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NLR-TP-2020-171 | May 2020

European TRANSCEND for Novel Aircraft Propulsion and Alternative Fuels Roadmaps towards 2050

CUSTOMER: Clean Sky Joint Undertaking

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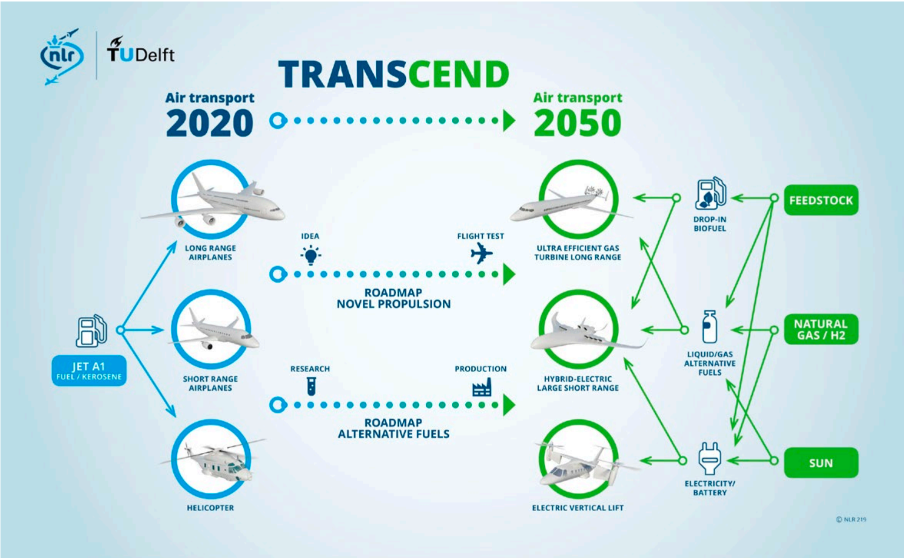
EXECUTIVE SUMMARY

UNCLASSIFIED

European TRANSCEND for Novel Aircraft Propulsion and Alternative Fuels Roadmaps towards 2050



Problem area

Mitigation of climate change and other environmental impacts is increasingly globally pursued by governments, international bodies, and industry. Alternative fuels and novel technologies are seen as major directions to achieve 50% reduction in CO2 emissions in aviation. In the timeframe 2014-2023 the European Clean Sky 2 programme is taking large steps in novel propulsion and its integration into aircraft towards achieving the environmental objectives as set out by ACARE for air transport in 2050. In various other programmes and projects, complementary developments like alternative energy sources are taken up as well. Whereas Clean Sky 2 evaluates its own environmental impact towards 2050, the parallel and later (after 2023) developments outside Clean Sky 2 in novel propulsion and alternative energy sources require their own evaluation and give rise to the questions: what can these developments contribute to achieving the ACARE 2050 goals? How could the most promising potential developments actually take place?

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Description of work

As Coordination and Support Action for the Clean Sky 2 Technology Evaluator instrument, TRANSCEND has been initiated by the NLR and TUD to address these questions. TRANSCEND provides an overview of potential future energy sources and innovative propulsion technology for aircraft and selects the most promising. For the most promising energy sources TRANSCEND provides ecological balance sheets taking into account their life-cycle from production onwards. TRANSCEND evaluates the environmental impact at aircraft and air transport levels of alternative energy sources and novel propulsion technologies in terms of gaseous emissions for aircraft with entry-into-service before 2050. In addition, TRANSCEND provides a TRL-based technology roadmap for the most promising propulsion technologies and a roadmap regarding economic viability and availability for the associated alternative energy sources. Exploitation routes for these roadmaps are investigated in interaction with the TRANSCEND Advisory Board, consisting of stakeholders, including industry and policy makers.

Results and conclusions

The first results from TRANSCEND's literature study indicate that there are various routes opening up to address the reduction of gaseous emissions with alternative fuels and with novel propulsion beyond Clean Sky 2 propulsive technologies.

In this tradition of co-operation, TRANSCEND invites the European aviation community and its fuel community to contribute, for example in workshops to the evaluation of environmental impact with associated roadmaps for alternative fuels and novel propulsion to pave the way for fully achieving the challenging environmental objectives for 2050.

