![CORE-JetFuel logo]

Coordinating research and innovation in the field of sustainable alternative fuels for aviation

Deliverable 4.4

Report on compilation, mapping and evaluation of R&D activities in the field of conversion technologies of biogenic feedstock and biomass-independent pathways (Final report)

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Report on compilation, mapping and evaluation of R&D activities in the field of conversion technologies of biogenic feedstock and biomass-independent pathways (Final report)

Submitted Version 1.0

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SUMMARY

The present "Final Report on compilation, mapping and evaluation of R&D activities in the field of conversion technologies of biogenic feedstock and biomass-independent pathways" contains the results yielded in the CORE-JetFuel Task 4.2 "Radical Concepts and Conversion Technologies". The report is divided into two parts.

Part A is focused on the analysis of conversion technologies. In this context, the technical specifics of the technologies are explained and brief descriptions of the technologies state of development and the suitability of the respective fuels as jet fuel are given. Furthermore, a mapping of the European landscape of the individual technologies has been conducted.

The following conversion technologies have been analyzed:

- Hydroprocessing of oils and fats (Hydroprocessed Esters and Fatty Acids, HEFA fuels)
- Gasification / Fischer-Tropsch synthesis (Biomass-to-Liquids, BtL fuels)
- Hydrothermal liquefaction (HTL fuels)
- Pyrolysis (Hydroprocessed Depolymerized Cellulosic Jet, HDCJ fuels)
- Aqueous Phase Reforming (APR fuels)
- Lignin-to-Jet conversion (LtJ fuels)
- Alcohol-to-Jet conversion (AtJ fuels)
- Direct microbial conversion of sugars to hydrocarbons (Direct Sugar to Hydrocarbons (DSHC) or Synthesized Iso-Paraffinic (SIP) fuel)
- Power-to-Liquid conversion (PtL fuels)
- Solar-thermochemical fuel production (Sun-to-Liquid conversion, StL fuels)

The analyzed technologies cover a broad range of maturity levels, from industrially mature HEFA conversion over well researched concepts, such as HTL and pyrolysis, to solar-thermochemical (StL) fuel production as long-term technology option. With the exception of PtL and StL, all analyzed technologies depend on biomass feedstocks. However, no technology capable of converting lignocellulosic material has reached a level of maturity that would allow immediate industrial implementation. Consequently, the large potential of lignocellulosic feedstock remains untapped for aviation.

Part B is concerned with the holistic assessment of production pathways. A set of relevant criteria was selected, corresponding to the following key questions in the context of renewable fuels:

- How much can potentially be produced?
- What is the potential environmental impact, particularly in terms of greenhouse gas emissions?
- How much would it cost?
- Drop-in capable or not?
- What is the current state of development (maturity)?

The following production pathways have been assessed according to those key questions:

- HEFA fuel from camelina oil (HEFA / Cam)
- HEFA fuel from used cooking oil (HEFA / UCO)
- HEFA fuel from microalgae oil (HEFA / μA)
- HTL fuel from microalgae (HTL / μA)
- AtJ fuel switchgrass or short-rotation coppice as a lignocellulosic feedstock (AtJ / LC)
- HDCJ fuel from lignocellulose (HDCJ / LC)
- BtL fuel from short-rotation coppice as a lignocellulosic feedstock (BtL / LC)
- PtL fuel: FT-SPK from syngas, supplied via conversion of water and carbon dioxide extracted from air (PtL / airCO2)
- StL fuel: FT-SPK from syngas, supplied *via* solar-thermochemical conversion of water and carbon dioxide extracted from air (StL / airCO$_2$)

A holistic multiple-criteria approach and trade-off analyses were performed on the integrated production pathways listed above. The multiple criteria matrix of results shows how fuel technologies perform on different criteria. While all selected renewable fuel productions pathways present significant *specific* GHG emission reductions, their *potential impact* on global or European scale is in some cases very limited due to limited production potential globally or in Europe, respectively.

Useful trade-off relations between criteria were identified. Specifically, the relation of the specific greenhouse gas balance vs. cost of production and the relation of the potential reward in terms of greenhouse gas emissions reduction potential vs. development risk were evaluated. The evaluation yielded a wealth of valuable information, with the key findings summarized in the following.

Specific greenhouse gas balance vs. cost of production

- In the light of the given variations and uncertainties, no obvious correlation of specific GHG emissions and cost of production can be found.

- All considered options provide substantially reduced specific GHG emissions in comparison to conventional jet fuel (Jet A-1), even though the upper values within the ranges of variation and uncertainty of some options would represent only insufficient reductions.

- All considered options are considerably more costly in comparison to conventional Jet A-1. Consequently, a price gap between conventional jet fuel and renewable alternatives is likely to remain at least in the medium-term future. Appropriate regulatory and/or economic measures will be needed to provide a market environment where renewable fuels can be competitive

Greenhouse gas emissions reduction potential vs. development risk

- All pathways in the "high potential reward" range either depend on lignocellulosic feedstock or do not require input of biomass at all. This finding reflects the fact that these pathways offer high specific GHG emissions reduction AND are potentially available in large quantities. However, none of these promising options is mature enough to-date for short-term industrial implementation, and consequently certain risks of failure or major challenges are associated with their further development.

- Pathways depending on microalgal feedstock show moderate absolute GHG emissions reduction potential at global level, while remaining insignificant at European level. This is a consequence of the negligible production potential for microalgae in Europe.

- For the same reason, the potential reward in terms of GHG emissions reduction of HEFA fuels from used cooking oil (UCO) is negligibly small, at European as well as global scale: While the specific GHG balance of this fuel is excellent, the availability of UCO is very limited.

TABLE OF CONTENT

CORE-JetFuel Deliverable D4.4 / Date 28.10.2016 / Version 1.0

2.11   SOLAR-THERMOCHEMICAL FUEL PRODUCTION 43

   2.11.1 Background 43

   2.11.2 State of development 46

   2.11.3 Quality of the fuel 46

   2.11.4 Analysis and mapping of R&D landscape focused on Sun-to-Liquid 46

PART B 48

HOLISTIC ASSESSMENT 48

3   ASSESSMENT OF INTEGRATED PRODUCTION CHAINS 49

   3.1   PRODUCTION CHAINS SELECTION FOR HOLISTIC ASSESSMENT 49

   3.2   CRITERIA SELECTION 51

     3.2.1   Technical maturity 52

     3.2.2   Economic competitiveness 53

     3.2.3   European and global substitution potential 54

     3.2.4   Specific greenhouse gas emission reduction 55

     3.2.5   Potential impact on European and global GHG emission reduction 57

4   EVALUATION OF PRODUCTION PATHWAYS 58

   4.1   MULTIPLE-CRITERIA MATRIX OF RESULTS 58

   4.2   SPECIFIC GHG EMISSIONS VS. COST OF PRODUCTION 60

   4.3   RISK/REWARD ANALYSIS OF PRODUCTION PATHWAYS 62

5   CONCLUSIONS 66

REFERENCES 70

Public   VIII

LIST OF FIGURES AND TABLES

LIST OF ABBREVIATIONS

Abbreviation / acronym	Description
AFTF	Alternative Fuels Task Force
AJF	Alternative Jet Fuel
APR	Aqueous Phase Reforming
ARA	Applied Research Associates
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
AtJ	Alcohol-to-Jet
BtL	Biomass to Liquid
CAAFI	Commercial Aviation Alternative Fuel Initiative
CCE	Camelina Company España
CH	Catalytic Hydrothermolysis
CtL	Coal to Liquid
DG	Directorate General
DME	Dimethyl Ether
DOE	Department of Energy
DSHC	Direct Sugar to Hydrocarbon (now called SIP)
EC	European Commission
EPA	Environmental Protection Agency
ETS	European Trading Scheme
EU	European Union
FAA	Federal Aviation Administration
FT	Fischer-Tropsch
FT-SPK	FT Synthetic Paraffinic Kerosene
FT-SPK/A	FT-SPK containing aromatics
GHG	Greenhouse Gas
GMBM	Global Market-Based Measure
HDCJ	Hydrotreated/Hydroprocessed Depolymerized Cellulosic Jet
HEFA	Hydroprocessed Esters and Fatty Acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ITAKA	Initiative Towards sustAinable Kerosene for Aviation
LCA	Lifecycle Analysis
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturers
PM	Particulate Matter
PtL	Power-to-Liquid
R&D	Research and Development
R&I	Research and Innovation
RED	Renewable Energy Directive

RTD	Research and Technology Development
RWGS	Reverse Water-Gas Shift
SIP	Synthetic Iso-Paraffins (formerly called DSHC)
SK	Synthetic Kerosene
SKA	Synthetic Kerosene with Aromatics
SME	Small and Medium Size enterprise
SNG	Synthetic Natural Gas
SPK	Synthetic Paraffinific Kerosene
SRC	Short Rotation Coppice
SRIA	Strategic Research and Innovation Agenda
STC	Solar thermo-chemical (conversion process)
StL	Sun-to-Liquid
TRL	Technology Readiness Level
UCO	Used Cooking Oil
VO	Vegetable Oil
WP	Work Package

Objective, scope and structure of the deliverable

The main scope of CORE-JetFuel is the support of the European Commission in its dynamic and informed implementation of research and innovation projects in the field of sustainable alternative fuels for aviation. A key objective on this mission is the evaluation of the research and innovation (R&I) "landscape" in Europe and beyond in order to analyze the state of progress, to identify bottlenecks and lessons learned, and to relate the current picture of R&I activities, as well as of the technologies in the focus of these activities, to the existing long-term R&I and technology goals. Examples of such goals are stated in the ACARE Flightpath2050 and ACARE's Strategic Research and Innovation Agenda (SRIA). Other goals, less technology-centered but rather focused on the implementation and the potential impact of alternative aviation fuels, for example the frequently cited "ATAG" goals [1], also represent important references for the assessment work carried out in CORE-JetFuel. More detailed information regarding the various goals relevant for CORE-JetFuel can be found in Chapter 2 of Deliverable 2.1, "Report on the Essential Sources, Metrics, Representations and Procedures for Research and Innovation Assessment" [2].

As the topic "alternative fuels for aviation" addressed in CORE-JetFuel is very complex, four tasks, grouped in two work packages (WPs), have been defined, each focused on a specific thematic domain:

- Task 4.1 (WP4): Feedstock and sustainability
- Task 4.2 (WP4): Conversion technologies and radical concepts
- Task 5.1 (WP5): Technical compatibility, certification and deployment
- Task 5.2 (WP5): Policies, incentives and regulation

Tasks 4.1 and 4.2 reflect the focus of the superordinate WP4 on topics related to the production of alternative fuels, while Tasks 5.1 and 5.2 are concerned with utilization and implementation-related issues.

The present Final Report describes the results yielded in Task 4.2. It is important to note that Task 4.2 was not only concerned with conversion technologies, but also included the holistic

assessment of production pathways, actually representing combinations of both, conversion technologies and feedstock. Consequently, the present Final Report is divided into two parts:

Part A is focused on the analysis of conversion technologies. In this context, the technical specifics of the technologies are explained and brief descriptions of the technologies state of development and the suitability of the respective fuels as jet fuel are given. Furthermore, a mapping of the European landscape of the individual technologies has been conducted.

Part B is concerned with the holistic assessment of production pathways. A selection of relevant criteria, covering aspects of suitability, scalability and sustainability, has been applied for that purpose.

The results described in the present Final Report feed the CORE-JetFuel deliverables D6.3 (Report on Recommendations) [3] and D6.4 (Report on Roadmaps) [4].

PART A

Conversion Technologies and Radical Concepts

1   Overview of identified technologies

One of the main objectives in CORE-JetFuel is the evaluation of the R&D landscape related to the production of alternative fuels, in particular for aviation. In order to do so, it is necessary to define categories, according to which identified technologies can be clustered. There are surely various ways to define such categories, but generally it is the type of feedstock in combination with a specific conversion technology that characterizes a production pathway. The landscape of production pathways that have been identified in CORE-JetFuel is schematically illustrated in Figure 1-1. This map of pathways has been constantly revised and updated in the course of the project, according to developments in the R&I landscape.

Task 4.2 is focused on conversion technologies. As can be seen in Figure 1-1, 10 different such technologies have been identified. These technologies are:

- Hydroprocessing of oils and fats (Hydroprocessed Esters and Fatty Acids, HEFA fuels)
- Gasification / Fischer-Tropsch synthesis (Biomass-to-Liquids, BtL fuels)
- Hydrothermal liquefaction (HTL fuels)
- Pyrolysis (Hydroprocessed Depolymerized Cellulosic Jet, HDCJ fuels)
- Aqueous Phase Reforming (APR fuels)
- Lignin-to-Jet conversion (LtJ fuels)
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- Direct microbial conversion of sugars to hydrocarbons (Direct Sugar to Hydrocarbons (DSHC) or Synthesized Iso-Paraffinic (SIP) fuel)
- Power-to-Liquid conversion (PtL fuels)
- Solar-thermochemical fuel production (Sun-to-Liquid conversion, StL fuels)

These technologies differ strongly in terms of reaction mechanisms and conditions, types of suitable feedstock, product spectrum and state of development. In the present report D4.4, a brief description of each of these technologies is presented, in combination with a detailed analysis and mapping of the European R&I landscape related to the respective technologies.
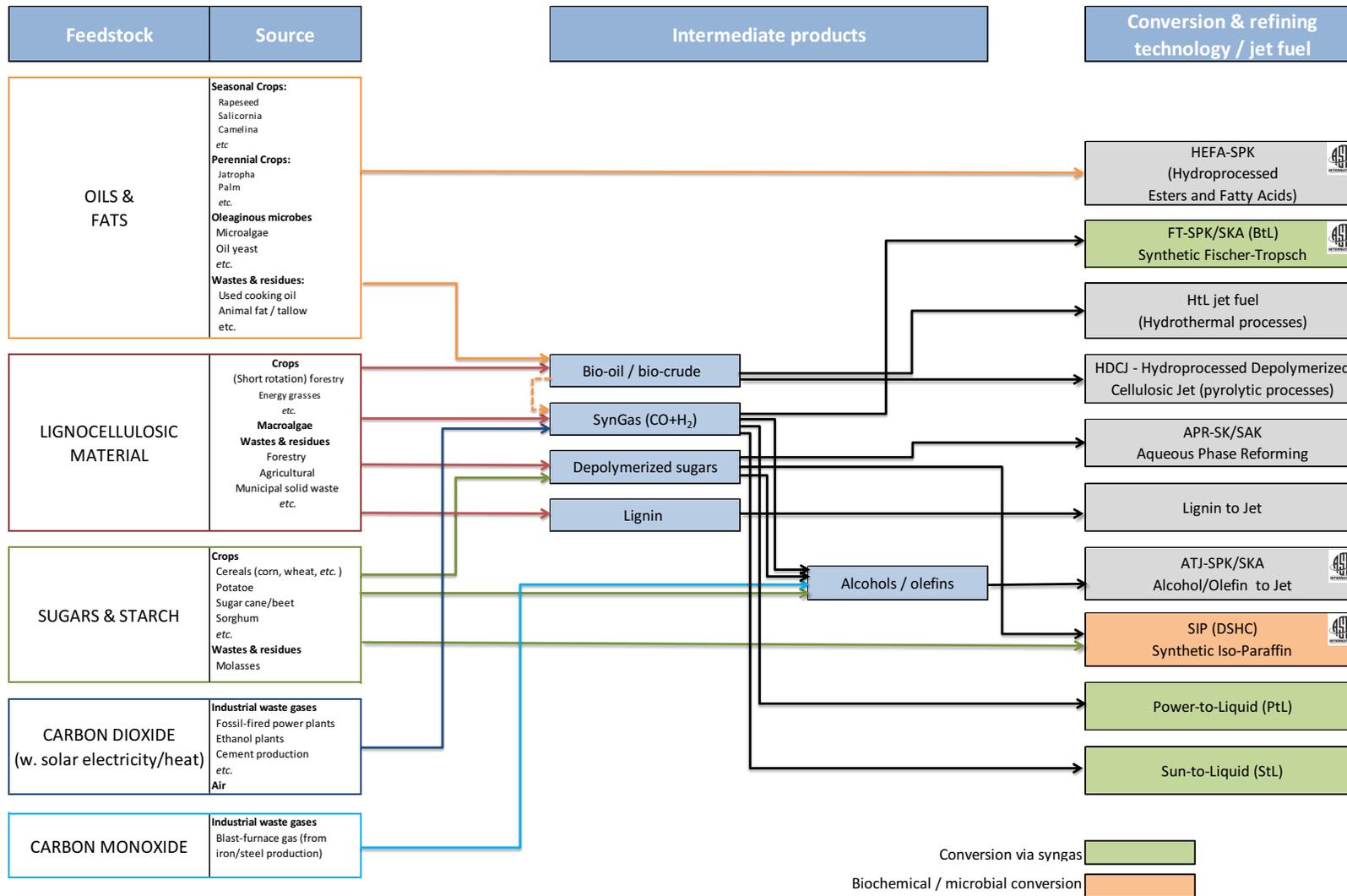
Figure 1-1: Schematic representation of the identified "landscape" of production pathways towards renewable jet fuel, defined by types of feedstock, conversion technologies and the feasible combinations thereof.

2 Conversion technologies: Mapping and evaluation of European R&D landscape

In this chapter, conversion technologies that have been identified as suitable for the production of synthetic jet fuel are examined. The principles and characteristics of each technology are described, including the current state of development, recent progress, identified obstacles as well as potentials and risks. Furthermore, the European R&D activities related to each conversion technology are mapped, and the resulting R&D landscape is analyzed with respect to number, scope and volume of the activities. National or non-European activities are not systematically included in the mapping, even if such activities are mentioned in some cases.

