprocessed renewable jet fuel)

HRJ fuels are processed via treatment with hydrogen gas to deoxygenate oils from various triglyceride feedstock including animal fats and oils (soy beans, palm, jatropha, salicornia.). The deoxygenated oils then hydroprocessed similar to F-T fuels in order to create hydrocarbons with a distillation range similar to Jet A1.

Hydroprocessed renewable jet fuel (HRJ/HEFA) from biomass derived oils has been study within SWAFEA project [22] and partner project [20]. The most promised feedstock considered in these studies is Rapeseed, Camelina, Palm oil, Jatropha and Algae. The results from the mentioned projects regarding HEFA (HRJ) fuels are illustrated in the Figure 21.

In Figure 21, the uncertainty bars represents the range of emissions as given by the up, low and middle results for each alternative fuel. The results from SWAFEA project expressed in this figure are based on three different data sources generating three different results. In the case of Camelina and Jatropha there are in addition two special scenarios, for Camelina the High Case (HC) corresponds to a case where all inputs are at the maximum of the rage i.e.: high fertilizers inputs and high yields, and the Low Case (LC) corresponds to the case where all inputs, as well as the yield are at the lowest. For the Jatropha the DRM1 case consider that all fruits and seeds are removed, so the credit are allocated to the different coproducts, for the DMR2 case, the coproducts of jatropha oil supposed to return to soil therefore, no co-product is removed out of the system and due to this fact the use of fertilizer is lower. The DRM1-2 min scenario involves Jatropha dry seed production yield of 500 kg/ha and theDRM1-2 max involves 1500kg dry seeds/ha. It is important to note that the alternative fuels analyzed in SWAFEA project do not include the land use change (LUC)[13].

The results form Partner Project showed in the Figure 21, the uncertainty bars represents the range of emissions as given by the low, baseline and high scenarios. In addition to the scenario where no land use is taken into account, Partner project evaluates the land use change (LUC) for the HRJ (HEFA) fuel. For HRJ from Soybean, it is been analyzed the scenario S1 and S2. The scenario S1 considers the conversion of Cerrado grassland in Brazil to soybean fields and the scenario S2 considers converting tropical rainforests in Brazil to soybean fields. For HRJ from Palm oil, three scenarios for land use change where considered, the scenario P1, P2 and P3. P1 scenario assumed land use change emissions from the conversion of previously logged forest to palm plantations. P2 and P3 cases assumed land use change emissions resulting from the conversion of tropical rainforest and peat land rainforest in Southeast Asia respectively. For HRJ from rapeseed the scenario R1 has been analyzed, where rapeseed production is expanded for biofuels production on set aside land (Land that was removed from agricultural production in order natural carbon and nitrogen stocks of the land are replenished. These lands could be available for rapeseed cultivation). For HRJ from Salicornia the scenario H1 for LUC is generally motivated by the option of soil carbon sequestration from the atmosphere, this fact happen when the land is converted from desertification to cultivation of Salicornia on saline lands and re-vegetation of degraded lands. [20]

In Figure 21 is clearly observed how LUC can change totally the results of the environmental benefit of biofuels, and as it was stated in Partner project, the object of the analysis is intended to provide an understanding of how land use change emissions can affect the overall results and it is essential not to simply assume the benefits of biofuels without a proper knowledge of how these fuels are produced.

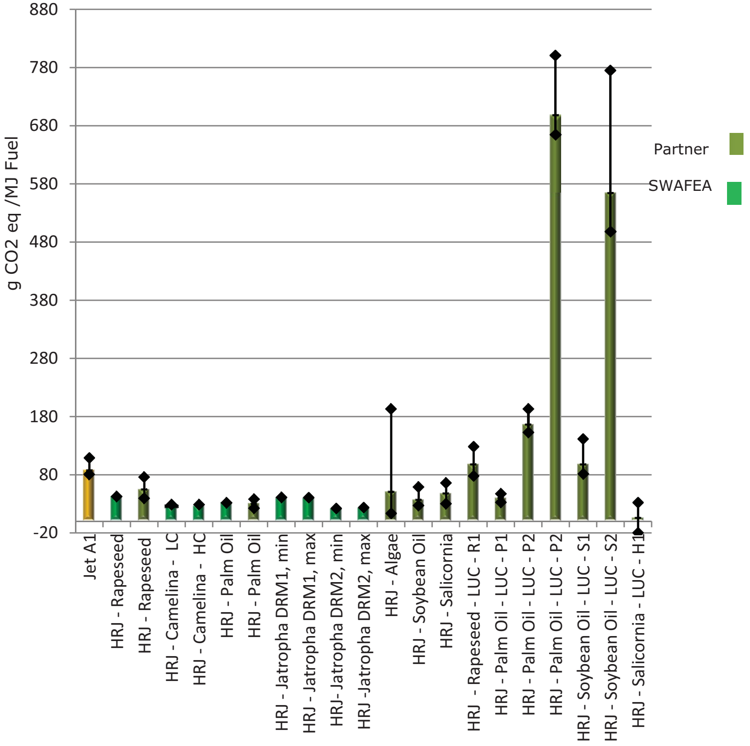

Figure 21: Life Cycle Assessment for HRJ (HEFA) – Partner/SWAFEA

5.6.1.1 Comparisons with other studies

The comparison of the different studies available (Partner, SWAFEA and IFPEN) is shown in Table 12. This comparison is based on the emissions of CO_{2eq} / MJ emitted in a WTW analysis for the different fuels.

As is Figure 21, the uncertainty bars in Figure 22represents the range of emissions as given by the low, baseline and high scenarios. Figure 22shows that there is not big difference between the results presented. The difference on the results is due to the differences on the data sources, conversion efficiencies, and general design of the FT plant. Assumptions in the treatment of data and allocation procedures are also important source of difference in results.

Without taking into account LUC, from Figure 22, it is observed that BtL and HRJ/HEFA have the potential to reduce GHG emissions due to the “biomass credit” that is generally equal to the CO_2 emissions from combustion. However, the life cycle GHG emissions for biofuels can be higher than those from fossil feedstock depending on the details of how the fuel is produced (converted land, type of crops grown and farming practices employed). The conversion of land represents can affect the results in a positive way like the case of HRJ from Salicornia or in a very negative way like HRJ from Palm oil scenario P3 (see Figure 23).The acronyms presented in Figure 21 and Figure 22 are explained at the end of the Table 12.

Table 12: Comparison of WtW LCA results of different available studies

Alternative fuels	Project	Upper Value gCO$_{2eq}$ / MJ	Low Value gCO$_{2eq}$ / MJ	Middle Value gCO$_{2eq}$ / MJ
Jet A1	Partner - MIT	109.3	80.7	87.6
CtL	Alfa-Bird - IFP	217.19	-	205.104
CtL	Partner - MIT	207.9	173.9	194.8
CtL	Alfa-Bird - EU-VRi	-	-	207
DCL	Alfa-Bird - IFP	80.311		70.067
CtL-CCS	Alfa-Bird - IFP	125.324	-	113.234
CtL-CCS	Partner - MIT	112.6	84.9	97.2
CtL-CCS	Alfa- Bird - EU-VRi	-	-	129.8
DCL-CCS	Alfa- Bird - IFP	47.423	-	36.907
GtL	SWAFEA	126.56	100.12	101.88
GtL	Alfa-Bird - IFP	137.233	107.597	112.301
GtL	Partner - MIT	102.4	100	101
GtL	Alfa- Bird - EU-VRi	130.3	-	116.2
GtL-CCS	SWAFEA	119.95	93.83	95.82
GtL-CCS	Alfa-Bird - IFP	125.128	91.723	96.904
GtL-CCS	Alfa- Bird - EU-VRi	112	-	94.8
HRJ - Rapeseed	SWAFEA	42.9	40.83	42.2
HRJ - Rapeseed	Partner - MIT	76	39.8	54.8
HRJ - Camelina - LC[1]	SWAFEA	28.78	28.70	25.58
HRJ - Camelina - HC[2]	SWAFEA	28.93	25.74	28.84
HRJ - Palm Oil	SWAFEA	32.22	29.11	31.82
HRJ - Palm Oil	Partner - MIT	38.2	22.6	30.2
HRJ - Jatropha DRM1, min[3]	SWAFEA	41.21	38.4	40.04
HRJ - Jatropha DRM1, max[4]	SWAFEA	40.74	37.92	39.62
HRJ - Jatropha DRM2, min[5]	SWAFEA	22.71	18.12	21.43
HRJ - Jatropha DRM2, max[6]	SWAFEA	23.7	19.24	22.52
HRJ - Jatropha	Partner	45.1	31.8	39.4
HRJ - Algae	Partner - MIT	193.1	14.1	50.6
HRJ - Soybean Oil	Partner - MIT	59.2	27.3	37
HRJ - Salicornia	Partner - MIT	66	30.5	47.7
BtL - Miscanthus	SWAFEA	64	29	60
BtL - Miscanthus	Alfa- Bird - EU-VRi	-	-	15.3
BtL - SRC	SWAFEA	12.84	10.59	11.31
BtL - SRC	Alfa-Bird - IFP	14.149	8.847	11.498
BtL - SRC	Alfa- Bird - EU-VRi	-	-	16
BtL - Switchgrass	SWAFEA	14.95	12.58	13.5
BtL - Switchgrass	Partner - MIT	26.1	12	17.8
BtL – Switchgrass – LUC –B1[7]	Partner - MIT	-1.7	-4.4	-2
BtL - Pellets	Alfa-Bird - IFP	40.578	25.482	33.03
BtL - Wood waste	Alfa-Bird - IFP	-	-	7.928
HRJ - Rapeseed - LUC - R1[8]	Partner - MIT	128.5	78.2	97.9
HRJ - Palm Oil - LUC - P1[9]	Partner - MIT	47.6	32.6	39.8
HRJ - Palm Oil - LUC - P2[10]	Partner - MIT	193.3	153.2	166
HRJ - Palm Oil - LUC - P3[11]	Partner - MIT	801.2	665.3	698
HRJ - Soybean Oil - LUC - S1[12]	Partner - MIT	141.7	81.7	97.8
HRJ - Soybean Oil - LUC - S2[13]	Partner - MIT	774.7	498.8	564.2
HRJ - Salicornia - LUC - H1[14]	Partner - MIT	32.2	-19.2	5.8

[1] HRJ - Camelina - LC Low Case LC: inputs/yields are at the lowest of the range

[2] HRJ - Camelina - HC High Case HC: inputs/yields are at the maximum of the rage

[3] HRJ - Jatropha DRM1, min All fruits and seeds are removed/ credit are allocated to other coproducts. Yield of 500 kg/ha

[4] HRJ - Jatropha DRM1, max All fruits and seeds are removed/ credit are allocated to other coproducts. Yield of 1500 kg/ha

[5] HRJ - Jatropha DRM2, min The coproducts return to soil, use of fertilizer is lower. Yield of 500 kg/ha

[6] HRJ - Jatropha DRM2, max The coproducts return to soil, use of fertilizer is lower. Yield of 1500 kg/ha

[7] BtL – Switchgrass – LUC –B1 Soil carbon sequestration

[8] HRJ - Rapeseed - LUC - R1 set aside land

[9] HRJ - Palm Oil - LUC - P1 conversion of previously logged forest in Southeast Asia

[10] HRJ - Palm Oil - LUC - P2 conversion of tropical rainforest in Southeast Asia

[11] HRJ - Palm Oil - LUC - P3 peat land rainforest in Southeast Asia

[12] HRJ - Soybean Oil - LUC - S1 considers the conversion of Cerrado grassland in Brazil

[13] HRJ - Soybean Oil - LUC - S2 converting tropical rainforests in Brazil

[14] HRJ - Salicornia - LUC - H1 soil carbon sequestration from the atmosphere

P: Partner project, I: IFPEN, S: SWAFEA, E: EU-VRi

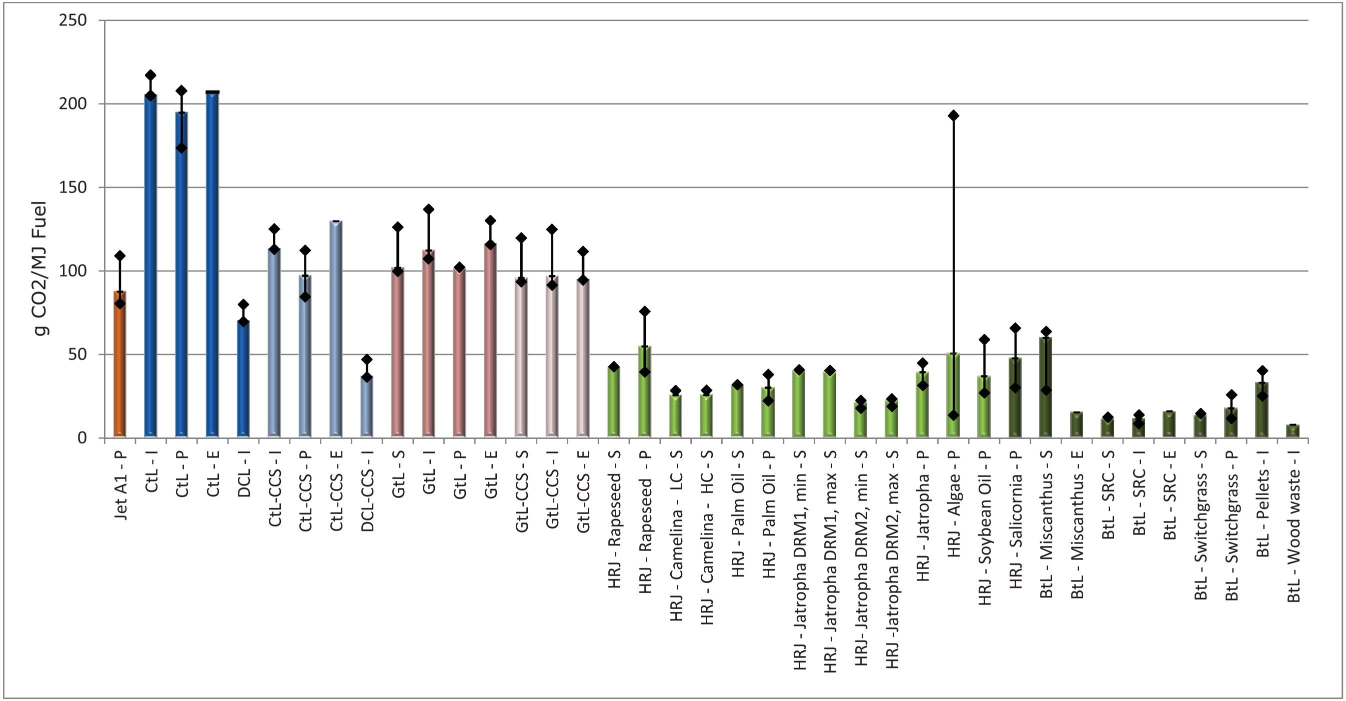

Figure 22: GHG emissions in a WtW basis for the pathways studied in Partner and SWAFEA projects and from the studies IFP and EU-VRi in ALFA-Bird project. – Without Land Used Change (LUC)

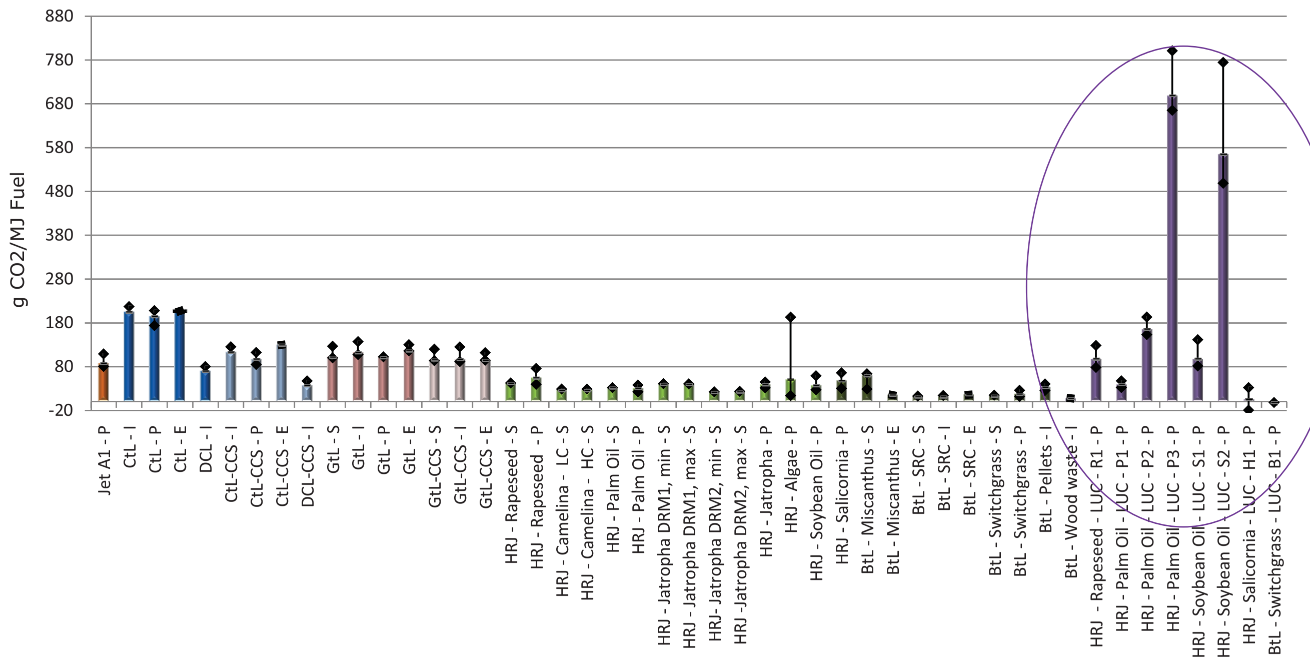

Figure 23: GHG emissions in a WtW basis for the pathways studied in Partner and SWAFEA projects and from the studies IFP and EU-VRi in ALFA-Bird project – Scenarios with Land Use Change (LUC) for HRJ (HEFA) fuels included

5.7 Life Cycle Analysis and Life Cycle Costing

Another approach providing relevant economical data is the Life Cycle Costing (LCC). Life Cycle costing can be analyzed thanks to the results from the economic evaluation carried out by IFPEN [24].

The different fuel alternatives studied could be compared by setting the costs related to the production of the feedstock, transport, fuel production at the refinery and use. To the extent that various environmental impacts (e.g. emissions of different pollutants and GHGs) are assessed, two alternative or complementary approaches are possible: a qualitative and a quantitative approach.

