

Electrified Aircraft Propulsion

What are the benefits of electrified propulsion for large aircraft? What technology advancements are required to realize these benefits? How can the aerospace industry transition from today's technologies to state-of-the-art electrified systems? Learn the answers with this multidisciplinary text, combining expertise from leading researchers in electrified aircraft propulsion. The book includes broad coverage of electrification technologies – spanning power systems and power electronics, materials science, superconductivity and cryogenics, thermal management, battery chemistry, system design, and system optimization – and a clear-cut road map identifying remaining gaps between the current state-of-the-art and future performance technologies. Providing expert guidance on areas for future research and investment and an ideal introduction to cutting-edge advances and outstanding challenges in large electric aircraft design, this is a perfect resource for graduate students, researchers, electrical and aeronautical engineers, policymakers, and management professionals interested in next-generation commercial flight technologies.

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Frontmatter
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Electrified Aircraft Propulsion

Powering the Future of Air Transportation

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**To all scientists and engineers working to make electrified aircraft propulsion
a reality**

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Preface

The genesis of this book was two special sessions on electrified aircraft propulsion (EAP) at the Institute of Electrical and Electronics Engineers (IEEE) Energy Conversion Conference and Exhibition (ECCE), held in Montreal, Canada, in September 2015. At that time, small two- to four-passenger electric aircraft were being developed, and the circumnavigation by the solar-powered, single-seat, all-electric *Solar Impulse 2* was underway, catching the imagination of the public. Although small electric planes could operate using 2015 technology, the consensus was that disruptive, breakthrough technologies in several areas would be required to enable electrified propulsion for the vast fleet of large commercial transport aircraft that accounted for most of the aviation industry's carbon emissions. To spark innovation, the US National Aeronautics and Space Administration (NASA) Aeronautics division, through its Advanced Air Transport Technology Project (AATT), had recently launched several significant NASA Research Agreements (NRAs) to develop technologies enabling megawatt-class electric propulsion systems. The ECCE sessions were organized to bring together technology experts and raise awareness of the significant challenges addressed by these NRAs. They were well attended and well received, revealing great enthusiasm in the technical community to overcome the challenges ahead.

The success at ECCE 2015 spawned numerous similar sessions at related conferences, and in April 2016, a technology road map for large electrical machines was drafted at a workshop hosted at the University of Illinois at Urbana–Champaign by the Grainger Center for Electric Machinery and Electromechanics and NASA. Joint workshops between the American Institute of Aeronautics and Astronautics (AIAA) and IEEE were then held, fostering stronger collaboration between the electrical engineering and aerospace communities and culminating in the creation of the annual Electric Aircraft Technologies Symposium (EATS), colocated with the popular AIAA Propulsion and Energy Forum. Seeing the momentum building in this burgeoning field, Cambridge University Press approached Nateri Madavan and Kiruba Haran to distill the important concepts discussed at these events into an edited book. Contributions were solicited from a large team of diverse technology experts to create a compendium of the emerging field. Tim O'Connell then joined the team of editors to perform detailed copyediting of the contributed works and help push the book across the finish line.

Electrified Aircraft Propulsion: Powering the Future of Air Transportation is intended for engineers, scientists, advanced undergraduate or graduate students,

management professionals in aerospace-related fields, and policymakers who want to understand the numerous obstacles to electrifying the propulsion systems of large, passenger-class (or similar-sized) aircraft. As these obstacles are many, the book necessarily spans a wide range of topics, including power systems and electronics, materials science, superconductivity/cryogenics, thermal management, battery chemistry, system design, and optimization. Rather than “deep-diving” into any one area, it contains general concepts, tools, and information, providing the reader with a solid top-level understanding of the material. Thus, while it may be used as a textbook for a university-level survey course, this book’s primary function is as a desk reference and launching point to deeper study.

In nine comprehensive chapters, this book addresses three main questions:

- (1) What are the benefits of electrified propulsion for large aircraft?
- (2) What technology advancements are required to realize these benefits?
- (3) How can the aerospace industry transition from today’s state of the art to these advanced technologies?

To address these in a logical way, the book has been arranged to create a natural progression through its wide range of topics. While every attempt has been made to ensure the consistent use of notation, variables, acronyms, etc., because each chapter has been written by a separate technology area expert (or group of experts), there may be some discrepancies. For example, for practical or historical reasons, it is common to find the same engineering concept taught and used slightly differently across disciplines, each with its own unique notations, equations, variables, etc. In such cases, no attempt has been made to unify the notations. Rather, it is the editors’ belief that each subject area should be presented in its “native” format so that the reader will more easily be able to apply the knowledge gained herein to other related sources.