2.1 Short introduction on mapping of R&D activities

The mapping is conducted according to the quadrant model of research introduced by Stokes [5], that has been described in detail in CORE-JetFuel deliverable D2.1 [2]. In this model, actions are mapped in a two-dimensional system with the scope of the mapped actions representing orthogonal coordinates (Figure 2-1). This two-dimensional system extends the classic one-dimensional approach of categorizing research actions as either "basic" or "applied" by the so-called "Pasteur's quadrant" for actions that are both, focused on fundamental understanding ("basic") as well as on product or service development ("applied").
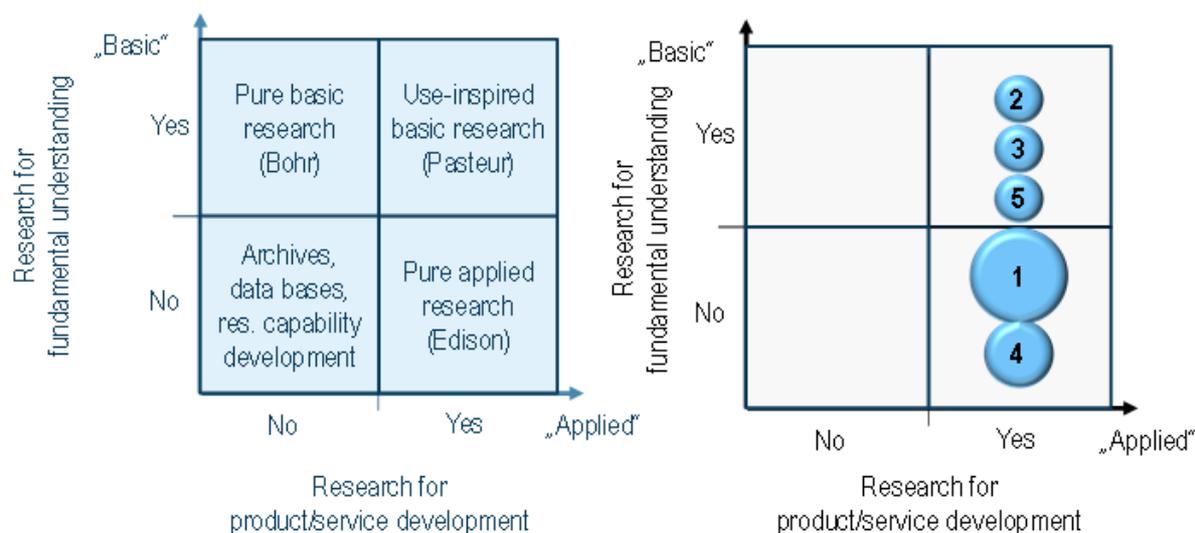
Figure 2-1: Left: Stokes' Quadrant Model of Research, introducing the quadrants "Bohr", "Edison" and "Pasteur" for research actions that are either basic or applied or both in nature, respectively. Right: Mapping of a fictional R&D project portfolio according to Stokes' Quadrant Model of Research, including the amount of funding as third dimension (corresponding to the area of disks).

Research on renewable fuel technologies is inherently product-oriented, and consequently most identified actions can be expected to be located in Pasteur's and Edison's quadrant. However, there are also research activities relevant for renewable fuel production without a directly product-oriented scope. For example, projects concerned with fundamental understanding of photosynthetic processes or of connections between genetic patterns and the efficiency of certain metabolic pathways are not immediately relevant for fuel production, but could mediately result in higher production efficiencies. However, it will be difficult to identify such actions without explicit "fuels-related scope" and to include them in the mapping.

The relevance of Pasteur's quadrant for mapping R&D action portfolios is also reflected by the fact that in the current EU funding framework for research, Horizon 2020, the types of action "Research & Innovation Actions" and "Innovation Actions" are distinguished. While the latter corresponds to purely applied R&D ("Edison"), actions of the first type are clearly located in Pasteur's quadrant: Research & Innovation Actions consist "*primarily of activities aiming to establish new knowledge and/or to explore the feasibility of a new or improved technology, product, process, service or solution. For this purpose they may include basic*

and applied research, technology development and integration, testing and validation on a small-scale prototype in a laboratory or simulated environment" [6].

2.2 Hydroprocessed Esters and Fatty Acids

2.2.1 Background

The production of HEFA fuels is based on hydroprocessing of fats and oils (triacylglycerols; also named triglycerides) of biogenic origin, i.e. from plants or animals. In Figure 2-2 the HEFA conversion process is schematically illustrated. In this context (and throughout the entire report), *hydroprocessing* (a process well established in classical petrochemical industry) is generally understood to include a family of thermochemical processes under hydrogen atmosphere, namely hydrogenation, hydrotreatment, hydrocracking and hydroisomerization. The definition of each of these processes is not always clear, as they can occur in parallel, i.e., in a single process step.

As exclusively unbranched paraffins (*n*-paraffins) are unsuitable for jet fuel (or diesel) applications due to disadvantageous cold flow and combustion properties, the yielded *n*-paraffins have to undergo hydrocracking (a more severe form of hydrotreatment, leading to a reduction of molecular weight through shortening of the average chain length) and hydroisomerization (conversion of linear into branched molecules) in order to meet specifications [7]. Hydrocracking and hydroisomerization are usually carried out in a single-step process.
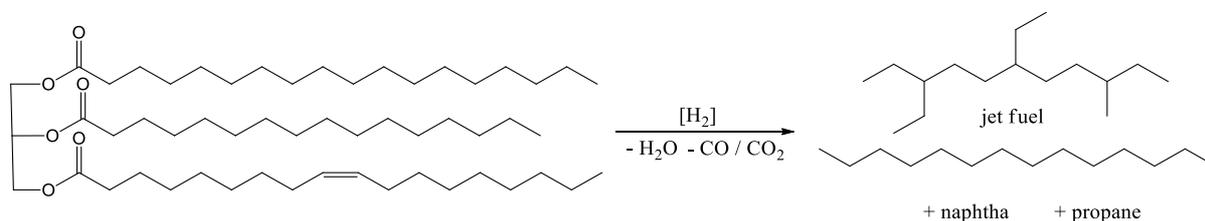
Figure 2-2: Schematic illustration of jet fuel production from oils and fats (triacylglycerols) via hydroprocessing. (Product molecules are shown to illustrate examples of branched (*iso*) as well as linear (*n*) paraffins in the jet fuel range. However, readily usable jet fuel (conventional or containing synthetic blending components) is far more complex in reality, containing a wide variety of linear, branched and also cyclic hydrocarbons.)

2.2.2 State of development

HEFA is currently the only production process of renewable jet fuel that is industrially implemented at substantial scale, and consequently HEFA-SPK is the only renewable jet fuel commercially available in relevant quantities at the moment[1]. A limited number of HEFA refineries are operational worldwide with production capacities ranging up to 800 000 t of middle destillate fuels per year. The most important producers are Neste Oil with plants in Finland, Singapore and the Netherlands, REG Synthetic Fuels with a plant in Geismar, Louisiana (USA), Eni in Venice (Italy) and AltAir Fuels with a plant in Paramount, California. It is important to note that the targeted product in the mentioned production facilities is mainly diesel, while jet fuel is usually produced only on demand and in limited quantities (see below). An exception is the AltAir plant in Paramount that has an integrated jet fuel production capability.

Since its ASTM certification in 2011 (see below), HEFA fuels have been successfully used in commercial aviation by numerous airlines. A prominent example is the former national project burnFAIR in Germany, in the course of which Lufthansa operated 1188 regular commercial flights between Hamburg and Frankfurt over a period of six months in 2011. In that project one engine of a single Airbus A321 was fueled with a 50% blend of HEFA-SPK [8]. However, up to now, utilization of HEFA fuels in commercial aviation has only been realized on a project basis, *i.e.* there is no regular continuous supply of such fuels to any airport so far. The Dutch initiative BioPort Holland, kicked off in 2013 and involving stakeholders along the entire supply chain, aims at establishing such a regular and continuous supply at Schiphol Airport in Amsterdam [9], but this project is still on-going. Meanwhile, a regular supply of limited quantities of HEFA jet fuel has been established at Oslo Airport, where the HEFA fuel is provided by Air BP [10]. Recent off-take agreements will support the ramp-up of HEFA jet fuel production and utilization in commercial aviation. For example, United Airlines agreed in March 2016 to purchase up to 15 million gallons (about 43 kt) of HEFA jet fuel from AltAir Fuel over a three-year period [11].

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[1] Synthetic Isoparaffinic (SIP) jet fuel provided by the company Amyris is the second commercially available renewable jet fuel. However, the current production capacity of SIP fuel is limited to about 25 kt/yr.

2.2.3 Quality of the fuel

Since 2011, Hydroprocessed Esters and Fatty Acids (HEFA or HEFA-SPK) are approved according to the standard ASTM D7566 for use in civil aviation. As the HEFA process exclusively yields paraffinic compounds (i.e. no aromatics), utilization is limited to blends with conventional jet fuel containing up to 50% HEFA components.

2.2.4 Mapping and analysis of R&D activities

The current overview of identified EU-funded R&D actions on HEFA production is presented in Table 2-1 and Figure 2-3. Please note that this list may not be exhaustive and represents a current result of the mapping efforts in CORE-JetFuel. Other actions might appear on the list upon further research, *e.g.* projects funded in national programs (national projects have not been included in Table 2-1). However, considering that HEFA conversion is technologically mature and already commercially implemented at industrial scale, a large number of publicly funded research projects could not be expected. Accordingly, the identified actions are concerned with complete production chains, within which the chemical conversion of the oleaginous feedstock represents only a single step that does not require innovation or research. The main focus of all identified projects connected to the HEFA process lies on other crucial aspects, *e.g.* feedstock production and supply as well as socio-economic and deployment issues.

Table 2-1: List of identified EU-funded R&D projects of relevance for HEFA conversion technology. Note: Volumes represent EU contributions and not total project volumes.

Nr.	Project of category "HEFA"	Basic	Applied	Volume
1	ABV	Yes	Yes	4.0 mio€
2	CAER	Yes	Yes	8.5 mio€
3	FUEL4ME	Yes	Yes	4.0 mio€
4	ITAKA	Yes	Yes	9.9 mio€
5	COSMOS	Yes	Yes	10.8 mio€
6	KANE	No	Yes	n/a
	Total volume			**37.2 mio€**
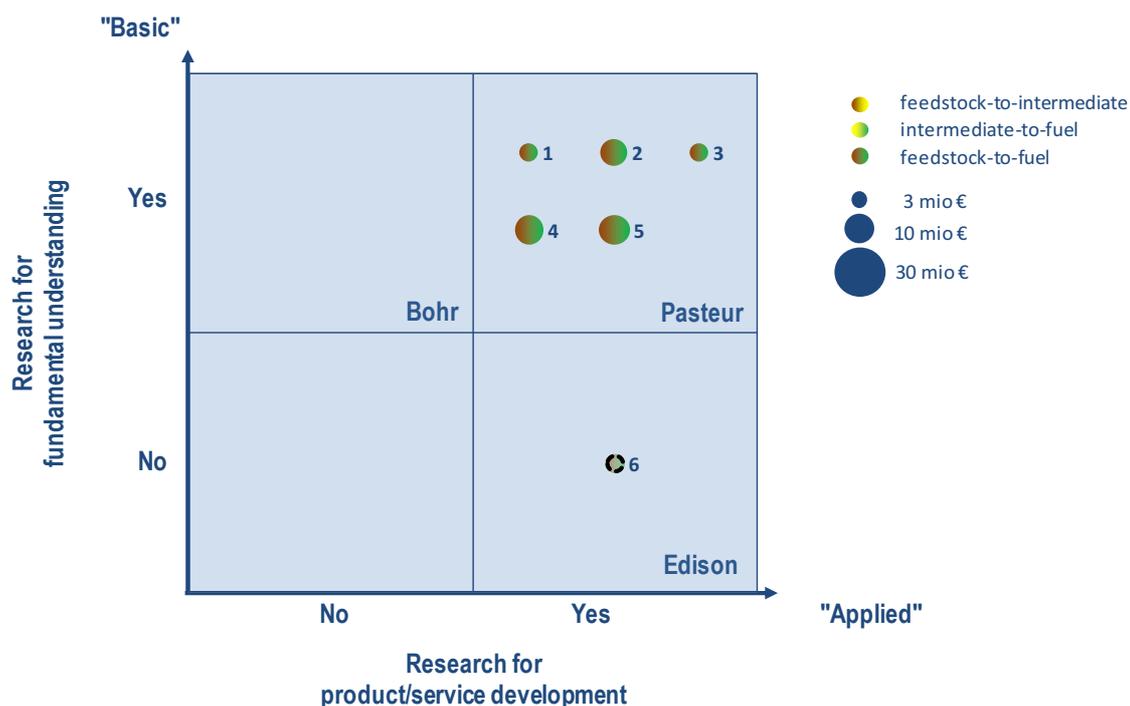
Figure 2-3: Mapping results of EU-funded R&D projects connected to HEFA conversion technology.

The reason why HEFA jet fuel has not yet been implemented in commercial aviation on a regular and continuous basis is not related to the conversion technology itself, but primarily in concerns related to production cost and, depending on the type of applied feedstock, to the environmental performance of the resulting fuel. It should also be noted that large-scale production of HEFA fuels is likely to be limited by the sustainable and economically reasonable availability of feedstock, as oils and fats represent starting materials of relatively high value and limited sustainable production potential.

With respect to the state-of-the-art of HEFA conversion and R&D gaps, it can be concluded that the technology itself is already industrial reality and does not require public funding for further development. However, it has to be emphasized that this conclusion does by no means include R&D efforts on feedstock production and supply for HEFA conversion or on economic and/or policy frameworks supporting the commercial deployment of HEFA fuels in aviation.

2.3   Biomass-to-Liquid via gasification/FT synthesis

The rather general name "Biomass-to-Liquid" (BtL) generally stands for the thermochemical conversion of biomass feedstock into liquid fuel products. However, in the public and

scientific discussion, BtL usually refers to a specific conversion technology, i.e., the gasification of a broad range of lignocellulosic feedstock, yielding synthesis gas, and subsequent liquefaction, as described in more detail below. In CORE-JetFuel, only Fischer-Tropsch (FT) synthesis, as the most prominent technology in this context, is considered for the liquefaction step. The authors acknowledge that alternative routes exist, most importantly the Methanol-to-Gasoline (MtG) process, for producing liquid hydrocarbon products from synthesis gas. However, in particular for the production of middle distillate fuels, such as jet fuel, FT synthesis is the by far most examined and applied technology.

In cases where the feedstock is sourced from waste streams (in particular municipal solid waste, MSW), the process is often referred to as Waste-to-Liquid (WtL). However, if the consumed feedstock is biogenic in nature, WtL is essentially equivalent to BtL production, with a particular source of feedstock, *i.e.* waste. Therefore, WtL is not considered as separate conversion technology here. However, if analyzed at the level of integrated pathways, i.e., feedstock production and supply, conversion and refining, WtL fuels can differ substantially from BtL fuels in terms of economic and environmental performance. This is taken into account in the assessment of integrated supply chains (Part B of the present deliverable).

2.3.1 Background

As the Fischer-Tropsch process was already invented in the 1920s with the first industrial FT reactor being constructed in 1935, there is a wealth of literature available on this topic. An informative and comprehensive book on Fischer-Tropsch technologies has been edited by Steynberg and Dry [12], and a very interesting review on the specific design requirements of an FT-refinery (the final step of BtL conversion or any other FT-based conversion) was published by de Klerk [13].

The BtL process (schematically depicted in Figure 2-4) comprises three basic steps:

1. Thermal gasification of the feedstock, yielding synthesis gas (syngas; a mixture of carbon monoxide and hydrogen). Typically, lignocellulosic biomass (also waste materials) is used as feedstock, but also more energy-dense intermediate products from other processes, such as pyrolysis or torrefaction, can be applied. In contrast to pyrolysis (see section 2.5), the presence of sub-stoichiometric quantities of oxygen and/or steam is required in the gasification step.

2. FT synthesis, converting the syngas mainly into hydrocarbons (FT crude)

3. Refining/upgrading of FT crude into a broad range of potential products; for the production of middle distillate fuels, such as diesel and jet fuel, at least hydroprocessing (hydrotreament, hydrocracking and hydroisomerization) is required
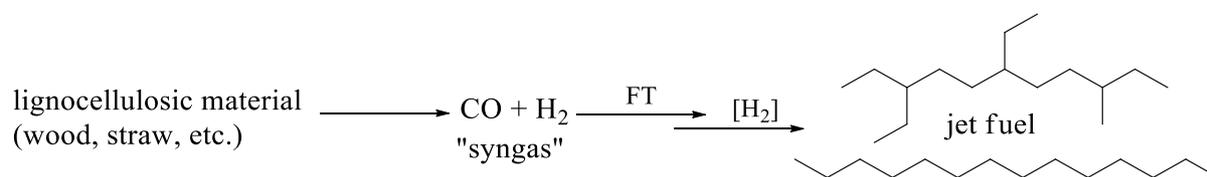
Figure 2-4: Simplified illustration of BtL process (Δ indicates a thermally driven process); [O] indicates the required addition of an oxidizing agent in the form of sub-stoichiometric quantities of oxygen and/or steam in the gasification step.

Each of the three basic steps poses its own challenges and requires application of a number of different technologies, depending on the type of carbonaceous feedstock used and the desired products. After gasification, the raw gas stream has to be purified and conditioned[2]. The FT crude represents a diverse mixture of compounds, the composition of which depending on the FT technology applied, that has to be further processed via conventional petrochemical technologies in an FT refinery. These technologies include hydroprocessing, as mentioned above, but also a number of other processes enabling the optimization of yields quality of the desired products.

The BtL process is closely related to the fossil-based technologies Gas-to-Liquid (GtL) and Coal-to-Liquid (CtL). Both, GtL and CtL, are commercially established processes at industrial scale, e.g., applied by SASOL (CtL) in South Africa and by Shell (GtL) in Qatar. This represents an advantage for BtL, since the basic process steps have already been developed and industrially demonstrated. This is especially true for the FT synthesis that has been industrially applied for decades. In a sense, BtL represents a renewable variation of these liquefaction technologies, particularly similar to CtL. However, utilization of biomass feedstock poses specific challenges, rendering the BtL process different from the established technologies.

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[2] Purification includes removal of unwanted volatile components, e.g., ash, and potential catalyst poisons, such as compounds containing sulfur or phosphorous. Conditioning includes adjustment of the H_2/CO ratio via Water-gas Shift Reaction (WSR): $CO + H_2O \leftrightarrow CO_2 + H_2$

All of the three technologies, BtL, GtL and CtL, are based on the production of syngas *via* gasification or steam reforming of carbonaceous feedstocks and subsequent FT synthesis. This means that downstream of the purified and conditioned syngas, all three processes are essentially identical, including requirements for the refinery design as well as yields, quality and distribution of the products.

However, the processes differ strongly in the properties of their feedstocks, e.g., in terms of heterogeneity, C/H ratio, content of heteroelements (S, N, P, metals), water content, mechanical properties, *etc*.

Natural gas, the feedstock for GtL, poses the least challenging requirements, as it does not have to be gasified and represents a relatively homogenous feed stream that can be purified via standard procedures. The situation in case of solid biomass and coal feedstock is more complicated. Both types of feedstock have to be gasified at high temperatures, around 800 – 1000 °C, with biomass decomposing at slightly lower temperatures compared to coal [14]. Furthermore, biomass and coal contain substantial amounts of metal salts as well as sulfur and nitrogen compounds, resulting in the formation of ash and potentially corrosive species in the gasification step. Alkaline components present in biomass are particularly problematic due to their corrosive nature. Utilization of biomass is also hampered by other issues. For example, while coal is relatively homogenous with respect to its carbonaceous components, lignocellulosic biomass is composed of several chemical constituents, mainly of cellulose, hemicellulose and lignin. The mass ratio of these components in the feedstock strongly influences gasification behavior and gasification product composition [14]. Furthermore, the high water content of biomass renders preprocessing through drying and torrefaction necessary, in order to achieve the required moisture content of below 10 – 15% prior to gasification [14].