Qualitative approach: This approach simply compares costs and environmental impacts of different life cycle phases to each other. Costs and impacts are not expressed in common units; instead, each alternative fuel would be accessed through a range of different indicators (See Figure 24 and Figure 25)

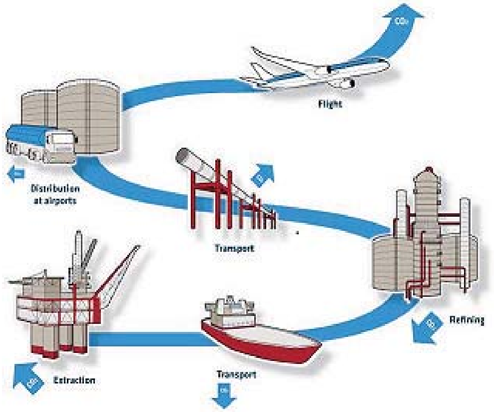

Figure 24: Life cycle Jet A1 (ATAG, Beginner's Guide to Aviation Biofuels, 2010)

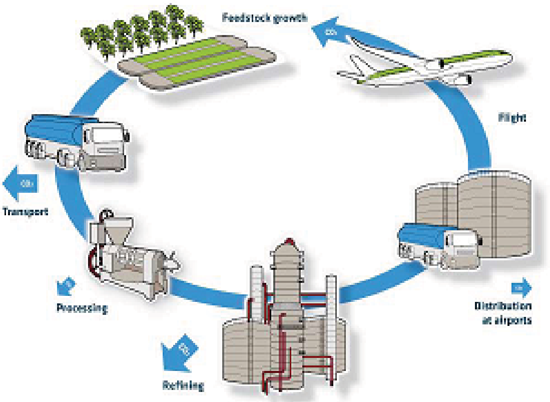

Figure 25: Life cycle Biofuel from biomass (ATAG, Beginner's Guide to Aviation Biofuels, 2010)

Quantitative approach: In cases where the different indicators do not allow for unambiguous conclusions, a quantitative approach may provide further insights. This approach would require bringing all externalities (the environmental impacts assessed in WP 1) on a common denominator. This can be either done by assessing an economic value of the respective environmental impacts, by using reference or shadow prices or by giving weights to different environmental impacts via normalisation methods. Once the different environmental impacts are made comparable, the impacts of each of the fuel alternatives can be directly set in relation to the costs of their production, distribution and use, and the cost-effectiveness of the alternatives can hence be compared.

5.8 Life Cycle Costing (LCC)

LCC is defined here as the costs induced by a product (good or service) in its life cycle as born directly and indirectly from public and private actors involved, and includes cost of external effects where possible. Social issues or social aspects related to sustainability are not included in LCC.

One of the approaches would consist in analyzing the costs related to the supply chain of alternative fuels: Feedstock production, transportation, fuel conversion at the plant and use.

Feedstock Production: It covers the costs of extraction and pre-treatment of the feedstock. It is included raw materials cost, necessary machinery and labor in agricultural production, as well as the costs of any further processing of the biological raw material into the final biofuels feedstock. For fossil-based fuels, it covers the cost of extraction and pre-treatment of the feedstock.

Transportation: it is closely related to costs of transport and logistics. In terms of transport requirements, bio-jet fuels production is likely to be more decentralized than conventional aircraft fuel production. Changes in transport means may also impact on overall distribution costs.

Fuel Conversion: it is the cost related to the production of the alternative fuels at the plant. It involves costs related to the total capital investment, capital expenditures (CAPEx), operational expenditures (OPEx) and operational and maintenance costs (O&M).

Use: As far as the considered fuels are drop-in fuels, there is no additional cost related to the changes in the aircraft, e.g. to the changes of engines.

Results for cost analysis at present were study in a very detailed an compressive way in the work performed by IFPEN within Alfa-Bird project. This work deals with the economic evaluation of the four technologies BtL, GtL, ICL (also called CtL) and DCL (named as “Naphthenic pathway”). Within this analysis, two cases were compared respectively: the “non CO_2 constrained case”, where the plant is not designed for carbon capture sequestration and no penalty is charged for any CO_2 emissions to the atmosphere and The “CO_2 constrained case” (CCS), where the plant is designed for carbon capture sequestration and recovers only the most economically recoverable CO_2. Fractions of un-captured CO_2 emissions are sent to the atmosphere and charged 50€/t. The four alternative fuels pathways were evaluated against ex-petroleum jet fuel on a tax free basis.

The Table 13 shows the results for the base investment scenario, where the BtL pathway can be economically justifies for an oil price of about 139€ to 186€/bbl. This pathway is penalized by the low biomass volume analyzed in this case which is 10% of the GtL plant. GtL pathway is more economically attractive and it justifies for an oil price ranging from 54€ to 65€/barrel. Finally, DCL and ICL (CtL) pathway are economically justified for an oil equivalent price of 54€/bbl to 85€/bbl) if the coal price is no more than 38€/ton.

Table 13: Fuel production costs [24]

Fuels	**GtL**		**DCL**		**ICL (CtL)**		**BtL**
Feedstock	3,09€/MMBTU		38,6€/ton		38,6€/ton		100€/ton dry
Capacity, BPSD	50 000		50 000		50 000		5 500
CO_2 constraint	with	without	with	without	with	without	-
C3+ production cost /(€/liter)	0,39	0,43	0,40	0,48	0,44	0,56	1,04
Brent equivalent price (€/bbl)	56	63	59	70	64	82	153

[1] Adapted to Euros currency from the data published by IFPEN (Euro (2012) =1,294 USD).

In addition to the results provided by IFPEN, it is also important to consider the results provided by business case of the SWAFEA study. [23]

Within the SWAFEA business case, it was considered that BtL plants are located close to the feedstock source, which is, in this case, a short rotation coppice (SRC). The cost for feedstock production involves costs related to the farming and pre-treatment (chipping, drying). Transport cost for BtL involves the cost related to the loading in the forest and the cost of transportation of feedstock with a truck. Expressed fuel price estimations are influenced by CAPEx (capital expenditure), feedstock cost, O&M (operation and maintenance) & benefits. The cost related to fuel blending and transport to the airport is also included.

The analysis for the HEJ (HEFA) is based on the production cost of European-grown oil crops, such as rapeseed. Cost related to the raw material production takes into account the pre-treatment (oil extraction). Cost related to the transport to the refinery is based on global sourcing from all over the world to the refineries in Europe. Production of the fuel is influenced by CAPEx, feedstock cost and O&M [23].

A comparison of BtL, HRJ, and BAU kerosene, in terms of the breakdown of the total fuel cost is shown in the following figures, Figure 26 and Figure 27, for the "Acceptance of Targets scenario". It can be observed how competitive these two fuels are projected to be with respect to conventional jet fuel. The primary component for BtL production cost is at the refinery (capital costs), whereas for HRJ the primary component is the raw material.

For BtL, the feedstock becomes an important factor for the total price of the fuel over the time. In cost basis BtL can be competitive with kerosene around 2030 and less costly by 2050, for a low feedstock price. This trend is the same for the other scenarios analyzed in the business case of SWAFEA when the price of the feedstock is low [23].

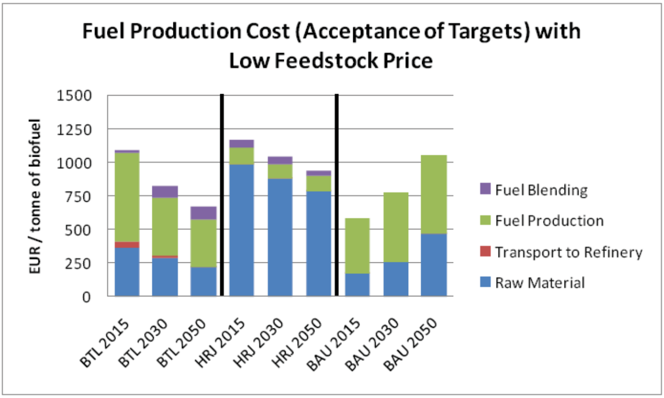

Figure 26: Fuel production costs Acceptance of Targets – Low Feedstock Price [23]

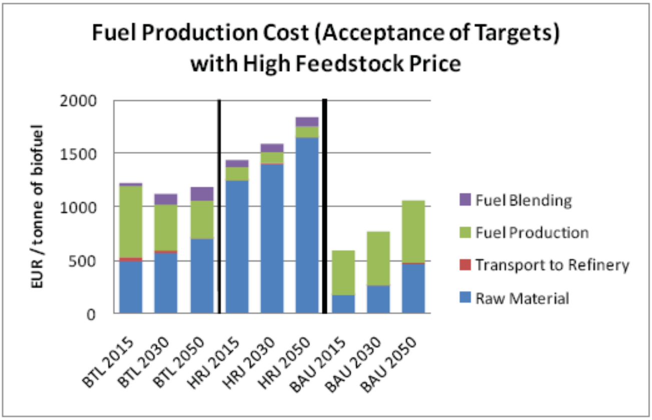

Figure 27: Acceptance of Targets – High Feedstock Price [23]

6 Fuel Substitution Model (Task 3.2.1)

6.1 Introduction

An economical analysis and evaluation of the future use of alternative fuels has already been undertaken in several works. The basic idea is to project fuel demand developments in the future. Supply of alternative fuels can be extrapolated by assuming that production cost and scale developments will follow the same trend as observed in bio-ethanol production. This approach has been carried out in a comprehensive way for GtL and BtL technologies by [26]. On this work the REFUEL project based its study of fuel competition (see [27]), on which in turn the results of the SWAFEA study are based. Our economic analysis acknowledges, builds on and extends these findings.

Prior studies (cf. SWAFEA) suggested to focus in particular on the use of carbon capture and storage (CCS) technology in GtL plants to make this route environmentally sustainable. In addition indirect land use change (iLUC) factors of extensive BtL production has until now not been satisfactorily addressed. Our analysis is thus geared towards extending prior results into exactly that direction.

The first half of the life cycle of a novel fuel technology is marked by two phases. In the “investment factor driven phase” production capacities have to be ramped up to allow sufficient market penetration. In this phase considerable reductions in production cost per unit are usually observed due to scale dependant learning. Once the up-scaling of production capacities has reached its upper limit (due to e.g. logistic or other constraints) the development enters a “market factor driven phase”. The candidate fuel reaches a market penetration which is economically viable given the fuel demand at a given production cost.

Here we model market and investment factors by developing a quantitative model, the fuel substitution model. This is a dynamical technology competition model. Supply, demand and price of each candidate fuel are dynamical variables. It is assumed that there is a growing overall demand for aviation fuel, market participants act rational and buy the cheapest fuel available on the market. If there is no more supply of the cheapest option, the next-cheapest option is bought, etc. According to this demand level the targeted supply of each fuel is adjusted. This allows for possible economy-of-scale effects, which may render a fuel more competitive. Since higher demand may lead to higher production capacities and thus higher scale effects, positive feedback cycles may occur, leading to a lock-in of a given fuel technology.

The model follows the neoliberal tradition in reflecting complete market information in the price. This does not only apply to production costs, but also to other socio-economic or environmental impacts. In particular, environmental characteristics of the technology are “priced-in” via the carbon tax or, where applicable, extra costs for CCS technologies. Land use related issues are reflected by using estimates for future production costs which take the availability of land not used for food supply into account.

6.1.1 Market and Investment Factor

In a scenario where a candidate alternative fuel is cheaper than conventional fuel (Jet A1), by increasing the percent of fossil fuels replaced with alternative fuels, savings are increasing (Figure 28). This scenario can be considered, as hypothetical, since prices of oil and alternative fuels are quickly changing.

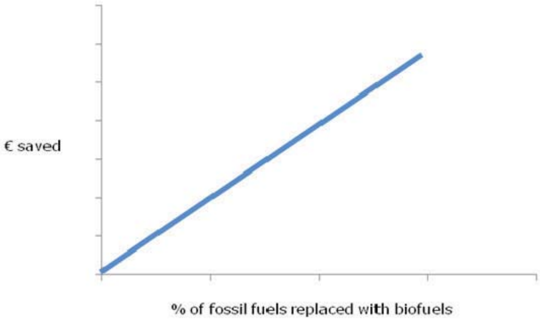

Figure 28: Correlation between biofuels savings and their share based on the simplistic assumption that the price of biofuel is constant and does not depend on the overall supply or details of the investment phase.

In a more realistic scenario the impact of alternative fuels on the economy depends on investments and market effects. From this the optimum value for biofuels replacement can be defined. Let us illustrate this using three different scenarios. Each scenario has defined investment and market factors.

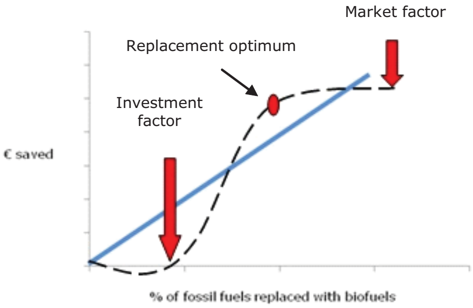

Figure 29: Biofuels saving impacted with investment and market factor

<u>In the first scenario</u> (Figure 30) we assume low investment factor and high market factor. This scenario could be considered as the actual situation in the area of biofuels, i.e. production of 1st generation of biofuels. There is low investment, due to well developed technologies for crops and high feedstock yields. Since 1st generation of biofuels uses crops as a feedstock, market effect on biofuels production is high. A negative effect is very quick market saturation and increasing of distribution costs.

Scenario I

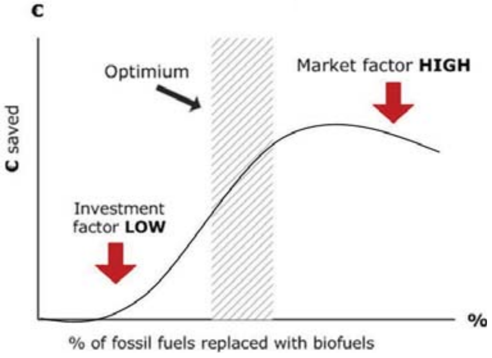

Figure 30: Scenario I- e.g. Biofuels 1st generation; Investment factor: LOW, Market factor: HIGH

<u>In the second scenario</u> (Figure 31) we assume high investment factor and low market factor. This scenario mimics the production of 2nd generation of biofuels. In this case investments are very high because technology is not developed at large scale yet, biomass as a feedstock needs additional R&D activities, for instance. Logistic networks and the entire biomass supply chain is not well developed, and needs further investments. Biomass as a feedstock does not compete with food supply and land use and has low market effect, and its by products can be used for heating or as a gas for transport.

Scenario II

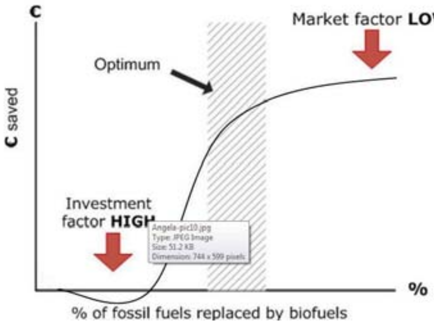

Figure 31: Scenario II- e.g. Biofuels 2nd generation HIGH investment factor, LOW market factor

<u>In the third scenario</u> (Figure 32), investment and market factor are low. Investments are low, due to well established technology for non-food feedstock, and do not compete for land availability. Thus, feedstock does not compete with food supplies; also feedstock supply does not depend on market price, so the market effect is low as well.

This third scenario, strategy for biofuels development, may result in biofuels of third generation. Each scenario has its optimum and they are not the same in each scenario. In the first scenario, due to high market effect the optimum is the lowest. In the second, scenario, we can assume that due to low market effect the optimum is higher. The third scenario is a hypothetical scenario.

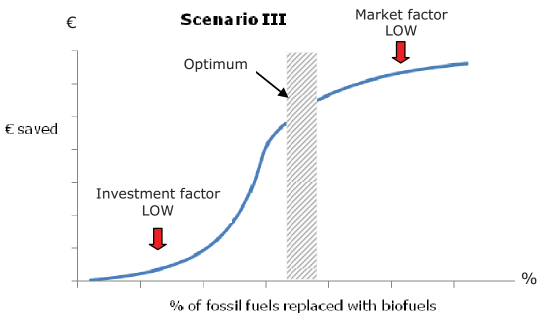

Figure 32: Scenario III- e.g. Biofuels "3rd "generation LOW investment factor, LOW Market factor

The third scenario will be the priority for future alternative fuel developments. In compliance with this scenario, future priorities in biofuels development can be defined. Main goals include to have low investment and low market factor. This can be achieved through development of large scale production facilities, which use different variety of biomass or lignocellulosic feedstock.

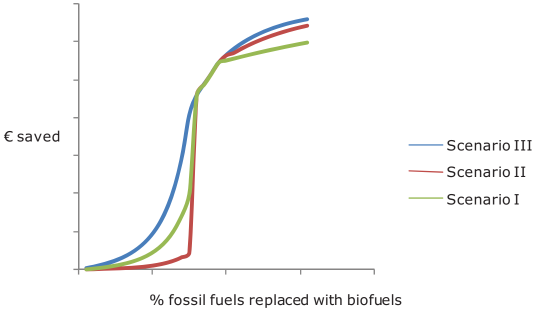

Figure 33: Scenario III- Future priority for biofuels development

6.1.2 Need for Dynamical Modeling

We have seen that each technology has its own unique economic benefits and drawbacks based on its production capacity and costs, as well as its socio-economic context (e.g. competition with food supply, emission pricing, feedstock supply …). It is equally true that the properties of the economic market impact the development of the technology, as the development of the fuel impacts and changes the market conditions. This mutual relationship leads to economic path dependence [28]. What this implies is that the future fuel mix may not depend on which fuel can be produced with the highest cost-efficiency once production capacities are fully ramped up. Instead it may strongly depend on the route which leads to the production of these fuels. That means it is imperative to not only assess the potential of a technology (e.g. its final cost-efficiency), but also the path along which this potential can be harvested. As a simplified example, suppose there are only two competing technologies, *A* and *B*. *A* becomes more cost-efficient than *B* after, say, twenty years of technological learning. However, in the first ten years *B* is more cost-efficient. Assume, due to limited resources, you can only invest to apply technological learning to one of the two. So which technology should you choose, *A* or *B*? The answer, of course, depends on the detailed margin between the two technologies, summed up over each point in time. This is exactly what the fuel substitution model quantifies.

If an inferior technology is dominant in early production phase, this may lead to a lock-in and hinder market penetration of more promising technologies. We have to pay close attention to the actual socio-economic dynamic process in which the respective fuel production is embedded. To this end we use a technological substitution model reflecting these realities. Changing production costs and limited supplies are modeled by changing the market's boundary conditions in the course of the dynamics. In the subsequent sections we develop this model as a set of coupled, dynamical differential equations.

6.2 Data and Methods

An alternative fuel substitution model is developed as a dynamic technological competition model for three candidate fuels: Jet A1 (conventional kerosene), GtL fuels and BtL fuels. Implications for CtL fuels from this model are also discussed. We start by describing economic, environmental and social aspects for each fuel which will be relevant for the model.