Further, because this field is rapidly evolving, some of its key identifying terms and definitions have undergone several iterations over the years. For example, when this book was first proposed, its working title was *Hybrid Electric Aircraft Propulsion*. The term “hybrid” was originally used in the community to describe systems that used any combination of traditional and nontraditional propulsion. When these concepts were new, hybrids were a natural stepping stone between traditional turbofan propulsion and fully electric propulsion. Over the years, as propulsion systems have become more fully electrified, terms such as “electric/electrified aircraft,” “electric propulsion,” and “propulsion electrification” have become more prevalent. At the time of this writing, a consensus seems to have been reached for the all-encompassing term “electrified propulsion,” which can include architectures that derive some or all of their propulsion energy from electricity. This includes those architectures previously called “hybrid.” The book’s final published title reflects this consensus. While we have made every attempt at a consistency of notation throughout, the legacy of diverse terminology lives on, and there are likely a few cases where alternative terms are used. In the context of this text, the reader can safely assume that all of these terms are essentially synonymous with each other.

Back to the three main questions: in Chapter 1, “Benefits of Electrified Propulsion for Large Aircraft,” Rodger Dyson, Ralph Jansen, and Nateri Madavan address the first one, making the case for EAP through numerous trade studies and the analysis of several concept vehicles. Because it introduces the architectures that are the focus of the text and lays the groundwork for the chapters that follow, Chapter 1 is recommended as a prerequisite to the other chapters. Beyond this, the chapters largely stand alone and can be studied in any order that suits the reader.

The subsequent eight chapters, while remaining focused on question 1, collectively address questions 2 and 3 in technical detail. In Chapter 2, “Aircraft Electric Power System Design, Control, and Protection,” Robert Bayles presents a modern aircraft electric power system (EPS), summarizing its design, control, and protection functions. Several key EPS components and features are described, which provide context to the rest of the book.

Electric machines (EMs) are the topic of Chapters 3 and 4. In Chapter 3, “Megawatt-Scale Electric Machines for Electrified Aircraft Propulsion,” Tim C. O’Connell and Xiaolong Zhang focus on the large, conventional (i.e., non-cryogenic), megawatt-scale EMs that are required to facilitate electric propulsion in large passenger-class aircraft. The material provides a comprehensive overview, with a focus on methods for mass reduction and specific power improvement. In Chapter 4, “Superconducting Machines and Cables,” Thanatheepan Balachandran, Timothy Haugan, and Kiruba Haran propose options for drastically increasing machine specific power and efficiency based on superconducting (SC) technology. The authors present several SC machine topologies being pursued by different research groups, followed by the physics and advantages of SC cables, and a look forward based on current SC technology trends.

Chapters 5 and 6 focus on power electronic circuits. In Chapter 5, “Conventional Power Electronics for Electrified Aircraft Propulsion,” Patrick Wheeler introduces the basic concepts of power electronics, focusing on those circuits and devices that are crucial for EAP. As with EMs, the push for ever-higher specific power requires power circuits capable of power levels and efficiencies well beyond the current state of the art. This motivates Chapter 6, “Cryogenic Power Electronics,” by Zheyu Zhang, Fei (Fred) Wang, Ruirui Chen, and Handong Gui. In it, the authors describe the development of cryogenic power electronics, from the component up to the converter level, highlighting their massive potential for high specific power.

In Chapter 7, “Electrochemical Energy Storage and Conversion for Electrified Aircraft,” Ajay Misra provides an overview of the electrochemical energy storage and conversion systems for electrified aircraft, including batteries, fuel cells, supercapacitors, and multifunctional structures with energy storage capability. He highlights the extremely high energy storage requirements of fully electric passenger-class aircraft and points to some promising technologies on the horizon that may help us get there.

Electric drivetrains for EAP have unique thermal management requirements. Charles E. Lents addresses these in Chapter 8, “Thermal Management of Electrified Propulsion Systems,” in which he walks through the fundamental equations and calculations for designing a notional TMS that includes both a liquid- and oil-cooling loop and multiple heat exchangers.

The book concludes with Chapter 9, “Performance Assessment of Electrified Aircraft,” in which Jonathan C. Gladin ties the material together by presenting a systematic performance assessment process for EAP concept architectures. Gladin calls upon concepts and conclusions from earlier chapters to present this comprehensive method for electric aircraft design.

This book represents years of work by a diverse community of engineers and scientists who are dedicated to making electrified propulsion a reality. As with any compendium of state-of-the-art technology, it provides a snapshot of a quickly evolving field and makes projections using the best knowledge available today. It is our hope that it will provide inspiration and stimulate continued research and rapid innovation. Paradoxically, this book will have successfully done its job if the material herein becomes dated quickly, meriting a second edition. We hope that you will enjoy reading and using it as much as we have enjoyed producing it.

Finally, we would like to thank all of our authors for taking time out of their busy schedules to contribute their knowledge to this collection, and Thanatheepan Balachandran for preparing many of the high-quality figures for production.