2.3.2 State of development

The above-described differences between BtL, CtL and GtL translate into very different requirements for production, purification and conditioning of syngas, and consequently into costlier procedures in case of CtL and especially BtL. This is surely an important reason for the fact that CtL and GtL are commercially applied at industrial scale, with CtL plants operated since decades by Sasol in South Africa and, more recently, in China and GtL plants operated by, *e.g.*, Shell in Bintutlu (Malaysia) and Qatar (Pearl GtL project). In contrast, BtL technologies have not been commercialized yet. However, a number of large-scale BtL and

WtL projects have recently been announced, *e.g.* by Red Rock Biofuels and Fulcrum, but none of them has entered the phase of operation yet.

A very promising project aiming for moving the gasification / FT technology towards commercial application is the French project BioTFuel, a joint undertaking by Total, IFPen, Thyssen Krupp Industrial Solutions, Sofiproteol, CEA and Axens. In the course of the BioTFuel project, two BtL production plants are constructed, one of which (located in Dunkirk, France) is projected to reach a production capacity of 200,000 tons of diesel and jet fuel per year from about one million tons of biomass by 2020 [15].

For the current technological maturity of the BtL conversion process, TRL 5-6 is estimated, with TRL 6 to be completed by 2017 (in the BioTFuel project).

2.3.3 Quality of the fuel

Liquid fuels derived from FT synthesis are generally of high quality and were the first to successfully pass the approval procedure according to the standard ASTM D7566 as *Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene* (FT-SPK) in 2009. FT-SPK fuel can now be used in blends of up to 50 % with conventional jet fuel. Annex A1 of ASTM D7566 defines FT-SPK synthetic blending components as "wholly derived from synthesis gas via the Fischer-Tropsch (FT) process using iron or cobalt catalyst". In principle, this definition includes all fuels produced via the FT pathway (BtL, CtL, GtL, but also PtL (Section 2.10) and StL (Section 2.11)), as long as iron or cobalt catalysts are used in the FT process and the fuels produced meet the chemical and physical specifications.

2.3.4 Mapping and analysis of R&D activities

The current list of identified EU-funded R&D actions concerned with BtL technology (or with key process steps, e.g. gasification) is presented in Table 2-2. Please note that this list may not be exhaustive and represents the current result of the mapping efforts in CORE-JetFuel. Other actions might appear on the list upon further research, *e.g.* projects funded in national programs (national projects have not been included). The current mapping of the listed actions according to Stokes' quadrant model is illustrated in Figure 2-5.

Table 2-2: List of identified EU-funded R&D projects of relevance for Fischer-Tropsch SPK (BtL) conversion technology. Note: Volumes represent public funding and not total project volumes.

Nr.	Project of category "BtL"	Basic	Applied	Volume
1	EnAlgae	Yes	Yes	7.3 mio€
2	EUROBIOREF	Yes	Yes	23.1 mio€
3	GREENSYNGAS	Yes	Yes	2.7 mio€
4	SECTOR	Yes	Yes	7.6 mio€
5	SUPRA-BIO	Yes	Yes	12.3 mio€
6	UNIQUE	Yes	Yes	2.7 mio€
7	Bio2G	No	Yes	203.7 mio€
8	BIODME	No	Yes	8.2 mio€
9	OPTFUEL	No	Yes	7.1 mio€
10	SYNDIESE	No	Yes	110.0 mio€
	Total volume			**384.7 mio€**
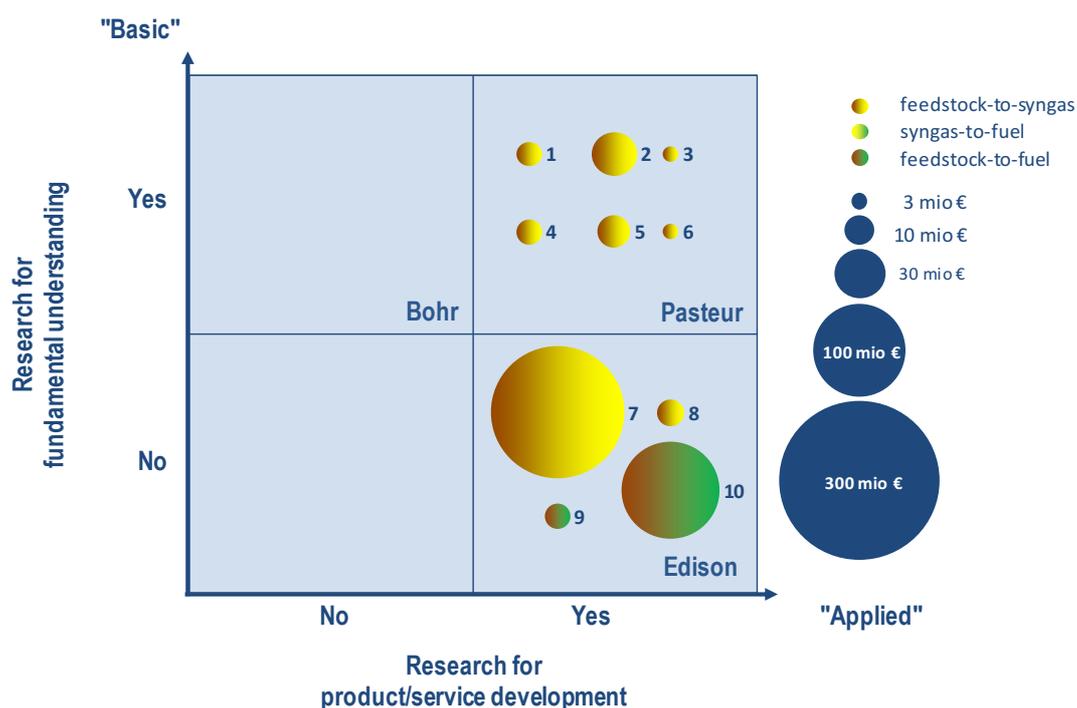
Figure 2-5: Mapping of identified EU-funded R&D projects of relevance for BtL conversion technology. Area of disks corresponds to the volume of public funding for the respective activity. Please note: No distinction in scope ("more basic" or "more applied") between activities within a specific quadrant can be deduced; individual placement within a quadrant is arbitrary.

In contrast to the HEFA technology, a number of R&D actions focused on BtL conversion or BtL-relevant technologies were identified. This reflects the fact that BtL conversion technology is substantially less developed than HEFA technology: While the latter is applied in several commercial plants (see Section 2.2), no commercial BtL plant is operational to-date. A prominent example of an ambitious, but unsuccessful, attempt to bring BtL technology to commercial scale is Choren Industries in Freiberg, Germany. With the French BioTFuel project (see above), there is now another commercialization project underway.

With respect to European R&D projects devoted to BtL, only two out of four pure-applied research projects show relevant R&D funding to boost industrial scale production capacities of fuels (see Figure 2-5). Further, only one of these two large and pure-applied projects (namely SYNDIESE) covers the entire value chain from feedstock supply to fuel production. Including the further processing Fischer-Tropsch (FT) step (from syngas to fuel) is an important but often challenging integration aspect for large scale production processes, as syngas production from biomass often requires severe downsizing efforts of a typical FT plant (as a consequence of limited local availability of feedstock), resulting in efficiency losses. Other R&D activities (*e.g.* UNIQUE) only concentrate on the gasification step and the supply of high-purity syngas, as required for downstream processes like FT synthesis.

These thematic orientations of R&D actions reflect the technical challenges associated with BtL conversion: Firstly, the production of clean syngas from the highly heterogeneous feedstock biomass is more difficult compared to the fossil feedstock coal and particularly natural gas, as described above. Secondly, the size of BtL plants is limited by feedstock availability: BtL conversion plants show positive economies of scale and therefore a large plant scale would be economically beneficial [16]. However, a large plant requires large quantities of feedstock, which, in case of lignocellulosic biomass, has a low energy density and is consequently costly to transport over long distances [17]. A local (remote) conversion of biomass into a more energy-dense, storable and transportable form, e.g., pyrolysis oil or bio-char, could therefore be an option in combination with a large-scale central plant for final conversion. In this context, R&D actions working on intermediate conversion of biomass are very relevant for BtL technology. For more details on pyrolysis research landscape please see Section 2.5.
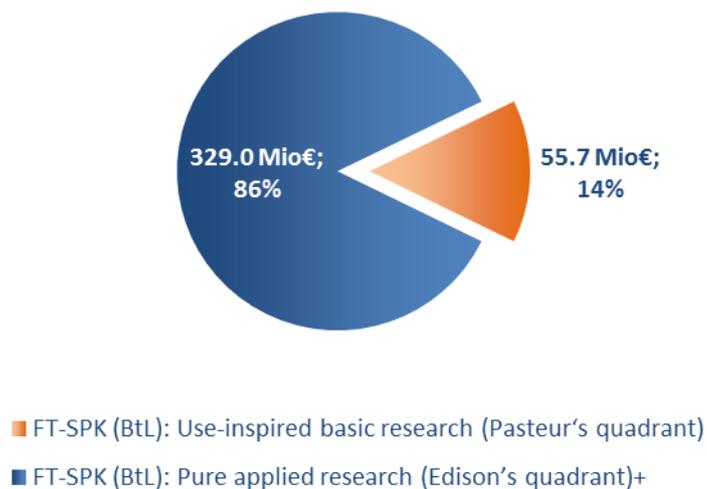
Figure 2-6: Distribution of European R&D funding of relevance for Fischer-Tropsch SPK (BtL) conversion technology conversion technology between Pasteur's and Edison's quadrant

Mapping of the currently identified R&D actions (Figure 2-5 and Figure 2-6) shows that all listed projects are located in the Pasteur's and Edison's quadrant with a 14 to 86 percent distribution of the respective quadrant's sum of public funding. This is in accordance to the fact that BtL is not a novel technology, but rather at the brink of industrial implementation. In this context, more efforts in Pasteur's quadrant for solving the remaining technological challenges especially in the area of feedstock gasification will be required. Likewise, an increase of large-scale R&D actions involving the entire value chain from feedstock to fuel in Edison's quadrant is needed for overcoming the often-cited "valley of death" towards commercialization.

2.4 Hydrothermal liquefaction

2.4.1 Background

Hydrothermal liquefaction (HTL) of biogenic feedstock represents a special case of hydrothermal conversion (hydrothermal processing). In hydrothermal processing hot-compressed water is applied as reaction medium at temperatures of 200-500°C, yielding products with increased specific energy densities. Depending on reaction conditions and products, three types of hydrothermal processes are distinguished: hydrothermal carbonization (HTC, 180-280°C), hydrothermal liquefaction (HTL, 280-375°C) and hydrothermal gasification (HTG, >375°C), as depicted in Figure 2-7. Each of these processes result in

energy densification by removal of oxygen from the feedstock to produce hydro-char (HTC), bio-crude (HTL) or combustible gas rich in either methane or hydrogen (HTG). These primary products can be directly used as fuels and burnt for, e.g., electricity production, or further processed and upgraded to products of higher value. In case of HTL, upgrading of the primary product bio-crude can yield liquid hydrocarbon fuels, including middle destillates, such as jet fuel.

Reaction conditions for HTL conversion are usually in the sub or near-critical regime, i.e., at temperatures and pressures below 374°C and 220 bar, respectively (Figure 2-7). Virtually all types of carbonaceous biogenic feedstock can be processed via HTL, rendering this technology highly flexible. As a particular advantage, no energy-intensive drying of the feedstock is required, as HTL is conducted in aqueous phase with water as reacting agent. Feedstock is applied as slurry, usually containing 10-30% solid material. This means that very wet feedstock with about 80% water content can be readily used, being one reason why considerable attention has emerged in hydrothermal processing of microalgae, where drying procedures often result in prohibitively high energy consumption. Other types of feedstock with high moisture and ash content are also suitable for hydrothermal processing, including waste streams, such as residues of anaerobic digestion (AD), manures, sewage sludge, dried distiller grains with solubles (DDGS), food wastes and municipal wastes. However, also "classical" types of biomass, including dedicated energy crops, such as energy grasses or woody biomass from short-rotation coppice, can be used.
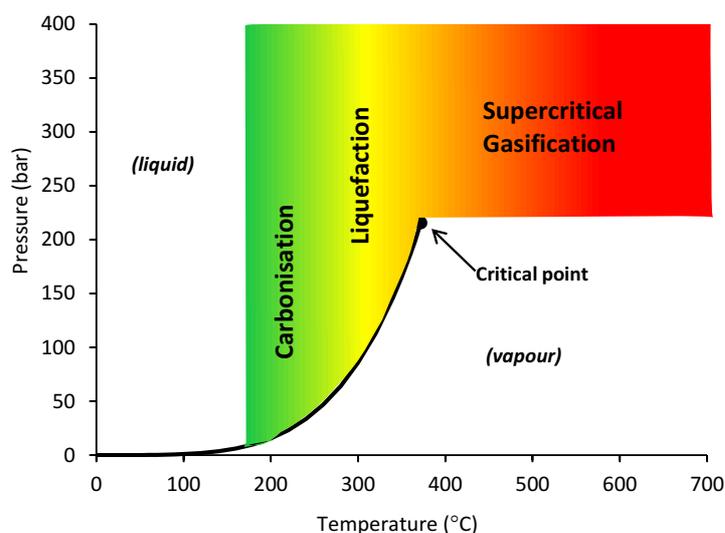
Figure 2-7: Hydrothermal processing of biomass in different pressure/temperature regimes of the phase diagram of water.

During hydrothermal liquefaction, biomass is decomposed to smaller reactive molecules that can re-polymerize into hydrophobic compounds, yielding an oily phase, usually referred to as bio-crude [18]. Formation of such a black and viscous raw product is the reason why HTL is often compared to liquefaction via pyrolysis (see section 2.5). However, reaction conditions and mechanisms as well as composition and properties of the raw products (bio-crude for HTL and bio-oil for pyrolysis) differ substantially.

The main reaction steps of HTL can be summarized as follows [19]:

1. Hydrolysis of macromolecules into oligomeric and monomeric components;
2. Conversion via dehydration and decarboxylation into smaller reactive species;
3. Rearrangement via condensation, cyclisation, and polymerization producing hydrophobic macromolecules.

The products from hydrothermal liquefaction consist of a hydrophobic bio-crude fraction, a water fraction (aqueous phase), a gaseous fraction (mainly CO and CO_2) and a solid residue fraction. The majority of the inorganic material is concentrated in the solid residue and the aqueous phase. The product distribution is largely affected by the biochemical composition of the feedstock. Lipids, for example, are almost entirely fractionated to the bio-crude in the

form of fatty acids and alkanes as reaction products. Carbohydrates on the other hand tend to form undesired char. This can be avoided by keeping the pH value of the reaction mixture in the alkaline regime to increase the bio-crude yields. Addition of alkali catalysts is particularly important when processing lignocellulosic feedstock to achieve satisfactory conversion of carbohydrates to bio-crude and to avoid excessive char formation. In the final step of HTL the bio-crude is typically upgraded via hydrotreatment to a fuel product which can be further processed through conventional refinery procedures to yield renewable drop-in replacement fuels for gasoline, kerosene and diesel engines.

2.4.2   State of development

Similar to other thermochemical technologies, HTL is not a novel concept. In fact, there have been industrial project already in the 1980s, for example by Shell with their HTU (hydrothermal upgrading) process. However, HTL was never commercially applied, mainly due to unfavorable costs in comparison to crude oil, especially in times of dropping oil prices. In recent times, interest in HTL has re-emerged and HTL-based conversion is pursued in several industrial projects all over the world. Most active examples are Muradel and Licella in Australia, Steeper Energies in Denmark and Canada and Genifuel in the U.S. Despite these activities, information regarding the specific state of development is scarce. It can be tentatively estimated that the technological maturity of the HTL conversion corresponds to a TRL of 5 to 6.

However, the pre-treatment of feedstock as well as the processes downstream of the HTL conversion step are considerably less developed. In particular the upgrading of bio-crude has received insufficient attention so far. Only few reported studies, e.g. refs. [20], [21] and [22], have been dedicated to upgrading of bio-crude and little is known about the relation of feedstock, chemical composition of the corresponding bio-crude and the quality of the upgraded fuel products. Other issues to be addressed in future R&D projects are related to the treatment of the aqueous phase after HTL conversion, a waste stream that contains substantial quantities of organic compounds. Two options currently discussed in this context are anaerobic digestion and hydrothermal gasification. In both cases the compounds dissolved in the water phase are converted into combustible gaseous species that can be used, e.g., for on-site electricity generation.

Taking the less developed process steps upstream and downstream of HTL conversion into account, the overall technological maturity of HTL-based fuel production can be estimated to amount to TRL 3 to 4, with TRL 5 to 6 for the HTL step itself.

2.4.3   Quality of the fuel

Given the knowledge gaps with regard to the upgrading of HTL-derived bio-crude, no clear assessment of the quality of HTL-derived fuels can be conducted here. However, the reported studies show that aliphatic as well as aromatic compounds potentially suitable as jet fuel components are present in the upgraded fuels in substantial quantities. Therefore, .it is likely that HTL-derived fuels after upgrading will prove suitable for application as renewable jet fuel.

2.4.4   Mapping and analysis of R&D activities

No European publicly funded R&D activities devoted to HTL technologies could be identified.

2.5   Pyrolysis: Hydroprocessed Depolymerized Cellulosic Jet

2.5.1   Background

Pyrolysis represents the thermochemical decomposition of organic material at elevated temperatures and in absence of oxygen. Reaction temperatures range from about 200 °C up to 900 °C, and the process yields a solid phase product (char), water and a broad mixture of gaseous products. The non-condensable part of the gaseous product stream mainly comprises of oxygenated carbon compounds (CO_2 and CO), and a few percent of light hydrocarbons. The condensable part of the gaseous product stream represents a highly complex mixture of organic compounds and water and is generally referred to as bio-oil. It forms the basis for further upgrading to valuable products, such as chemicals and fuels.

There are many modes of pyrolysis, differing in reaction temperatures, times and other process details which have been extensively reviewed elsewhere, for example in references [23] and [24].