6.2.1 Kerosene (Jet A1)

6.2.1.1 Economic Aspects

Current price of Jet A1 is assumed as 107€/barrel, corresponding to the average price in the first half of 2012. We assume that kerosene is a mature technology and there is no decrease in price due to technological learning or an improvement in production facilities to be expected. The price of Jet A1 is tied to the oil price which is notoriously difficult to forecast. In the absence of more reasonable assumptions we assume the oil price to increase annually with a rate of 2% (which extrapolates the long-term price trend since the oil crises of the 1970s into the future). From now on and for the other fuels, all prices will be measured in €/GJ.

Environmental and Social Aspects

As for the production costs we assume there to be no further significant optimization possible in terms of reduction of GHG emissions for Jet A1 production. Well-to-tank emission data is taken from literature values [29]. Supply is assumed to be infinite, or at least large enough to have no influence on kerosene's market factor.

6.2.2 Gas-to-Liquids fuel

6.2.2.1 Economic aspects

The costs have been split into three main contributions, raw materials, OPEX and CAPEX. They have been estimated based on existing and planned GtL plant projects, in particular the Sasol-Chevron plants in Qatar and Nigeria, as well as a plant by Shell in Qatar, see [24] for details. It is assumed that scale independent learning reduces capital and operating expenditures by a net value of 1% each year. Gas prices are forecasted by assuming that there long-term price trend is coupled to oil price movements.

6.2.2.2 Environmental and Social Aspects

CCS (carbon capture and sequestration/storage) is a technology for capturing carbon dioxide (CO_2) emissions from a facility. There are several sources from which a GtL plant can emit carbon dioxide [30]. It enters with the inlet natural gas and can form in the syngas generation step, the Fischer-Tropsch reactor, the hydrogen plant reforming furnace and in the process heating furnaces. Assumptions for the efficiency of the CCS technology for GtL plants are taken from [24]. Here it is assumed that roughly for 60% of emissions can be controlled for. Investment and O&M costs for the CCS facilities have also been taken from [24]. They are projected by assuming the same scale dependant and independent learning relations as for the GtL plant itself.

The separated carbon dioxide is transported to a storage location for long-term isolation. Leaks in these storage facilities pose global and local environmental. Leaks may lead to contaminated ground water or massive release of CO_2 into the atmosphere. These issues have already raised public awareness. CCS is perceived as a bridging technology with the potential to delay the transition into a post-carbon era [31]. Public surveys suggest medium to low public knowledge of this issue, cautious approval but no enthusiasm, as well as the potential for protest and opposition. Acceptance of this technology is thus an ongoing challenge and a widespread adoption should be complemented by intensified efforts in risk communication, i.e. making people able to understand risks and benefits of this solution, as well as build trust in the involved risk managers.

6.2.3 Biomass-to-Liquids fuel

6.2.3.1 Economic aspects

The projection method of BtL production capacities and costs is based on [26] Costs can be split into capital investment costs, operation and maintenance costs, and raw materials. Capital costs depend on the BtL plant scale through the relation

$$\frac{Cost_I}{Cost_{II}} = \left(\frac{Scale_I}{Scale_{II}}\right)^{\alpha} \tag{1}$$

Here I and II represent to different production processes and their associated cost and scale. Assumptions for the lifetime of a plant, its maximum scale L, maximal allowed doubling time T of production scale and the growth parameter R are in line with [27].The growth rate for a plant's maximum production capacity is then

$$Scale_i(t) = Scale_i(t-1)\left[1 + \frac{\ln 2}{T} t \left(1 - \frac{Scale_i(t-1)}{L}\right)\right] \tag{2}$$

The development of OPEX costs for BtL is driven by scale independent learning. On both capital and operating expenditures acts the process of scale-independent learning as in [26], amounting to an annual decrease in price of 2%. Efficiency improvements in feedstock productions are modeled using the methodology outlined in [26]As input for the current breakdown of production costs the results from [24]where used.

CAPEX and OPEX costs for BtL plants can be calculated along the same route as for GtL. The main difference lays in the feedstock handling and preparation procedures, which are much more extensive for a solid feedstock than a gaseous one. In particular, the air separation unit and the gasifier units are assumed to be 50% more expensive. An additional cost item is the rectisol unit. This amounts to 60% higher investment costs for a BtL plant compared to a GtL plant of the same scale. Note that the same approximations can in principle be applied to infer cost developments of a CtL plant from GtL investment costs.

6.2.3.2 Environmental and Social Aspects

We calculate greenhouse gas emissions due to indirect land use change of expanding agricultural areas for second generation biofuel production following [32]. In this work an economic partial equilibrium model, of the global forest, agriculture and biomass sectors, is used (GLOBIOM). The land used for biofuel production is assumed to be either short rotation tree plantations or managed forest, thereby excluding competition with land use for food supply. This is considered important since substantial upwards movements in food prices correlated with spikes in the oil demand have already been observed [33]. The global energy production is assumed to follow the POLES (Prospective Outlook on Long-Term Energy Systems, [34]) scenario, with first generation biofuels substituted by second generation biofuels. Roughly 25% of the total biomass output goes into fuels in this scenario, amounting to roughly 280 Mtoe as of 2030 (including all biofuels, not only for aviation). This figure equals the global production capacity for bio-fuels, without competition with land used for food supply. Note that this option has been identified by the authors as the environmentally favored one, having a carbon payback time (for emission due to iLUC) of zero years. It is also the option with a comparably low impact on water irrigation use.

The land use change effects reported in the following are calculated using the following methodology. The induced GHG emissions per unit of second generation biofuel produced is taken from [31]. We then calculate the increase in BtL demand due to aviation per year, and the realized increase in production capacity per year. The implied GHG emissions due to this up-scaling are then calculated, as a temporary, one-off effect.

Two important caveats to note here are the following. First generation biofuels trigger much more negative externalities and effects than second generation fuels [32] with respect to water irrigation and land use. Second generation biofuels are in turn only a sustainable option if they do not compete with food products, i.e. agricultural land as production source should from this perspective be avoided. A recent quantitative analyses of the impact of ethanol conversion in the US on the FAO Food Price Index (1991-2010) found firm evidence for an increasing feedback between food prices and biofuel production [33]. With a quadratic increase in the amount of corn converted, the same upward movements of food prices can be observed (once filtered for speculative bubbles).

6.3 Results

A detailed description of the implemented methods in the Alternative Fuel Substitution Model is given in Annex 2, along with a table listing required inputs and their sources. The study focuses on three model scenarios.

6.3.1 Selected model scenarios

We will now discuss three example scenarios. In each one the target installed capacity for GtL and BtL fuel is 40%, for sake of better comparison. Furthermore, in each scenario the oil price development is the same and following the long-term trend of the last twenty years. We will then outline some general trends irrespective of the actual specifications of the scenario.

6.3.1.1 "Business as usual" scenario

In the "Business as usual" scenario the oil price keeps following its long term trend. We assume a medium amount of environmental awareness reflected in the required use of CCS technology at GtL plants. The carbon tax is set to 8 ct/kg CO_2eq. This scenario is developed consistently with the "CO_2 constrained case" of the economical evaluation inputs from IFPEN. This scenario will serve as a baseline case. We also develop two alternative scenarios where we vary the amount of environmental incentives with respect to the baseline, "business as usual" case.

6.3.1.2 "Low environmental incentives" scenario

In the "Low environmental incentives" scenario we change the requirement for CCS technology at GtL plants and abandon the carbon tax. This scenario corresponds to the "non- CO_2 constrained case" studied by IFPEn [24]. Target capacities for GtL and BtL, as well as the oil price development have the same values as in the "Business as usual" scenario, but there are no additional payments for GHG emissions or other actions to reduce emissions required.

6.3.1.3 "High environmental incentives" scenario

We also study a scenario where we tighten and increase environmental incentives. In the "High environmental incentives" scenario there is again requirement for CCS at GtL plants, and also higher monetary incentives to reduce GHG emissions. The carbon tax is set to 10 ct/kg. In addition it is assumed that due to intense policy incentivizing R&D activities with respect to BtL technologies have been considerable increased, leading to a decrease of 20% in the doubling time for the production capacity up-scaling. We will turn now to a discussion and comparison of the model results for these three scenarios.

6.3.2 Comparison of the scenarios

Let us first examine how the market shares for each of the scenarios develop.

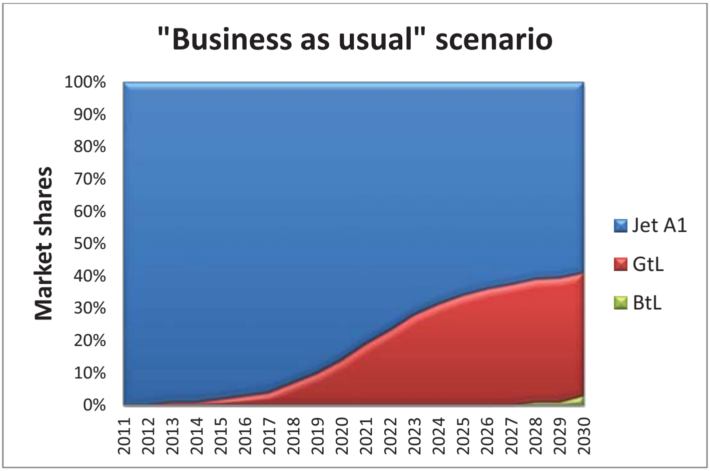

Figure 34: Development of market shares for Jet A1, GtL and BtL fuels for the "Business as usual" scenario. Initially, Jet A1 dominates the market. Upon market introduction GtL steadily gains market shares until 2027, where BtL reaches price parity with the other fuels and starts to substitute Jet A1.

6.3.2.1 Jet Fuel Market Shares

Projected market shares for different jet fuel options under the "business as usual" case are shown in Figure 34. GtL gains shares on the jet fuel market upon introduction, significantly growing after 2015. This trend comes to a halt around 2027 when BtL reaches price parity with the other options. Then there is a phase of fast growth for BtL fuels until the end of the considered time-span.

Results for the jet fuel market shares in the "Low environmental incentives" scenario are shown in Figure 35. BtL does not become cost competitive within the next twenty years. GtL starts to substitute Jet A1 upon market introduction; no turning point for this trend is seen within the time range of interest.

In the "High environmental incentives" scenario, see Figure 36, BtL reaches price parity with other fuel options a couple of years earlier than in the "Business as usual" case, around 2022.

We compare developments for GtL shares for the three different scenarios in Figure 37. They keep increasing until 2030 in the "Low environmental incentives" scenario, where BtL does not become cost-competitive. It approaches the targeted capacity of 40% in this scenario. In the "Business as usual" case GtL shares start to decrease after 2027, in the "High environmental incentives" case they start to decrease as soon as 2022. This is due to BtL reaching price parity in the respective scenarios.

This is seen in clearer detail in Figure 38, where BtL market shares for the scenarios are compared. They remain practically zero in the "Low environmental incentives" case and gain momentum in 2022 or 2027 in the "High environmental incentives" and "Business as usual" cases respectively. While in the latter scenario BtL shares are still at modest levels in 2030 (although with a strongly increasing trend), they already reach 30% in the "High environmental incentives" scenario.

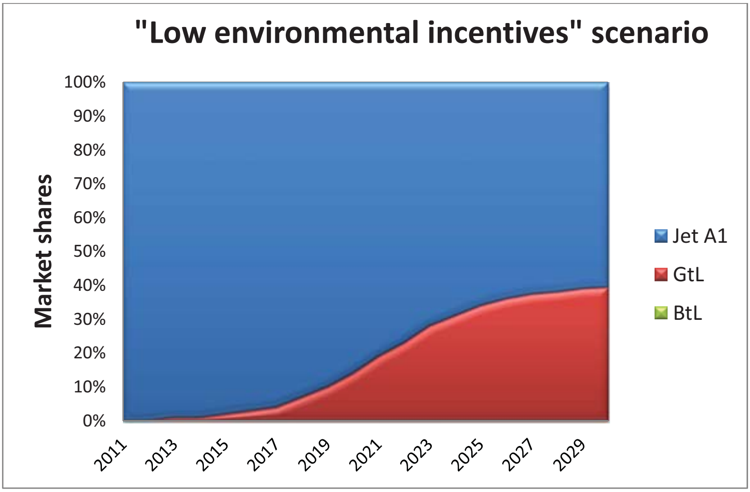

Figure 35: Development of market shares for Jet A1, GtL and BtL fuels in the "Low environmental incentives" scenario. In the absence of the requirement of CCS technology and with low carbon tax BtL does not become cost-competitive within the next twenty years. GtL steadily gains market shares, coming close to the targeted 40% in this scenario.

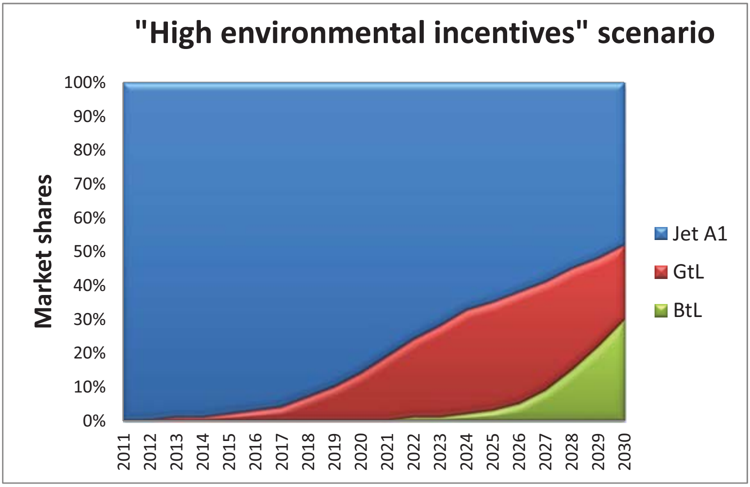

Figure 36: Development of market shares for Jet A1, GtL and BtL fuels in the "High environmental incentives" scenario. BtL reaches price-parity with other options earlier and starts to substitute other fuels around 2022.

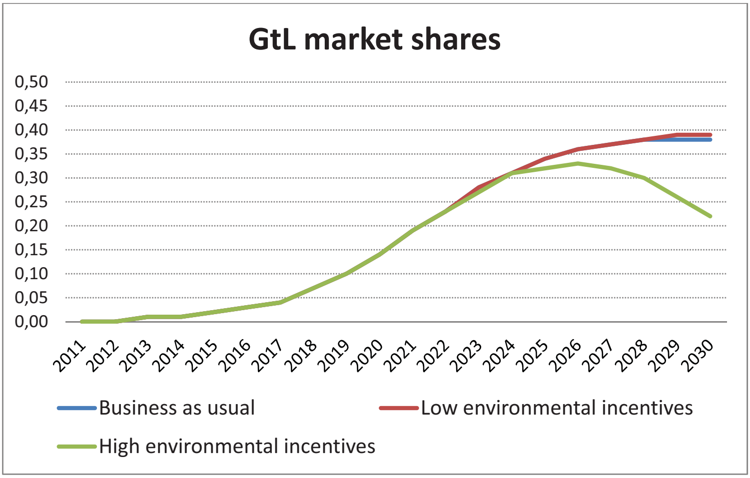

Figure 37: Comparison of the development of GtL market shares. They steadily increase over the entire time-span in the "Low environmental incentives" case. With increasing incentives, the transition from GtL to second generation biofuels occurs earlier.

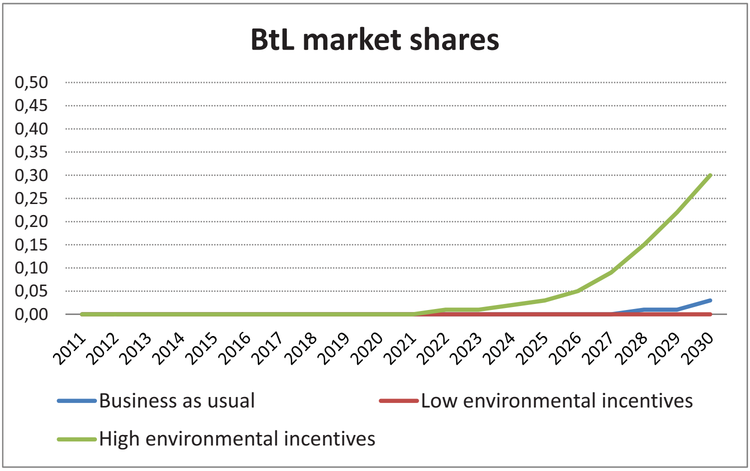

Figure 38: Comparison of BtL market shares developments for the three studied scenarios. They stay practically zero in the "Low environmental incentives" case. By increasing them – from the "Business as usual" to the "High environmental incentives" case – the transition into second generation biofuel technologies occurs earlier.

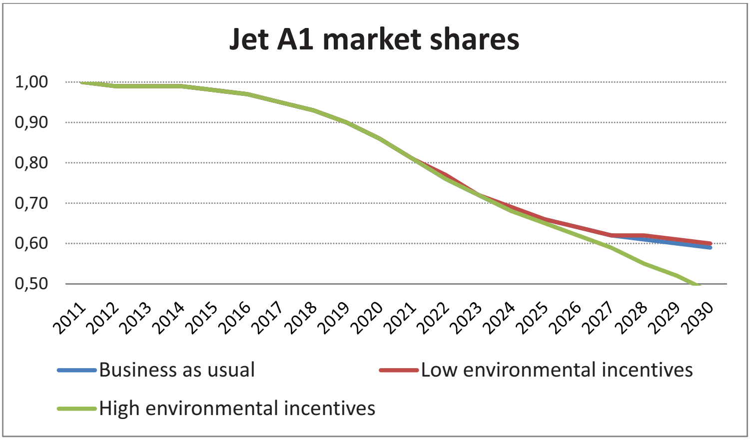

Figure 39: Comparison of Jet A1 market shares for the three different scenarios. There is no significant difference before 2020. By 2030 the lowest shares are reached in the "Business as usual" case. The "Low environmental incentives" scenario exhibits the highest market shares for Jet A1.

The development of Jet A1 shares on the jet fuel market are compared across the three different scenarios in Figure 39. There is no significant difference before 2022. The highest values can be found in the "Low environmental incentives" case, where they are at 60% as of 2030. In the "Business as usual" case they are higher than in the "High environmental incentives" case in the considered period of time.

In the "Low environmental incentives" case BtL does not reach price parity with GtL fuels (or Jet A1). BtL production costs at the plant are substantially more expensive than those for GtL, also due to the requirement of handling and processing of solid feedstock material. In the "Business as usual" and "High environmental incentives" this gap is compensated by payments for actions against GHG emissions. Note that in the absence of any of these actions, GtL technology would reach much higher levels of market penetration, thus requiring higher production capacities which in turn lead to higher technological learning effects and even lower production costs. So even if within a range of plausible oil price scenarios BtL fuels may be the most cost effective solution, a transition into this technology may not be observed due to this "technological lock-in" effect. To understand this, let us take a closer look at investment and market factors.

