NTNU | Kunnskap for en bedre verden

Introduction to NTNU Clean Aviation

September 27th – NTNU Innovation Hub, Gruva

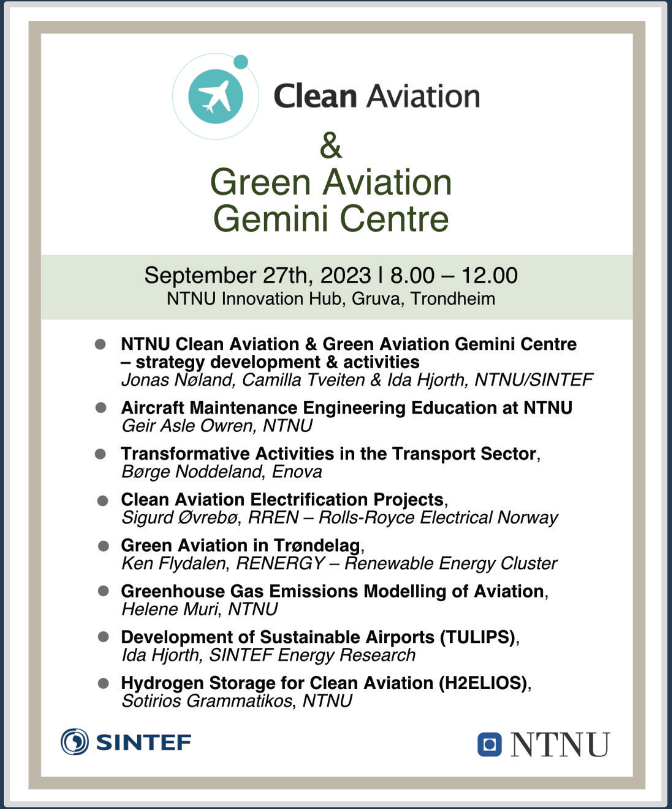
Jonas Kristiansen Nøland & Camilla Knudsen Tveiten

Objective of this event

- Dessiminate NTNU Clean Aviation’s activities
- Highlight what is going on at NTNU & SINTEF, in the aviation sector, and the broader public
- We want to widen out NTNU’s perspectives on Clean Aviation

Agenda for the day

- Coffee & mingling (08:00–08:20, 09:00–09:20, 10:00–10:20, 11:00–11:20)
- Presentations (08:20–09:00, 09:20–10:00, 10:20–11:00, 11:20–12:00)
- Lunch (12:00–)



Clean Aviation

&

Green Aviation
Gemini Centre

September 27th, 2023 I 8.00 – 12.00
NTNU Innovation Hub, Gruva, Trondheim

- **NTNU Clean Aviation & Green Aviation Gemini Centre – strategy development & activities**
  Jonas Nøland, Camilla Tveiten & Ida Hjorth, NTNU/SINTEF
- **Aircraft Maintenance Engineering Education at NTNU**
  Geir Asle Owren, NTNU
- **Transformative Activities in the Transport Sector**,
  Børge Noddeland, Enova
- **Clean Aviation Electrification Projects**,
  Sigurd Øvrebø, RREN – Rolls-Royce Electrical Norway
- **Green Aviation in Trøndelag**,
  Ken Flydalen, RENERGY – Renewable Energy Cluster
- **Greenhouse Gas Emissions Modelling of Aviation**,
  Helene Muri, NTNU
- **Development of Sustainable Airports (TULIPS)**,
  Ida Hjorth, SINTEF Energy Research
- **Hydrogen Storage for Clean Aviation (H2ELIOS)**,
  Sotirios Grammatikos, NTNU

SINTEF
NTNU

CLEAN AVIATION

Before jouning as an associated member:

- Autumn 2020: Submitted proposal with Expression of Ideas for Clean Aviation JU.
- Spring 2021: SINTEF/NTNU one out of seven short-listed proposals (90 in total).
- July 30th, 2021: Call for Expression of Ideas/Potential Members (CEI) signed.
- October 21th, 2021: Letter of Intent (LoI) signed.
- December 7th, 2021: Letter of Commitment (LoC) signed.

Areas addressed by the 7 short-listed ideas

90 proposals in total

CEI-2020-61 “WET2030+” (coordinated by MTU Aero Engines AG; Germany; total cost: 160 m€)

- Development of the **Water-Enhanced Turbofan (WET)** for ultra-efficient SMR aircraft

CEI-2020-25 “HEROPS” (coordinated by MTU Aero Engines AG; Germany; total cost: 242 m€)

- Development of **hydrogen fuel-cell based propulsion** for regional hybrid electric/full electric aircraft

CEI-2020-53 “TOOP” (coordinated by Airbus; Germany; total cost: 170 m€)

- Development of **superconducting and cryogenic powertrain** for regional hybrid/full electric aircraft

CEI-2020-52 “HYPE” (coordinated by GE Avio Aero; Italy; total cost: 160 m€)

- Development of **hydrogen-combustion turbine** for large-scale hydrogen-powered regional aircraft

CEI-2020-42 “HYTALIA” (coordinated by RISE SICOMP; Sweden; total cost: 3.5 m€)

- Development of aircraft ultralight, safe and reliable **tanks for liquid hydrogen storage** for regional hybrid/full electric aircraft

CEI-2020-32 “Certif2035” (coordinated by Dassault Aviation; France; total cost: 39.4 m€)

- Development and establishment of **certification regulations and means of compliance** for disruptive technologies

CEI-2020-79 “GREAT” (coordinated by SINTEF AS; Norway; total cost: 25 to 40 m€)

- Development of technologies to **increase performance/reliability of electrical components** and **optimise efficiency of hydrogen-based propulsion system using superconductive power components**

Clean Aviation Technical Committee meeting, Brussels, September 19th, 2023

Camilla delivers a message regarding fast-tracking low-TRL technologies, de-risking currently planned technologies, and the need for academic involvement to ensure the development of next-generation engineers to the TC meeting, representing the Academic Member Forum (AMF).

Hydrogen-powered aviation

A fact-based study of hydrogen technology, economics, and climate impact by 2050

May 2020

FCH
FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

Clean Sky 2

CLEAN AVIATION
JOINT UNDERTAKING

Strategic Research and Innovation Agenda

Courtesy of DLR

Version December 2021

Facts and figures

34
SMALL AND MEDIUM-SIZED ENTERPRISES

120
INDUSTRY MEMBERS

51
UNIVERSITIES

33
RESEARCH CENTRES

244
PARTICIPATIONS IN FUNDED PROJECTS

€654M
EU FUNDING

24
COUNTRIES

CLEAN AVIATION'S JOURNEY TO CLIMATE NEUTRALITY

ACITURRI

AERnnova

DLR

AIRBUS

CIRA

DASSAULT AVIATION

AVIO

Fraunhofer

Honeywell

Fokker

GKN AEROSPACE

ITP Aero

LEONARDO

LIEBHERR

nlr

Lufthansa Technik

Łukasiewicz

Rolls-Royce®

SAFRAN

MTU
Aero Engines

INCAS
National Institute for Aerospace Research "Elie Carafoli"

UNIVERSITY OF
PATRAS
ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ

PIPISTREL

Raytheon
Technologies

ONERA
THE FRENCH AEROSPACE LAB

PIAGGIO
AEROSPACE

THALES

COSTRUZIONI AERONAUTICHE
TECNAM

tecnalia

HELLENIC AEROSPACE INDUSTRY S.A.