If targeting the production of liquid fuels and chemical products, bio-oil fraction represents the desirable product stream of pyrolysis, while the non-condensable part of the gaseous stream is of lesser value and usually used for on-site heat generation. Depending of the process type, the formed char can also be burned for on-site heat generation or recovered to produce active carbon that offers various commercial applications, e.g. for soil improvement or as ultra-low sulfur bio-coke. The formation of bio-oil is favored by very short residence times of less than two seconds at reaction temperatures of about 500 °C or higher [25]. Depending on the feedstock the bio-oil mass yield typically ranges from 55 to 75 %. Therefore, current interest is mainly focused on fast pyrolysis, where very fast heating rates of 1000 °C/s or even higher, rapid quenching and reaction temperatures of 450 – 650 °C favor formation of liquid products with mass-based yields of up to 75% [23][26]. The high required heating rate requires a small particle size of the feedstock, typically in the range of 0.5 to 2 millimeters [26], as heat conductivity of biogenic feedstock materials is generally low.

The yielded bio-oil represents a viscous liquid of brown or black color with a high water content of 20-30 %. Several of its properties pose serious challenges with respect to handling, storage, transport and upgrading. Examples of challenging properties of bio-oil are

- acidity, caused by organic acids and potentially resulting in corrosion of vessels and pipework,
- aging, caused by condensation and polymerization reactions of reactive species and resulting in increasing viscosity as well as potential phase separation and filter clogging, and
- high content of heteroelements (O, S, N, metals) posing risks of, i.a., catalyst poisoning, ash formation, toxicity.

The challenging properties of bio-oil render the application of an upgrading step necessary. Depending on the purpose of its further use, various physical and chemical upgrading techniques can be applied. If targeting production of liquid hydrocarbon fuels, severe hydroprocessing, including (hydro-)cracking and hydrotreatment, is required. As a consequence of the broad variety of compounds present in bio-oil, the resulting hydrocarbon fuels contain all types of compounds typically present in conventional fuels, i.e. linear,

branched and, in particular, cyclic paraffins as well as aromatics. The actual fuel composition, however, depends on the type of feedstock and the process condition (pyrolysis and upgrading) applied.

2.5.2 State of development

Pyrolytic conversion of biomass feedstock has been subject to industrial development for decades, and several commercial projects lead to industrial-scale pyrolysis plants becoming operational.

One of the first commercial fast pyrolysis units to become operational (in 2014) is the Fortum Joensuu plant (Finland) with a capacity of 240 t feedstock processed per day (50 000 t bio-oil produced per year). The bio-oil is used for combined heat and power (CHP) generation in an adjacent power plant.

The Canada-based company Dynamotive Energy Systems constructed and commissioned a fast pyrolysis demonstration plant in West Lorne, Ontario, with a production capacity of 100 t per day, as well as a large plant in Guelph, Ontario, with a capacity of 200 t per day. Dynamotive targeted to market the bio-oil directly, i.e. without upgrading to readily usable liquid fuel products. The plants appears to have been shelved as a consequence of difficult market situation for bio-oil [26].

Another industrial player devoted to pyrolysis is Canada-based company Ensyn. Similarly to Dynamotive, Ensyn business is based on marketing bio-oil as fuel for heating and cooling purposes and as feedstock for co-processing in conventional refineries. Ensyn operates a commercial-scale bio-oil production facility in Renfrew, Ontario, with a production capacity of 3 million gallons (more than 11 million liters) per year [27]. Ensyn is applying UOP Honeywell's Envergent® technology.

However, while pyrolysis itself can be considered an industrially established process (corresponding to TRL 9), the upgrading and refining of the primary product bio-oil into readily usable transportation fuels is by far less developed. The only company aiming for marketing refined fuel products was KiOR, explicitly including jet fuel. Their technology, named *Biomass Fluid Catalytic Cracking* (BFCC), a catalytic pyrolysis process, yielded a bio-oil that was subsequently refined into *Hydroprocessed Depolymerized Cellulosic Jet* (HDCJ) and was already on its way towards ASTM approval for use in civil aviation, potentially as 100% drop-in fuel. However, KiOR went bankrupt in 2014 and HDCJ production as well as the ASTM approval process have been shelved. KiOR has recently been

renamed into Inaeris Technologies and is still pursuing the development and marketing of its BFCC technology [28].

Other activities devoted to upgrading of bio-oil are limited to laboratory or pilot-scale facilities, e.g. at Batelle and the Pacific Northwest National Laboratory (PNNL) [29]. Therefore, an overall technological maturity of pyrolysis-based jet fuel production corresponding to TRL 5-6 can be concluded, even though pyrolysis itself has been readily developed.

2.5.3 Quality of the fuel

As described above in Section 2.5.1, fuels produced via pyrolysis tend to be rich in cyclo-paraffins and aromatics. If refined accordingly, renewable jet fuel obtained from bio-oil offers the potential of 100% drop-in capability.

2.5.4 Mapping and analysis of R&D activities

The current list of identified EU-funded R&D actions concerned with Hydroprocessed Depolymerized Cellulosic Jet (HDCJ) conversion technology is presented in Table 2-3. Please note that this list may not be exhaustive and represents the current result of the mapping efforts in CORE-JetFuel. Other actions might appear on the list upon further research, *e.g.* projects funded in national programs (national projects have not been included). The current mapping of the listed actions according to Stokes' quadrant model is illustrated in Figure 2-8.

Table 2-3: List of identified EU-funded R&D projects of relevance for Hydroprocessed Depolymerized Cellulosic Jet (HDCJ) conversion technology. Note: Volumes represent public funding and not total project volumes.

Nr.	Project of category "HDCJ"	Basic	Applied	Volume
1	Residue2Heat	Yes	Yes	5.5 mio€
2	CHP Biomass pyrolysis	No	Yes	3.9 mio€
3	EMPYRO	No	Yes	4.9 mio€
4	N.N. (Fast pyrolysis)	No	Yes	6.9 mio€
5	TORR	No	Yes	25.0 mio€
	Total volume			**46.2 mio€**
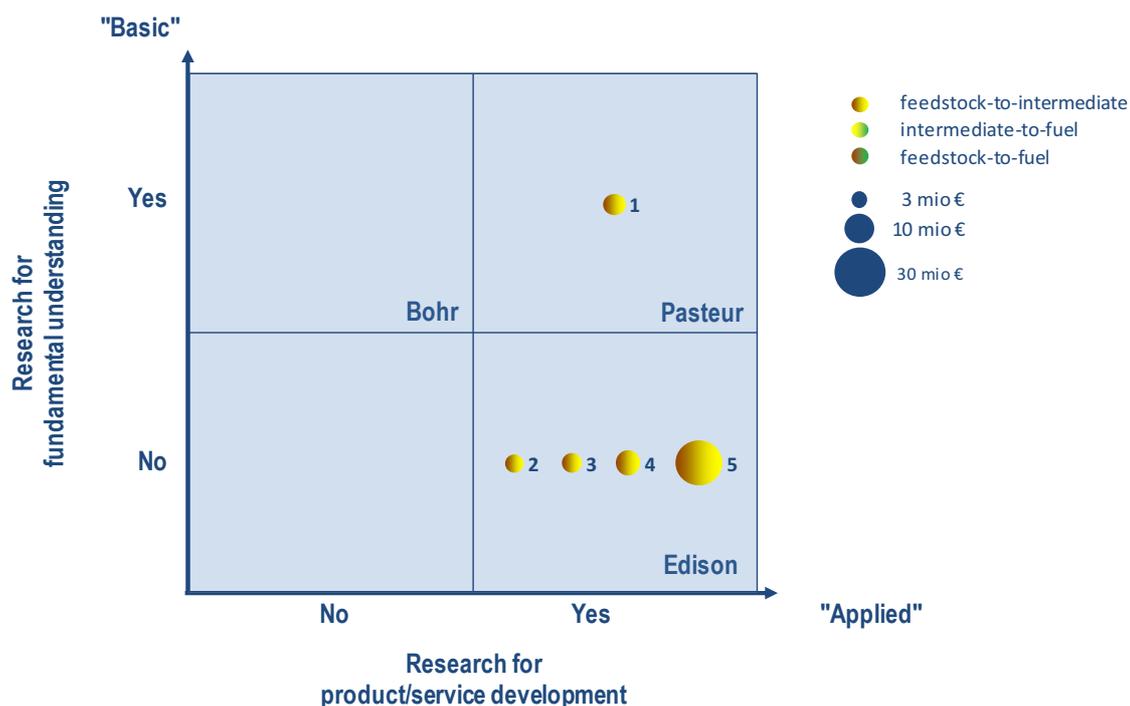
Figure 2-8: Mapping of identified EU-funded R&D projects of relevance for Hydroprocessed Depolymerized Cellulosic Jet (HDCJ) conversion technology. Area of disks corresponds to the volume of public funding for the respective activity. Please note: No distinction in scope ("more basic" or "more applied") between activities within a specific quadrant can be deduced; individual placement within a quadrant is arbitrary.

With only one research project in Pasteur's Quadrant (Residue2Heat) and four projects in Edison's Quadrant the budget distribution between use-inspired basic research and pure-applied research is much lower than the 20-80 per cent distribution which can be observed e.g. in the field of BtL (cf. Section 2.3) or AtJ (cf. Section 2.8). Additionally, the overall number of activities and volume of projects is quite small, i.e. not exceeding 7 mio.€ even in the case of pure-applied research projects except TORR (25 mio.€).

As currently no activity covers the entire value chain from feedstock to fuel, more activities are needed that focus on upgrading of crude intermediates to refined liquid fuels. Moreover, large production-oriented projects are needed to progress technologies (including the upgrading) towards industrially relevant scale and maturity. Generally, the conversion of lignocellulosic feedstock by HDCJ enables to exploit major resources of biomass in Europe with a significant potential impact in GHG emission reduction.

2.6 Aqueous Phase Reforming

2.6.1 Background

The process Aqueous Phase Reforming (APR) is based on the thermocatalytic conversion of soluble carbohydrates in aqueous solution. The carbohydrate feed can be sourced from conventional sources, such as 1st generation starch or sugar crops, as well as lignocellulosic material. The APR feed stream can contain a broad range of compounds, including various monomeric, oligomeric or polymeric sugars, organic acids, furfurals or other oxygenated compounds.

The chemistry underlying the APR process is highly complex, with a number of competing reaction pathways and a highly diverse mixture of educts, intermediate and final products. In the past decade it was discovered by a team at the University of Wisconsin that APR can be used for the production of renewable alkanes [30][31]. R. D. Cortright, a member of that team, later founded the company Virent, located in Madison, Wisconsin, USA, that endeavors the commercialization of the APR technology in cooperation with Shell. Currently, Virent is the only industrial company devoted to the APR production pathway

The production chain, referred to as Bioforming® by Virent, comprises of two steps, as illustrated in Figure 2-9.
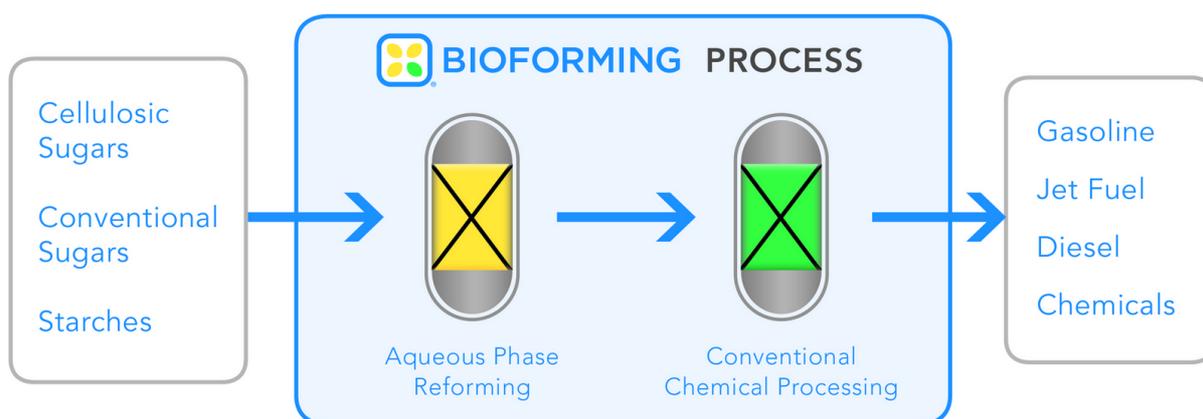
Figure 2-9: Schematic illustration of Virent's Bioforming® process. (Source: Virent, http://www.virent.com/technology/bioforming)

In the first step, the actual APR step, the highly oxygenated feed stream is upgraded, so that it can be further processed via conventional refining technologies, resulting in a range of

renewable drop-in products, such as platform chemicals and liquid fuels. One of the key processes in the APR step is the reforming of carbohydrates to produce hydrogen and, as a by-product, carbon dioxide. Another key process is the dehydration of oxygenated compounds, yielding unsaturated intermediates that undergo further reaction, e.g. hydrogenation by the in-situ generated hydrogen. In essence, the feed stream is partly reformed to produce hydrogen that is needed for the catalytic upgrading of the remaining feed stream of the APR step. The required hydrogen can also be added from an external source, e.g. from a dedicated reforming reactor, in order to simplify the APR step and increase carbon efficiency of the main reaction pathway [32].

The intermediate products from the APR step still represent a broad mixture of compounds, including saturated and unsaturated hydrocarbons, alcohols, ketones etc. These intermediates can be converted via condensation reactions into higher-molecular compounds and then be hydroprocessed into middle-destillate fuels, such as jet fuel. As another option, the intermediate product stream can be processed over a zeolite catalyst to yield gasoline blendstock with a high aromatic content. The generation of aromatic hydrocarbons is also interesting with respect to the drop-in capability of renewable jet fuel produced via APR.

2.6.2   State of development

Jet fuel production through APR is currently exclusively developed by Virent, where the technology has been implemented in "pilot demonstration plant" [33]. The plant has a capacity of about 19 000 liter of diesel and jet per year [34]. Therefore, a technological maturity of the APR-based jet fuel production corresponding to TRL 5-6 can be concluded.

2.6.3   Quality of the fuel

Virent has developed two different APR-based production pathways towards renewable jet fuel:
-   Hydrodeoxygenated Synthesized Kerosene (SK), also named Cyclo-Paraffinic-Kerosene (CPK) represents a mainly aliphatic product with a high content of cycloparaffins of close to 80%, with carbon numbers ranging from C9 to C16.
-   Hydrodeoxygenated Synthesized Aromatic Kerosene (SAK) consisting of mono-aromatic compounds with carbon numbers ranging from C9 to C11. SAK fuel is intended for use as aromatic blendstock, particularly for fuels lacking aromatics.

Neither SK nor SAK fuels alone qualify as 100% drop-in jet fuel, since SK lacks the required aromatic compounds, while SAK fuels are purely aromatic and therefore lack the necessary aliphatic content. However, the capability to produce an aromatic stream suitable for jet fuel application offers the potential to formulate a 100% drop-in capable blend of SK and SAK components.

However, current efforts to achieve technical approval focus on SK and SAK fuels individually. Recent test of jet fuel blends containing SAK showed advantageous results with regard to engine performance [35] and pollutant emissions [33].

2.6.4   Mapping and analysis of R&D activities

No European publicly funded R&D activities devoted to APR technologies were found.

2.7   Lignin-to-Jet conversion

2.7.1   Background

The approach to use a lignin-rich feed stream for the production of renewable jet fuel is currently developed and pursued by the Italian company Biochemtex, notably within the EU-FP7-funded project BIOREFLY. The thermochemical process named *Moghi* utilizes the lignin-rich waste material from ethanol production based on lignocellulosic feedstock. The targeted products are naphtha and aromatic compounds, but also aliphatic compounds suitable for jet fuel application [36]. Unfortunately, there is no publicly available information regarding the technical details of the applied, and consequently no evaluation of this technology can be conducted at this point. However, the limited availability of lignin-rich waste material as well as the complicated chemical structure of lignin (including substantial contents of impurities) potentially pose considerable challenges.

2.7.2 State of development

In the BIOREFLY project, Biochemtex is targeting the construction of "an industrial demonstration-scale plant" with a capacity of 2000 t of jet fuel per year [37]. The actual state of development cannot be evaluated based on the information currently available in the public domain.

2.7.3 Quality of the fuel

Given the scarce information available with regard to the technical details of the process and the resulting fuel, no fact-based assessment of the quality and, hence, the potential suitability for jet fuel application can be conducted. However, if the project is successful in producing aliphatic compounds in the jet fuel range (carbon numbers in the range of C8 – C15), it is conceivable that a fully drop-in capable jet fuel could be produced, if these aliphatic compounds are blended with suitable aromatic fractions that are also claimed to be produced in the Moghi process. Considering the highly aromatic constitution of lignin, the production of aromatic compounds from this kind of feedstock is highly credible.

2.7.4 Mapping and analysis of R&D activities

Only a single project could be identified that is devoted to liquid hydrocarbon fuel production from lignin, namely BIOREFLY (see above and Table 2-4).

Table 2-4: List of identified EU-funded R&D projects related to Lignin-to-Jet conversion.

Acronym	BIOREFLY
Call	FP7-Energy.2013.3.2.1
Duration	2014 – 2018
EU funding (total cost) [10^6 €]	13.8 (22.4)
Feedstock	Lignin-rich waste material from ethanol production
Product	Jet fuel
Stokes' quadrant	Edison (pure applied research)

2.8 Alcohol-to-Jet

The pathway Acohol-to-Jet (AtJ) essentially consists of two independent processes, namely the production of alcohols, generally via microbial fermentation of carbohydrates from biomass or waste industrial gases, and the subsequent conversion of alcohols (the actual AtJ step) into hydrocarbons, *e.g.* jet fuel. Both processes are described briefly in the present section.

2.8.1 Background

Fermentative production of alcohol

The biochemical production of ethanol is an ancient metabolic process. Most microbial species are capable of fermenting sugar (mono- and disaccharides) into ethanol as an "emergency pathway" for energy generation, *i.e.* under anoxic conditions when no oxygen is available for the more effective respiration pathway. This alcoholic fermentation in yeast has been used by mankind since several millennia for producing alcoholic beverages and is now globally applied in the industrial production of ethanol as biofuel (about 40 Mt produced worldwide in 2007 [38]).

Conventional feedstock for ethanol production are sugar crops (sugarcane, sugar beet) and starch crops (potato, corn, wheat, *etc.*). This conventional production pathway is industrial and commercial reality and will therefore not be further addressed here.

An unconventional, yet highly abundant, type of feedstock for alcohol production is lignocellulosic material. As in case of starch, cellulose consists of polymeric glucose (Figure 2-10). Disadvantageously, glucose from cellulose is not as easily accessible as in case of starch. Firstly, cellulose forms a highly resilient composite with lignin, and secondly, the chemical link between the glucose units in cellulose is much stronger than in case of starch and thus requires harsher conditions to be hydrolyzed.