6.3.2.2 Investment and market factors

We show the "S-Curve" of savings versus fuel substitution for the "Business as usual" case in Figure 40. The S-Curve can be understood as the "economic force" driving the substitution of conventional with alternative fuels at the given level of installed capacities. They are relatively small in the investment phase, gain momentum after the first phase of up-scaling is completed (which seems to occur around a market penetration of 20%), and starts to level off after 40% where we come close to the targeted installed capacities.

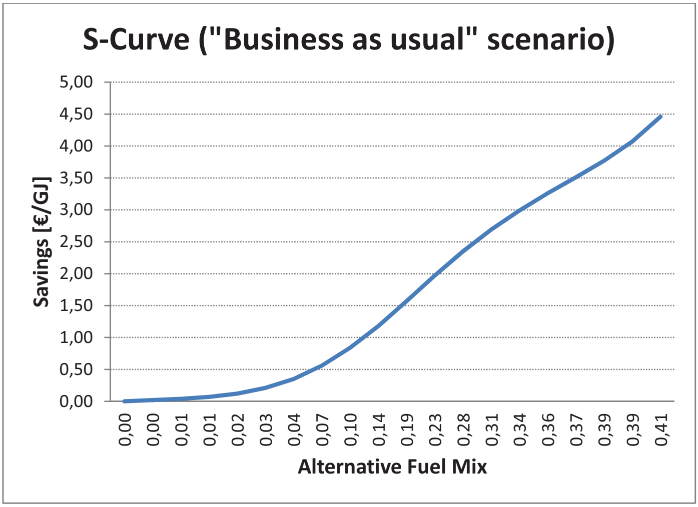

Figure 40: S-Curve for the "Business as usual" scenario. We see the expected shape of investment and market factor, which we can now compare to results obtained in the other scenarios.

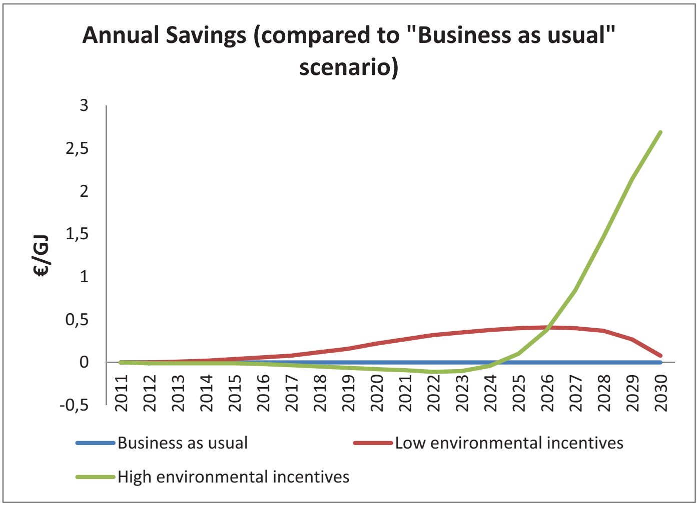

Figure 41: Using Figure 40 as reference, we compare the savings in the investment-driven and market-driven phase to the other scenarios. In the "Low incentives" case savings are higher than in the reference case at each point in time, but by a slowly decreasing margin after 2025. We see the effect of the investment phase in the "High incentives" case before 2024, as well as the payoffs of these investments afterwards.

We are interested in whether the "High" or "Low environmental incentives" scenarios show a different behavior in their investment and market driven phases. To this end we take the annual savings for the "S-Curve" displayed in Figure 40 and use them as reference in a comparison to the other scenarios. For each year we show the difference in savings for the "High" or "Low environmental incentives" scenarios compared to the "Business as usual" case in Figure 41.

In the investment phase of the "Low environmental incentives" scenario (the red line in Figure 41 between 2011 and 2022) the savings are much higher. This is because there is no need to invest in CCS technology and carbon credits are cheaper. In the "High environmental incentives" case we can read of the investment factor as the negative savings before 2024. Once BtL reaches price parity and the according production capacities are scaled up the savings in the BtL investment phase ramp up and reach the highest values across the three scenarios.

Extrapolating the trend observed between 2025 and 2030 further into the future, one sees that there are good chances that the "Low incentives" case may even fall behind the baseline case in terms of savings (due to the beginning ramp-up of the then-efficient BtL production). This may be a technological lock-in effect at work. Early investments in BtL technology are hindered through the much cheaper GtL alternative. On the long run, however this picture reverses in terms of savings.

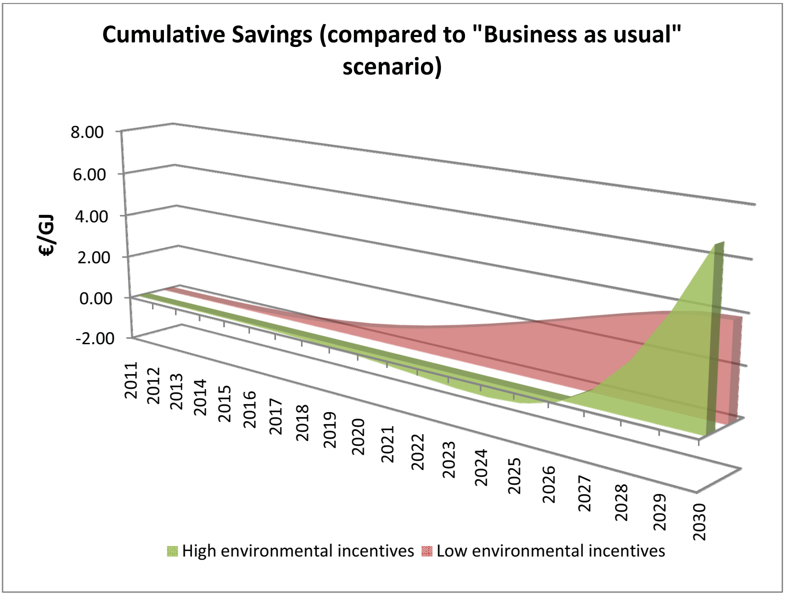

Figure 42: Cumulative savings for "High" and "Low environmental incentives" scenario with respect to the "Business as usual" case. In the latter case, without BtL, cumulative savings climb much faster but start to level off after 2025, whereas they are at first negative, but then spiraling upwards in the CO_2 constrained case.

We compare the cumulative savings for "High" and "Low environmental incentives" with respect to the "Business as usual" case in Figure 42. Here we sum the annual savings up to this year for each of the scenarios. We see that they climb much faster in the first ten years for the "Low environmental incentives" case due to the absent investment in BtL and CCS technology, as well as cheaper carbon credits and. In this case, however, they start to level off once the development becomes market driven. In the case with BtL investments ("High environmental incentives") they still increase in this phase, exceeding the levels of the other case.

Until now we have only discussed economic aspects of the alternative fuel substitution developments. The development of the GHG emissions is summarized in Figure 43.

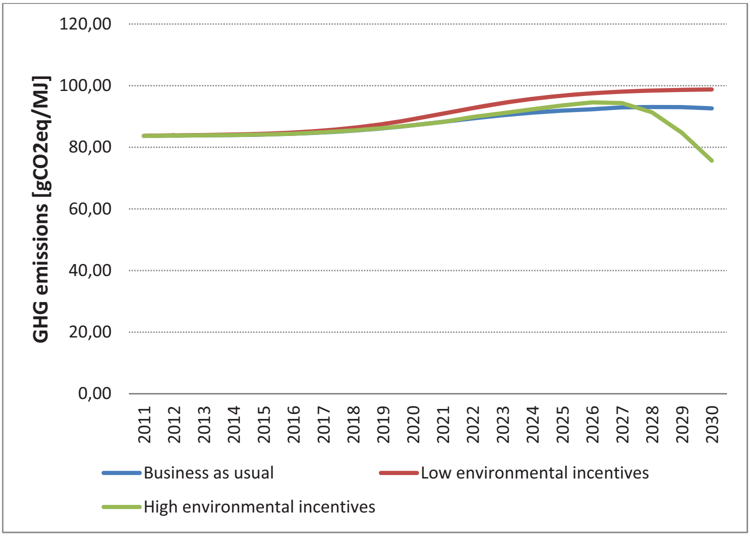

Figure 43: Development of the relative amount of GHG emissions per one MJ for the three scenarios. In the "Low environmental incentives" case they increase by about 20%, in the "Business as usual" case they also increase, albeit slower. In the initial phase of BtL development there is an increase in GHG emissions due to indirect land use change emissions. Once this iLUC effect has taken place, GHG emissions start to decrease, falling significantly below 2010 levels in 2030. These results are discussed in detail in Section 8.

In the "Low environmental incentives" scenario there is no decrease in GHG emissions, even a marked increase. This is different in the "High environmental incentives" and "Business as usual" scenarios where BtL fuels are adopted at some point. This point is marked by an actual increase in GHG emissions due to indirect land use change (iLUC) effects. Once these effects have been taken into account (e.g. deforestation) and the required land has been made available for BtL production, the balance changes again. By 2030 GHG emission levels have decreased significantly below 2010 levels in these cases. These results will be discussed in greater detail in Section 7 using decoupling indicator.

6.3.3 Implications for CtL

CtL fuels can also be studied employing the methodology outlined above and have been implemented in the Alternative Fuel Substitution Model as a fossil alternative to GtL. The required inputs are taken from [24]. To keep the focus of this section sharp, CtL has not been included in the above considerations since it comes with both, higher initial production costs than GtL. At the same time, GHG emissions are significantly higher for CtL than GtL without the use of CCS, and may be reduced down to similar levels if CCS is used. To allow for a cross-comparison, the "Business as usual" scenario is also studied with CtL instead of GtL.

The main difference between GtL and CtL, from an economic perspective, is that the production costs are much less sensitive to raw material costs fo CtL than Gtl. This may render it a useful portfolio option. Concerning the dynamics observed in the model, results for the observed market shares are shown in Figure 44. We find the same qualitative patterns as for GtL as alternative fossil fuel option. Market shares for CtL start to grow significantly after 2015; BtL reaches price parity after 2028.

Putting these aspects together, a feasibility or usefulness to invest in CtL on a large scale should be evaluated in terms of energy security due to diversification of the fuel portfolio. From the point of view of production costs and sustainability, under the necessary condition of controlling for GHG emissions with CCS technology, CtL may serve as a viable alternative to GtL fuels.

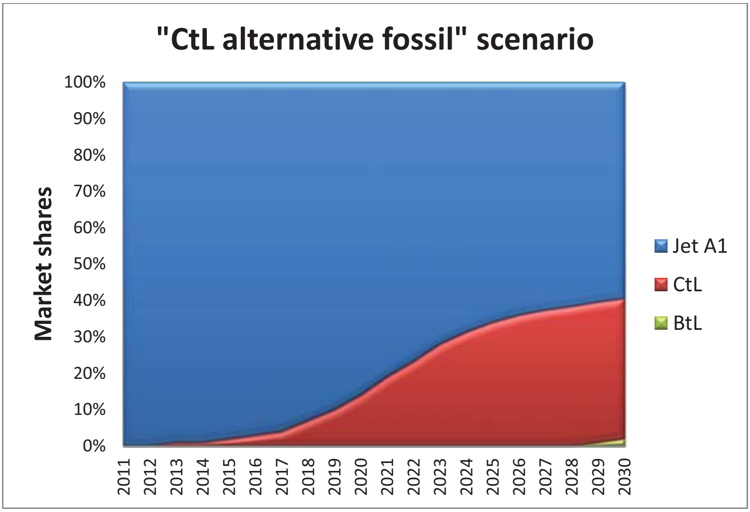

Figure 44: Market share development in the "Business as usual" scenario with CtL replacing GtL as alternative fossil fuel. Qualitatively we find the same results as discussed before, with BtL reaching price parity after 2028.

6.3.4 *Comparison to other studies*

Since by design our modeling approach is deeply interconnected with the modeling approach undertaken within the REFUEL study [27], on which in turn SWAFEA results on the economic impact analysis of alternative fuels are based, we reproduced their results and extended them by paying close attention to GtL developments in connection with CCS technologies, as well as land use change associated with second generation biofuel productions.

In particular it is possible through up-scaling of second generation biofuel production facilities to reach their cost competitiveness within the next twenty years. Since reaching this point may take a decade, or even longer, incentives to invest as soon as possible in BtL technologies should be provided to allow sufficient market penetration, as exemplified in the "High environmental incentives" scenario.

As reported in the SWAFEA study, GtL and CtL are not suitable to reduce GHG emissions, even with CCS technology. The best that can be achieved is to roughly hold the current level, however there may be economic benefits to be expected. The expected point of price parity of BtL fuels to Jet A1 can be expected to lie in the next two decades, depending on the scenario under scrutiny.

Let us compare the results of the economic impact analysis between the SWAFEA and ALFA-BIRD project in a bit more detail. SWAFEA looked closer at BtL, CtL and HRJ technologies, we consider BtL and GtL in detail here. One of the main differences in the modeling approaches is that the SWAFEA study fixes a certain emission target (50% of 2005 emissions in 2050) and seeks the most cost-efficient path to this goal. Our work here is based on a totally complementary approach. In our model each market participant acts rationally at each point in time and we only fix a couple of economic boundary conditions (i.e. the overall demand and the maximum production capacities).

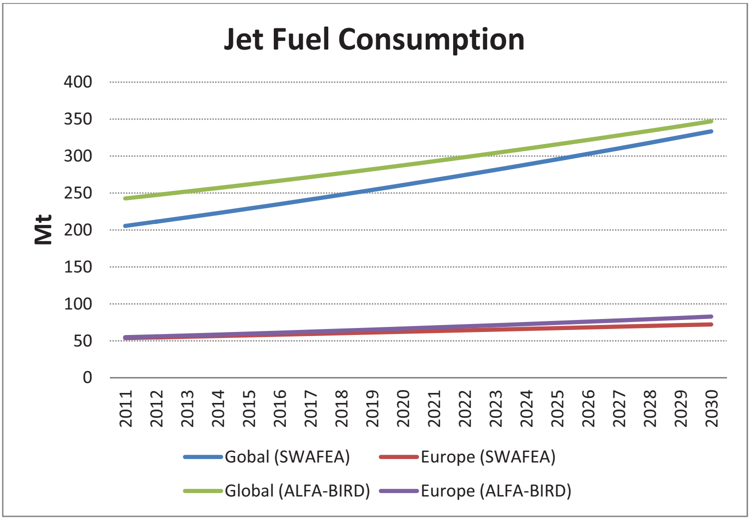

Figure 45: Comparison of jet fuel consumption (in Mt) projections between the SWAFEA and the current study. Results are shown for the years 2011-2030, for global and European consumption respectively. Hence, the studies start with similar forecasts on the expected demand for jet fuel.

Both of the considered studies, SWAFEA and ALFA-BIRD, start with similar assumptions concerning the expected growth in jet fuel consumption, both on European and global levels, see Figure 45

Of particular interest is a detailed comparison of the projections for the production costs for different alternative fuel technologies, see Figure 46.

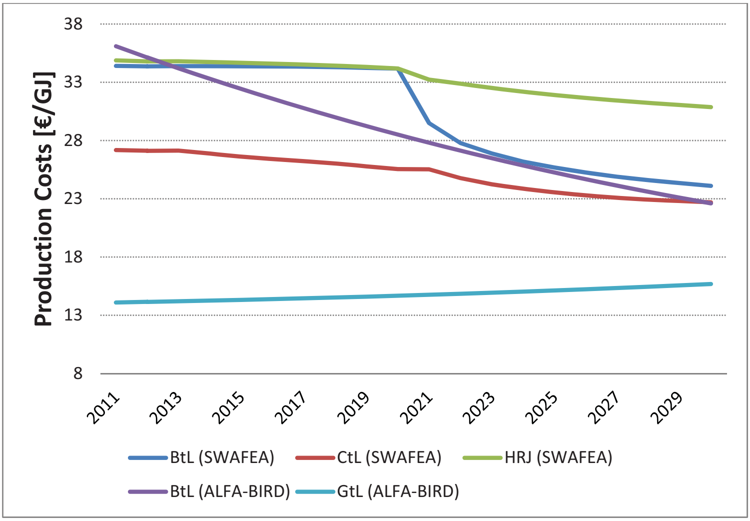

Figure 46: Comparison of forecasts for production costs (in €/GJ) for SWAFEA fuels (BtL, CtL, HRJ) and fuels considered in the fuel substitution model. The BtL fuels show initially a different behavior, but approach similar values after 2020.

By comparing the development of production costs for BtL, considered in both the SWAFEA study and the fuel substitution model, we see that the forecasts deviate before 2020, but approach similar values in the years afterwards. GtL and CtL are available at cheaper production costs, GtL being cheaper than CtL by a significant margin. This is what one would expect, given the more expensive feedstock handling required in CtL plants. Results are also shown for HRJ from the SWAFEA study, which is not studied in the fuel substitution model.

In both studies, SWAFEA and ALFA-BIRD, scenarios have been developed where no or a very small amount of GHG mitigation actions was undertaken. For SWAFEA, this is the "No mitigation" scenario, where kerosene is the only aviation fuel. In the case of the fuel substitution model we consider the "Low environmental incentives" case, where the least reduction of GHG emissions is observed, see Figure 47.This figure shows the development of overall GHG emissions in percent of 2011 emissions, as projected by the different scenarios.

In the first couple of years the results overlap. In the "Low environmental incentives" scenario GtL gradually gains market shares, leading to an increase in GHG emissions. This results in an even higher growth than observed in the "No mitigation" scenario, where the fuel mix consists entirely of kerosene.

We compare the "Business as usual" and "High environmental incentives" case studied in the fuel substitution model to two different scenarios of the SWAFEA study in Figure 48. GHG emissions are reported in percent relative to 2011 levels. The shown SWAFEA scenarios are based on the following assumptions. Both cases are constructed as to reach fifty percent of 2005 emissions as of 2050. In the "Reference scenario" case the expected values for the 2020 emission level has been set to a reduction of 1.4% compared to 2005, in the "Quota mandate" scenario 2020 levels have been set to 5%. The targets for the years in the ranges 2010-2020 and 2020-2050 are obtained by interpolation respectively.

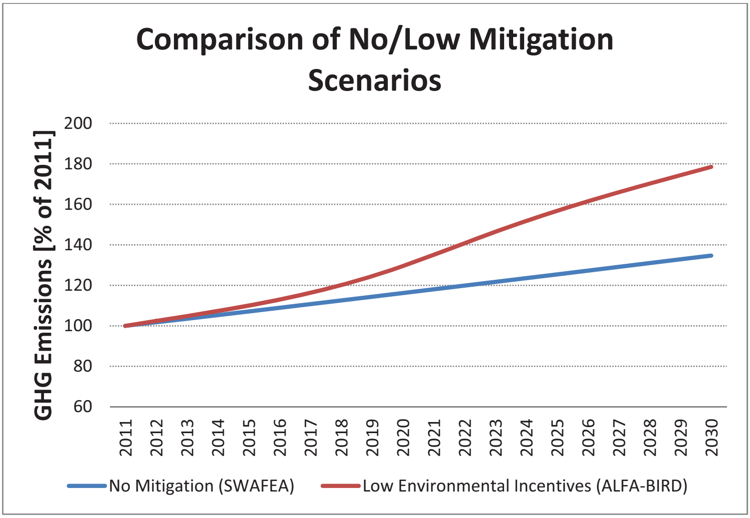

Figure 47: Comparison of scenarios from SWAFEA and fuel substitution model where no or only a small amount of GHG mitigation actions are undertaken. Results are shown in percent of 2011 emissions for the studies respectively. In the first years the results follow the same trend. Later a deviation becomes discernible, due to the advent of GtL in the "Low environmental incentives" case.