NTNU

IAI ELTA

University of
Stuttgart

SOLVAY

sonaca

SIEMENS

SINTEF

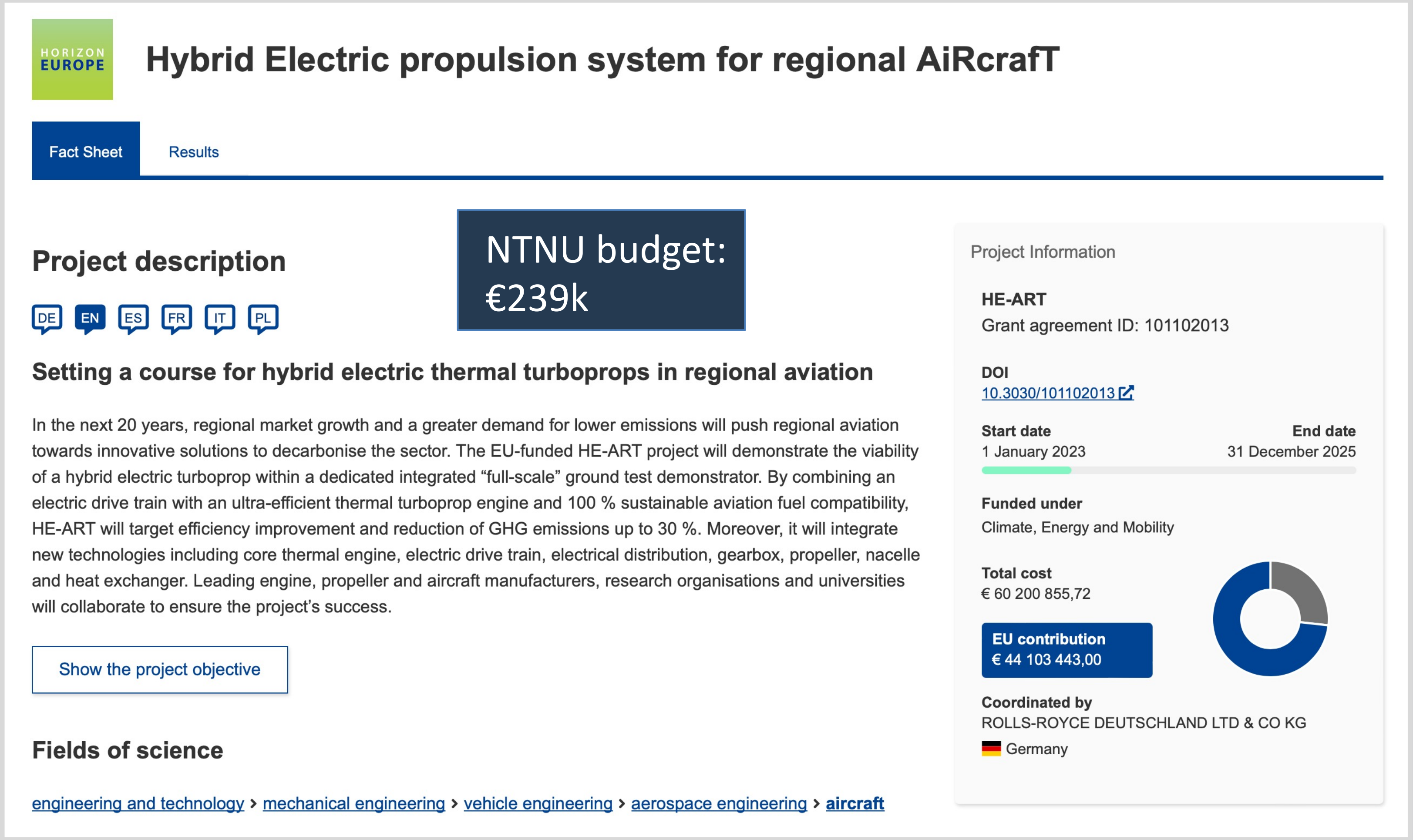
Technische
Universität
Braunschweig

UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

TU Delft
Delft
University of
Technology

KIT
Karlsruher Institut für Technologie

1859
Politecnico
di Torino



NTNU budget: €239k

HORIZON EUROPE

Hybrid Electric propulsion system for regional AiRcrafT

Project description

Setting a course for hybrid electric thermal turboprops in regional aviation

In the next 20 years, regional market growth and a greater demand for lower emissions will push regional aviation towards innovative solutions to decarbonise the sector. The EU-funded HE-ART project will demonstrate the viability of a hybrid electric turboprop within a dedicated integrated "full-scale" ground test demonstrator. By combining an electric drive train with an ultra-efficient thermal turboprop engine and 100 % sustainable aviation fuel compatibility, HE-ART will target efficiency improvement and reduction of GHG emissions up to 30 %. Moreover, it will integrate new technologies including core thermal engine, electric drive train, electrical distribution, gearbox, propeller, nacelle and heat exchanger. Leading engine, propeller and aircraft manufacturers, research organisations and universities will collaborate to ensure the project's success.

Fields of science

engineering and technology › mechanical engineering › vehicle engineering › aerospace engineering › **aircraft**

Project Information

HE-ART
Grant agreement ID: 101102013

DOI
10.3030/101102013

Start date
1 January 2023

End date
31 December 2025

Funded under
Climate, Energy and Mobility

Total cost
€ 60 200 855,72

EU contribution
€ 44 103 443,00

Coordinated by
ROLLS-ROYCE DEUTSCHLAND LTD & CO KG
Germany

NTNU budget: €603k

nOVel low-prEssure cRyogenic Liquid hydrogEn storAge For aviation.

Project description

Better hydrogen storage can make air travel greener

The future of green, more sustainable flying will depend on hydrogen-powered aviation. At the moment, this technology is limited by the hydrogen storage aboard aircraft, whose energy-to-mass ratio is too low to be practical. The EU-funded OVERLEAF project will solve this by employing a design that utilises innovative materials to develop an innovative liquid hydrogen storage tank. This tank will seamlessly integrate with an aircraft's fuselage and structure, while simultaneously achieving a gravimetric index of approximately 50 % for 500 kilograms of hydrogen. This high energy-to-mass ratio will make the transition to hydrogen-powered flight viable for the first time and help achieve the European Green Deal by lowering the environmental burden of air travel.