Applicability

TRANSCEND supports research policy making for the European Green Deal. In addition, the research contributes to research policy making for the Dutch Klimaatakkoord and the Dutch Roadmap Aeronautics. TRANSCEND fits within NLR's strategic ambition for Electric Flight.

GENERAL NOTE

This report is based on the paper that has been submitted for and has been presented at the Aerospace Europe Conference, Bordeaux, 25-28 February 2020.

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CUSTOMER: Clean Sky Joint Undertaking

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Contents

Abbreviations

ACRONYM	DESCRIPTION
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
CNG	Carbon-neutral growth
CSA	Coordination and Support Action
CS2	Clean Sky 2
GHG	Greenhouse gas
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
NLR	Royal Netherlands Aerospace Centre
PtL	Power-to-Liquid
SAF	Sustainable Alternative Fuel
TE	Technology Evaluator
TRANSCEND	Technology Review of Alternative and Novel Sources of Clean Energy with Next-generation Drivetrains
TRL	Technology Readiness Level
TUD	Technical University Delft

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EUROPEAN TRANSCEND FOR NOVEL AIRCRAFT PROPULSION AND ALTERNATIVE FUELS ROADMAPS TOWARDS 2050

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ABSTRACT: The Clean Sky 2 programme (2014-2023) takes large steps in novel propulsion and its integration into aircraft, contributing to global reduction of aviation's emissions. Parallel and potential later developments in both novel propulsion and alternative energy sources give rise to the questions: what can these developments contribute to achieving the global environmental goals for 2050? How can the most promising potential developments actually take place? The TRANSCEND Coordination and Support Action (CSA) will answer these questions with involvement of the European aviation community.

1 INTRODUCTION

Mitigation of climate change and environmental impact are increasingly addressed globally by governments, international bodies, and industry. The European Commission has recently published the European Green Deal – a roadmap with actions for making the EU's economy sustainable. The actions include a proposal on a European "Climate Law", scheduled for March 2020, enshrining the 2050 climate neutrality objective [1].

Globally, ICAO addresses the emissions from international aviation. In [2] ICAO presented the following pillars to reduce aviation emissions: Aircraft Technology and Standards, Operational improvements, Sustainable Alternative Fuels, and Market based measures. These pillars have been further addressed in collaboration with the industry (IATA/ATAG) to achieve carbon-neutral growth (CNG) from 2020 until 2035, with an aspirational target to reduce total CO_2 emissions by 50% in 2050 in comparison to 2005 (see Fig.Figure 1).

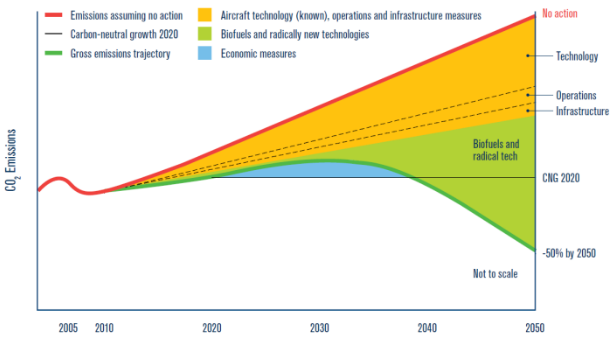

Figure 1 IATA CO2 emissions roadmaps ([3])

In conclusion, alternative fuels and novel technologies are globally seen as major directions to achieve significant reductions in CO_2 emissions.

Europe, already in 2011, set aviation goals in FlightPath 2050 [3] to protect the environment. One of the 2050 goals is to have technologies and procedures available to allow a 75% reduction in

CO_2 emissions per passenger kilometre and a 90% reduction in NO_x emissions. An additional 2050 goal is to have Europe established as a centre of excellence on sustainable alternative fuels, including those for aviation, based on a strong European energy policy.

In the time frame 2014-2023 the Clean Sky 2 (CS2) programme is taking large steps in novel propulsion (and aircraft) technologies and their integration into aircraft towards achieving the environmental objectives for air transport in 2050. The environmental progress of each demonstration platform in Clean Sky 2 will be monitored by the Technology Evaluator (TE) of CS2.