For these two reasons, the provision of monomeric glucose, as needed for alcoholic fermentation, from lignocellulosic material represents a substantially more challenging process than from conventional sugar or starch crops. Various options for hydrolyzing cellulosic feedstock are currently applied or under development, covering physical, chemical as well as biochemical processes [39]. The impurities from these procedures can pose considerable for the downstream fermentation process.

In terms of industrial production of so-called cellulosic ethanol this translates into technically more demanding and consequently costlier process conditions. This is the reason why, despite of the sustainability-related advantages of lignocellulosic feedstocks compared to first-generation feedstocks, commercialization of cellulosic ethanol production is advancing slowly, facing severe economic challenges [40].
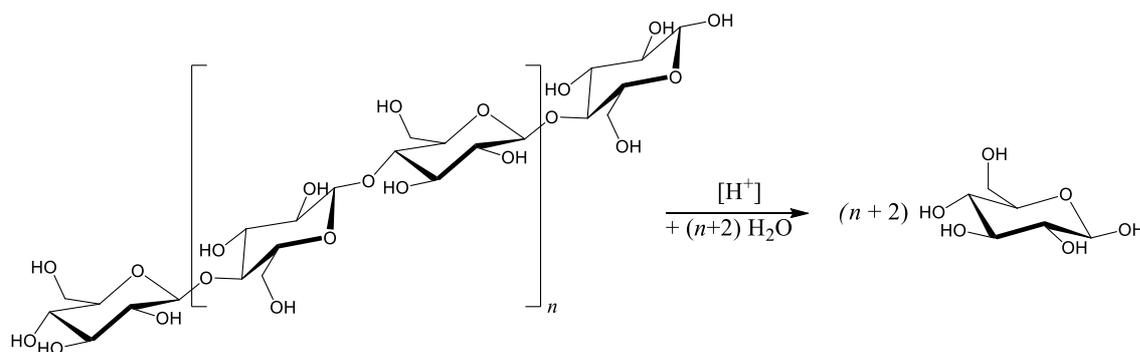
Figure 2-10: Acid-catalyzed hydrolysis of a linear cellulose polymer (left), yielding monomeric glucose molecules (right).

In addition to ethanol, other alcohols can be produced via fermentation of sugars, even though these alternative processes are technically less mature. The probably most prominent example is the production of isobutanol via fermentation in genetically engineered microorganisms, as done by the company Gevo [41].

Alternatively to fermentation of carbohydrates, it is also possible to produce alcohols via fermentation of gases rich in carbon monoxide, e.g. waste gas streams supplied from ironworks. This technology has been developed by the company LanzaTech [42].

AtJ conversion

From a chemical point of view, there are several pathways conceivable for converting alcohols into liquid hydrocarbon fuels. However, only the one most prominently pursued in the current efforts to bring AtJ conversion to commercial application will be addressed here. In this pathway alcohols are first dehydrated, yielding the corresponding alkenes, which are subsequently oligomerized to the desired chain length. Final hydrogenation yields saturated hydrocarbons that could serve, e.g., as blendstock in jet fuel production, if process conditions are chosen accordingly. Figure 2-11 illustrates these processes for the two alcohols most commonly discussed as educts for the AtJ conversion, *i.e*. ethanol and isobutanol.
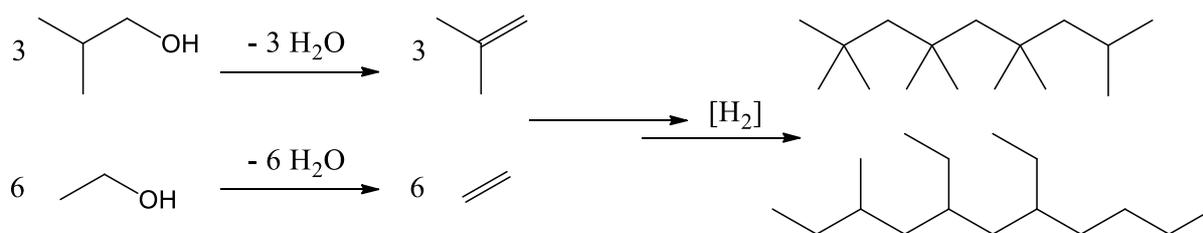
Figure 2-11: Schematic illustration AtJ conversion of isobutanol (top) and ethanol (bottom) into molecules in the jet fuel range. Note: Conversion efficiency and selectivity are not 100%, *i.e.* other products than depicted are formed.

In this process, the molecular structure of the products are specific for the alcoholic educt and the chosen process pathway. This means that AtJ process starting from ethanol yields products that differ from AtJ conversion starting from isbutanol. In case of both alcohols, product molecules show even carbon numbers (multiples of C_2 for ethanol and of C_4 for isobutanol). Formation of the branched AtJ product based on ethanol as feedstock, as shown in Figure 2-11 (bottom), assumes dimerization of ethylene to 1-butene and 2-butene which are then oligomerized and hydrogenated, yielding C_8, C_{12} and C_{16} (as in Figure 2-11) isoparaffins in the jet fuel range (AtJ-SPK). Alternatively, ethylene can be oligomerized directly, resulting in linear paraffins from C_8 to C_{16} in the jet fuel range. In contrast, in case of isobutanol as feedstock, oligomerization and hydrogenation also yields C_8, C_{12} and C_{16} isoparaffins, but with a higher degree of branching (Figure 2-11 top).

In addition to the AtJ-SPK conversion route, it is also possible to convert alcohols (or more precisely: the corresponding alkenes) into aromatic compounds which, if blended with the paraffinic products, yield a potentially 100% drop-in AtJ fuel (AtJ-SKA, *i.e.* Synthesized Kerosene with Aromatics). This is done, *e.g.*, by Gevo (isobutanol pathway) and Swedish Biofuels (from ethanol and other alcohols).

2.8.2   State of development

As mentioned above, several companies are pursuing commercialization of AtJ production, most prominently Swedish Biofuels and Gevo. Gevo's isobutanol production facility is located in Luverne, Minnesota, while AtJ conversion plant is located in Silsbee, Texas. Gevo's AtJ production has reached demonstration scale.

Swedish Biofuels is currently developing its AtJ technology towards industrial-scale production in the course of the EU-finded project BFSJ, in collaboration with LanzaTech and

other partners[3]. The projected overall production capacity of the plant to be constructed by 2019 is 10,000 t of fuel (jet fuel, diesel and gasoline) per year.

Therefore, the current technological maturity of AtJ production is estimated as TRL 6, with the perspective to reach TRL 7-8 by 2019 (upon completion of the BFSJ project).

2.8.3 Quality of the fuel

AtJ-SPK produced by Gevo based in isobutanol has been tested in a 50/50 blend with JP-8 in a military aircraft without any problems [43] and is ASTM qualified since April 2016 (ASTM D7566-16, Annex 5) for use in civil aviation with a maximum blending ratio of 30%.

Approval of other AtJ fuels is pending. As mentioned above, AtJ-SKA can expected to be approved in higher blending ratios than the purely paraffinic AtJ-SPK, potentially even as 100% drop-in fuel [44].

2.8.4 Mapping and analysis of R&D activities

The list of identified EU-funded R&D actions thematically related to the AtJ pathway is presented in Table 2-5. Please note that this list may not be exhaustive and represents the current results of the mapping efforts in CORE-JetFuel. Other actions might appear on the list upon further research, *e.g.* projects funded in national programs (national projects have not been included in Table 2-5). The mapping of the listed actions according to Stokes' quadrant model of research is illustrated in Figure 2-12. Additionally, the distribution of the sum of public funding between use-inspired basic research (Pasteur's quadrant) and pure applied research (Edison's quadrant) can be found in Figure 2-13.

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[3] http://cordis.europa.eu/project/rcn/197830_en.html

Table 2-5: List of identified EU-funded R&D projects of relevance for Alcohol-to-Jet (AtJ) conversion technology. Note: Volumes represent public funding and not total project volumes.

Nr.	Project of category "AtJ"	Basic	Applied	Volume
1	BABETHANOL	Yes	Yes	3.2 mio€
2	BIOCORE	Yes	Yes	13.9 mio€
3	BIOFAT	Yes	Yes	7.4 mio€
4	ButaNexT	Yes	Yes	4.6 mio€
5	CaneBioFuel	Yes	Yes	1.7 mio€
6	CELLULOSOMEPLUS	Yes	Yes	4.0 mio€
7	HYPE	Yes	Yes	3.7 mio€
8	MacroFuels	Yes	Yes	6.0 mio€
9	PROETHANOL2G	Yes	Yes	1.0 mio€
10	STEELANOL	Yes	Yes	10.2 mio€
11	SUNLIBB	Yes	Yes	3.4 mio€
12	WASTE2FUELS	Yes	Yes	6.0 mio€
13	2G BIOPIC	No	Yes	20.0 mio€
14	BFSJ	No	Yes	27.8 mio€
15	BIOLYFE	No	Yes	8.6 mio€
16	COMETHA	No	Yes	17.9 mio€
17	CoRYFee	No	Yes	0.9 mio€
18	DEMA	No	Yes	4.9 mio€
19	FibreETOH	No	Yes	8.6 mio€
20	KACELLE	No	Yes	9.1 mio€
21	LED	No	Yes	8.6 mio€
22	MET	No	Yes	39.3 mio€
23	MSWBH	No	Yes	n/a
24	NPLCT	No	Yes	2.8 mio€
25	SUNLIQUID	No	Yes	23.0 mio€
26	W2B	No	Yes	29.2 mio€
	Total volume			**265.8 mio€**
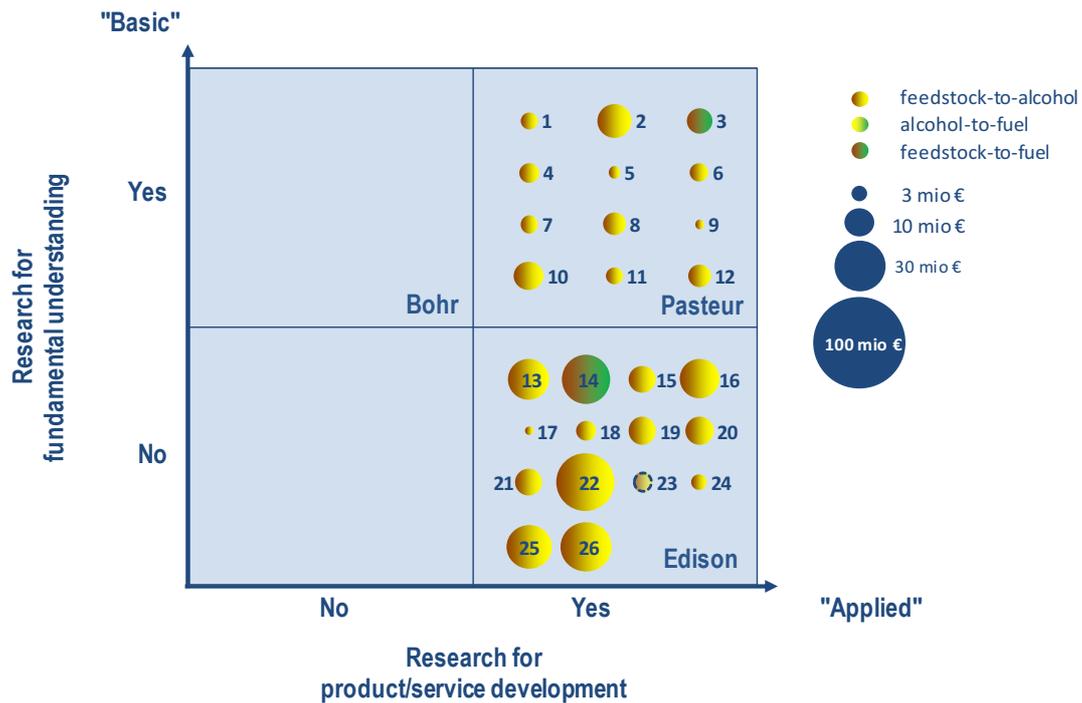
Figure 2-12: Mapping of identified EU-funded R&D projects of relevance for Alcohol-to-Jet (AtJ) conversion technology. Area of disks corresponds to the volume of public funding for the respective activity. Please note: No distinction in scope ("more basic" or "more applied") between activities within a specific quadrant can be deduced; individual placement within quadrant is arbitrary.
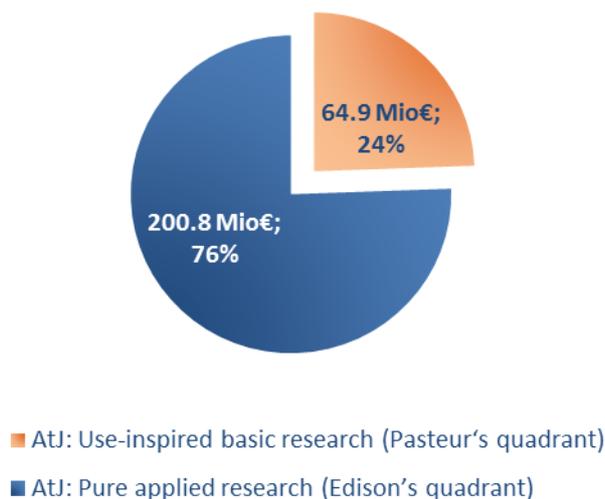
Figure 2-13: Distribution of European R&D funding of relevance for Alcohol-to-Jet (AtJ) conversion technology between Pasteur's and Edison's quadrant.

It is obvious from Table 2-5 and Figure 2-12 that nearly all identified projects are concerned with alcohol (ethanol) production, while only two publicly funded activities (at least at European level) could be found that are focused on AtJ conversion, *i.e.* the conversion of alcohols into hydrocarbon fuels. Since ethanol is a globally used biofuel for road transport and ethanol production from so-called first-generation feedstocks (*i.e.* food crops) is very controversially discussed, great efforts are focused worldwide on the commercialization of second-generation ethanol from cellulosic biomass. However, as described above, (ligno-)cellulose is chemically and mechanically much more stable than starch, and therefore an economically viable production of cellulosic ethanol at industrial scale is challenging.

As in case of BtL, all identified actions related to ethanol production are located either in the Pasteur's or Edison's quadrant. This reflects the fact that the technologies underlying cellulosic ethanol production are not novel, but have to be further developed towards industrial application and commercialization. Further, the distribution of the sum of public funds for use-inspired basic research (Pasteur's quadrant) and pure applied research (Edison's quadrant) displays a 24 to 76 percent ratio (Figure 2-13). Even though alcohols can be used as AtJ feedstock independently of their origin, it is of great importance and interest for the aviation industry that the alcoholic feedstock is produced from sustainably sourced biomass. In this context cellulosic materials, being highly abundant and often available in the form of waste streams, offer the lowest risk in terms of sustainability.

2.9   Direct-Sugar-to-Hydrocarbon

The Direct-Sugar-to-Hydrocarbon (DSHC) pathway represents the microbial (fermentative) conversion of carbohydrates (sugars) to hydrocarbon products. This general approach is pursued by several companies, most prominently Amyris (in collaboration with Total). But also the company Global Bioenergies is developing a DSHC technology. While Amyris is producing a middle-destillate product (see Section 2.9.1 below), Global Bioenergies is targeting isobutene as product, which can then be processed into longer hydrocarbon fuels. Since the intermediate compound in this case, i.e. isobutene, is the same as in case of Gevo's AtJ-SPK production (Section 2.8.1), the resulting middle-destillate fuels are identical.

However, as the Amyris technology is far more developed, the present Section 2.9 will entirely focus on that technology. Nevertheless, it should be noted that Global Bioenergies are

working on the scale-up of their technology, projecting isobutene production of 50,000 t per year from 2018 [45]. However, this scale-up does not (yet) cover further upgrading of isobutene into hydrocarbons in the jet fuel range.

2.9.1 Background

The conversion route Direct-Sugar-to-Hydrocarbon (DSHC) developed by Amyris represents a process (depicted in Figure 2-14) in which sugar (mainly glucose or sucrose) is converted by genetically engineered microorganisms into the C_{15}-alkene farnesene. In a second step, farnesene is saturated *via* hydrogenation, yielding the final fuel product farnesane.

Figure 2-14: Scheme of the DSHC (SIP) pathway (Amyris process).

This process has been developed by the company Amyris, which has now partnered with Total. In the course of ASTM approval, the fuel was re-named into SIP (synthetic isoparaffinic) fuel. Unfortunately, owing to the fact that the technology (especially the microbial step) is proprietary and has been exclusively developed by Amyris, little is known about production conditions, efficiencies, yields as well as economic and environmental performance of the process.

2.9.2 State of development

Amyris is producing SIP fuel at a demonstration-scale facility in Brazil from sugar cane, with a production capacity of about 25,000 t of fuel per year. SIP jet fuel is commercially available, but only in small quantities for demonstration flight purposes. A technology maturity corresponding to TRL 6 is estimated for SIP fuel production.

2.9.3 Quality of the fuel

In 2014, the farnesane produced in the Amyris process was approved according to ASTM D7566 for use in civil aviation at a maximum blending ratio of 10%. The reason for this

comparably low blending limit is the fact that the synthetic fuel component consists of a single chemical compound, *i.e.* farnesane.

2.9.4 Analysis and mapping of R&D landscape focused on Direct-Sugar-to-Hydrocarbon

No EU-funded (or other publicly funded) R&D actions related to the DSHC pathway other than the one pursued by Amyris could be identified.

2.10 Power-to-Liquid conversion

2.10.1 Background

Power-to-Liquids (PtL) is a production pathway for liquid hydrocarbons based on electric energy, water and carbon dioxide (CO_2) as main resources [46] (schematic illustration of the PtL process is presented in Figure 2-15). If the electric energy and CO_2 is generated from renewable sources, PtL represents a renewable but biomass-independent (non-biogenic) pathway towards liquid fuels. The basic principle of PtL is to "fuel" the energy-demanding (endergonic) process of synthesizing energy carriers (fuels) from the low-energy compounds water and carbon dioxide by electric energy.