Fields of science

engineering and technology › mechanical engineering › vehicle engineering › aerospace engineering › **aircraft**

engineering and technology › environmental engineering › **energy and fuels**

social sciences › economics and business › economics › **sustainable economy**

Project Information

OVERLEAF
Grant agreement ID: 101056818

DOI
10.3030/101056818

Start date 1 May 2022

End date 30 April 2025

Funded under
Climate, Energy and Mobility

Total cost
€ 5 951 731,25

EU contribution
€ 5 951 729,00

Coordinated by
ACITURRI ENGINEERING SL
Spain

HydrogEn Lightweight & Innovative tank for zerO-emisSion aircraft

NTNU budget: €964k

Objective

To enable a technologically and economically feasible H2-powered aviation, new integral LH2 tank solutions are required that could serve as part of the airframe main structure and capable of withstanding its respective loads.
The H2ELIOS project will develop an innovative and effective lightweight LH2 storage system for aircraft. It will be implemented as demonstrators in two fuselage-like cylinder section with approximately 1.9 m of external diameter and approximately 2.3 m of external length. These demonstrators would be duly supported by component and subsystem ground tests at appropriate scale at project completion (TRL 5 at storage level). The aim is that the concept is ready to be embedded and integrated in a specified aircraft architecture for flight demonstration in later stages.
H2ELIOS will provide a feasible and novel low-pressure double-layer composite tank-based system, enabling the tank shape to be either conformal or non-conformal to the profile of the aircraft. Its general effectiveness will be assessed in terms of high GI performance and easiness of integration within the aircraft structure.
This concept will be supported by latest evolutions of innovative methods and technologies in terms of multidisciplinary design development, manufacturing processes and means of compliance and shall be demonstrated in operational conditions: first on ground up to TRL5 and then in flight by the end of Clean Aviation Phase 2 clearing a TRL6 maturation gate. Finally, delivery to the market is expected in the 2030-2035 period. In this way this project shall contribute to accomplish the objectives of the European Green Deal regarding decarbonization of the aviation industry.
The activities of H2ELIOS will be supported by explicit agreed support of EASA and an External Advisory Board comprising commercial aircraft OEMs, H2 management and cryogenics experts, MRO services, airlines, aircraft system integrators, materials developers and suppliers and airports operation

Project Information

H2ELIOS
Grant agreement ID: 101102003

DOI
10.3030/101102003

Start date	**End date**
1 January 2023	31 December 2025

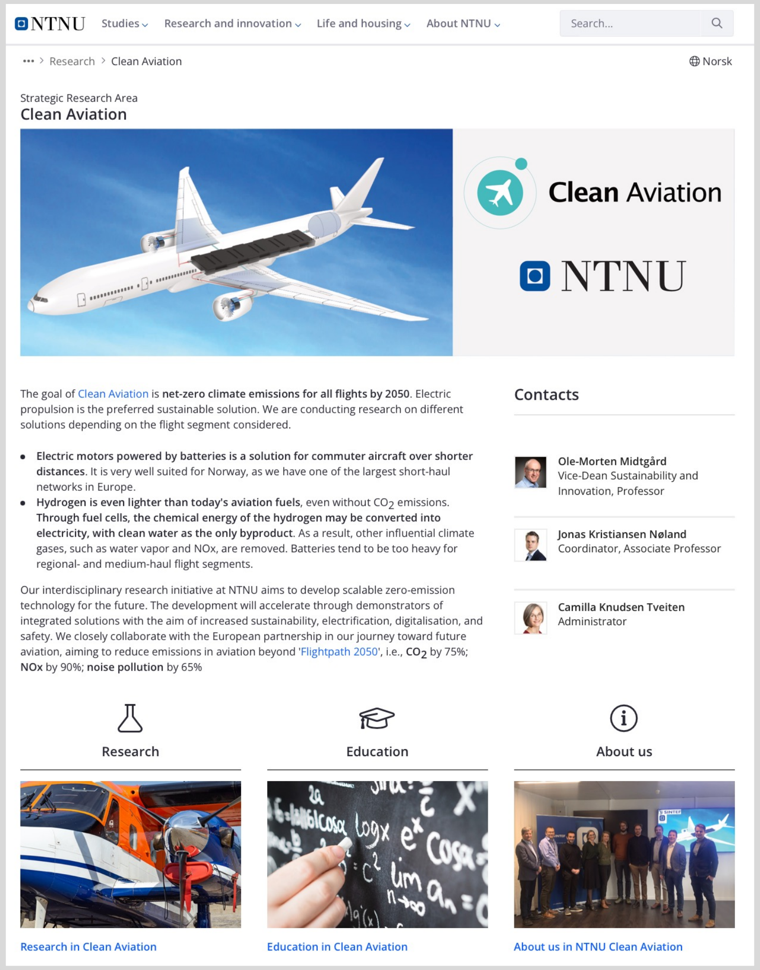
Funded under
Climate, Energy and Mobility

Total cost
€ 12 059 762,50

EU contribution
€ 9 959 306,89

Coordinated by
ACITURRI ENGINEERING SL
Spain

Gemini Centre Green Aviation, 40 k€, 2022 - 2025: "Create a hub for national collaboration on R&D towards zero-emission aviation and accelerate international collaboration with other research institutes, universities, and industrial partners", NTNU & SINTEF.



Strategic Research Area

Clean Aviation

The goal of Clean Aviation is **net-zero climate emissions for all flights by 2050**. Electric propulsion is the preferred sustainable solution. We are conducting research on different solutions depending on the flight segment considered.

- **Electric motors powered by batteries is a solution for commuter aircraft over shorter distances**. It is very well suited for Norway, as we have one of the largest short-haul networks in Europe.
- **Hydrogen is even lighter than today's aviation fuels**, even without CO_2 emissions. **Through fuel cells, the chemical energy of the hydrogen may be converted into electricity, with clean water as the only byproduct**. As a result, other influential climate gases, such as water vapor and NOx, are removed. Batteries tend to be too heavy for regional- and medium-haul flight segments.

Our interdisciplinary research initiative at NTNU aims to develop scalable zero-emission technology for the future. The development will accelerate through demonstrators of integrated solutions with the aim of increased sustainability, electrification, digitalisation, and safety. We closely collaborate with the European partnership in our journey toward future aviation, aiming to reduce emissions in aviation beyond 'Flightpath 2050', i.e., **CO_2** by 75%; **NOx** by 90%; **noise pollution** by 65%