In various other programs and projects, complementary developments are taken up as well, also for alternative energy sources for aviation. The parallel and potential later (after 2023) developments require their own evaluation and give rise to the questions: what can these developments contribute to achieving the climate goals? How could the most promising potential developments actually take place?

Against this global and European background, the TRANSCEND (Technology Review of Alternative and Novel Sources of Clean Energy with Next-generation Drivetrains) CSA of the CS2 TE will answer these questions for novel propulsion technology and alternative energy sources for aviation, both key technologies for reducing the environmental impact of aviation.

2 PRELIMINARY INVENTORY OF ALTERNATIVE FUELS AND NOVEL PROPULSION

TRANSCEND investigates sustainable reduction of gaseous emissions through drop-in fuels, novel propulsion technology for current aviation fuels (including drop-in fuels), and alternative energy sources in combination with novel propulsion technology. This section gives a preliminary overview of these classes of fuel and propulsion technologies and the technology development routes towards their use in aviation in 2035/2050.

2.1 Drop-in fuels

An important class of alternative energy sources is Sustainable Alternative Fuels (SAFs) that decrease the net GHG emission footprint and can be used as drop-in fuel (also in a blend). There are currently 6 ASTM Approved Pathways for SAFs to be blended with Jet-A/Jet-A1 [5]. These SAFs can be produced from biological raw material (biofuels) or be synthetically produced from the basic compounds.

Present ASTM Approved Pathways allow for Jet-A/Jet-A1 fuel blends with up to 50% SAFs, for which mostly biological raw material is used. Taking into account the full life-cycle of the SAFs, they are not 100% sustainable yet as energy is need to produce the renewable fuel. Overall reduction of CO2 emission by use of present SAFs is hence below 50%. Current production levels of SAFs are very low.

Towards and beyond 2035 the use of SAFs may increase and provide a significant contribution to reduction of greenhouse gas (GHG) emissions of aviation. For such significant emission reduction the production capacity of sustainable biofuels needs to be increased by multiple scales.

Development and approval of new ASTM pathways is required to secure the business cases I for such increased production. This includes both fully synthetic processes as well as novel biofuels. There is currently increased attention to Power-to-Liquids (PtLs) and electrofuels. Both domains are aimed at production of both drop-in and non-drop-in fuels, whereby the first domain focuses on realizing a liquid form of the fuel for on-board storage and the latter focuses on the process of using electric energy to produce these alternative fuels. In this section we limit their consideration to drop-in fuels; see Section 2.3 for the non-drop-in fuels and a comparison between several drop-in and non-drop-in fuels.

The full life-cycle of such drop-in fuels need to be considered to make conclusions on their sustainability and economic viability, including total energy needed for chemical processes and logistics, feedstock production and logistics for biological processes, sustainability of source and waste materials, and in-flight emissions (e.g. reduced contrail forming as an additional benefit).

Important methods for the life-cycle analysis are defined by EU Renewable Energy Directive and US Renewable Fuel Standard.

For a larger environmental impact new ASTM pathways could be investigated, developed and approved for jet fuels with blends up to 100% of SAFs. The investigation would address the impact of such 100% SAF blends on present engines and any associated measures to increase the percentage of SAF in jet fuel blends.

2.2 Novel propulsion technology for current aviation fuels

For current aviation fuels, including drop-in fuels, new propulsion technology with increased fuel efficiency is developed in CS2, thus contribution to reduction of CO_2 emissions. The propulsion technology that will be evaluated by the CS2 TE include amongst others advanced geared engine architectures, very high bypass ratio turbofan demonstrators as well as various individual nacelle, compressor, combustion and turbine technologies aiming at improving overall engine fuel efficiency and noise characteristics.

Further fuel efficiency gains may be obtained by more disruptive propulsion technologies. For example, turbo-electric propulsion is based on electrically-driven fans or propellers, fed by generators that are driven by gas turbines operating on aviation fuels. In many studies on turbo-electric propulsion the fans or propellers are distributed over the airframe and boundary layer ingestion is exploited. For an overview see Table 4.1 with the references therein and the pictures of aircraft concepts in [6] and, in addition, the CENTRELINE study [7]).