Looking only at the emission levels of 2030, one sees that the "High environmental incentives" case approaches the same value as the "Reference scenario" and "Quota Mandate" scenario of the SWAFEA project. Especially in the 2020s large deviation are discernible. This is mostly due to the pronounced growth of GtL usage, and further amplified by the land use change effect. In the "High incentives" case these effects have been accounted for by 2025, in the "Business as usual" case this turning point is expected to occur at a later point.

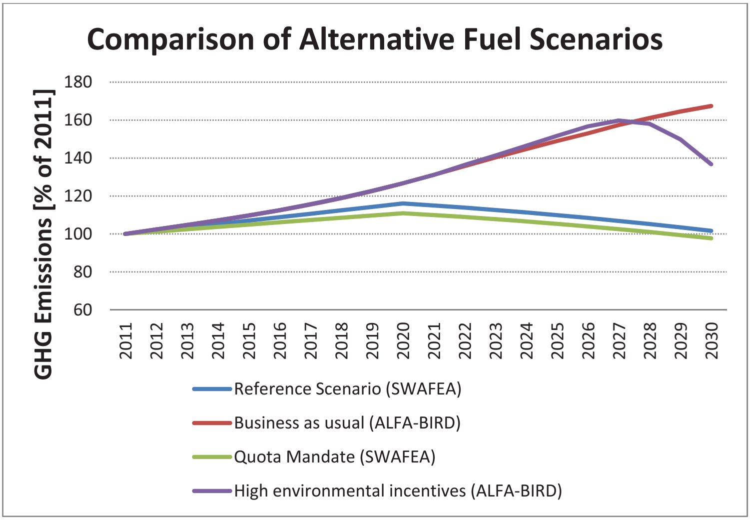

Figure 48: GHG emissions (in percent of 2011 levels) for two different scenarios from the SWAFEA and ALFA-BIRD study. Large deviations can be seen in the 2020s in the ALFA-BIRD scenarios, due to the take off of GtL usage in combination with the land use change effect. Once this has been accounted for, especially for the "High environmental incentives" case there is an accelerated trend towards decreased overall emission levels, as also projected by the SWAFEA study. For the "Business as usual" case this turnover point occurs later.

6.4 Possible model extensions requiring additional data

This modeling work could be extended in a countless number of ways. We will now list a number of issues which could be addressed in future work, provided that additional data would be accessible:

- How does the efficiency of CCS technology develop? Which efficiency gain in the rate of carbon capture can be expected? Right now there is no reason to believe that an actual reduction of GHG emissions can be achieved through CCS, but depending on the progress rate made this may change.
- Do some possible by-products of the BtL/GtL production process have a significant impact on the fuel prices? Currently the same assumptions as in [26] are made, but if some chemicals demanded by the pharmaceutical industry can be produced, this may have far-reaching consequences.
- Currently all GtL and BtL technologies are thrown within one basket. Given sufficiently fine-grained data, it may also be possible to measure the economic competition between different GtL and BtL fuels.

7 Decoupling indicators: Monitoring progress in Sustainable Consumption and Production in the EU

The decoupling indicators method quantifies to which extent economic goods may outweigh environmental bads. In particular, resource efficiency indicators aim to show how the overall economic growth is related to the overall environmental impact of resource use. In the consequence it will inform whether and to which extent we can decouple growth from impact.

The Decoupling Indicators have two components: an environmental impact component and an economic component which can be respectively the GDP[1] and the resource impact. It is important to notice that all resources that we use are taken into account. For instance, it can be material, energy and land resources as well as air, water and soil as sink for emissions.

The overall approach for the resource impact indicators is a combination of macro-level resource/emission inventories with micro-level Life Cycle Inventory (LCI) data and trade statistics. On macro-level emission and resource extraction/use data are obtained for the territorial inventory. On the micro-level, to assess the environmental impacts of imported and exported products to capture the trade-related shifting of burdens abroad, Life Cycle Inventory (LCI) data (i.e. resource extraction/use and emissions associated with the production of products) are combined with trade statistics.

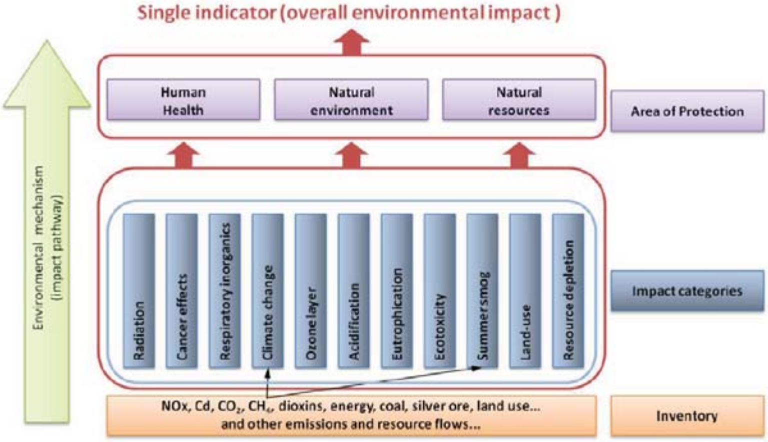

Figure 49: Calculating the overall environmental impact
(European Commission, Joint Research Centre (JRC),[5])

Then these results are converted into environmental impacts (such as climate change, land use, eco-toxicity, summer smog, energy resource depletion, etc.) thanks to a weighting scheme.

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[1] Gross Domestic Product

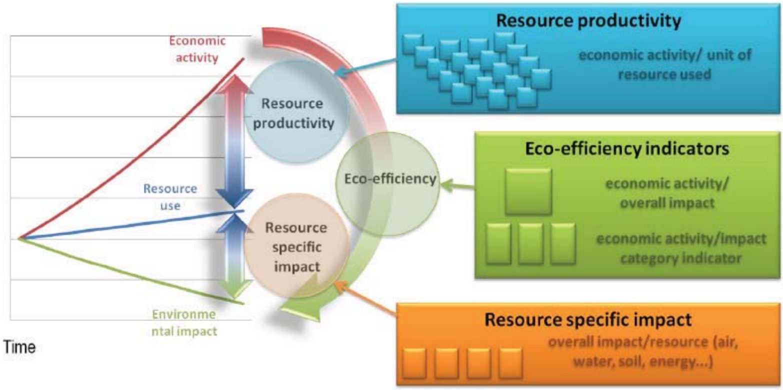

Figure 50: Three different application levels of decoupling indicators. The resource productivity indicator measures progress related to the productivity of the use if the natural resource. Resource specific impact indicators assert how negative environmental impacts relate to the resource use. Eco-efficiency indicators monitor decoupling of the overall environmental impact associated with natural resource use. (From [5])

We will use three types of decoupling indicators for monitoring purposes, as outlined in Figure 50. They correspond to different application levels, be it the overall macro-level of economic growth or the detailed micro-level of environmental impacts of specific life-cycle instruments.

The resource productivity indicator assesses progress in the productivity of the use of a natural resource. To this end the development of an economic indicator associated with the resource is put into relation with the amount of individual natural resources used and compared over time.

Resource specific impact indicators evaluate to which extent negative environmental impacts decouple from resource use over time, they are impact-to-resource ratios.

The eco-efficiency indicator is the ratio of overall economic performance per overall environmental impact, associated with the use of a given natural resource.

In the following we will develop these indicators for GtL and BtL use. This requires compiling data from a wide variety of sources. One main input is the Alternative Fuel Substitution model and thus the references therein. The economic development and its correlation to the jet fuel market development is based on the Alfa-Bird T1.1.2 results. Yield improvements for BtL feedstock, as well as productivity improvements for GtL and BtL are based on the REFUEL study, i.e. [26] and [27]. ILUC effects from BtL use are calculated with values from [32], life-cycle data (e.g. impacts of CCS use) are consistent with the economic and environmental evaluation of the SWAFEA study. All these inputs are brought together as described in Section 7 and projected forward in time.

7.1 Resource Productivity

The resource productivity indicator measures the economic activity per unit of resource used for a given technology over time. The economic activity of interest here, for both GtL and BtL fuels, is how much jet fuel a unit of resource can deliver. Concerning the thermal efficiency in the refinery a similar progress can be expected for both GtL and BtL technologies. Current values for the BtL fuel efficiency (in GJ(fuel) per GJ(feedstock)) are around 50 %, for GtL around 60%. Note that GtL has a comparably low thermal efficiency, for e.g. liquid natural gas processing offers a thermal efficiency of approximately 90%. Existing GtL plants are expected to show an increase in efficiency up to 60% in the time period of interest here. We extrapolate from this assumption and assume for BtL the same rate of progress (due to the technological similarities).

For BtL, however, there is a second source of improvements, namely the yield improvements of the feedstock. This has been evaluated by the REFUEL study. The BtL resource productivity is thus measured in [GJ/m²], that is by energy which can be used as jet fuel produced from a given land unit in a given year, see Figure 51

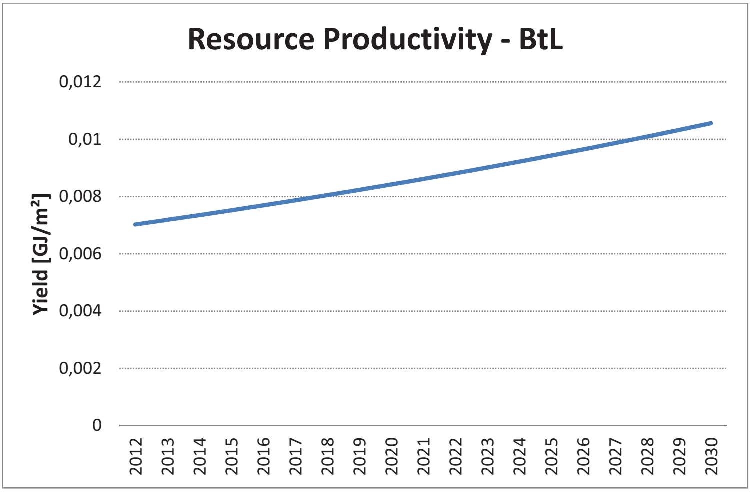

Figure 51: Resource productivity for BtL technology. For each year we measure the yield, i.e. the amount of energy which can be used for aviation per unit land used for feedstock cultivation. A steady increase in observable, the yield almost doubles.

Until 2030 the projected yield, measured as the amount of energy used for aviation per unit land required for feedstock cultivation, almost increases from 0.007 GJ/m² to 0.011 GJ/m².

For the resource productivity of GtL we consider the development of the thermal efficiency of the conversion from feedstock to fuel, shown in Figure 52. In this case we find an increase from the current values of 50% to approximately 60% in 2030.

To summarize, resource productivity for BtL shows greater potential than for GtL. This is due to the additional yield improvements from the crops. Since, by definition, GtL and BtL are based on different resources, these values should be read with care.

Note that the progress ratios studied here are independent of the actual scenario, i.e. whether ‘Business as usual”, “high” or “low environmental incentives”, since each of them is captured within the scale-independent learning aspects.

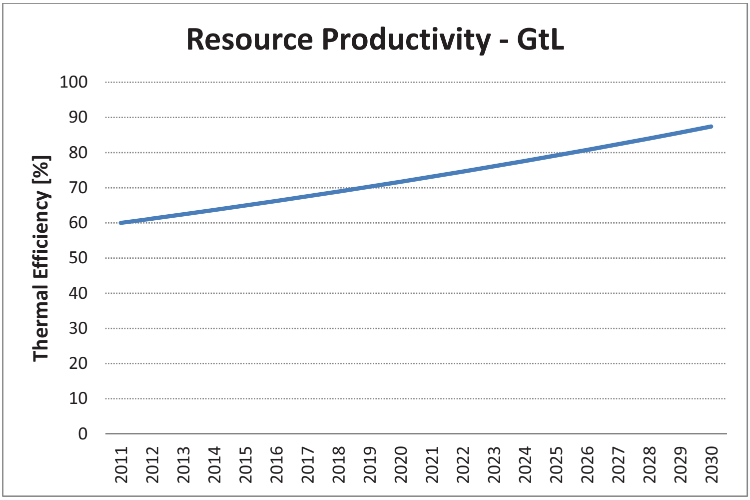

Figure 52: Resource productivity for GtL technology. The development of annual values for the thermal efficiency of conversion from feedstock to fuel in GtL plants due to technological learning is shown. We find an increase from 60% to almost 90%, i.e. levels achieved with liquid natural gas nowadays.

7.2 Resource specific impact

We turn to the discussion of overall environmental impact of each of the resources used for aviation in our model. The environmental impact is measured in life-cycle emission (g CO_2eq). They have different sources for each technology. Most importantly, for BtL the main source turns out to be indirect land use change (iLUC). These emissions follow a different logic to account for. They are inflicted only once, namely when the actual land use change occurs together (through e.g. deforestation or afforestation actions). These emissions 'pay back' in the next couple of years by allowing to produce BtL fuels and substitute them for GtL emissions requiring a much higher degree of life-cycle emissions in their production process.

The amount of resources used depends on the scenario under study. We will adopt the following strategy to measure this. We use the market shares for Jet A1, GtL and BtL as predicted by the Fuel Substitution Model. For each unit of energy used in aviation we obtain the average contribution from the three different energy sources. Each energy source has a specific environmental impact. To calculate the GHG emissions from a unit of energy used we combine the GHG emissions for each fuel technology, weighted by the corresponding market share. For BtL, for example, we have to measure the increase in production capacities and infer carbon emissions due to iLUC and incorporate them in the analysis.

7.2.1 Resource specific impact for the "Business as usual" scenario

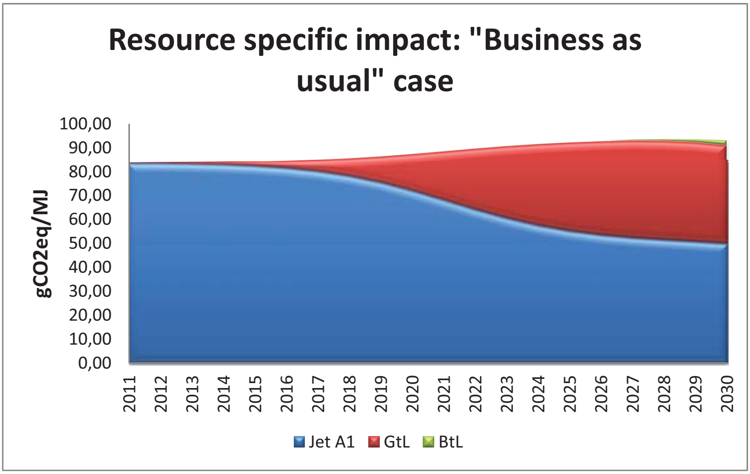

Figure 53: Resource specific impacts for Jet A1, GtL and BtL in the "Business as usual" scenario. The share of emissions due to Jet A1 decreases at the expense of emissions due to GtL production. We find increasing GHG emissions when the BtL production is ramped up due to iLUC. This effect is small here, due to the very modest production scale of BtL in this scenario.

Figure 53 shows the resource specific impacts for Jet A1, BtL and GtL fuels in the "Business as usual" scenario. For each year the carbon emissions due to the production of each fuel are calculated. Each unit of energy used as jet fuel is then broken down into the respective shares of each fuel and the overall impact is calculated as the weighted sum of these contributions. The total emissions (the sum of the three curves) stay constant until 2015. Then GtL production capacities start to be ramped up and overall emissions increase. Between 2027 and 2030 BtL production capacities start to grow. The comparably low production capacities in this case lead to a relatively small iLUC effect.

It is found true that the widespread adoption of BtL technology causes a substantial amount of GHG emissions due to iLUC. Those have to be evaluated in terms of their carbon payback time. So the question is if the substitution effects are strong enough that the overall balance shows a decrease in carbon emissions after a sufficient time-span. For the production of second generation biofuels this carbon payback time has been found to lie in the range of a couple of years [32], a finding which we can reproduce independently for the life-cycle emissions of fuel for the aviation sector (in the current scenario).

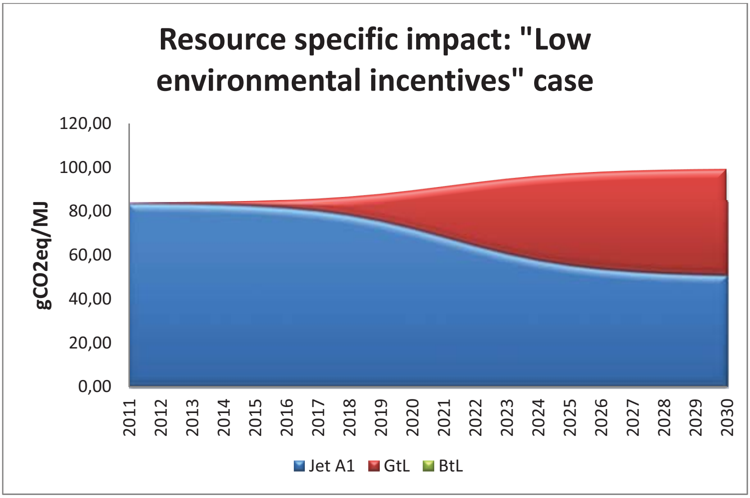

Figure 54: Resource specific impacts in the "Low environmental incentives" scenario. There is no market penetration of BtL fuels, no increase in GHG emissions due to iLUC and finally no substitution effect. The overall balance shows a slow increase in carbon emissions.

Figure 54 shows the development of resource specific impacts in the "Low environmental incentives" scenario. In this case BtL technology does not reach price parity and cost competitiveness with Jet A1 and GtL. There is no iLUC effect since BtL production facilities are never ramped up. In turn there is also no substitution effect, since Jet A1 and GtL remain dominant in the market.

In contrast to the "Business as usual" scenario there is no need for CCS technology at the GtL plants. This leads to a larger increase in GtL specific GHG emissions over the years 2011-2022 compared to the case with CCS. This suggests that what can be achieved with CCS is to keep the overall GHG emissions at a constant level at best. Without CCS GtL is inferior to conventional fuels from a sustainability perspective.

Reductions in GHG emissions can only be observed through substitution of GtL and Jet A1 by BtL.