Contacts

Ole-Morten Midtgård
Vice-Dean Sustainability and Innovation, Professor

Jonas Kristiansen Nøland
Coordinator, Associate Professor

Camilla Knudsen Tveiten
Administrator

Research

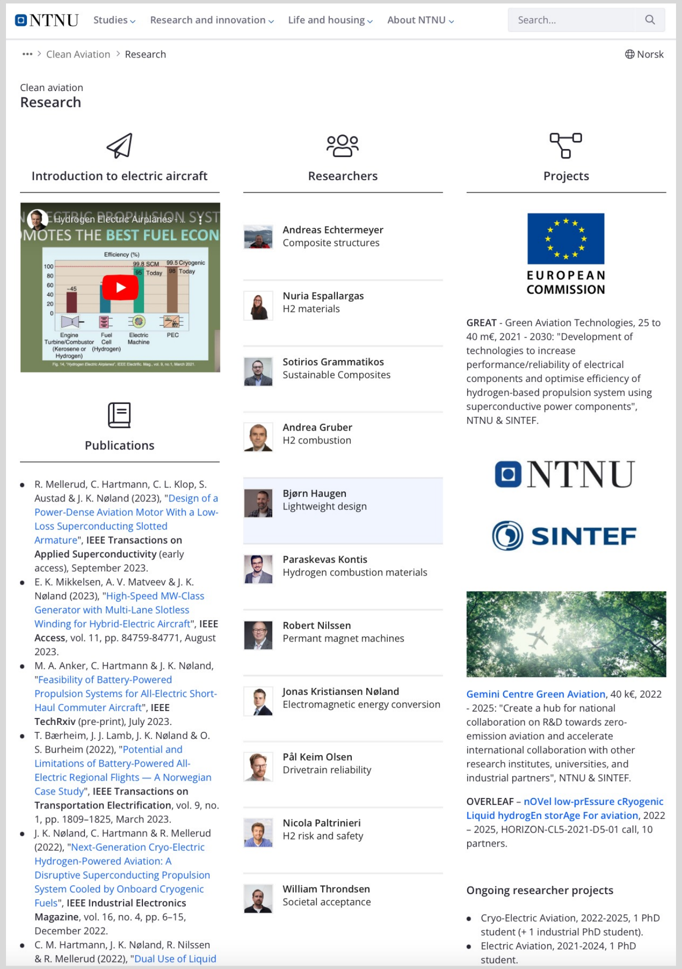
Research in Clean Aviation

Education

Education in Clean Aviation

About us

About us in NTNU Clean Aviation



Clean aviation

Research

Introduction to electric aircraft

Researchers

Andreas Echtermeyer
Composite structures

Nuria Espallargas
H2 materials

Sotirios Grammatikos
Sustainable Composites

Andrea Gruber
H2 combustion

Bjørn Haugen
Lightweight design

Paraskevas Kontis
Hydrogen combustion materials

Robert Nilssen
Permant magnet machines

Jonas Kristiansen Nøland
Electromagnetic energy conversion

Pål Keim Olsen
Drivetrain reliability

Nicola Paltrinieri
H2 risk and safety

William Throndsen
Societal acceptance

Projects

GREAT - Green Aviation Technologies, 25 to 40 m€, 2021 - 2030: "Development of technologies to increase performance/reliability of electrical components and optimise efficiency of hydrogen-based propulsion system using superconductive power components", NTNU & SINTEF.

Gemini Centre Green Aviation, 40 k€, 2022 - 2025: "Create a hub for national collaboration on R&D towards zero-emission aviation and accelerate international collaboration with other research institutes, universities, and industrial partners", NTNU & SINTEF.

OVERLEAF – nOVel low-prEssure cRyogenic Liquid hydrogEn storAge For aviation, 2022 – 2025, HORIZON-CL5-2021-D5-01 call, 10 partners.

Ongoing researcher projects

- Cryo-Electric Aviation, 2022-2025, 1 PhD student (+ 1 industrial PhD student).
- Electric Aviation, 2021-2024, 1 PhD student.

Publications

- R. Mellerud, C. Hartmann, C. L. Klop, S. Austad & J. K. Nøland (2023), "Design of a Power-Dense Aviation Motor With a Low-Loss Superconducting Slotted Armature", **IEEE Transactions on Applied Superconductivity** (early access), September 2023.
- E. K. Mikkelsen, A. V. Matveev & J. K. Nøland (2023), "High-Speed MW-Class Generator with Multi-Lane Slotless Winding for Hybrid-Electric Aircraft", **IEEE Access**, vol. 11, pp. 84759-84771, August 2023.
- M. A. Anker, C. Hartmann & J. K. Nøland, "Feasibility of Battery-Powered Propulsion Systems for All-Electric Short-Haul Commuter Aircraft", **IEEE TechRxiv** (pre-print), July 2023.
- T. Bærheim, J. J. Lamb, J. K. Nøland & O. S. Burheim (2022), "Potential and Limitations of Battery-Powered All-Electric Regional Flights — A Norwegian Case Study", **IEEE Transactions on Transportation Electrification**, vol. 9, no. 1, pp. 1809–1825, March 2023.
- J. K. Nøland, C. Hartmann & R. Mellerud (2022), "Next-Generation Cryo-Electric Hydrogen-Powered Aviation: A Disruptive Superconducting Propulsion System Cooled by Onboard Cryogenic Fuels", **IEEE Industrial Electronics Magazine**, vol. 16, no. 4, pp. 6–15, December 2022.
- C. M. Hartmann, J. K. Nøland, R. Nilssen & R. Mellerud (2022), "Dual Use of Liquid