Further disruptive propulsion technologies may improve gas turbines beyond Clean Sky 2. Such disruptive technologies include for example alternative combustion processes such as constant volume/pressure gain combustion, flameless combustion, inter turbine combustion or closed volume combustion (composite engine). Other examples are variable gas turbine engine cycle (by adaption of the flow path), improved heat exchange by recuperation and inter-cooling, and semi-closed gas turbine cycles. Also even more radical non-gas-turbine systems may be developed such as ionic thrust [8], though this is likely to enter the aviation market for passenger transport beyond the 2050 horizon.

Once developed and matured, the disruptive novel propulsion technologies may contribute to significant increase of fuel efficiency. Combined with present unsustainable Jet-A/Jet-A1 fuel the novel propulsion technologies are unlikely to reach net zero emission on their own; however combined with advanced drop-in fuels the novel propulsion technologies may reach up to net zero emission, while contributing to reduced use of potentially scarce and costly SAFs.

2.3 Alternative energy sources in combination with novel propulsion

Alternative, potentially sustainable energy sources for on-board aircraft include batteries, solar power, hydrogen, and other non-drop-in fuels. Such alternative energy sources may be combined with combustion engine driven propulsion, full electric propulsion, or hybrid-electric propulsion.

As an illustration a part of the initial inventory for hydrogen as on-board energy source is shown in Fig. Figure 2. The two main routes for hydrogen towards propulsion are, firstly, direct combustion in a gas turbine that has been adapted for hydrogen and, secondly, generation of electricity in a fuel cell, which can be based on different technologies, and subsequent propulsion by an electrically driven fan or propeller.

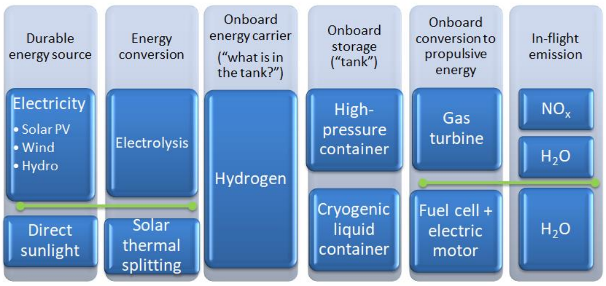

Figure 2 Initial inventory of hydrogen as on-board energy source

Important characteristics for aviation fuels are the gravimetric and volumetric densities of the fuel. In

Table 1 Evaluation matrix of the selected electrofuels in [9] (5: excellent; 4: good; 3: satisfactory; 2: challenging; 1: problematic)

Property	Jet A-1	nC_8H_{18}	CH_3OH	CH_4	H_2	NH_3	NH_3/H_2
CO_2 emission	1	4	4	4	5	5	5
Electro-synthesis	-	3	3	4	5	5	5
Specific energy	4	4	2	4	5	2	2
Energy density	5	5	2	3	1	2	2
Storage	5	5	4	2	1	3	3
Toxicity	3	3	2	4	5	1	1
Combustion properties	5	5	4	5	5	2	5
NO_x & soot emissions	2	2	4	4	4	3	4
Drop-in capability (combustion)	5	4	2	2	2	2	4
Turbine power output	4	4	4	4	5	5	5
Drop-in potential (turbine)	5	5	4	3	2	2	3
Structural considerations	4	4	3	3	2	2	3

case of fuel cell based electric propulsion, these densities need to be considered for the full propulsion system, from on-board fuel storage to propulsive energy. Even in compressed gas and in liquid form, the hydrogen densities may lead to different aircraft configurations optimised for the integration of hydrogen.

Due to the low volumetric density of gases, there is a lot of attention for PtLs. The power needed is often assumed to be sustainable electric power (e.g., sun or wind energy). Therefore there is also a lot of attention for electrofuels. Alternatives for hydrogen including their integration into aircraft have been recently compared technically in [9], see Tab.Table 1.

