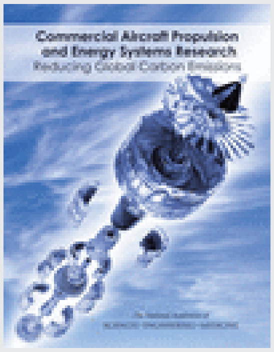

Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions

DETAILS

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Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

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Preface

Commercial aviation, like every means of mass transportation, releases carbon dioxide into the atmosphere. Substantial, ongoing investments in air transportation technologies continually increase the efficiency of air transportation, moving passengers and cargo over the same distance with less fuel consumed and, hence, fewer carbon emissions. Even so, given the high demand for commercial air transportation and its expected growth, more effort is needed to mitigate the contribution that commercial aviation makes to climate change.

A great many public and private organizations, including engine and aircraft manufacturers, academia, the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration, the Environmental Protection Agency, and the U.S. Departments of Agriculture, Commerce, Defense, and Energy, are already engaged in developing advanced technologies, policies, and standards that will help reduce carbon emissions from commercial aviation. Accordingly, NASA's Aeronautics Research Mission Directorate requested that the National Academies of Sciences, Engineering, and Medicine convene a committee to develop a *national* research agenda for propulsion and energy systems research to reduce commercial aviation carbon emissions. In response, the Aeronautics and Space Engineering Board of the Division on Engineering and Physical Sciences assembled a committee to carry out the assigned statement of task (see Appendix A). The committee members (see Appendix B) met four times during 2015 and early 2016, three times at the Academies' facilities in Washington, D.C., and once at the Academies' Irvine, California, facility. As specified in the statement of task, the committee developed a research agenda consisting of a set of high-priority research projects that, if completed by NASA and other interested parties, would advance the four high-priority approaches for developing propulsion and energy system technologies that could be introduced into service during the next 10 to 30 years to reduce global carbon emissions by commercial aviation.

Karen Thole, *Co-Chair*
Woodrow Whitlow, Jr., *Co-Chair*
Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Michael Armstrong, Rolls-Royce North American Technologies,
John R. Birge, University of Chicago,
Bill Borger, W U Borger Consulting,
Fokion N. Egolfopoulos, University of Southern California,
Neil Gehrels, NASA Goddard Space Flight Center,
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Louis J. Lanzerotti, New Jersey Institute of Technology,
Jonathan Male, Department of Energy,
George W. Sutton, Analysis and Applications,
Wallace E. Tyner, Purdue University, and
Jeanne Yu, Boeing Commercial Airplanes.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Edward M. Greitzer, Massachusetts Institute of Technology, and Maxine L. Savitz, Honeywell, Inc. (retired), who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Synopsis

At the request of the National Aeronautics and Space Administration (NASA), the National Academies of Sciences, Engineering, and Medicine[1] convened a committee to develop a national research agenda for reducing carbon dioxide (CO_2) emissions from commercial aviation. The report focuses on propulsion and energy technologies for reducing carbon emissions from large, commercial aircraft—single-aisle and twin-aisle aircraft that carry 100 or more passengers—because such aircraft account for more than 90 percent of global emissions from commercial aircraft. Moreover, while smaller aircraft also emit CO_2, they make only a minor contribution to global emissions, and many technologies that reduce CO_2 emissions for large aircraft also apply to smaller aircraft. Excluding from consideration other research areas such as air traffic management systems and policy approaches such as carbon taxes, the committee identified 12 high-priority research projects[2] divided among four key topics related to propulsion and energy technologies.

Recommendation. *High-Priority Approaches.* Agencies and organizations in government, industry, and academia with an interest in developing propulsion and energy system technologies that could reduce CO_2 emissions from global civil aviation and that could be introduced into service during the next 10 to 30 years should execute a national research agenda that places the highest priority on four approaches:

- **Advances in aircraft–propulsion integration,**
- **Improvements in gas turbine engines,**
- **Development of turboelectric propulsion systems, and**
- **Advances in sustainable alternative jet fuels.**

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council (NRC) are used in a historical context to refer to activities before July 1.