Zero emission

STATUS QUO

Shut down aviation

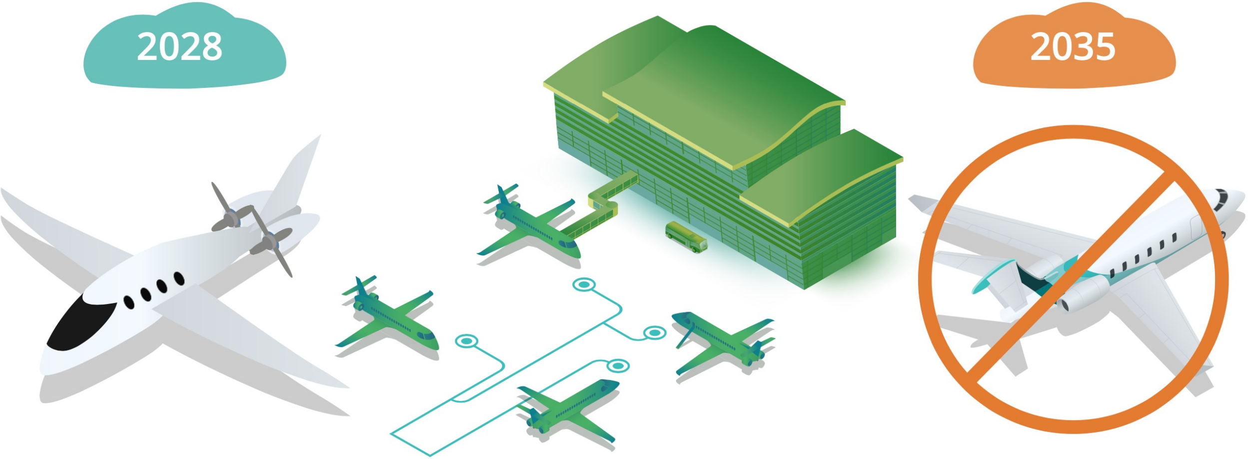
A

B

C

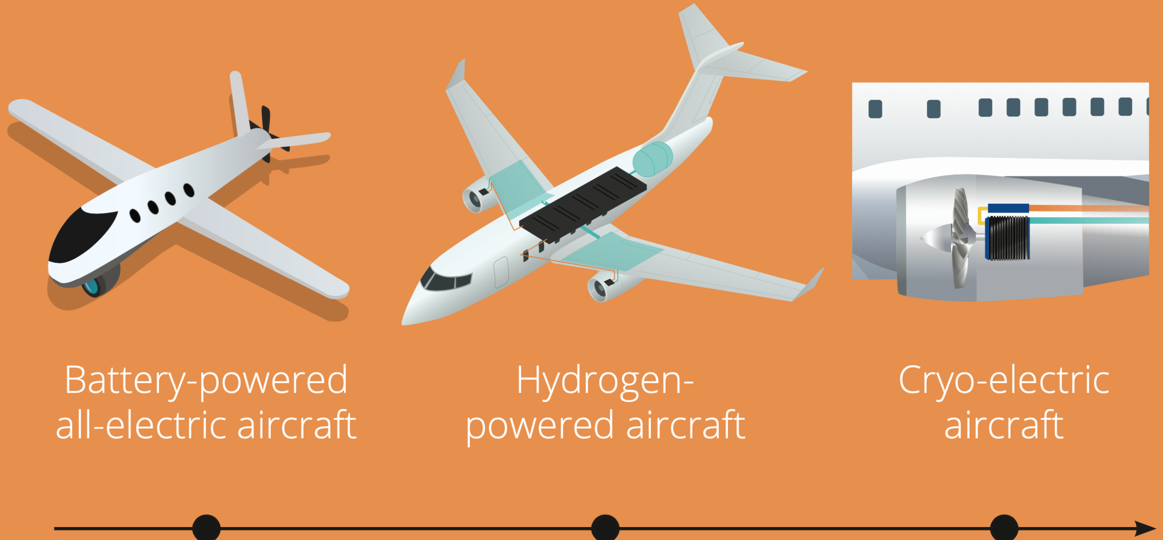
2028

2035



Clean Aviation NTNU

Application areas



Battery-powered all-electric aircraft

Hydrogen-powered aircraft

Cryo-electric aircraft

2028

2035

2050

Leadership in education

Basic research for next-generation disruptive technologies

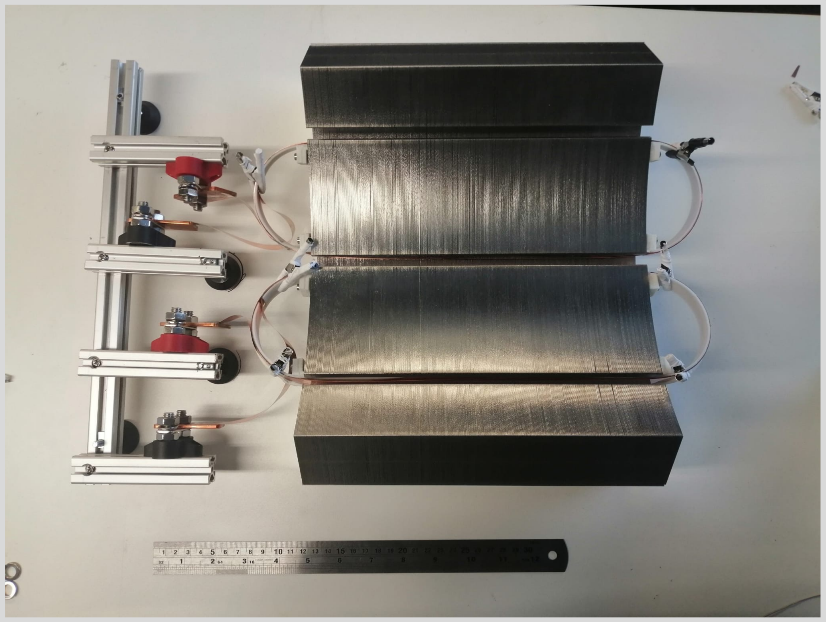
Complete demonstrators from source to propulsion

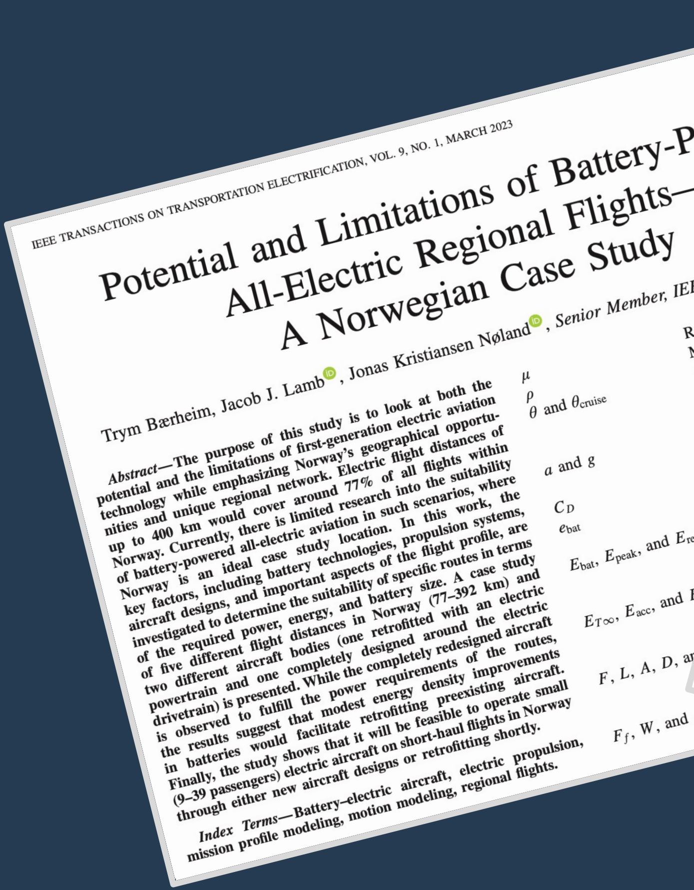
Public perception and societal acceptance

Socio-economic drivers & techno-economic benefits

Strategic measures NTNU (ambition)

Cryo-Electric Aviation Lab @ NTNU





IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, VOL. 9, NO. 1, MARCH 2023

Potential and Limitations of Battery-Powered All-Electric Regional Flights—A Norwegian Case Study

Trym Bærheim, Jacob J. Lamb, Jonas Kristiansen Nøland, *Senior Member, IEEE*, and Odne S

***Abstract*—The purpose of this study is to look at both the potential and the limitations of first-generation electric aviation technology while emphasizing Norway's geographical opportunities and unique regional network. Electric flight distances of up to 400 km would cover around 77% of all flights within Norway. Currently, there is limited research into the suitability of battery-powered all-electric aviation in such scenarios, where Norway is an ideal case study location. In this work, the key factors, including battery technologies, propulsion systems, aircraft designs, and important aspects of the flight profile, are investigated to determine the suitability of specific routes in terms of the required power, energy, and battery size. A case study of five different flight distances in Norway (77–392 km) and two different aircraft bodies (one retrofitted with an electric powertrain and one completely designed around the electric drivetrain) is presented. While the completely redesigned aircraft is observed to fulfill the power requirements of the routes, the results suggest that modest energy density improvements in batteries would facilitate retrofitting preexisting aircraft. Finally, the study shows that it will be feasible to operate small (9–39 passengers) electric aircraft on short-haul flights in Norway through either new aircraft designs or retrofitting shortly.**

***Index Terms*—Battery–electric aircraft, electric propulsion, mission profile modeling, motion modeling, regional flights.**

μ

ρ

θ and θ_{cruise}

a and g

C_D

e_{bat}

E_{bat}, E_{peak}, and E_{res}

$E_{T\infty}$, E_{acc}, and E_{au}

F, L, A, D, ar

F_f, W, and N

Rolling friction

Mass density o

Aircraft's ins

ing flight

tively [°]