The full life-cycle of such non-drop-in fuels need to be considered to conclude on their sustainability and economic viability, including total energy needed, the sustainability of source and waste materials (e.g., recycling of batteries), in-flight emissions (e.g. increased contrail forming in case of hydrogen) and social aspects.

Whereas these alternative energy sources widen the potential of on-board sustainable energy sources beyond SAFs, they may require significant changes in the present kerosene-based infrastructure at and near airports.

Hybrid drop-in/non-drop-in based propulsion concepts may take benefit of sustainable fuels that are not able to cover the full aircraft mission within present aircraft configurations (such as batteries for large single aisle aircraft). In particular hybrid-electric configurations have been shown to provide environmental benefits (see [6], in particular Table 4.1 with the references therein and the pictures of aircraft concepts). Hybrid-electric configurations are also studied in Clean Sky 2, see for example [10]. The parallel paper [12] summarizes all hybrid-electric propulsion aircraft design activities in the Large Passenger Aircraft IADP of Clean Sky. A recent overview of hybrid-electric propulsion is given in [11].

3 FURTHER WORK: CONCEPT AND METHODOLOGY

The inventory of the alternative energy sources and novel propulsion technologies will be completed with evaluations of the environmental and socio-economic impact and of the viability and the availability of these energy sources and propulsion technologies.

3.1 Evaluation of environmental impact

The evaluation of environmental impact splits into the environmental impact of alternative energy sources from production to intake on-board aircraft and the environmental impact of alternative energy sources and novel propulsion technology during operation. The evaluation includes ecological balance sheets for the alternative energy sources.

For the evaluation during operation the novel propulsion technology needs to be embedded into appropriate, possibly novel propulsion system architectures within possibly novel aircraft architectures. Such aircraft architecture will best scale to certain aircraft types (in terms of seat classes). This results in TRANSCEND concept aircrafts, each being a combination of alternative energy source, novel propulsion technology, propulsion system architecture and aircraft architecture. Such concept aircrafts are evaluated on their environmental impact. Different concept aircraft, with different combinations of alternative sources and novel propulsion technology, are joined to a fleet of aircrafts in different seat classes. The environmental impact of this fleet is evaluated at air transport system level.

3.2 Scenarios and evaluation of viability and availability

Evaluations of the environmental impact are complemented with evaluations of the viability and availability of the alternative energy sources and novel propulsion technologies and the associated aircraft architectures, according to a wide range of technical, economical, and social evaluation criteria.

To have realistic evaluations on a realistic prediction of air transport in 2050, the economic viability and availability of the TRANSCEND concept aircraft and their alternative fuels need to be taken into account. External legal and economic factors, such as policies, laws and regulations (e.g., blending obligation, certification, public-private partnerships), CO_2 prices and the price of crude oil have impact on the time when alternative energy sources and propulsion technologies are viable and available, taking into account as well the business impact of stakeholders such as aircraft and engine manufacturers, airlines, and airports.

Such external factors will be identified and scenarios for these external factors will be described, aligned with the scenarios underlying the TE evaluation of the environmental impact of Clean Sky 2 technology in 2035-2050.

The scenarios define also a realistic distribution of flights over various routes, countries and continents on world scale in 2050.

The aim is to align these scenarios with the scenarios in GLIMPSE2050 ("Global Impact Assessment of Regulations and Policies for Sustainable Aviation by 2050"). GLIMPSE2050 is a Clean Sky 2 TE project, running in parallel to TRANSCEND. Its objective is to assess the environmental impact at global air transport system level up to 2050 of currently discussed regulations and policies, complementary to the assessment of the Clean Sky 2 technologies.

3.3 Roadmapping

Based on the pool of concept aircraft and their evaluation results, the first logical step towards the roadmaps is to identify risks. Whereas external risks and opportunities are already considered in relation to the evaluation, the focus is on risks related to the development of these technologies. Special attention will be paid to cross-links between roadmaps for different seat classes regarding scalability: e.g., electric propulsion technology for small aircraft at high technology readiness level (TRL) may contribute to achieving lower TRLs of electric propulsion technology for large aircraft.