PtL production comprises three main steps:
1. Hydrogen production from renewable electricity using the electrolysis of water.
2. Provision of renewable CO_2 and conversion into liquid raw product. Fischer-Tropsch (FT) synthesis is typically considered and used for the liquefaction step. Therefore, a preceding reverse water-gas shift (RWGS) has to be implemented in order to convert CO_2 to the required carbon monoxide (CO).
3. Upgrading and refining into readily useable fuel products.
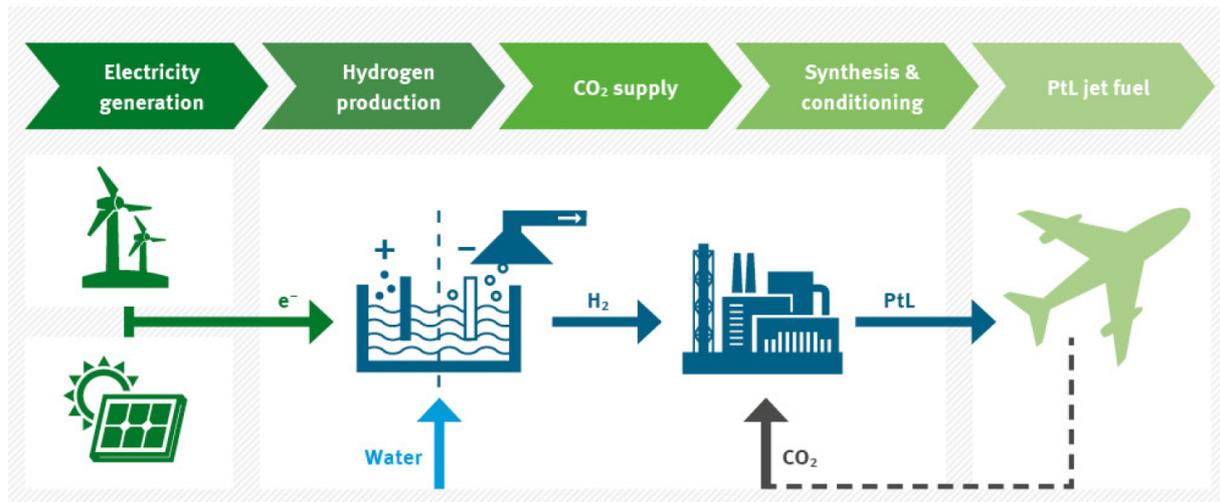
Figure 2-15: Basic principle of the PtL process. (Source: PtL Background Paper, German Environment Agency, 2016 [47]; diagram produced by Ludwig-Bölkow-Systemtechnik GmbH).

The electrolysis of water represents the process step where electric energy is converted into chemically stored energy, i.e. where the first chemical energy carrier (fuel) is generated in the form of hydrogen. Pure oxygen is generated as by-product that can add value to PtL production. Electrolysis of water, notably alkaline water electrolysis, is an industrially established technology already applied for many decades. However, in order to achieve high process efficiencies, more advanced electrolytic technologies are required. For example, application of high-temperature steam electrolysis using a solid oxide electrolysis cell (SOEC) significantly improves overall energy efficiency, as the waste heat of FT synthesis can be recuperated and used to evaporate water required for electrolysis. Most importantly, electricity demand of high-temperature steam electrolysis is significantly lower compared to conventional low-temperature electrolysis. The technology also offers the potential for co-electrolysis of steam and CO_2 [48][49], producing hydrogen and carbon monoxide in a single step and thus avoiding a RWGS step (see below). However, application of high-temperature steam electrolysis requires further development and validation (Section 2.10.2).

In the next process step, hydrogen is reacted with carbon dioxide (CO_2). In order to feed the Fischer-Tropsch (FT) synthesis, the CO_2 has to be converted into the more reactive carbon monoxide (CO) in the reverse water-gas shift reaction (RWGS):

$$H_2 + CO_2 \leftrightarrow H_2O + CO$$

In this context it has to be noted that there is currently considerable effort devoted to the development of catalyst systems that allow a direct feeding of FT synthesis with CO_2. However, such catalysts are not yet commercially available.

The CO generated through RWGS is then fed with hydrogen as synthesis gas into the FT synthesis, and downstream fuel production is identical to other FT-based processes, such as BtL / WtL (Section 2.3) and the solar-thermochemical process (StL, Section 2.11).

An aspect of crucial importance for PtL as well as for all processes depending on external supply of CO_2 as feedstock, such as solar-thermochemical fuel production (Section 2.11) and pathways based on microalgae, is the source of applied CO_2. Recent studies show that only a renewable CO_2 supply enables a truly renewable fuel production [50][51]. Even though various renewable point sources of carbon dioxide can be used, such as ethanol production or biogas plants, only direct extraction from air (direct air capture, DAC) would allow for a supply quantity that could match the huge production potential of PtL fuels. To date, CO_2 extraction from air has been developed to demonstration scale (TRL 6), e.g. by Swiss-based company Climeworks, but substantial development efforts are needed to bring this key enabling technology to industrial maturity.

2.10.2 State of development

Important individual process steps of PtL fuel production have been already industrially implemented: Conventional (low-temperature alkaline) water electrolysis and FT synthesis are mature technologies readily available for large-scale production. However, more efficient concepts, e.g. polymer membrane or high-temperature solid-oxide water electrolysis, are not yet ready for industrial production. As considerable R&D efforts are currently devoted to these technologies, i.a. in the course of various industrial Power-to-Gas (PtG) projects under construction worldwide, rapid progress in this domain can be expected.

Reverse water-gas shift (RWGS) is another process step requiring further development. In contrast to the water.-gas shift (WGS) reaction that is commercially applied for hydrogen production, the backward RWGS reaction has not been yet used in industrial processes. Finally, as described above, remains the crucial aspect of renewable CO_2 supply a yet unresolved challenge. Direct capture from air (direct air capture, DAC) represents the only viable and generally applicable option for a supply at sufficient scale, particularly in remote locations. Nevertheless, the low concentration of CO_2 in air of about 400 ppm renders

economically efficient DAC difficult. The technology has been technically demonstrated, e.g. by the company Climeworks, but not yet implemented at relevant scale.

Even though individual process steps of PtL production are already mature or, at least, developing quickly at present, it has to be emphasized that it is important to develop and demonstrate the entire integrated production chain. An almost complete PtL pathway with diesel as a final product is being demonstrated by the company Sunfire. In autumn of 2014, the demonstration plant was inaugurated in Dresden (Germany). The installed production capacity currently corresponds to about 1 barrel of crude FT product per day. The concept comprises a high-temperature (solid-oxide) electrolyzer using excess heat from Fischer-Tropsch synthesis. No upgrading/refinement of crude FT product has been installed to date. However, being a readily available technology that is used in large-scale CtL and GtL facilities, upgrading/refinement does not present a major challenge.

Considering the maturity of the individual process steps, an overall technological maturity corresponding to TRL 5-6 is concluded for PtL-based fuel production. Larger projects covering the entire production chain, including renewable CO_2 supply and upgrading to readily usable fuels products, are required to move this promising technology further towards industrial implementation.

2.10.3 Quality of the fuels

If produced via FT synthesis, PtL-derived jet fuel is already approved as FT-SPK for use in civil aviation (see Section 2.3.3).

2.10.4 Mapping and analysis of R&D activities

Only a single project could be identified that is devoted to Power-to-X conversion technologies, namely MefCO2 (see Table 2-6).

Table 2-6: List of identified EU-funded R&D projects related to Power-to-Liquid (PtL) conversion technology.

Acronym	**MefCO2**
Call	H2020-SPIRE-2014
Duration	2014 – 2018
EU funding (total cost) [10^6 €]	8.6 (11.0)
Feedstock	captured carbon dioxide and surplus electricity
Product	methanol
Stokes' quadrant	Edison (pure applied research)

This single project is devoted to the Power-to-Gas technology, i.e. not to liquid fuel production. However, development in the field of PtG technologies is also highly relevant and valuable for PtL development, as key process steps of both pathways are essentially identical: electrolysis of water, CO_2 capture and conversion of CO_2 and H_2 into carbonaceous fuel products.

2.11 Solar-thermochemical fuel production

2.11.1 Background

The solar-thermochemical production pathway, also referred to as Sun-to-Liquid (StL), schematically depicted in Figure 2-16, comprises the solar-driven thermochemical splitting of CO_2 and water, resulting in the formation of syngas (a detailed description of the StL process is given by Chueh *et al.* (2010) [52]). Downstream of this thermochemical reaction, the StL pathway is essentially identical to the BtL pathway: syngas is converted into syncrude *via* Fischer-Tropsch synthesis, followed by refining of the syncrude *via* hydroprocessing finally, yielding jet fuel (and/or other fuels, depending on refinery design) in the form of FT-SPK.
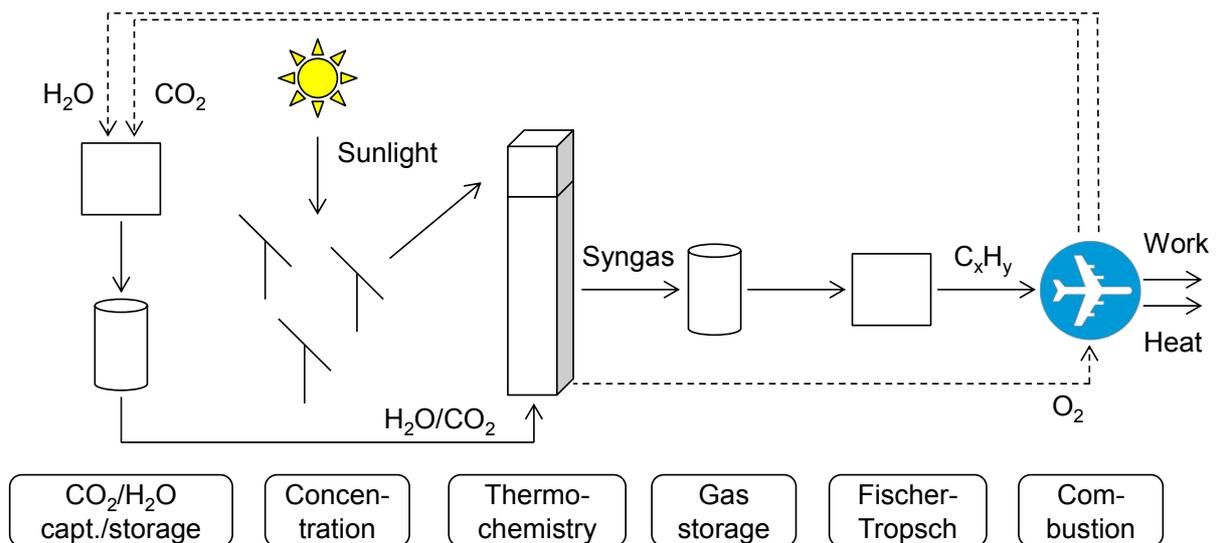
Figure 2-16: Schematic illustration of solar-thermochemical fuel production (Sun-to-Liquid, StL). (Source: SOLAR-JET project)

The StL process is driven by solar high-temperature heat which is supplied by concentrated solar irradiation. The required concentration of 1500 times and more is achieved through the use of solar tower or dish concentrating systems, analogous to Concentrated Solar Power (CSP) plants.

The thermochemical reaction represents the "heart" of the StL process. The reaction is mediated by a metal oxide, e.g. by CeO_2 (ceria), as shown in Figure 2-17. The metal oxide partly decomposes at high temperatures around 1800 K, releasing oxygen. The partly reduced metal oxide is then re-oxidised at lower temperatures around 1000 K by CO_2 and water that are fed into the reactor, thereby forming hydrogen and carbon monoxide, *i.e.* syngas.

$$reduction: \qquad MeO_x \leftrightarrow MeO_{x-\delta} + \frac{\delta}{2}O_2$$

$$oxidation: \quad MeO_{x-\delta} + \delta H_2O \leftrightarrow MeO_x + \delta H_2$$

$$MeO_{x-\delta} + \delta CO_2 \leftrightarrow MeO_x + \delta CO$$
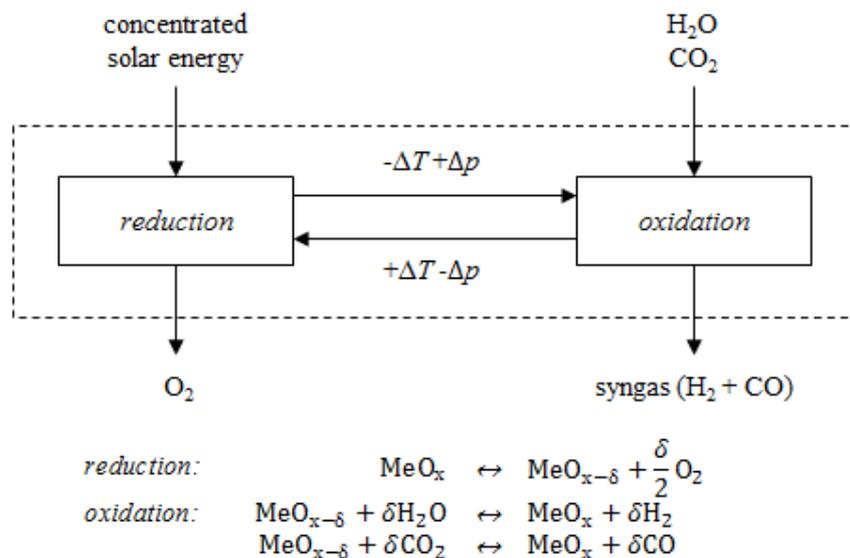
Figure 2-17: Metal oxide-mediated thermochemical reaction of the StL process. (Source: Roth *et al*. (2015) [53])

The advantage of the StL pathway is that it offers a process of renewable fuel production without relying on biomass as feedstock. The efficiency of biomass production is limited by the inherently low efficiency of photosynthetic conversion of solar into chemically stored energy [54][55]. Moreover, locations with the highest potential for StL production are characterized by a very high solar irradiation and low humidity; conditions that are detrimental to agricultural cultivation. Therefore, the risk of competition for agricultural land associated with the large-scale implementation of StL is very low.

Another advantage of the StL pathway is the vast production potential. Rigorous GIS[4]-based evaluations of suitable land areas for concentrated solar power generation revealed a technical potential of 3,000,000 TWh$_{el}$ yr^{-1} [56]. This means that less than 1% of the most favorable areas for solar energy generation would be sufficient to meet the entire global electricity demand. It also means that the global aviation fuel demand could easily be met with StL fuels.

However, even if there are undoubtedly huge potentials associated to StL technologies, there are also substantial risks and obstacles, with the most relevant being attributed to the thermochemical reaction. While all other process steps, *e.g.* solar concentration technologies,

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[4] Geographic Information System

have already been proven at industrial scale, the state of development of the solar-thermochemical reaction system is still at laboratory-scale. It is the efficiency of this processes step that mainly determines the economic and environmental performance of the entire process [53].

2.11.2 State of development

The solar-thermochemical conversion of water and carbon dioxide into liquid hydrocarbon fuels is currently in the state of research, going from laboratory to pilot scale. The objective of EU-funded project SUN-to-LIQUID is the validation of the StL technology in a relevant environment, corresponding to a projected TRL 4-5 at the end of the project in 2019. The current technological maturity corresponds to TRL 3-4.

2.11.3 Quality of the fuel

If produced via FT synthesis, StL-derived jet fuel is already approved as FT-SPK for use in civil aviation (see Section 2.3.3).

2.11.4 Analysis and mapping of R&D landscape focused on Sun-to-Liquid

The only EU-funded projects currently or recently concerned with StL fuel production are SOLAR-JET and SUN-to-LIQUID (Table 2-7). It seems reasonable to conclude that more R&D efforts are required to bring this promising technology to a degree of higher maturity that would allow the evaluation of the process performance in a relevant operational environment at continuous operation conditions. Considering the current early stage of development especially of the solar-thermochemical conversion, near-term future R&D actions should be located in the Pasteur's quadrant and aim at fundamental understanding as well as product development.

Table 2-7: List of identified EU-funded R&D projects of relevance for solar-thermochemical conversion technology (StL). Note: Volumes represent public funding and not total project volumes.

Nr.	Project of category "StL"	Basic	Applied	Volume
1	SOLAR JET	Yes	Yes	2.2 mio€
2	SUN-to-LIQUID	Yes	Yes	4.5 mio€
	Total volume			**6.6 mio€**

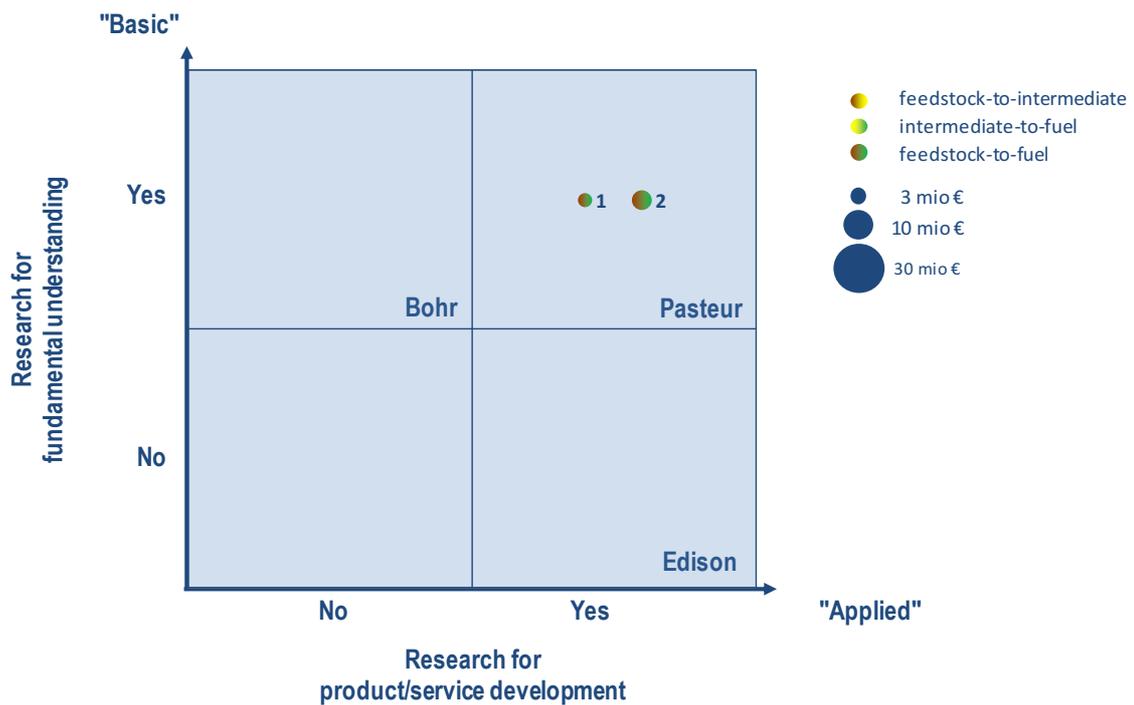**Figure 2-18:** Mapping of identified EU-funded R&D projects of relevance for Sun-to-Liquid (StL) conversion technology. Area of disks corresponds to the volume of public funding for the respective activity. Please note: No distinction in scope ("more basic" or "more applied") between activities within a specific quadrant can be deduced; individual placement within quadrant is arbitrary.

PART B

Holistic Assessment

3 Assessment of integrated production chains

The chart depicted in Figure 1-1 in Part A of the present report shows a great number of fuel production pathways from a combinatorial variety of renewable feedstocks and conversion technologies. From this variety, a few production pathways are selected based on relevance to the various aspects of CORE-JetFuel. In the following, nine selected integrated supply chains for renewable "drop-in" jet fuel are compared, combining feedstock and conversion technologies, first for overview in a multiple-criteria matrix and second for the visualization and evaluation of combinations of selected criteria.