7.2.2 Resource specific impact for the "High environmental incentives" scenario

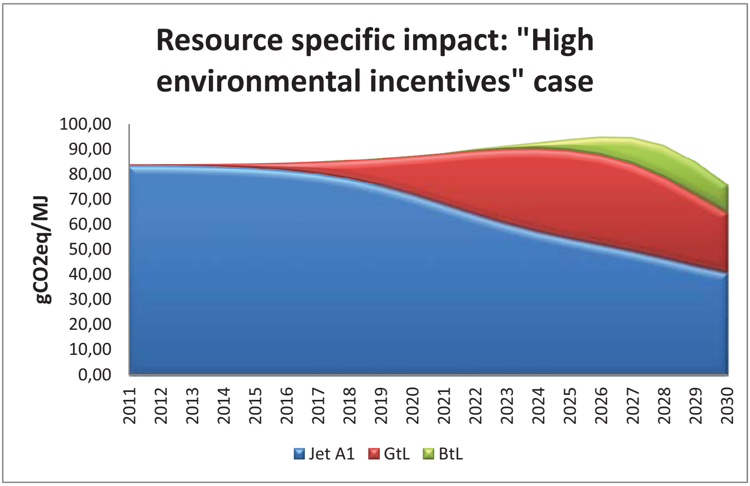

Figure 55: Resource specific impacts for the "High environmental incentives" case. Here BtL reaches price parity around 2020. Then BtL production capacities are ramped up leading to the iLUC effect. In subsequent years this allows to substitute GtL and Jet A1 by BtL fuels leading to an overall decrease in carbon emissions.

The development of resource specific impacts in the "High environmental incentives" case is shown in Figure 55. In this scenario, due to higher monetary incentives to lower GHG emissions, BtL reaches the point of cost-competitiveness earlier than in the "Business as usual" case. As result we observe the land use change effects in the last five years when BtL production capacities are ramped up.

In the subsequent years the substitution effect weighs in and overall emissions are expected to start to decrease due to replacement of GtL fuel and Jet A1 by BtL technology.

7.3 Eco-efficiency indicator

The eco-efficiency indicator monitors the ratio of overall economic activity to overall environmental impact over time. Economic activity is measured as Europe's GDP which is projected according to the "IMF GDP growth rates" scenario as defined in Alfa-Bird T1.1.2. This scenario is consistent with the World Economic Outlook provided by the IMF on an annual basis. The overall environmental impact is asserted in the following way. The European jet fuel consumption is projected from this GDP scenario. For each of our three scenarios we can then measure the total emission, taking the time-depending market shares of the three fuels into account.

This is shown in Figure 56. In each scenario we find an increase in total carbon emissions until 2020. Then the iLUC effect sets in for the "High environmental incentives" case, and a couple of years later in the "Business as usual" case. For this case the total emissions can be reduced down to 2010 levels. In the "Low environmental incentives" scenario, on the other hand, total emissions keep increasing.

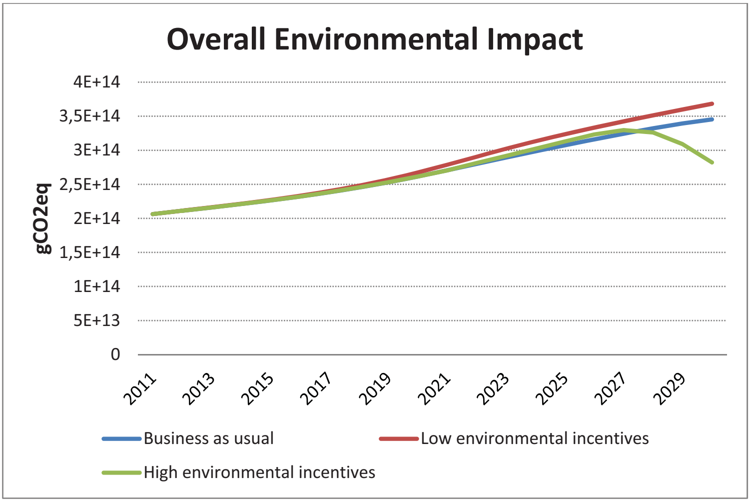

Figure 56: Overall environmental impact of aviation fuels measured in gCO_2eq. The "High environmental incentives" scenario shows a peak due to the iLUC effect and a decrease in total emissions afterwards. There is no such decrease in the "Low environmental incentives" case. For the "Business as usual" case the turnover point is expected to occur in the years following the forecast horizon.

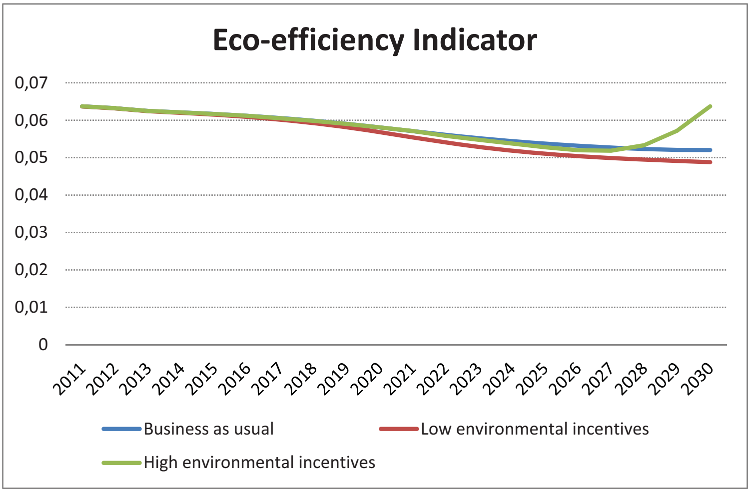

Figure 57: Eco-efficiency indicators for the three scenarios. The "High environmental incentives" scenario is the most eco-efficient case, followed by the "Business as usual" case. The "Low environmental incentive" case ranks last.

This has to be compared with the associated economic growth as expressed in Europe's GDP (in trillion €), see Figure 57. In all three cases economic growth per environmental impact is coupled to a constant until 2020, then the scenarios start to decouple in different ways.

We see that the land use change effects in the "High environmental incentives" scenarios are quickly compensated for. At the end of the time range of interest the "High environmental incentives” scenario has the highest eco-efficiency, followed by the “Business as usual” case (which still assumes a moderate carbon tax and requires CCS technology). The “Low environmental incentives” scenario, where there is a low carbon tax and no requirement for CCS technologies, ranks last in terms of eco-efficiency.

8 MCDM – Multi-criteria decision making matrix

8.1 Motivation

Within the Alfa-Bird project a multitude of alternative fuels have been studied with respect to a wide range of criteria, such as technical, technological, environmental, social and economical aspects. As part of WP 3.3 a fuel ranking matrix is developed with the aim to provide an overview and synthesis of these diverse results. In this matrix the candidate fuels are compared to two different reference fuels (Jet A1 and FSJF) in terms of their performance in each of the studied criteria. From this comparison a hierarchical ranking of the studied fuels in terms of their overall viability is to be deduced. However, given this abundance of information, it is not at all clear how an unambiguous ranking can be obtained, especially since this ranking may be stakeholder dependent. While, for instance, for turbine manufacturers and airlines the technological aspects may be prevalent, fuel producers may put more weight on the economical aspects while regulators keep an eye on the environmental balance. This high complexity of the decision making problem (multiple criteria, multiple stakeholder) calls for a sophisticated approach in the construction of the final ranking. A technique satisfying the demands is Multi-criteria decision making (MCDM), as described in this section.

8.2 Fuel matrix criteria

In this section we provide an overview of the criteria used in the fuel matrix, along which the candidate fuels are compared.

- Technical and Technological
    - Fuel chemistry, fuel characterization
    - Fuel production, storage and distribution
    - Infection and combustion
    - Engine system integration
    - Aircraft system integration
- Regulation
    - Safety, standards, regulation
- Environmental
    - Environmental balance
- Economical
    - Economical balance

Each of these sections is again split up into multiple sub-criteria (see table at the end of this section). The analyses within this sub-criteria are thoroughly conducted by the Alfa-Bird project partners, which are also asked to provide a qualitative assessment of each candidate fuel of whether it performs better, worse or as good as Jet A1 and FSJF. In this way a comprehensive overview of the Alfa-Bird project results can be achieved, see the WP 3.3 documentation for more information.

8.3 MCDM technique

Multi-criteria decision making (MCDM) is a discipline aimed at supporting decision makers who are faced with making numerous and conflicting evaluations. MCDM aims at deriving a quantitative and unambiguous way to come to an optimal compromise in a transparent process.

Unlike methods that assume the availability of measurements, measurements in MCDM are derived or interpreted subjectively as indicators of the strength of various preferences. In the present case, this indicator is whether a given candidate fuel performs better (quantified as “+1”), worse (say,” -1”) or as good as (judgment “0”) the reference fuel.

The general form of an MCDM problem consists in choosing a number of strategies (also called: alternatives / actions) and a number of criteria (also called: aspects / dimensions) by which they are ranked. The alternatives correspond to the studied candidate fuels, the dimensions to the criteria of the fuel matrix.

Let us denote each strategy or alternative i by a function $f_i(\vec{x_i})$, where the vector $\vec{x_i}$ contains as elements the judgments along each criteria or dimension. A suitable function may just be the algebraic sum of each judgment, combined with a stakeholder-dependent weighting of the different criteria. The high dimensional vector space of possible solutions S is the span of all vectors $\vec{x_i}$ In this way a different set of priorities can be introduced in the decision making problem. The problem may also be phrased such that we are interested in an optimal portfolio of fuels, where we assign each candidate i a weight parameter w_i. This parameter quantifies how much of a given fuel should be used in an optimal portfolio.

Given the above definitions, we can phrase the MCDM problem for the Alfa-Bird fuel ranking matrix mathematically as finding

$$\max\left[\sum_i \boldsymbol{w_i f_i}(\vec{x_i})\right], s.t.\, \vec{x_i} \in S. \qquad (3)$$

Here $w_i \geq 0$ are the weighting coefficients representing the relative importance of the objectives. They are usually normalized such that $\sum w_i = 1$. Although this assumption of additive and linear utilities is not easily satisfied, this method can be used to generate non-dominated solutions by utilizing various values of w_i.. The weighting coefficients w_i. do not necessarily reflect the relative importance of the objectives in the proportional sense, but are only parameters varied to locate the non-dominated solution points. Mathematically, the above task can be phrased and solved as a vector maximum problem [37].

8.4 Results

Results of the application of MCDM tool to the fuel ranking matrix are shown in Figure 59. A brief explanation in how to read the diagrams is provided in the Figure 58.For a better comprehension, the criteria have been divided in: Fuel Chemistry-Fuel Production – Combustion (See Figure 60), Engine System Integration– Aircraft System Integration (See Figure 61), Environmental and Economical (See Figure 62) and Regulation (See Figure 63).

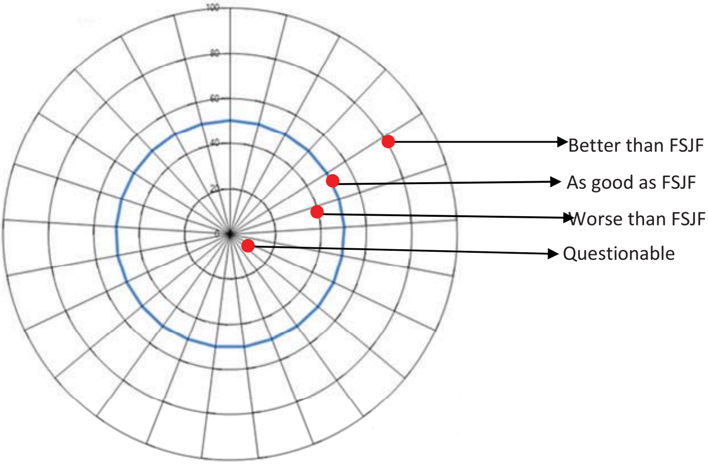

Figure 58: Instructions to read the radar chart from the MCDM tool

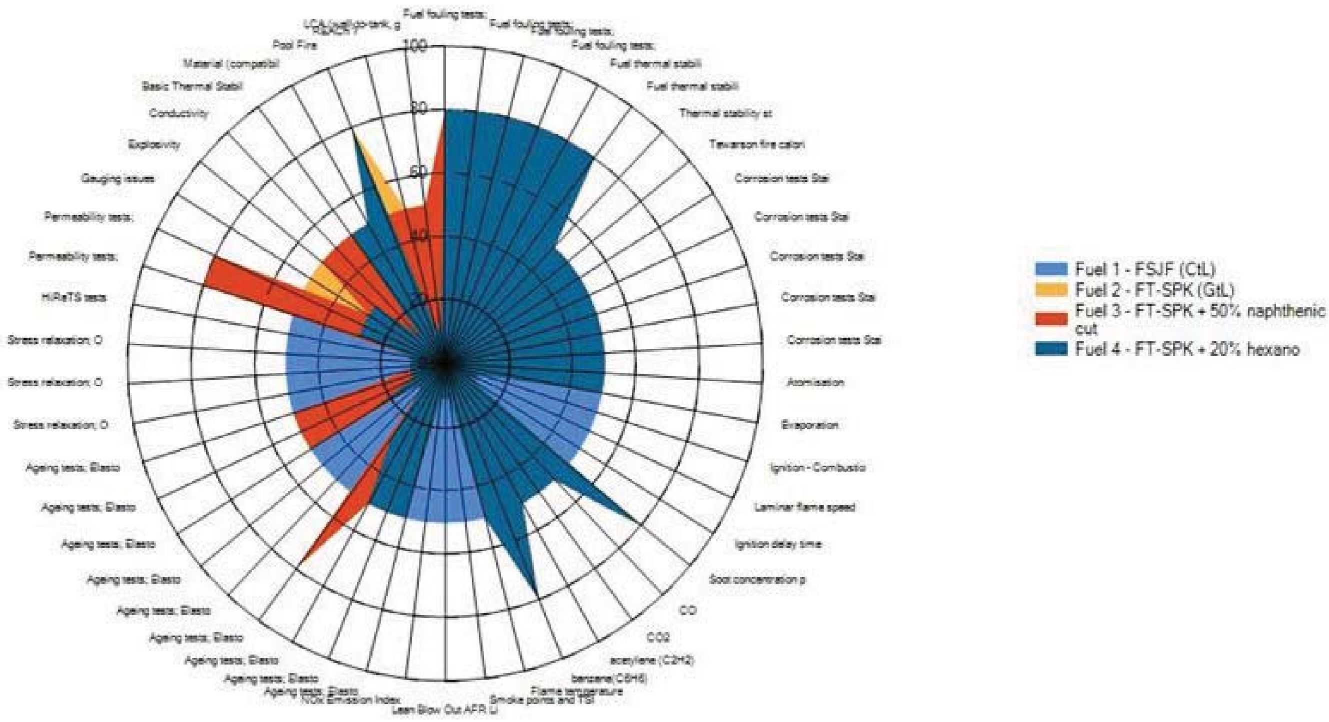

Figure 59: Application of the MCDM analysis with all criteria

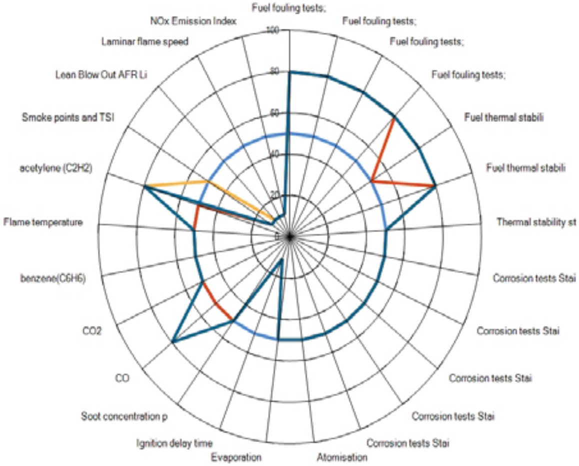

Figure 60: Fuel Chemistry-Fuel Production - Combustion

🟦 Fuel 1 - FSJF (CtL)
🟨 Fuel 2 - FT-SPK (GtL)
🟥 Fuel 3 - FT-SPK + 50% naphthenic cut
🟦 Fuel 4 - FT-SPK + 20% hexano

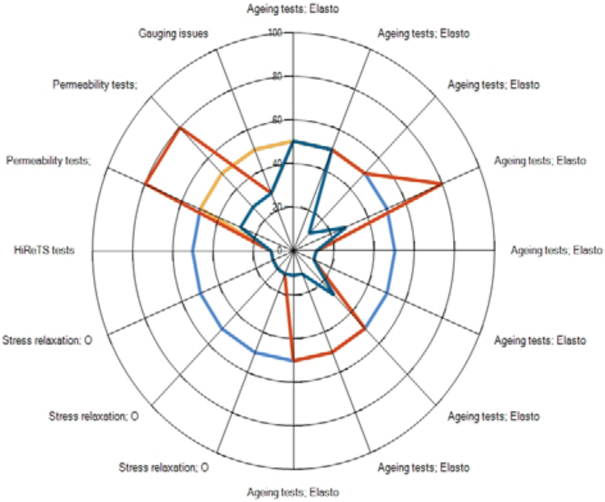

Figure 61: Engine System Integration – Aircraft System Integration

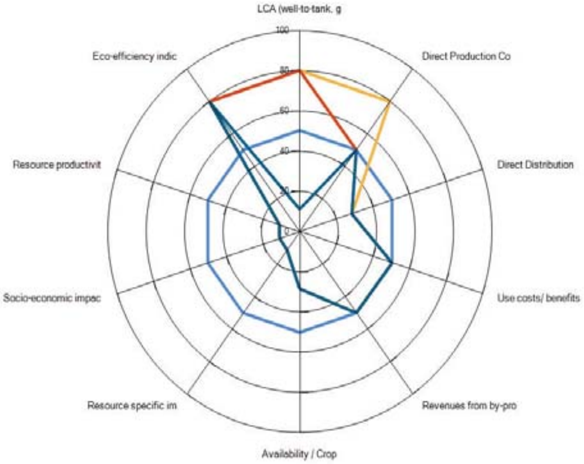

Figure 62: Environmental and Economical

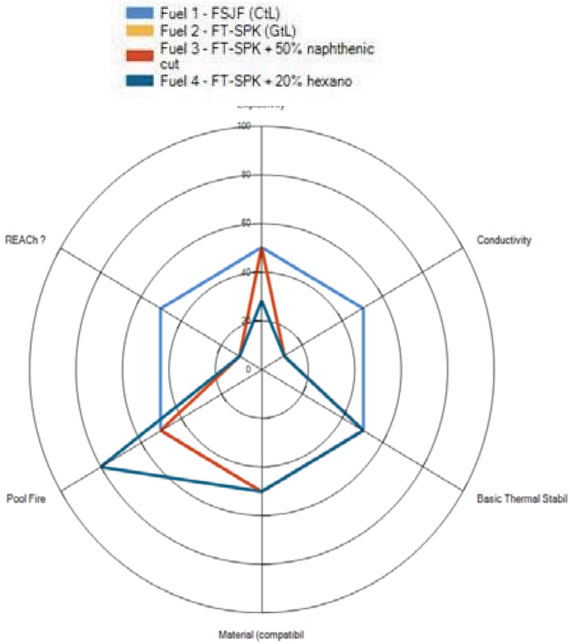

Figure 63: Regulation

Table 14: Fuel ranking matrix

Reference Fuel: Fully Synthetic Jet Fuel (FSJF) **Fuel 1**	
★★★	better than FSJF
★★	as good as FSJF
★	worse than FSJF
?	Questionable