3.4 Collaborative methodology

TRANSCEND' seeks wide involvement of experts through expert workshops and interviews. In the first year the goal is to support the selection of 5 alternative fuels in its first year for deeper evaluation later. In later years the expert's involvement contributes to the roadmapping.

In addition, TRANSCEND investigates exploitation routes for the roadmaps are in interaction with its Advisory Board, which is already involved from early in the project. The Advisory Board includes various policy makers and industries. The evaluations will help policy makers and investors to choose the right technologies and value chains to support the implementation of producing the required sustainable solutions.

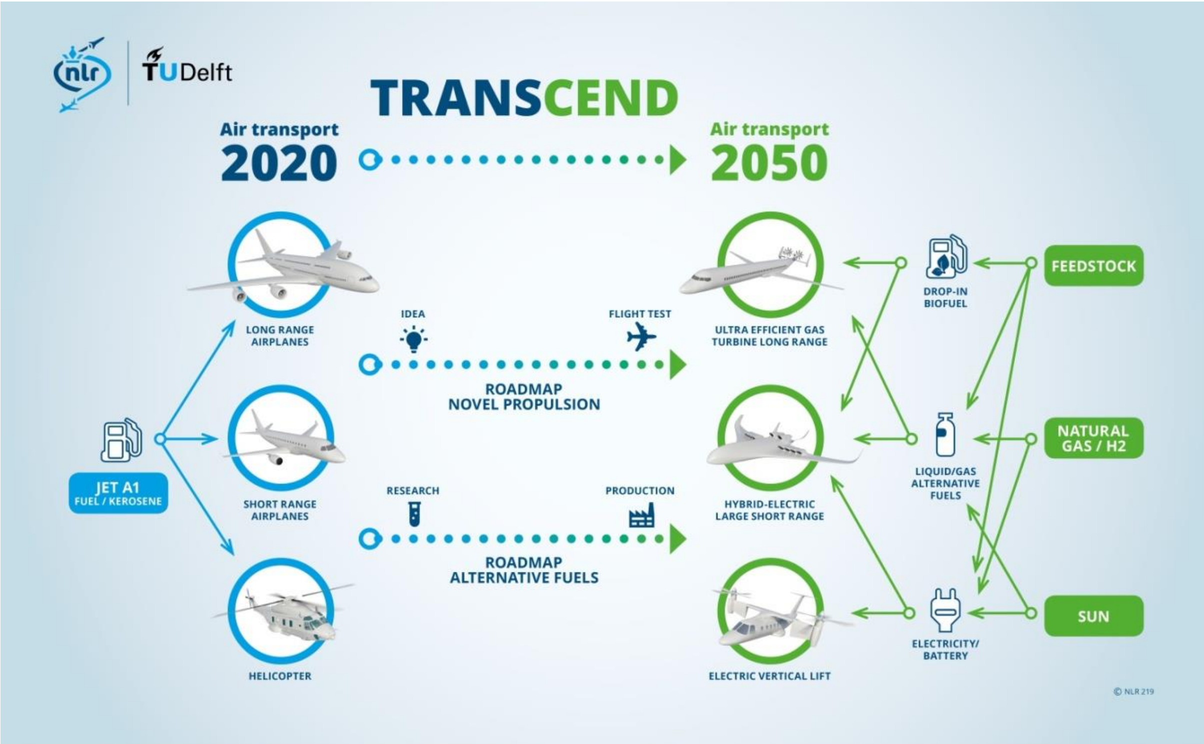

Figure 3 Infographic on TRANSCEND's evaluations of environmental impact and roadmapping

4 CONCLUSION

Strong co-operation in the aeronautics sector in European research and innovation, in European Horizon 2020 programme and national programmes, like Clean Sky 2 and its predecessors, has already led to significant reductions in global environmental emissions. The first results from TRANSCEND's literature study indicate that there are various routes opening up to address the reduction of gaseous emissions with alternative fuels and with novel propulsion beyond Clean Sky 2 propulsive technologies.

In this tradition of co-operation, TRANSCEND invites the European aviation community and its fuel community to contribute to the evaluation of environmental impact with associated roadmaps for alternative fuels and novel propulsion to pave the way for fully achieving the challenging environmental objectives for 2050.

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