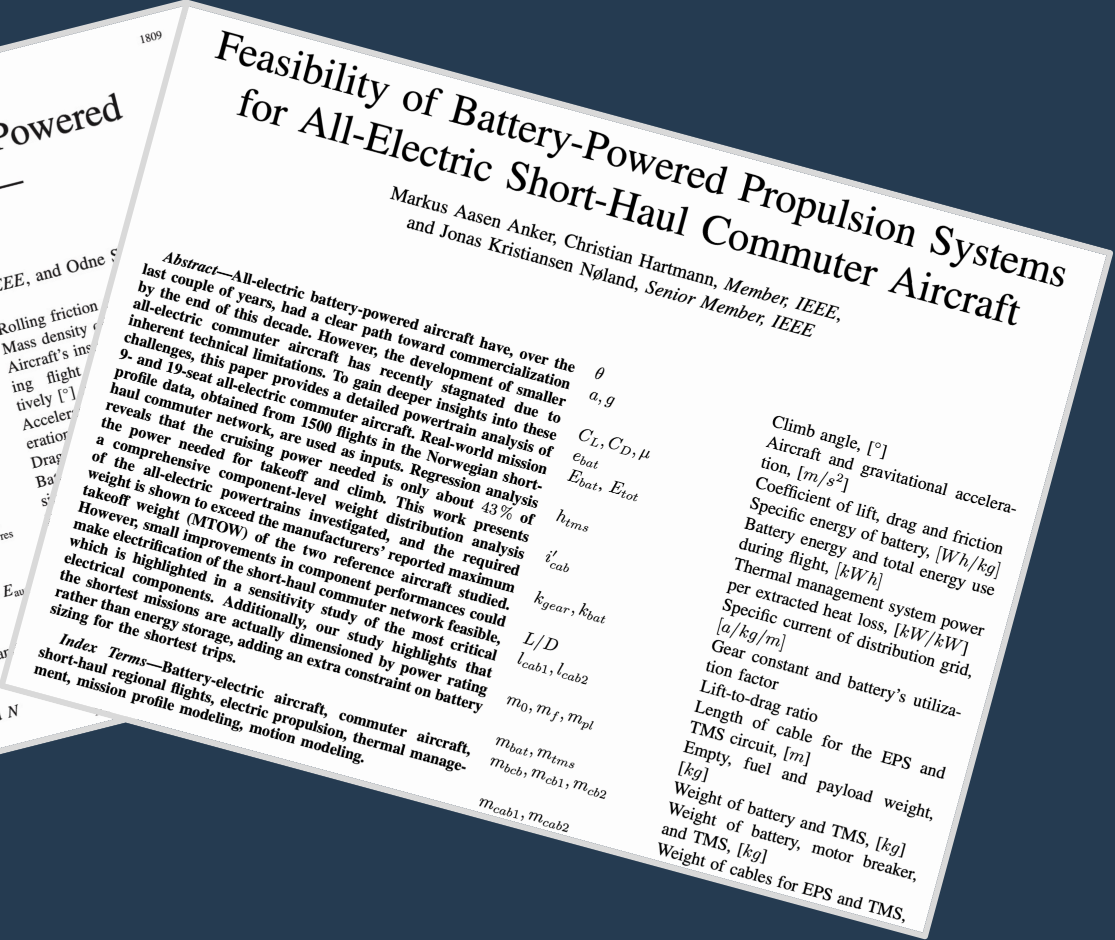
Acceler

eration

Drag

Ba

si



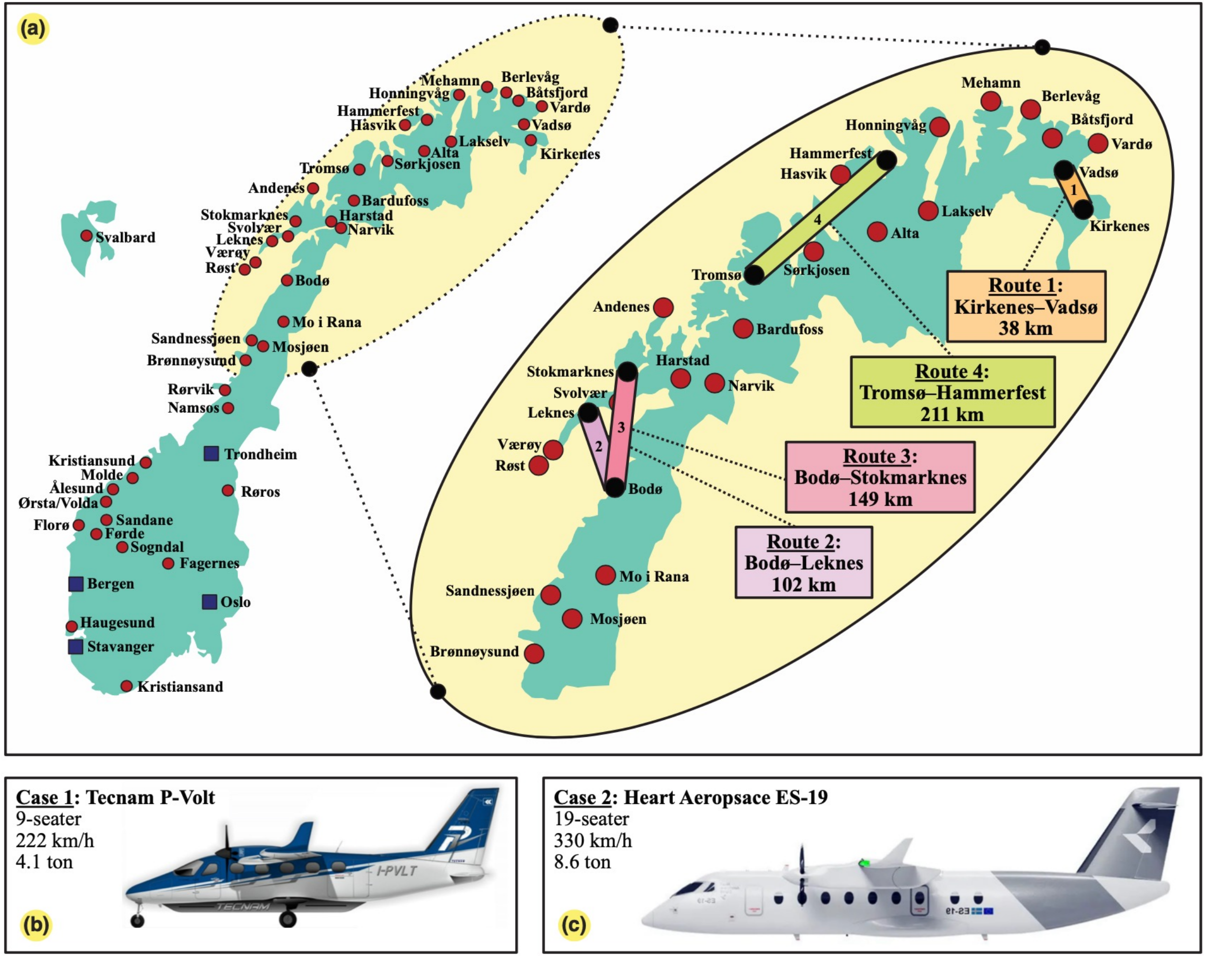
Feasibility of Battery-Powered Propulsion Systems for All-Electric Short-Haul Commuter Aircraft