In Chapter 1, the production pathways are briefly specified and their key aspects are presented.

In Section 3.2, the set of criteria for the general assessment, the methodology which was laid out in detail in CORE-JetFuel reports D2.1 [2], D4.3 [[57] and the basic literature cited therein, see refs [58],[59],[60],[61] and [62], is adapted and complemented by Europe-specific criteria for the assessment of the selected production pathways.

In Section 4, the fuel pathways are evaluated, and results and specific recommendations are summarized.

We present a selection of pathways that cover the entire range of integrated supply chain research from high-risk high-gain technologies for long-term perspectives, in order to achieve a balance in the assessment approach.

3.1 Production chains selection for holistic assessment

The selection of technologies for intermediate assessment comprises nine production pathways for renewable "drop-in" jet fuel covers various aspects relevant to the CORE-JetFuel objectives in this workpackage, such as the evaluation of technologies and R&D perspectives in the field of

- **feedstock diversity**: vegetable oils, non-food oils, lingocellulosic and biomass-independent resources
- **conversion technology diversity**: mature HEFA technology in combination with well-researched and radically new feedstocks and processes (e.g. sun-to-liquid, StL) as well as new conversion technologies, such as Alcohol-to-Jet (AtJ), hydrothermal liquefaction (HTL) and hydrotreated depolymerized cellulosic jet (HDCJ)

- **TRL diversity**: from high-TRL deployment-oriented research in more mature integrated supply chains for (partially) certified pathways as well as low-TRL use-inspired basic research in high-risk high-gain technologies for long-term perspectives

The selected nine production pathways, consisting of feedstock and conversion technologies, are

(1) HEFA fuel from camelina oil (HEFA / Cam)

The oleaginous energy crop camelina (*Camelina sativa*) is described in CORE-JetFuel deliverable D4.1 and D4.2. The HEFA conversion of oils and fats is analyzed in Section 2.2 of the present report. The main data source is the FP7-project ITAKA[5]

(2) HEFA fuel from used cooking oil (HEFA / UCO)

Used cooking oil as feedstock for HEFA conversion is described in CORE-JetFuel deliverable D4.2 [63].

(3) HEFA fuel from microalgae oil (HEFA / µA)

Microalgal oil as feedstock is described in CORE-JetFuel deliverable D4.2 [63].

(4) HTL fuel from microalgae (HTL / µA)

In contrast to the HEFA / µA process, microalgal biomass is converted through hydrothermal liquefaction (HTL), a process described in Section 2.4 of the present report.

(5) AtJ fuel from ethanol, supplied via advanced fermentation technologies using switchgrass or short-rotation coppice as a lignocellulosic feedstock (AtJ / LC)

Switchgrass (*Panicum virgatum*) is a perennial, warm season bunchgrass native to North America that is cultivated as a promising energy crop. For a detailed introduction to switchgrass and other lignocellulosic feedstock, please refer to CORE-JetFuel deliverables D4.1 and D4.2. The AtJ conversion of lignocellulosic feedstock is described in Section 2.8 of the present report.

(6) HDCJ fuel from lignocellulose (HDCJ / LC)

In contrast to the AtJ´/ LC process, lignocellulosic biomass fed into the conversion process called hydrotreated depolymerized cellulosic Jet. The process described in Section 2.5.

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[5] http://www.itaka-project.eu/default.aspx

(7) BtL fuel from short-rotation coppice as a lignocellulosic feedstock (BtL / LC)

The conversion of lignocellulosic feedstock via BtL technology is subject of Section 2.3 of the present report; feedstock production of short-rotation coppice is described in CORE-JetFuel deliverables D4.1 and D4.2, and in the burnFAIR final report [5].

(8) PtL fuel: FT-SPK from syngas, supplied via conversion of water and carbon dioxide extracted from air (PtL / airCO2)

The PtL pathway is introduced in Section 2.10 of the present report.

(9) StL fuel: FT-SPK from syngas, supplied *via* solar-thermochemical conversion of water and carbon dioxide extracted from air (StL / airCO$_2$)

The StL pathway is introduced in Section 2.11 of the present report. A comprehensive source of data are the FP7-project SOLAR-JET[6], related publications and expert communication

3.2   Criteria selection

The general assessment methodology, as laid out in detail in Section 3.6 in CORE-JetFuel report D2.1 [64], D4.3 [57] and the basic literature cited therein, see refs. [58],[59],[60],[61] and [62], is applied to selected criteria and combinations thereof. A multiple-criteria set of core performance indicators is defined and their application results are visualized and discussed. The basic set of criteria pertains to aspects of sustainability and other relevant characteristics, e.g., economic performance or potential availability on a European and a global scale.

For future decision making for funding of research and innovation of various technologies it is important to choose a set of criteria that covers all significant aspects for accurately reflecting the pre-decision "conflict" [65], yet to limit the set of criteria to essential elements that can be assessed with sufficient confidence and quality of information.

The criteria selected for assessment are the following:

- Technical maturity
  - o   Technical maturity of feedstock production
  - o   Technical maturity of conversion technology

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[6] http://www.solar-jet.aero

- Economic competitiveness

- European and global substitution potential

- Specific greenhouse gas (GHG) emission reduction

- Potential impact on European and global GHG emission reduction

In the following, sections, each criterion is explained and the according metrics are defined. Most of the criteria definition information below is recited from the intermediate assessment presented in D4.3 in order to make this report D4.4 self-contained in the presentation pf metrics and interpretation of results. However some essential amendments pertaining to the European perspective and to the evaluation of the potential impact on GHG emission reduction are implemented in this updated criteria presentation.

3.2.1 Technical maturity

The technical maturity criterion is described in Sections 3.6.2-3.6.4 (pages 52-54) in CORE-JetFuel report D2.1 [64]. In short:

- For evaluating the maturity of feedstock production, a simplified version of the *Feedstock Readiness Leve*l (FSRL) metric[7] is used, as described in Report D2.1 [64].

- For evaluating the maturity of conversion technologies, application of a *Conversion Technology Readiness Level* (CTRL) scheme is proposed, as shown in Report D2.1[64].

- For evaluating the *Technology Readiness Level* (TRL) of the integrated production pathway (combining feedstock and conversion technology), it has to be acknowledged that the *lower* of the two complementary readiness levels, FSRL and CTRL, defines the maturity of the entire production chain, i.e.

$$TRL = Min[FSRL, CTRL]$$

according to the principle that the weakest link defines the strength of the whole chain. In other words, the integrated TRL is interpreted as metric for the readiness level of a system of all integrated sub-system technologies and therefore reflects the level of

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[7] FSRL originally introduced by the Commercial Aviation Alternative Fuels Initiative (CAAFI), 2011.
http://www.caafi.org/information/pdf/FeedstockReadinessLevel_posted_2011_12.pdf (accessed March 31, 2014)

uncertainty of success for this integrated system, i.e. the feedstock and fuel production technology.[8]

For CORE-JetFuel we use the classical TRLs as defined in the Annex of the Horizon 2020-Work Programme [66]

Table 3-1: Definition of the integrated Technology Readiness Levels (TRL)

TRL	Short description
1	Basic principle observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment („from lab to pilot scale")
6	Technology demonstrated in relevant environment („from pilot to demonstration scale")
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

3.2.2 Economic competitiveness

The criterion of economic competitiveness of a fuel production pathway is determined by the well-to-tank (WtT) cost of production per unit output in comparison to the cost of production of the same unit of established product on the market. Therefore, not the absolute, but the relative costs are important. As a reference, not the actual production cost but the spot price for Jet A-1 was used, which constitutes the upper bound of WtT production cost [8]. As a basis for the comparison of the various estimates from literature, the currency USD ($) is

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[8] Simply calculating an arithmetic average of the technology readiness levels is meaningless, since the individual TRLs are a non-numerical metric that have a certain meaning in a look-up table. Following the method of an additive value function in an MCA scheme, a combination of weighted FSR and CTR sores would be suitable alternative approach if we interpret the integrated TR score as metric for the effort (not uncertainty) that has still to be spent on the way of development towards market maturity. See details in Section 3.6.4 of CORE-JetFuel report D2.1 [64] (confidential). Here we obtain the overall TRL (and then score the TRL) in order to be able to report the TRL of the integrated value chain.

chosen (09/2013 value). Where necessary, the original information was converted into this unit by using historical inflation and exchange rates. Whenever an original document did not contain distinct information about the time needed to calculate the inflation of the currency, the year of publication was used instead.

Metric: For the current assessment we use the *production cost relative to the market value of conventional jet fuel*. This relative metric is denoted as γ, is without units and is defined as

$$\gamma(\text{Fuel}) = \frac{C(\text{Fuel}) - C_{\text{Ref}}}{C_{\text{Ref}}} \ ,$$

where C is the WtT production cost and C_{Ref} the 2013 market price[9] of the reference fuel, i.e. of conventional Jet A-1, which is approximately 1000 USD/t.

Economic measures like emission trading give added value to renewable fuels with a favorable greenhouse balance. These are benefits are not included in the cost-based metric used here in order to present a clear picture the expected price gap. Measures for enhancing the competitiveness by adding value to emission reduction can be implemented separately.

As prices for jet fuel will probably rise in the long term due to increasing oil prices, future fuels with production costs above the 2013 spot price of conventional Jet A-1 may become competitive at a future value of γ larger than the 2013 jet fuel benchmark "zero" due to the 2013 spot price. Ideally however, the anticipated renewable fuel costs should be at or below the 2013 spot price ($\gamma \leq 0$) for early entry into the market.

3.2.3 European and global substitution potential

The criterion substitution potential is used to account for the scalability of the fuel production technology. Its specific property is the quantity of jet fuel that can be produced per year in a given region in relation to the region's annual jet fuel demand. The production potential of a fuel pathway can be calculated from its areal productivity and the size of the available, suitable land area under sustainable conditions. For fuel production only those areas are considered that are not required for food production and that exclude environmental protection zones.

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[9] International Air Transport Association (IATA), "Fuel Price Analysis: Current price of aviation jet fuel", 2013

In CORE-JetFuel, the primary focus of the assessment lies on the *European* substitution potential, according to the objective of "increasing energy production in the European Union" as one of the eight key pillars of the European Energy Security Strategy.[67] It is, however, acknowledged that aviation represents a global sector and, consequently, renewable jet fuel has to be provided globally in order to enable a sustainable energy transition for the entire sector. Therefore, *global* substitution potentials are also discussed in the present report, if data are available.

It is also important to note that the European/global jet fuel demand *anticipated for 2050* is used as reference for the European/global substitution potential. This is consistent with the fact that most of the assessed production technologies are not yet technically mature and thus represent options for medium to long-term deployment. Therefore, their potential needs to be evaluated against future demand, not the present one.

Metric: For the current assessment we use the *substitution potential in year 2050 relative to the demand conventional jet fuel*, i.e. the percent substitution of conventional jet fuel. This relative metric is denoted as σ [or σ_{EU}], is without units and is defined as

$$\sigma(\text{Fuel}) = \frac{\dot{M}(\text{Fuel})}{\dot{M}_{\text{Ref}}} \quad ,$$

where $\dot{M}$ is the mass rate, i.e. the annual global [resp. European] production potential of the fuel under assessment and $\dot{M}_{\text{Ref}}$ is the mass rate that represents the global [resp. European] annual demand of the reference fuel, i.e. conventional Jet A-1.

3.2.4 Specific greenhouse gas emission reduction

Lifecycle greenhouse gas (GHG) emissions are also called "well-to-wake" (WtW) emissions and include the fuel combustion. The main difference in fossil and renewable drop-in fuels originates from the source of carbon and other GHG emissions for the well-to-tank contribution, whereas the tank-to-wake emissions differ only slightly. More specifically, the GHG contribution in some biofuel production paths is dominated by the specifics of biomass production and may vary largely for identical fuel products.

For a assessment we have to clearly define the scope of the "GHG emission reduction". A specific renewable fuel technology that has potentially a strong positive impact on emission reduction of the global aviation fleet needs to excel in three categories: it requires

- a low well-to-wake emission of the unblended fuel,
- a high maximum blending ratio and
- a large production potential.

Here we evaluate only the *specific GHG emission reduction of the unblended fuel relative to conventional jet fuel*, i.e. the first category.

Besides a strong contribution from carbon dioxide (CO_2), the fuel production process may also release other greenhouse gases like methane (CH_4) or nitrous oxide (N_2O) into the atmosphere. The primary metric is the carbon dioxide equivalent (CO_2-eq.) emission that takes the equivalent global warming potential of gases into account. For example, methane is considered to have 26 times the global warming potential of carbon dioxide, thus 1 g of methane is expressed as 26 g (CO_2-eq.).

Metric: For the current assessment the cumulative greenhouse gas emissions of a certain fuel production pathway and combustion are determined and expressed as carbon dioxide equivalents. These emissions divided by the amount of produced jet fuel (g (CO_2-eq.)/kg (fuel)) yield the specific WtW greenhouse gas emissions.

For the current assessment we use the *specific GHG emission reduction of the unblended fuel relative to conventional jet fuel*, i.e. the percent reduction potential by substitution of the same amount conventional jet fuel. This relative metric is denoted as ε, is without units and is defined as

$$\varepsilon(\text{Fuel}) = \frac{\text{CI}(\text{Fuel}) - \text{CI}_{\text{Ref}}}{\text{CI}_{\text{Ref}}} \quad,$$

where CI is the equivalent carbon intensity of the fuel under assessment and CI_{Ref} is the equivalent carbon intensity of the reference fuel, i.e. conventional Jet A-1. We obtain $\varepsilon(\text{Jet A-1}) = 0$. Negative values of $(-100\%) < \varepsilon < 0\%$ show GHG reduction potential relative to Jet A-1.

3.2.5 Potential impact on European and global GHG emission reduction

Future technology assessment leads (a.o. objectives) to a better understanding of the possibilities for additional advances of respective technologies, and their future impact. In strategic decisions e.g. in the case of the development of future work programmes and funding strategies, the potential impact of a future technology on European or global scale has to be taken into account. The term "potential" impact assumes that this impact is within the physical and/or technical performance limits of a technology assuming it is mature (TRL6-9) in the future, not the impact at the state of the art or at a future intermediate (<TRL6) decision point. This potential impact represents a potential "reward" for the risk and effort of maturing the technology and is therefore the necessary corresponding trade-off metric for risk and effort. As mentioned above, the impact on the climate depends on the amount of fossil fuel displaced by alternative fuels on the market, and on the lifecycle emission reduction of this alternative fuel. We recommend to complement the set of core metrics with the following performance indicator:

The "*potential impact on GHG emission reduction*" is greenhouse gas emissions reduction potential relative to future fuel emission impacts. This performance indicator reflects the fact that an advantageous specific GHG balance alone is not sufficient; such fuel would also have to be supplied in large quantities to have a real impact. Any strategy to achieve climate mitigation targets is obviously linked to both volumes of fuels and their carbon intensity. By relating the absolute reduction potential to the absolute fossil emission trend, the relative potential impact is obtained.

Metric: For the current assessment the "*potential impact on global [European] GHG emission reduction*" it is straightforward to verify that the product of the metrics defined earlier, σ [or σ_{EU}] (global [European] production potential relative to the global [European] demand in 2050) and ε (specific lifecycle GHG emissions relative to conventional jet) represents this potential impact ψ [or ψ_{EU}] of the technology under assessment, i.e.

$$\psi(\text{Fuel}) = \sigma \cdot (-\varepsilon) \ ,$$

with σ and ε as defined above.

4 Evaluation of production pathways

In the present chapter, production pathways are evaluated with respect to the set of criteria and metrics described in the previous chapter. The evaluation has been conducted based on the referenced sources of information, such as scientific publications, data bases and other sources, complemented with own estimations where necessary.

The evaluation of the pathways is complex, since various technologies and criteria as well as many data and data sources are involved.

4.1 Multiple-criteria matrix of results

In the following we use the set of key performance indicators (metrics), i.e. quantitative and measurable properties, for the assessment of different production pathways. In this context it is important to emphasize that there is no single most important performance indicator, as the desired solution has to fulfill several highly weighted criteria reasonably well. However, the assessment shows that a production chain that exhibits favorable performance in one criterion might be compromised by disadvantageous performance with respect to other criteria of equal importance.

The collected data cover a broad range of values and are associated with considerable variation and uncertainties which we show in graphical presentations in later sections of the report. In this section we first present the "typical" values in the multiple-criteria matrix of results (Table 4-1), without specifying confidence intervals or range of variation in the matrix.

Table 4-1: Results of the evaluation of the production pathways introduced at the beginning of Chapter 3 with respect to the selected criteria (Section 3.2). Listed values represent "typical" values; variations and uncertainties are addressed later in present Chapter 4.

Criterion	Metric		HEFA / Cam	HEFA / UCO	HEFA / μA	HTL / μA	AtJ / LigC	HDCJ / LigC	BtL / LigC	PtL / airCO₂	StL / airCO₂	Ref.: Jet A-1
Technical maturity	Technology Readiness Level	TRL (1-9)	8	9	6	4	6	6	6	4	3	9
Feedstock production maturity	Feedstock Readiness Level	FSRL (1-9)	8	9	6	4	8	8	8	5	5	9
Conversion technology maturity	Conversion Technology Readiness Level	CTRL (1-9)	9	9	9	6	6	6	6	4	3	9
Economic competitiveness	WtT production costs relative to spot price in 2013	γ [%]	68%	67%	~600%	91%	190%	62,0%	130%	~250%	206%	0%
European substitution potential	Production potential relative to European demand in 2050	σ_{EU} [%]	<1%	<1%	5,0%	2,8%	62%	87%	>100%	>100%	n/a	100%
Global substitution potential	Production potential relative to global demand in 2050	σ [%]	n/a	<1%	>100%	87,0%	>100%	>100%	>100%	>100%	>100%	100%
specific GHG emission reduction	Specific lifecycle GHG emissions relative to conventional jet	ε [%]	-65%	-85%	-67%	-58%	-87%	-60%	-80%	-96%	-84%	0%
Potential impact on European GHG emission reduction	Total impact on GHG emissions relative to conventional jet at European deman in 2050	ψ_{EU} [%]	<0,7%	<0,9%	3,4%	1,6%	54%	52%	80%	96%	n/a	0%
Potential impact on global GHG emission reduction	Total impact on GHG emissions relative to conventional jet at global deman in 2050	ψ [%]	n/a	<0,9%	67%	50%	87%	60%	80%	96%	84%	0%

The main results and recommendations of the comparison of fuels can be summarized as follows:

- All renewable fuel productions pathways present significant specific GHG emission reduction while their potential impact on global or European scale may be very limited due to limited production potential globally or in Europe, respectively.