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
Technical and Technological						
Fuels Chemistry, fuels characterization	**1.2**	**IFPEN**				
Standard characterization	**1.2.1**	**Shell, Sasol, IFPEN**				
Fuel fouling tests; Iron	1.2.1	IFPEN	★★★	★★★	★★★	TGA equipment Same effect for all materials and all temperatures Fouling tendency: FT-SPK=Ft-SPK+hexanol<FT-SPK+NC<FSJF At low temperature, only deposit phenomenon, no degradation of metal Cokink effect on iron at high temperature
Fuel fouling tests; Nickel	1.2.1	IFPEN	★★★	★★★	★★★	
Fuel fouling tests; Chromium	1.2.1	IFPEN	★★★	★★★	★★★	

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
Fuel fouling tests; Haynes 75 (Ni 77% - Cr 20% - Fe 3%)	1.2.1	IFPEN	★★★	★★★	★★★	
Detailed chemical analysis	**1.2.2**	**IFPEN, DLR-VT**				
Fuel thermal stability and oxidation tendency	1.2.2	IFPEN, ONERA	★★	★★	★	Use of Pressurized Differential Scanning (PDS) Test to determine the thermal stability instead of JFTOT "A fuel that oxidizes slowly is likely to form more deposits than a fuel that oxidizes rapidly" Stability behavior seems to be linked to aromatic content Hexanol acts like an antioxidant when blended with GtL but shows the formation of mode deposits
Fuel thermal stability	1.2.2	ONERA	★★★	★★★	★★★	To measure the "oxidation tendency" Constant supply of O2 --> amplification of the oxidation phenomenon Solids formed with the CtL and the blend GtL/naphthenic cut due to the cycloalkanes and aromatics molecules The increase of temperature leads to an increase of the quantity of solid products Thermal stability: GtL+Hexanol> GtL> GtL/NC > CtL= Jet A-1
Fuel coking tendency	1.2.2					
<u>Fuel production,</u>	**<u>1.3</u>**	**<u>INERIS</u>**				

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
storage and distribution						
Thermal stability studies related to ageing	1.3.1	ONERA	★★	★★	★★	ASTM D4625 procedure The tested fuels seem to be perfectly stable under long-term storage conditions (4 years simulated)
Tewarson fire calorimetry tests	1.3.1	IFPEN, Technologica				
Corrosion tests Stainless; Steel 304L	1.3.1.3	IFPEN	★★	★★	★★	Temperature: 23°C and 120°C Duration: 1 month No variation of weight observed for all alt. Fuels and all temperature No degradation observed on surfaces --> No corrosive effect of alternative fuels on selected metallurgies ASTM D….
Corrosion tests Stainless; Inconel 625	1.3.1.3	IFPEN	★★	★★	★★	
Corrosion tests Stainless;Aluminuim Al2024-T3	1.3.1.3	IFPEN	★★	★★	★★	
Corrosion tests Stainless; Alloy Cu/Ni 90/10	1.3.1.3	IFPEN	★★	★★	★★	
Corrosion tests	1.3.1.3	IFPEN	★★	★★	★★	

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
Stainless; Hastelloy						
Injection and Combustion	**2.1**	**ONERA**				
Atomization – Evaporation	**2.1.1**	**ONERA, TU Graz**				Use of a preindustrial injection system (LACOM test rig) Operating conditions close to reality
Atomization	2.1.1	ONERA	★★	★★	★★	Same behavior for each operating condition in terms of injection and atomization characteristics
Evaporation	2.1.1	TU Graz	★★	★★	★★	Same behavior for each operating condition in terms of injection and atomization characteristics
Ignition – Combustion	**2.1.2**	**DLR-VT**				
Laminar flame speed	2.1.2.1	DLR-VT	**?**	**?**	**?**	Experiments at Tpre=473K, p=970mbar (ambient pressure), eq. Ratio varying
Ignition delay time	2.1.2.1	DLR-VT	★★	★★	★★	Stoichiometric conditions, 16 bar pre-ignition pressure All the same within the parameter range choosen for the test (ignition delay time) / all the same than JetA1 (yellow code?)
Soot concentration profiles	2.1.2.3	University of Toronto		★★	★★	Benzene and acetylene have to be checked for soot emissions (WS - 5 and 6 October) Soot concentration trends with benzene concentration In the order of decreasing sooting tendency: Jet-A1> FSJF> SPK+NC> SPK> SPK+Hexanol
CO	2.1.2.3	University of Toronto	★★	★★	★★	Similar CO and CO2 concentrations on the centerline
CO2	2.1.2.3	Universi	★★	★★	★★	Similar CO and CO2 concentrations on the

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
		ty of Toronto				centerline
acetylene (C2H2)	2.1.2.3	University of Toronto				Higher concentrations of light hydrocarbons in SPK and SPK+hexanol flames
benzene(C6H6)	2.1.2.3	University of Toronto		★★	★★★	Similar C6H6 concentrations in FSJF and SPK+NC C6H6 concentrations too low in SPK and SPK+hexanol flames
Flame temperature	2.1.2.3	University of Toronto	★★	**?**	**?**	Similar maximum temperature as a function of z
Smoke points and TSI	2.1.2.3	University of Toronto	**?**	**?**	**?**	Smoke point by ASTM D132 TSI = Threshold Sooting Index
<u>Towards Real Conditions</u>	**2.1.3**	**ONERA**				
Altitude Relight (Mercato)	2.1.3.1	ONERA				
Lean Blow Out AFR Limit	2.1.3.2	KIT	**?**	**?**	**?**	Ultra Low Nox burner provided by AVIO LBO limits were observed to be higher for all alt. Fuels tested
NOx Emission Index	2.1.3.2	KIT	**?**	**?**	**?**	EI Nox are higher than JetA1 / Which color do you want to attribute? Alternative fuels have comparatively higher emissions than standard kerosene
Lean Blow Out AFR Limit (high pressure)	2.1.3.5	KIT				
NOx Emission	2.1.3.5	KIT				

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
Index (high pressure)						
Engine System Integration	**2.2**	**USFD**				
Performance elastomers/ non-metallic materials	**2.2.2**	**IFPEN**				
Ageing tests; Elastomer: Fluocarbon FKM; property: hardness	2.2.2	IFPEN	★★	★★	★★	No thermal effect Very slight or no effect with all the alternative fuels
Ageing tests; Elastomer: Fluocarbon FKM; property: tensile	2.2.2	IFPEN	★★	★★	★★	No thermal effect Very slight or no effect with all the alternative fuels
Ageing tests; Elastomer: Fluocarbon FKM; property: swelling	2.2.2	IFPEN	★★	★★	**?**	No big differences for CtL, GtL and GtL+nap; More sensitivity to presence of alcohol
Ageing tests; Elastomer: Nitrile NBR; property: hardness	2.2.2	IFPEN	**?**	**?**	**?**	Strong thermal effect Increase of hardness
Ageing tests; Elastomer:	2.2.2	IFPEN	**?**	**?**	**?**	Strong thermal effect

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
Nitrile NBR; property: tensile						
Ageing tests; Elastomer: Nitrile NBR; property: swelling	2.2.2	IFPEN	**?**	**?**	**?**	Fuel sorption depends on the aromatic contents expect with alcohol
Ageing tests; Elastomer: fluorosilicone FVMQ; property: hardness	2.2.2	IFPEN	★★	★★	**?**	No thermal effect Very slight or no effect with CtL, GtL and GtL+nap Strong effect and embritlement with hexanol
Ageing tests; Elastomer: fluorosilicone FVMQ; property: tensile	2.2.2	IFPEN	★★	★★	**?**	No thermal effect Very slight or no effect with CtL, GtL and GtL+nap Strong effect and embritlement with hexanol
Ageing tests; Elastomer: fluorosilicone FVMQ; property: swelling	2.2.2	IFPEN	★★	★★	**?**	No big differences for CtL, GtL and GtL+nap; More sensitivity to presence of alcohol
Stress relaxation; O-rings: nitrile	2.2.2	USFD	**?**	**?**	**?**	Old standard Nitrile O-rings are easily affected by the fuel's composition, especially the aromatic content
Stress relaxation; O-rings: fluorocarbon	2.2.2	USFD	**?**	**?**	**?**	Current standard Best compatibility for fluorocarbon O-rings

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
Stress relaxation; O-rings: fluorosilicone	2.2.2	USFD	**?**	**?**	**?**	
Performance of the alloys in the fuel system	**2.2.3**	**ONERA**				
Fuel-metal reactions	2.2.3	ONERA				
Alloys performance in the hot end of the engine	**2.2.4**	**USFD**				
carousel test rig	2.2.4	USFD				
Single Crystal, Nickel based alloy (CMSx-4)	2.2.4	USFD	delayed	delayed	delayed	
Equi-axial crystal structure (IN713LC)	2.2.4	USFD	delayed	delayed	delayed	
Typical coating (Platinum Aluminide)	2.2.4	USFD	delayed	delayed	delayed	
Evaluation of the fuel thermal stability (AFTSTU)	**2.2.5**	**USFD**				

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
HiReTS tests	2.2.5	USFD	**?**	**?**	**?**	HiReTS testing give an indication of how the AFTSTU test would perform
Validation of the use of AF in engine control systems	**2.2.6**	**Airbus F**				
Aircraft System Integration	**2.3**	**AUK**				
Test on selected fuels	2,3.2	AUK				
Permeability tests; Elastomer: NBR	2.3.2.2	IFPEN	★★	★★	★	Pe NBR> Pe FVMQ>> Pe FKM Slight differences between FSJF, FT-SPK, and FT-SPK+50% nap; Huge increase with FT-SPK+20% hexanol
Permeability tests; Elastomer: NBR	2.3.2.2	IFPEN	★★	★★	★	Pe NBR> Pe FVMQ>> Pe FKM Slight differences between FSJF, FT-SPK, and FT-SPK+50% nap; Huge increase with FT-SPK+20% hexanol
Permeability tests; Elastomer: FVMQ	2.3.2.2	IFPEN	★★	★★	★	Pe NBR> Pe FVMQ>> Pe FKM Slight differences between FSJF, FT-SPK, and FT-SPK+50% nap; Huge increase with FT-SPK+20% hexanol
Elastomer seals	2.3.2.2	AUK, IFPEN, DASSAV				
Composite materials and composite repair systems	2.3.2.2	AUK, IFPEN, DASSAV				

Ranking criteria	Task number	Partner	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
Microbiological effects	2.3.2.2	AUK, IFPEN, DASSAV				
Gauging issues	2.3.2.2	DASSAV	★★	★	★	Principle is capacitive gauging Capacitive gauging is limited in accuracy to measure fuel density For alt. Fuels: tolerance: 3% error in $\delta\rho/\rho$ For this test: GtL:$\delta\rho/\rho<1\%$ --> Drop-in; For CtL: $\delta\rho/\rho\sim3\%$--> Drop-in with a warning GtL+NC and GtL+hexanol --> Not drop-in
			Regulation			
Safety, standards, regulations	**2.4**	**INERIS**				
Explosivity	Explosivity	INERIS	★★	★★	★	
Conductivity	Conductivity	INERIS	**?**	**?**	**?**	
Storage Stability (operational viewpoint)	Basic Thermal Stability (operational viewpoint)	INERIS	★★	★★	★★	
Material (compatibility and corrosivity)	Material (compatibility and corrosivity)	INERIS	★★	★★	★★	
Pool Fire	Pool Fire		★★★	★★	★★★	
REACH?	REACH?		?	?	?	

Ranking criteria	**Task number**	**Partner**	**Fuel 2 FT-SPK (GtL)**	**Fuel 3 FT-SPK _ +50% naphthenic cut**	**Fuel 4 FT-SPK_+20% hexanol**	**Comments from support documents**
			Environmental			
Environmental balance	**3.1**	**DLR-AT**				
Impact evaluation(tank-to-wake)	3.1.2	DLR-AT	**?**	**?**	**?**	
NOx emissions	3.1.2	DLR-AT	**?**	**?**	**?**	
CO2 emissions	3.1.2	DLR-AT	**?**	**?**	**?**	
Particles/ Soot emissions	3.1.2	DLR-AT	**?**	**?**	**?**	
Potential consequences on the environment	3.1.3	Airbus F	**?**	**?**	**?**	
LCA (well-to-tank, greenhouse gas emission)	3.1.4	IFPEN	★★★	★★★	-	
Availability			**?**	**?**	**?**	
LUC (Land Use Change)			**?**	**?**	**?**	
iLUC (indirect Land Use Change)			**?**	**?**	**?**	
			Economical			
Economical balance	**3.2**	**EU-VRi**				We need to establish a timeframe for this

Ranking criteria	Task number	Partne r	Fuel 2 FT-SPK (GtL)	Fuel 3 FT-SPK _ +50% naphthenic cut	Fuel 4 FT-SPK_+20% hexanol	Comments from support documents
Direct Production Costs	3.2	EU-VRi	★★★	★★	★★	CTL more expensive than crude oil refining; GTL less expensive than CTL (CTL likely has more process steps); BTL more expensive than CTL (new technology, raw material costs); HEFA more expensive than CTL (raw materials, efficiencies); Jet A1 still cheapest
Direct Distribution Costs	3.2	EU-VRi	★	★	★	CTL, GTL, Jet A1, HEFA (all likely have similar distribution costs - tankers, pipelines), BTL more expensive - must transport less dense materials and has more complicated and distributed logistics.
Use costs/ benefits	3.2	EU-VRi	★★	★★	★★	price of biofuels higher than CTL
Revenues from by-products	3.2	EU-VRi	★★	★★	★★	All xTL processes will likely have electricity as a by-product. How to define product fuels other than aviation? (xTL produces a range of molecules), HEFA and FAE will have animal feed/starches as a by-product
Availability / Crop Prices and Costs	3.2	EU-VRi	★	★	★	Of the biofuels, only FAE is "available" - the others will not be available in large quantities within the next decade. Availability of feedstock is also a serious concern (iLUC, etc.)
Resource specific impact indicator	3.2	EU-VRi	**?**	**?**	**?**	What does this indicator measure?
Socio-economic impacts	3.2	EU-VRi	**?**	**?**	**?**	HEFA & FAE: food vs fuel debate; all biofuels: opportunities for developing economies; question of sustainable agriculture, iLUC; crude oil, coal and gas reserves not uniformly distributed globally;

Ranking criteria	**Task number**	**Partner**	**Fuel 2 FT-SPK (GtL)**	**Fuel 3 FT-SPK _ +50% naphthenic cut**	**Fuel 4 FT-SPK_+20% hexanol**	**Comments from support documents**
Resource productivity indicator	3.2	EU-VRi	**?**	**?**	**?**	Biofuels: renewable resource; Coal/gas/oil: non-renewable; BTL makes highest use of biomass feedstock directly for fuel;
Eco-efficiency indicator	3.2	EU-VRi	★★★	★★★	★★★	BTL has best impact on emissions, CTL has worst; GTL likely better than CTL (lower initial carbon ratio); HEFA and FAE will struggle to bring meaningful carbon emission reductions in the long-term

9 Conclusion

9.1 Conclusions from Life Cycle Assessment

- Concerning the results developed here and the comparison with different studies fuels from fossil feed stocks like GtL and CtL do not show reduction of GHG emissions compared with current fossil fuels.
- Carbon Capture Sequestration in GtL and CtL technologies has also been analyzed, but this option does not show reduction in GHG emission compared with Jet A1.
- BtL has also been analyzed in this report; however it followed the assumption of the Renewable Energy Directive of being carbon neutral. Under this assumption BtL can lead to the reductions of GHG emissions.
- In order to assess the results in other impact categories Ecoindicator method was applied, and despite BtL having less impact for climate change, it shows high impact for acidification, land use, ecotoxicity, and minerals.
- Comparison of different LCA studies available was made within this report, and showed that: BtL and HRJ/HEFA have the potential to reduce GHG emissions due to the "biomass credit" that is generally equal to the CO_2 emissions from combustion. However, the life cycle GHG emissions for biofuels can be much higher than those from fossil feedstock depending on the details of how the fuel is produced. The conversion of land represents important potential of source of emissions for biofuels and should be evaluated in detail and carefully in order to guarantee the potential "green energy" of biofuels.
- The evaluation of land use change (LUC) is the key issue for biofuels development, because the main potential harm is increased due to LUC. LUC could lead to competition for food production, loss of forest and the release of large amounts of carbon from soils and vegetation. In the other way around, biofuels can also increase the carbon stock of very degraded areas (e.g. HRJ: Salicornia) to a very positive environmental and social impact.

9.2 Conclusions from Fuel Substitution Model

- GtL technologies can achieve cost-competitiveness with conventional fuel upon market availability, irrespective of the use of CCS technology.
- BtL technologies still require a considerable ramping up of production facilities until scale effects make them cost-competitive.
- CtL technologies may offer the same cost-benefit profile than GtL fuels, under the necessary condition that emissions are controlled for using CCS technology. In case of more volatile energy availability, they may offer an option for portfolio diversification.
- BtL technologies are only sustainable if neither their agricultural feedstock, nor the required land is in competition with food supply.
- There is already public awareness on the issue of sequestration and storage of carbon dioxide, albeit low to medium knowledge of involved risks and benefits. Increased adoption of CCS technologies would pose an ongoing challenge in risk communication.
- Monetary instruments targeting GHG emissions can influence the point when BtL fuels reach price parity with conventional fuels.
- GHG emission depending costs may foster the market penetration of second generation biofuels and prevent a technological lock-in of less sustainable technologies. Timing is essential for this. The earlier, the better.

9.3 Conclusions from Decoupling Indicators Analysis

- There is an indirect land use change effect on carbon emissions in the up-scaling phase of BtL production capacities. This effect is compensated by the substitution of other fuels.
- Carbon payback times for carbon emissions due to land use change effects for second generation biofuels are of the order of a couple of years.
- Even with the use of CCS at GtL plants, they do not offer a route to reduce GHG emissions, but only to retain the current levels.
- Scenarios with high incentives to reduce carbon emissions have the highest eco-efficiency on the mid- to long-term forecasts. Scenarios with low incentives to do so have the lowest eco-efficiency.

9.4 General conclusions and outlook

The work performed shows clearly that the SEA, including LCA and decoupling indicators is

- complex
- dependent on many inputs parameters and assumptions (some of them extremely difficult to reliably assess)
- very sensitive to the uncertainties in the above parameters, especially for long term analysis (say up to 2050).

On the other hand the models developed, used and presented in the work show that the transparent what-if analysis is possible.