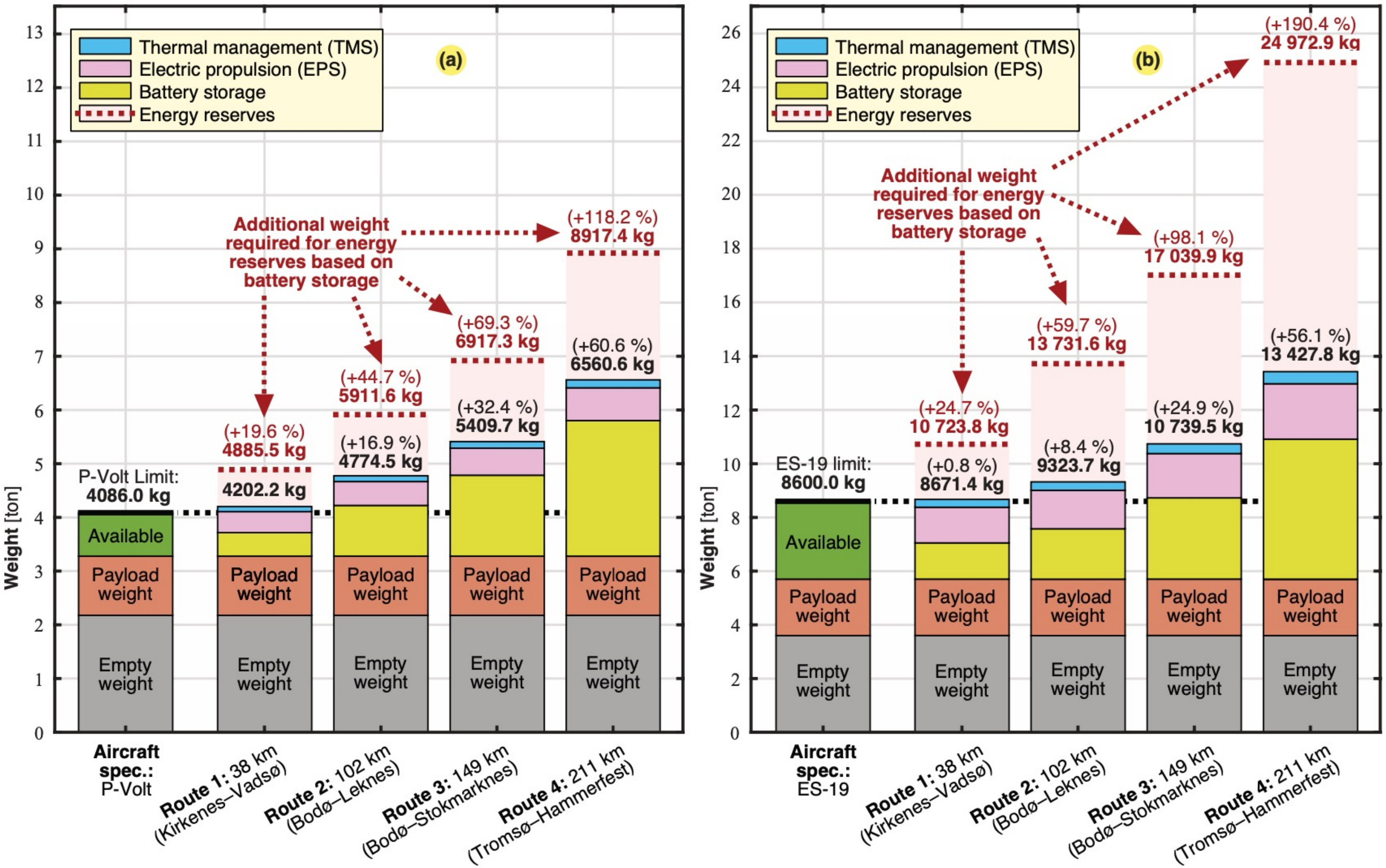
Markus Aasen Anker, Christian Hartmann, *Member, IEEE*, and Jonas Kristiansen Nøland, *Senior Member, IEEE*

***Abstract*—All-electric battery-powered aircraft have, over the last couple of years, had a clear path toward commercialization by the end of this decade. However, the development of smaller all-electric commuter aircraft has recently stagnated due to inherent technical limitations. To gain deeper insights into these challenges, this paper provides a detailed powertrain analysis of 9- and 19-seat all-electric commuter aircraft. Real-world mission profile data, obtained from 1500 flights in the Norwegian short-haul commuter network, are used as inputs. Regression analysis reveals that the cruising power needed is only about 43% of the power needed for takeoff and climb. This work presents a comprehensive component-level weight distribution analysis of the all-electric powertrains investigated, and the required weight is shown to exceed the manufacturers' reported maximum takeoff weight (MTOW) of the two reference aircraft studied. However, small improvements in component performances could make electrification of the short-haul commuter network feasible, which is highlighted in a sensitivity study of the most critical electrical components. Additionally, our study highlights that the shortest missions are actually dimensioned by power rating rather than energy storage, adding an extra constraint on battery sizing for the shortest trips.**

***Index Terms*—Battery-electric aircraft, commuter aircraft, short-haul regional flights, electric propulsion, thermal management, mission profile modeling, motion modeling.**

θ	Climb angle, [°]
a, g	Aircraft and gravitational acceleration, $[m/s^2]$
C_L, C_D, μ	Coefficient of lift, drag and friction
e_{bat}	Specific energy of battery, $[Wh/kg]$
E_{bat}, E_{tot}	Battery energy and total energy use during flight, $[kWh]$
h_{tms}	Thermal management system power per extracted heat loss, $[kW/kW]$
i'_{cab}	Specific current of distribution grid, $[a/kg/m]$
k_{gear}, k_{bat}	Gear constant and battery's utilization factor
L/D	Lift-to-drag ratio
l_{cab1}, l_{cab2}	Length of cable for the EPS and TMS circuit, $[m]$
m_0, m_f, m_{pl}	Empty, fuel and payload weight, $[kg]$
m_{bat}, m_{tms}	Weight of battery and TMS, $[kg]$
$m_{bcb}, m_{cb1}, m_{cb2}$	Weight of battery, motor breaker, and TMS, $[kg]$
m_{cab1}, m_{cab2}	Weight of cables for EPS and TMS,