- No selected renewable fuel production pathway under assessment reaches the 0-% benchmark of conventional jet fuel for economic competitiveness, even for the high-TRL alternatives. This indicates that further work should focus on

  o a more detailed assessment on hidden potentials for significant cost reduction, including the impact of interest rate reduction by de-risking the investment

  o a cost-of-development estimate and risk analysis for a longer-term perspective that assumes TRL $\geq$ 6 for those technologies are now at a low-TRL, and

  o the potential benefits of various economic measures such as emission trading.

In the following section we present a *trade-off analysis* on various criteria for the selected production chains.

4.2   Specific GHG emissions vs. cost of production

Useful trade-off relations between criteria were identified. In CORE-JetFuel there are the specific greenhouse gas reduction potential vs. cost of production (Figure 4–1) and the potential reward vs. risk (Figure 4–2).

In Figure 4, the specific GHG emission reduction potential of the unblended fuel relative to conventional jet fuel, i.e. the percent reduction potential by substitution of the same amount conventional jet fuel (denoted as ε), is plotted versus the production cost relative to the market value of conventional jet fuel (denoted as γ).
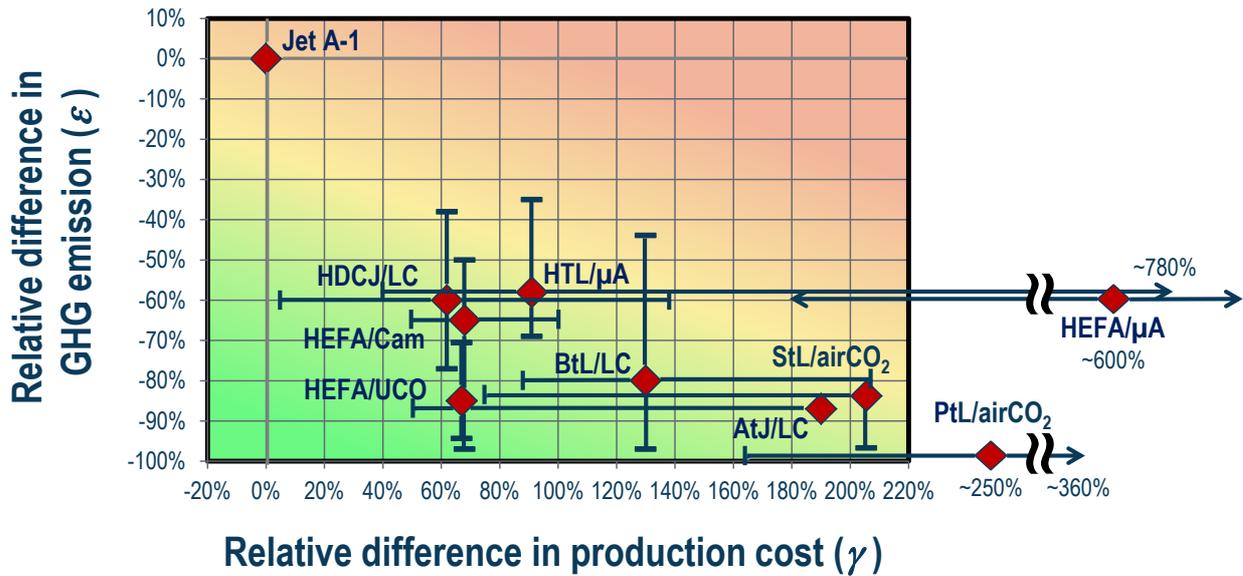
Figure 4–1: Specific GHG emissions vs. cost of production of analysed production pathways, each relative to conventional jet fuel. HDCJ/LC: Hydroprocessed Depolymerized Cellulosic Jet from lignocellulosic feedstock; HTL/µA: Hydrothermal Liquefaction of microalgae; HEFA/µA, HEFA/UCO, HEFA/Cam: Synthetic paraffinic kerosene using Hydroprocessed Esters and Fatty Acids from microalgae, camelina and used cooking oil, respectively; BtL/LC: FT-SPK from lignocellulosic feedstock; StL/airCO$_2$: Sun-to-Liquid based on solar-thermochemical conversion of water and CO$_2$ captured from air; AtJ/LC: Alcohol-to-Jet from lignocellulosic feedstock; PtL/airCO$_2$: Power-to-Liquid using CO$_2$ captured from air.

As can be seen from Figure 4–1 (and also from Figure 4–2 below), the collected data cover a broad range of values and are associated with considerable variation and uncertainties. There are several reasons for such variation and uncertainties. As mentioned earlier, the data was extracted from numerous different sources, such as scientific articles and reports. The variations originate from the variations in the underlying assumptions, methodologies, system boundaries etc. of different studies and event of systematic variation of assumptions within such studies, e.g. to find typical results and performance envelopes. Uncertainty intervals in the primary assumptions further add uncertainty intervals to the results.

The evaluation yielded a wealth of valuable information, with the key findings summarized in the following.

- In the light of the given variations and uncertainties, no obvious correlation of specific GHG emissions and cost of production can be found.

- All considered options provide substantially reduced specific GHG emissions in comparison to conventional jet fuel (Jet A-1), even though the upper values within the ranges of variation and uncertainty of some options would represent only insufficient reductions.

- All considered options are considerably more costly in comparison to conventional Jet A-1. Consequently, a price gap between conventional jet fuel and renewable alternatives is likely to remain at least in the medium-term future. Appropriate regulatory and/or economic measures will be needed to provide a market environment where renewable fuels can be competitive.

4.3 Risk/reward analysis of production pathways

Research and development comes with some probability of success and failure and with potential benefits of incremental to substantial magnitude. As presented in the assessment framework Report D2.1, Section 3.5., the research landscape is also characterized by the distribution of funding on high- and low-risk technologies and by their relation to potential rewards. If R&D funding is spent on easy-to-attain objectives, the technology development will probably succeed but scientific leadership and long-term technological innovation in a competitive environment is at stake. High-risk long-term R&D projects therefore have a place in pro-active aggressive innovation and there must be a balance of risk and reward.

Here we use a risk-*related* metric and a metric for potential environmental rewards on European and global scale. For the selected fuel production pathways we analyze the relation between TRL and the potential impact on European/global GHG emission reduction, both metrics as defined in the previous chapter.

In Figure 4–2, the **potential reward vs. risk analysis**, the potential reward is represented by the *potential impact on GHG emission reduction* (which is the share of fossil fuel displaced by alternative fuels in the market, i.e. the substitution potential, multiplied with the specific

GHG emission reduction ε shown in Figure 4–1) which is plotted versus the *technology readiness level (TRL)* of the fuel production path as a risk-related metric[10].

In the potential impact on GHG emissions reduction the entire fleet (European and global) in 2050 is considered. The interpretation of the upper limit value of 100% for the potential impact on GHG emission reduction is that 100% of the emissions are eliminated which can only be the case if 100% of conventional fossil fuel is substituted with an absolute zero carbon intensity ($\varepsilon = -100\%$) fuel. This performance indicator reflects the fact that an advantageous specific GHG balance alone is not sufficient; such fuel would have to be supplied in large quantities to have a real impact. This is an issue often neglected in discussions about renewable fuels.

The evaluation yielded the following key findings:

- All pathways in the "high potential reward" range either depend on lignocellulosic feedstock (including waste streams) or do not require input of biomass at all. This finding reflects the fact that these pathways offer high specific GHG emissions reduction AND are potentially available in large quantities. However, none of these promising options is mature enough to-date for short-term industrial implementation, and consequently certain risks of failure or major challenges are associated with their further development.

- Pathways depending on **microalgal feedstock** show moderate absolute GHG emissions reduction potential at **global level**, while remaining insignificant at **European level**. This is a consequence of the negligible production potential for microalgae in Europe.

- For the same reason, the potential reward in terms of GHG emissions reduction of HEFA fuels from **used cooking oil (UCO)** is negligibly small, at European as well as global scale: While the specific GHG balance of this fuel is excellent, the availability of UCO is very limited.

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[10] It is important to understand that TRL is not identical to a risk metric but is not unrelated to it. TRL is used as indicator for the risk associated with the further development of a technology: The lower the actual degree of development, the higher the risk of failure on the way towards industrial maturity and commercialization.
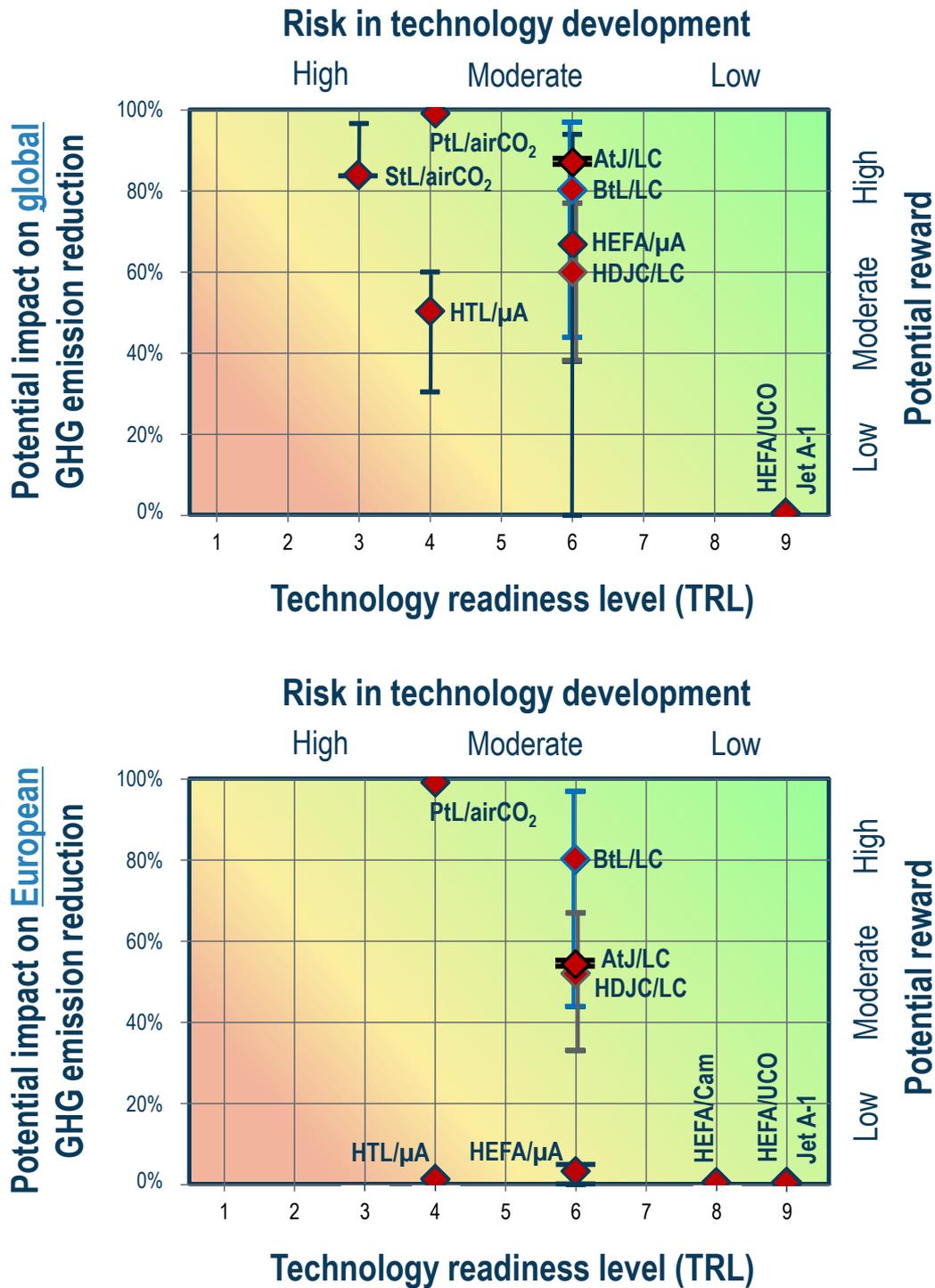
Figure 4–2: Relational plot of *technology readiness* and *potential impact* (derived from the product of specific GHG reduction potential and the global substitution potential) of fuel production technologies. Greenhouse gas emissions reduction potential relative to future fuel emission impacts in the GLOBAL (top) and EUROPEAN (bottom) context, vs. current overall TRL of the analyzed production pathways (for explanation of abbreviations of pathways, see caption of Figure 4–1).

In future studies, potential socio-economic benefits and aspects of competitive advantage for the EU are interesting criteria to be included in the evaluation. As presented in the assessment framework Report D2.1, Section 3.6, suggested *European policy-relevant criteria for the impact assessment* are:

- The feasibility for European feedstock and fuel production considering the agricultural and industrial potential,
- the ability to reduce the energy import volume into European territory,
- the ability to prepare the ground for future highly innovative businesses in a potentially large market (fuel, by-products, plant infrastructure, services),
- enhancing innovation capacity and integration of new knowledge,
- expert-defined indicators for inventive merit and strategic importance, such as the potential contribution to the development in economically challenged regions in Europe.

While it is straightforward to include such criteria in a MCA scheme and in a portfolio analysis, it remains a challenge to define objectively measurable properties. Both the quantification and information gathering for these aspects remain a challenge for future work. Of particular interest will be the *European substitution potential for energy import* which relates to a contribution to the future European supply security. By relating the absolute energy production potential to the absolute energy import trend, the relative substitution potential is obtained.

5   Conclusions

The results presented in this report lead to a number of observations and recommendations in the following domains:

- Technology monitoring and key set of performance indicators
- Balance of risks and potential rewards of technology development
- Holistic multiple-criteria approach in a future R&I strategy
- Balance and linkage of efforts in basic science and technology development

The relevant conclusions in these four domains are as follows:

Complement the set of key performance indicators with future potentials for climate impact and European energy supply security

Advantageous specific GHG balance alone is no sufficient metric, as it does not yield an indication regarding the potential impact of a technology, e.g. a specific type of renewable fuel, could have on a sector's GHG emissions.

In strategic decisions, e.g. in the case of the development of future work programmes and funding strategies, the potential impact of a future technology on European or global scale has to be taken into account. By considering the suggested metrics, a better understanding of the possibilities for additional advances of respective technologies and their future impact is obtained.

To this end, the indicator *"Greenhouse gas emissions reduction potential relative to future fuel emission impacts"* was evaluated and proved to be useful in analyzing a risk-vs.-reward situation of technologies. The indicator represents a combination of the specific GHG emissions and the potential availability (the production potential) of a specific type of renewable fuel in relation to a sector's overall fuel consumption. It indicates the GHG emissions that are saved as a consequence of substituting the potential maximum share of the overall fuel consumed by the considered renewable fuel. By relating the absolute reduction potential to the absolute fossil emission trend, the relative potential impact is obtained.

Based on the "potential reward" idea of technology assessment, we recommend to also include the indicator *"European substitution potential energy import"* which was not evaluated in CORE-JetFuel, but is nevertheless expected to be useful in future technology analyses. The indicator relates to a contribution to the future European supply security. By relating the absolute energy production potential to the absolute energy import trend, the relative substitution potential is obtained.

The term "potential" impact suggests that this impact is within the physical and/or technical performance limits of a technology under the assumption that it is mature (TRL6-9) in the future, not the impact at the state of the art or at a future intermediate (<TRL6) decision point.

Balance technology development risks with an adequate level of rewarding GHG reduction potentials

Some production pathways are key to achieve large-scale reduction of GHG emissions of the entire aviation sector. Therefore, it is recommended to foster the technology developments where the risks are worthwhile in view of a high impact potential of GHG reductions.

The decision maker has to understand which technologies potentially present the greatest source of change, what is the right level of risk for the expected potential reward of technologies to develop, i.e. the balance of risk and reward needs to be observed.

We recommend to support the progress of

- conversion technologies based on lignocellulosic and/or waste feedstock, such as HDCJ, HtL and FT-SPK, and of
- renewable non-biogenic pathways, such as the core conversion technologies of PtL and StL, and their aerial CO_2 supply technologies towards higher technological maturity to demonstrate their viability in an industrially relevant environment.

Develop fuel technologies with simultaneous advantages in cost efficiency, scalability, sustainability and feedstock supply security

Single-criteria improvements should not compromise a holistic solution.

Simultaneous improvements in terms of costs, scalability and GHG emissions are necessary and should not compromise other important environmental or social aspects, such as water consumption, emission of pollutants, land use rights etc.

We recommend to

- base the future strategy for R&I in aviation fuels on a holistic, multiple-criteria approach, developing fuels with simultaneous benefits in costs, scalability, sustainability and feedstock supply security.

- base the future strategy for R&I in aviation fuels on scalable production technologies, with each single technology showing potential to substitute at least 10% of the European jet fuel demand anticipated for 2050, while at the same time offering large specific GHG emissions reduction potentials,

- base the future strategy for R&I in aviation fuels on feedstock-flexible production technologies that enable efficient utilization of a broad range of feedstock types, thus reducing dependencies on single feedstock sources, minimizing risk of supply shortfall and increasing scalability.

- Set up and maintain a holistic standard reference of a multiple-criteria evaluator for future fuel technologies with:
  - o single-criteria threshold conditions (defining specific reference performance potentials),
  - o single-criteria premise conditions (defining mandatory minimum required performance potentials) and
  - o multiple-criteria trade-off conditions (acknowledging the fact that certain trade-offs can exist with respect to individual performance indicators, e.g. cost of production and GHG balance).

Maintain a balanced R&D portfolio to enable short-term innovation and to create long-term innovation opportunity

In Part A of this deliverable the European project "landscape" was represented in a Stokes Quadrant Model along with associated project costs, showing the share of research efforts in basic and applied research domains. A well-balanced R&D portfolio is crucial to achieve three objectives,

- to enable short-term industrial implementation of mature technologies,

- to pave the way for less mature technologies to progress from laboratory-scale research towards demonstration in industrially relevant environments, and

- to enable novel and radical concepts offering large long-term potentials ("high risk / high gain" concepts) to be researched at laboratory-scale, thus creating future innovation opportunity and developing, retaining and attracting the required highly skilled human capital.

Therefore we recommend to

- support basic research in other scientific domains, such as physics, chemistry, biotechnology etc., to
- support engagement of industrial stakeholders in use-inspired research and technology development, thus ensuring that industrially important issues are addressed and minimizing risk of failure, and to
- increase the effort in R&D activities in the use-inspired research domain (Pasteur's quadrant), forming the technology base for subsequent industrialization.

In order to de-risk the final development step towards industrial maturity, we recommend the support of large-scale technology development projects, provided these show sufficient potential as defined above.

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