9.5 (Some) End-user’s comments

(April 16, 2012)

The EU-VRI Alfa-Bird team presented its economic model for aviation biofuel implementation to IATA on 3 April 2012. This model is flexible enough to include modules describing the behavior of relevant stakeholders. The team has the skills needed to create realistic models of relevant human behavior. The model development is still in progress and would need the inclusion of further modules, mainly for the description of other production pathways as well as different variants of incentivizing policy instruments. Also the inclusion of exogenous factors such as the influence of other industry sectors competing for resources would be needed. The current stage of development appears appropriate for a decision on such model enhancements, and IATA is happy to support this process further and also to provide relevant data and information.

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Aviation Environment – Technology

International Air Transport Association IATA

9.6 Possible Economic Model Extensions

a. Adjustment of learning curve:
    i. How to speed things up?
    ii. how do our values compare to other sources
    iii. scale-dependant vs. scale independent contributions
    iv. policy implications
b. Implementation of exogenous factors
    i. Competition with automotive sector
    ii. Competition with food
    iii. Policy instruments (subsidies, taxes) targeting CAPEx & OPEx
    iv. Pricing in of biofuel as diversification strategy
c. Opportunity radar?
d. Other production pathways
    i. HRJ/HEFA
    ii. Alc 2 jet

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Annex 1 Comments in D3.2.2: Economic Evaluation

N°	IFP Comments	Replies from EU-VRi
	Input data main sources	
1	The D3.2.2 deliverable does not take advantage nor even mentions the IFPEN report about xTL production costs, although the IFPEN report has been ordered by Alfa Bird and as such is one Alfa Bird official source of information, and has been validated by the Alfa Bird partners, among which Shell and Sasol companies having a unique experience in xTL technologies.	So far, the IFP report pertaining to xTL production costs has not been taken into account. However, the updated version of the deliverable 3.2.2 will considered the main highlighted aspects of this report and also the development of a new scenario.
2	The D3.2.2 deliverable is based on prior studies from open literature, some of them quite old now: A DOE report dated 2001 for ICL and GTL, and the RENEW project for BTL. Without any justification, BTL computed performances are based on a very specific process configuration (massive introduction of electrolytic hydrogen onto the process, i.e. a massive electricity import of 500 MW). Please note that due to the lack of economic performances, this configuration has been rejected for most BTL demo plants. It is also radically different from the GTL and ICL selected configuration, which creates sort of a distortion between the different substitutions pathways studied in the report and impacts the final picture. In the same way, we noticed that the DCL pathway (also referred as "naphthenic pathway" in some of the Alfa Bird documents) has not been studied	Life Cycle Inventories were based on the mentioned references due to the lack of available information in the literature. Various data were requested to ALFA-BIRD partners related to Life Cycle Assessment. Unfortunately, partners could only provide rather general data. For the BtL pathway, data were gathered from the scenario developed within the RENEW project entitled “*Starting point calculation*”. This scenario, based on the world´s first commercial BtL Plant under construction, i.e. the Choren Carbo-V Process, dealt with the possible production pathways in the near future and considers for instance that the transformation of biomass into biofuel is a self-sufficient process, which requires no direct external electricity. Data of this scenario are provided in this version.
3	In table 6, coal inlet should be expressed in tons and not in Mscf as reported. Please also take note a lack of consistency between CO_2 emissions reported (0,12 tons), the overall carbon efficiency (40%) and coal inlet (0,37 tons) or liquid effluent (0,13 tons).	Corrected in the current version..
	Information disclosed in the D3.2.2. report	
	The economic evaluation D3.2.2 relies on a conventional calculation for jet substitutes production cost as well as the monetization of all side effects (human health, environment,..). Study results are therefore a translation of these input data and cannot be	

understood without a list of them. We therefore would expect to find the following in this report :

5	ICL, BTL and GTL 2011 investment costs per barrel (or per ton) of liquid product,	As already cited in the report, we use investment costs figures provided in the deWit et al. (2008), Boerrigter (2006) and Havlik (2011) references. We will also develop a scenario using IFP numbers (see below). We will act on these comments by introducing a table in the report which comprehensively lists each data input and its source(s) in the next version of the document.
6	Electricity (either by product or imported) market price, and the grid mix considered (coal, wind, nuclear, gas, ...)	
7	A table summarizing the different side effects in terms of intensity (per barrel or per ton) and costs	

Main results

Jet fuel substitution rate at 2030

The final number (figure 36) shows an optimum jet fuel substitution rate of 40% , most of it from BTL (35% of the total market). This rate is far higher than in the AIE scenario, and would require a comparative analysis.

Regardless the impact of the missing information as described in part 2, we understand this result is the cumulated consequence of a series hypothesis systematically optimistic:

8	constant jet fuel price increase of 2% a year over the 2011-2030 period, starting from year 2011 (90€/barrel),	This is an extrapolation from historic data on the long-term price trend (over the last forty years) and was agreed upon together with IATA. We also acknowledge that oil price developments are notoriously hard to model, hence our development of a web tool allowing the user to specify individual scenarios.
9	dramatic jet substitutes production cost reduction (2% a year over the same period). Which production cost was considered at the starting point?	In general, our answer to points 5-7 applies here too. We assume this comment addresses the progress ratio for the scale-independent technological learning component, which is only one of several effects with impact on the production costs. Again, this number is taken from the literature. We plan to accumulate further empirical data in order to verify these literature values.
10	GTL energy yield (fig 48) jumping from a good enough value of 60% in 2011 to an incredible 90% in 2030. Is there any technical background for this 90% yield?	Thank you for pointing this out, we will check the figures which went into this projection.
11	Same question for ICL and BTL performances	Please, see our response to points 5-7 and 9.

Various xTL ranking and biomass availability concern

The D3.2.2 deliverable conclusions ranks BTL (35%) in first position far higher than GTL and ICL, which is quite a different picture to the AIE, and to already announced industrial projects. One tentative explanation can be :

12	BTL resource productivity (GJ biofuel per m² of land cultivated for biofuels) overestimated with a 87% increase between 2011 and 2030, which also looks quite optimistic (which background?),	Please note that the 35% biofuel share is only the result of specific scenarios. We also report scenarios, where there is no break-even point in terms of price of BtL fuels (w.r.t. Jet A1 and GtL). We will also incorporate a scenario with the IFP assumptions in the next iteration of the manuscript and provide a more detailed explanation on the main dependences on and drivers of the time of this break-even point.
13	And the lack of land competitive use assessment for : ○ Food production, ○ Production of other grades of biofuels (gasoline and diesel) ○ Electricity from biomass, ○ Biomass to Chemicals, ○ Domestic heating (collective, individual, ...).	Our report does not lack these assessments. Please note that the POLES scenario for land use developments until 2030, described in Havlik et at. (2011) and cited at several points in the report, serves as an input for our model and assesses these issues in a comprehensive way. More concretely, we incorporate their second generation biofuel availability scenario, using the constraint that land can only be devoted to feedstock production if there is no competition with food supply. This is estimated from a large-scale global simulation model called GLOBIOM, for the details please refer to Havlik et al. (2011). We will try to make this point more visible in the next version of the report, to avoid such confusions in the future.

Annex 2 Alternative Fuels Substitution Model: Data and Methods

In this section we provide more comprehensive details on the inner mechanisms of the Alternative Fuel Substitution Model. First, we will discuss the implemented cost and demand projection methods. Secondly, an overview over the main data inputs and their sources is given.

The Lotka-Volterra competition equations are a paradigmatic modeling approach for changing and developing systems where different species or technologies compete over a finite set of resources or market shares [25], [35], [36]. Within this framework both emerging and declining competitors can be represented. For the case of alternative fuel substitution Jet A1 is currently the dominant competitor with alternative fuels as “invading” technologies. The Lotka-Volterra competition equations are a set of coupled first-order differential equations which can be numerically solved for.

Investment and market factor are the qualitative basis and motivation for this quantitative model for the substitution of fossil by alternative fuels. The model combines features of market diffusion and competition dynamics, technological learning, experience curves and scenario modeling.

It is assumed that in the absence of competitors a technology’s market share grows logistic. For small starting values market shares grow exponential (or vanish otherwise). As the market penetration and diffusion increases, the growth decelerates and eventually hits an upper bound given by either the market size or the technology’s production capacity, whichever limit is hit first. Lotka-Volterra dynamical systems introduce competition to this process. The upper growth limit depends here also on the market shares of the competitors in a dynamical fashion.

We will now introduce the Lotka-Volterra competition equations in full generality. Let $X_i(t)$ be the relative market share of technology $i = 1, \dots, N$ with $\sum_i X_i(t) = 1$. Denote the growth rate of the market by R and the production capacity of technology i by K_i. The competition between two technologies i and j is introduced via the competition parameter $0 \leq c_{ij} \leq 1$. In general the Lotka-Volterra model is then given by

$$\frac{d\boldsymbol{X}_i(\boldsymbol{t})}{d\boldsymbol{t}} = \boldsymbol{R}\boldsymbol{X}_i(\boldsymbol{t}) \left[\mathbf{1} - \frac{\mathbf{1}}{\boldsymbol{K}_i} \left(\boldsymbol{X}_i + \sum_{j \neq i} \boldsymbol{c}_{ij} \boldsymbol{X}_j(\boldsymbol{t}) \right) \right] \tag{4}$$

In the present example there will be three competing technologies ($N = 3$), Jet A1 ($i = 1$), GtL ($i = 2$) and BtL ($i = 3$). The initial conditions of the market shares are determined by current market shares, that is Jet A1 dominates the market with a relative market share of $X_1(t = 0) \cong 1$, other market shares are initialized close to zero. The growth rate R is taken from the result of Alfa-Bird task T1.1.2, the long-term forecast of jet fuel demand. We work with the “Business as usual” scenario, i.e. GDP growth rate forecasts following IMF predictions and heterogeneous energy gains. For Europe, this amounts to an annual market growth of 2.2%. Note that the results to be reported are robust to different choices of jet fuel market demand scenarios developed in T1.1.2, The competition parameter c_{ij} depends on the price difference between i and j. It can be interpreted at the probability that a unit of i is replaced by a unit of j (if available). Let p_i be the price of technology i. A reasonable assumption is that $c_{ij} = 1$ iff $p_i > p_j$ and $c_{ij} = 0$ otherwise. That is, consumers seek to buy the cheapest available fuel on the market. Note that the model assumes that complete market information is captured in the price, e.g. environmental incentives are “priced-in” via the carbon tax or additional costs for the CCS mechanism. Land use considerations are priced-in by using the POLES energy scenario as input for the up-scaling of biofuel technologies.

Our case presents the additional property that the model production capacities K_i for GtL and BtL are not static over time but itself dynamical variables, as is the price. So for each model year prices and production capacities are adjusted with the technological learning procedure described above.

The total GtL and BtL production capacities are not only given by the scale of the plants, but also on how many of them are installed. So $K_i(t)$ is a product of the plant scale $Scale_i(t)$, the number of installed plants and a parameter quantifying which fraction of the plant's output is used for aviation fuel (assumed to be 25% here).

Price dynamics for BtL fuel follow the specification outlined above. We denote the scale-independent progress ratio by $\boldsymbol{PR}$, CAPEX and OPEX by $p_{i,CAPEX}(t)$ and $p_{i,OPEX}(t)$. The raw material price is $p_{i,raw}(t)$. Putting everything together, the price $p_i(t)$ for fuel $i = 3$ develops as

$$\boldsymbol{p_i(t) = PR\left[\left(\frac{Scale_{II}}{Scale_I}\right)^{\alpha-1}\left(p_{i,CAPEX}(t-1)\right) + p_{i,OPEX}(t-1) + p_{i,raw}(t)\right]} \tag{5}$$

A.2.1 Description of the web tool

The model was developed as an ASP.NET 4.0 WebSite. A screenshot of the model's user interface is shown in Figure 64. The user can specify target capacities for market shares of both GtL and BtL fuels. It is also possible to study CtL as alternative fossil option instead of GtL. The number of plants required to reach the targeted market shares is then computed and used to compute the development of production capacities. An additional user input is a carbon tax, i.e. a monetary penalty on CO_2 emissions. This costs are calculated for the three model fuels and added to the price $p_i(t)$. The tool also allows to study a scenario with intensified research activities, resulting in a decrease in doubling time in 20% for the BtL production ramp-up. Oil price scenarios are also selected by the user by specifying mean annual change rates over five year intervals. The model projects over the next twenty years. The model calculates the dynamics of Jet A1, GtL and BtL market shares according to the described model. From these dynamics the S-curve is measured (see top right of Figure 64). From the market shares at each year the development of GHG emissions are displayed too. The WebSite allows comparing two runs with different settings (i.e. the "current" run to a "baseline" scenario), each run is stored in a history, from which it can be retrieved, updated or deleted. The history itself can be stored and loaded locally. Detailed information on the price and capacity development projection is displayed as a data table and can be downloaded in standard formats for post-processing. The model is accessible under http://apps.eu-vri.eu/apps/SCurve/.

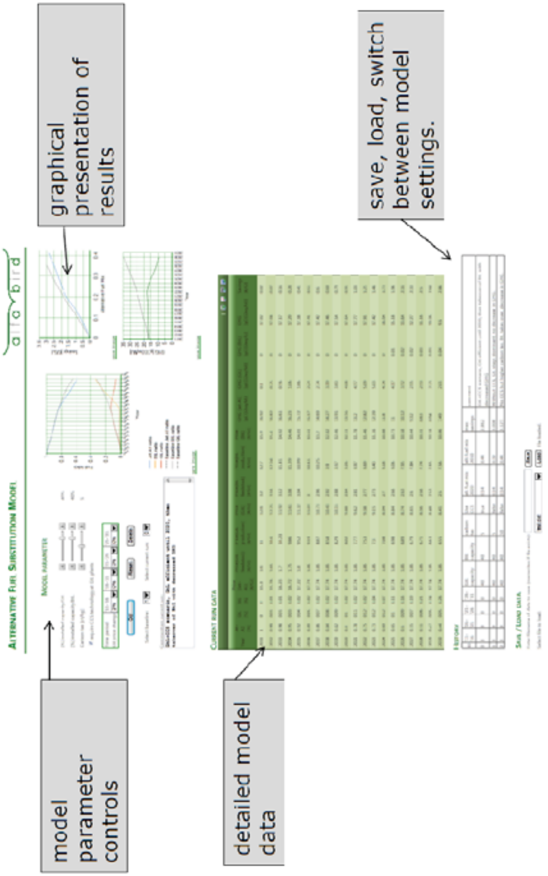

Figure 64: Screenshot of the model’s user interface

A.2.2 Data

This table lists the main required inputs for the Alternative Fuel Substitution Model, their values and the source for this value. If a value is not listed here,

Table 15: List of main inputs for the Alternative Fuel Substitution Model. We show the variable, its value in the model and the reference for the adopted value.

Variable	Value	Source
Jet A1 Price	107 €/barrel	IATA Fuel Price Monitor
GtL Raw Material Price	6.4 €/GJ	[24]
GtL CAPEX with CCS	4.7 €/GJ	[24]

Variable	Value	Source
GtL CAPEX without CCS	3.8 €/GJ	[24]
GtL OPEX with CCS	3.0 €/GJ	[24]
GtL OPEX without CCS	2.6 €/GJ	[24]
CtL Raw Material Price	2.7 €/GJ	[24]
CtL CAPEX with CCS	7.8 €/GJ	[24]
CtL CAPEX without CCS	6.8 €/GJ	[24]
CtL OPEX with CCS	4.1 €/GJ	[24]
CtL OPEX without CCS	3.7 €/GJ	[24]
BtL Raw Material Price	13.7 €/GJ	[24]
BtL CAPEX	15.2 €/GJ	[24]
BtL OPEX	7.2 €/GJ	[24]
Jet A1 emissions	84 gCO_2eq/MJ	[11]
GtL emissions with CCS	108.4 gCO_2eq/MJ	[11]
GtL emissions without CCS	122.4 gCO_2eq/MJ	[11]
CtL emissions with CCS	119.3 gCO_2eq/MJ	[11]
CtL emissions without CCS	211.2 gCO_2eq/MJ	[11]
BtL max production capacity 2030	112 Mtoe	[33]
BtL LUC max land use change emissions 2030	0.85 $MtCO_2eq$	[33]
BtL progress ratio	2%	[27]
BtL upscaling doubling time	5y	[27]
GtL progress ratio	1%	[27]
CtL progress ratio	1%	[27]
Jet fuel market growth rate	2.2%	ALFA-BIRD D1.1.2
BtL learning scale factor	0.7	[27]

Annex 3 Acronyms

- *BAU:* Business as usual
- *BtL:* Biomass to Liquid
- *CCS:* Carbon Capture Sequestration
- *Cef-D8:* Centralized Entrained Flow Gasification
- *CSR:* Coporate Social Responsibility
- *CtL:* Coal to Liquid
- *DALY:* Disability Adjusted Life Years
- *DS:* dry substance
- *ETS:* Emission Trading System
- *FAO:* Food Price Index
- *FSJF:* Fully Synthetic Jet Fuel
- *FT:* Fischer-Tropsch
- *GDP:* Gross Domestic Product
- *GHG:* Greenhouse gas
- *GLOBIOM:* model of the global forest, agriculture and biomass sectors
- *GtL:* Gas to Liquid
- *iLUC:* indirect land use change
- *IPCC:* Intergovernmental Panel for Climate Change
- *JRC:* Join research center
- *LCA:* Life Cycle Assessment
- *LCC:* Life Cycle Costing
- *LCI:* Life Cycle Inventory
- *MCDM:* Multi-criteria decision making
- *PAF:* Potentially Affected Fraction
- *PDF:* Potentially Disappeared Fraction
- *POLES:* Prospective Outlook on Long-Term Energy Systems
- *SEA:* Socio – Economic Analysis
- *TtW:* Tank to Wake
- *Toe:* tons oil equivalent with 42,6 MJ/kg
- *WtT:* Well to Tank
- *WtW:* Well to Wake
- *CAPEx:* Capital Expenditures e.g. cost of investment in fixed assets (buy or upgrade the physical assets).

This document presents the summary report of the work package on socio-economic analysis in the EU project Alfa-Bird (Alternative Fuels and Biofuels for Aircraft Development, No. ACP7-GA-2008-213266). The work package has been coordinated by Steinbeis Advanced Risk Technologies (R-Tech), as member of EU-VRi (European Virtual Institute for Integrated Risk Management), in collaboration with the project partners IFPEN (IFP Energies Nouvelles), INERIS (Institut National de l'Environnement Industriel et des Risques), and AIRBUS. The overall coordination of the project was done by EU-VRi.

The work package has achieved its goals by delivering a methodology and the tool for economic and environmental impact analysis of different possible scenarios for the production and use of biofuels and other alternative fuels in aviation, involving various decisions and market development options / parameters. The time-horizon of the economic model is up to the year 2030.

Excerpts from end-user comments:

... congratulation for achieving this report ... a truly interesting read ...

(AIRBUS)

... This model is flexible enough to include modules describing the behavior of relevant stakeholders. The team has the skills needed to create realistic models of relevant human behavior.

(IATA)

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