(a)
Svalbard
Mehamn
Berlevåg
Honningvåg
Båtsfjord
Hammerfest
Vardø
Hasvik
Vadsø
Lakselv
Alta
Kirkenes
Tromsø
Sørkjosen
Andenes
Bardufoss
Stokmarknes
Harstad
Svolvær
Narvik
Leknes
Værøy
Røst
Bodø
Mo i Rana
Sandnessjøen
Mosjøen
Brønnøysund
Rørvik
Namsos
Trondheim
Kristiansund
Molde
Ålesund
Ørsta/Volda
Røros
Sandane
Florø
Førde
Sogndal
Fagernes
Bergen
Oslo
Haugesund
Stavanger
Kristiansand
1
2
3
4
Route 1: Kirkenes–Vadsø 38 km
Route 4: Tromsø–Hammerfest 211 km
Route 3: Bodø–Stokmarknes 149 km
Route 2: Bodø–Leknes 102 km
Case 1: Tecnam P-Volt
9-seater
222 km/h
4.1 ton
(b)
Case 2: Heart Aeropsace ES-19
19-seater
330 km/h
8.6 ton
(c)


(a)
Thermal management (TMS)
Electric propulsion (EPS)
Battery storage
Energy reserves
Weight [ton]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
P-Volt Limit:
4086.0 kg
Available
Payload weight
Empty weight
Additional weight required for energy reserves based on battery storage
(+19.6 %)
4885.5 kg
4202.2 kg
(+44.7 %)
5911.6 kg
(+16.9 %)
4774.5 kg
(+69.3 %)
6917.3 kg
(+32.4 %)
5409.7 kg
(+118.2 %)
8917.4 kg
(+60.6 %)
6560.6 kg
Aircraft spec.: P-Volt
Route 1: 38 km (Kirkenes–Vadsø)
Route 2: 102 km (Bodø–Leknes)
Route 3: 149 km (Bodø–Stokmarknes)
Route 4: 211 km (Tromsø–Hammerfest)
(b)
Thermal management (TMS)
Electric propulsion (EPS)
Battery storage
Energy reserves
Weight [ton]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
ES-19 limit:
8600.0 kg
Available
Payload weight
Empty weight
Additional weight required for energy reserves based on battery storage
(+24.7 %)
10 723.8 kg
(+0.8 %)
8671.4 kg
(+59.7 %)
13 731.6 kg
(+8.4 %)
9323.7 kg
(+98.1 %)
17 039.9 kg
(+24.9 %)
10 739.5 kg
(+190.4 %)
24 972.9 kg
(+56.1 %)
13 427.8 kg
Aircraft spec.: ES-19
Route 1: 38 km (Kirkenes–Vadsø)
Route 2: 102 km (Bodø–Leknes)
Route 3: 149 km (Bodø–Stokmarknes)
Route 4: 211 km (Tromsø–Hammerfest)

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Digital Object Identifier 10.1109/ACCESS.2023.3302772

RESEARCH ARTICLE

High-Speed MW-Class Generator With Multi-Lane Slotless Winding for Hybrid-Electric Aircraft

EIRIK KVÅLE MIKKELSEN[1], **ALEXEY MATVEEV**[1,2], **AND JONAS KRISTIANSEN NØLAND**[1], **(Senior Member, IEEE)**
[1] Department of Electric Energy, Norwegian University of Science and Technology (NTNU), 7034 Trondheim, Norway
[2] Alva Industries AS, 7038 Trondheim, Norway
Corresponding author: Jonas Kristiansen Nøland (jonas.k.noland@ntnu.no)

ABSTRACT This paper presents a comprehensive design and analysis of a high-speed, multi-lane,
15 000 rpm, 3 kV slotless generator system tailored for hybrid-electric aircraft. The armature of this
incorporates FiberPrinting^{TM} technology, featuring four galvanically isolated concentric win
An assessment of the generator's performance metrics was conducted through finite element anal
The 2.5 MW slotless 8-pole generator achieved a power density of 24.4 kW/kg (for active m
efficiency above 99 % at the current density of 15 A/mm^2. To further enhance the system
we investigated the possibility of incorporating a filter between the generator and freque
However, this investigation revealed that the weight and losses associated with the filte
potential gains in generator efficiency. Additionally, the study explored the impact of ele
density to levels comparable to the state-of-the-art (SotA) machines (20-27.5 A/mm^2). T
that such an enhancement would significantly raise the power density to 35-40 kW
increasing the number of poles from 8 to 12, in combination with the elevated current
the threshold of 40 kW/kg. Comparing our findings against the SotA, we demonstr
topology exhibits the potential to outperform conventional technologies, provided ade
are implemented.

INDEX TERMS Generator, hybrid-electric aircraft, slotless machines, fault-tole

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Design of a Power-Dense Aviation Motor with a Low-Loss Superconducting Slotted Armature

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***Abstract*—This article describes the design and analysis of a 2.5-MW, 5000-rpm electric motor with a slotted armature employing REBCO high-temperature superconductors (HTS). The alternating current and field in the armature induces AC losses in the superconductors, requiring cryogenic cooling. Therefore, the aim is to design a machine with sufficiently low losses to make this cooling realistic, which simultaneously outperforms the state-of-the-art. The reasoning behind the key design choices is presented before the model used for two-dimensional (2-D) finite element analysis (FEA) is described. Then, HTS AC losses are studied with the T-A-formulation, examining the impact of various operating conditions. Aligning the HTS tapes with the field was found to successfully reduce AC losses, while filamentization was only successful for more than 10 filaments. The final design had an active torque density of 50.9 Nm/kg and an estimated efficiency of 99.8% when the HTS are operated at 40 K.**

***Index Terms*—AC loss, armature superconducting, aviation motor, filaments, finite element analysis (FEA), high-temperature superconductors (HTS), REBCO, Roebel cables.**

I. INTRODUCTION

MOST of the climate impact from the aviation sector is not caused by CO_2, but contrails and NOx, produced by the high temperatures required in combustion engines [1]. Electrically powered fans or propellers can avoid these emissions altogether, and the development of fully electric or fuel cell electric powertrains is required for a true zero-emission scenario. Nevertheless, it has proven a challenge to design electric components meeting the extreme weight and efficiency requirements posed by the aviation sector.

compromise the machine benefits [4]. For example, Haran *et al.* (2017) argues that losses in a superconducting armature must be significantly less than 0.1 % of the machine's rated power to be competitive with its alternatives [5]. Even higher losses could be tolerated if using liquid hydrogen (LH_2) fuel as a cryogenic heat sink [6], but also this has a limited cooling capacity [7].

The recent development of the mixed **T**-**A**-formulation has enabled accurate AC loss estimations with low computation times [8], making it a powerful tool in the design of electric machines with a large number of HTS tapes [9]–[12]. Although aviation machines with HTS armatures have been explored in multiple previous papers [13]–[21], none have conducted a detailed finite element analysis (FEA) of AC losses in a power-dense full-scale aviation motor. In this paper, the **T**-**A**-formulation is therefore used to explore the potential of a 2.5 MW aviation motor with a slotted stator and HTS armature windings while assessing its feasibility with respect to cryogenic cooling requirements. This is done through a comprehensive AC loss analysis, studying special HTS design considerations, as well as the impact of multiple design modifications and loss mitigation methods. Lastly, the design is compared with the state-of-the-art (SotA) within power-dense conventional machines.

The paper starts with an overview of the machine design choices in Section II, followed by the FEA modeling approach and material properties in Section III. In Section IV, the HTS AC losses are studied for several operating conditions and loss reduction methods. In Section V, the key machine parameters