[2] While the committee identified some of the most promising approaches that could be successfully implemented in the next 30 years, only time will tell which technological breakthroughs will prove most effective. By putting forward a set of research priorities, the committee is not recommending that all research to support other technologies be discontinued.

AIRCRAFT–PROPULSION INTEGRATION RESEARCH

The committee identified two high-priority research projects to support advances in aircraft–propulsion integration:

- Nacelles for ultrahigh bypass ratio gas turbines and
- Boundary layer ingestion.

Advances in aircraft–propulsion integration are needed to support low-carbon innovations that are not achievable by discrete improvements to individual component technologies. This includes developing lighter, more efficient nacelles to increase propulsion efficiency for standard aircraft as well as nonstandard configurations that require a much higher level of propulsion–aircraft integration to enable boundary layer ingestion.

GAS TURBINE ENGINE RESEARCH

The committee identified three high-priority research projects to support advances in gas turbine engines:

- Low pressure–ratio fan propulsors,
- Engine materials and coatings, and
- Small engine cores.

Gas turbine engines have considerable room for improvement, with a potential to reach overall efficiencies 30 percent greater than the best engines in service today. This magnitude of gain requires investment in a host of technologies such as developing advanced materials to reduce weight and improve engine performance and designing smaller, more efficient engine cores.

TURBOELECTRIC PROPULSION RESEARCH

The committee identified three high-priority research projects to support advances in turboelectric propulsion:

- Turboelectric aircraft system studies,
- Core turboelectric technologies, and
- Megawatt-class research facilities.

Turboelectric systems are electric propulsion systems that use gas turbines to drive the electrical generators that power electric motors, which in turn drive propulsors (fans or propellers). These systems are probably the only approach for developing electric propulsion systems for a large passenger aircraft that can be feasibly achieved in the next 30 years. Combined with other technologies, turboelectric systems could potentially reduce fuel burn by up to 20 percent or more compared to aircraft in service today. These projects would include research to better understand the benefits and design trade-offs related to key aircraft systems and the creation of system research facilities to better develop the core megawatt-class technologies for turboelectric aircraft propulsion systems.

SUSTAINABLE ALTERNATIVE JET FUELS RESEARCH

The committee identified four high-priority research projects to support advances in SAJF:

- SAJF industry modeling and analysis,
- Low-cost feedstocks,
- Conversion processes, fuel production, and scale-up, and
- SAJF fuel testing, qualification, and certification.

This report uses SAJF to describe drop-in replacements for conventional jet fuel that meet current jet fuel specifications either on their own or when blended with conventional jet fuel. SAJF would be produced primarily from nonpetroleum sources and have the potential to immediately lower the net global CO_2 emissions from commercial aviation. As drop-in fuels, SAJF are compatible with existing aircraft and infrastructure, so their widespread use would not be limited by the time it takes for a new technology to slowly propagate through an aviation fleet. SAJF research projects would include detailed evaluations of the benefits of SAJF, developing sustainable and low-cost feedstocks, determining the most cost-effective conversion technologies for full-scale fuel production from these feedstocks, and fuel testing and qualification for commercialization.

CHALLENGES AND NEXT STEPS

The technical, economic, and policy challenges facing each of the high-priority approaches are detailed in this report. In addition, two systemic challenges apply to all four of the approaches:

- Commercial aviation is a highly competitive industry for which reduction in fuel burn (and, thus, CO_2) is a major technology driver. Cost considerations can be a challenge and have to be taken into account as new systems are proposed for commercial development.
- Commercial aircraft are composed of many distinct systems that are carefully integrated and regulated to maximize performance and safety. Disciplined system integration is required to introduce new technologies so that the improvement of one system does not adversely impact the performance of other systems or the performance of the aircraft as a whole.

Developing new technology for large commercial aircraft requires substantial time and resources, and it will not be possible to execute the recommended research agenda without the continued efforts of and coordination among federal agencies, industry, and academia. These entities can each play an important role in reducing CO_2 emissions by focusing their efforts on the projects that best align with their own organizational objectives and expertise.

Summary

The primary human activities that release carbon dioxide (CO_2) into the atmosphere are the combustion of fossil fuels (coal, natural gas, and oil) to generate electricity, the provision of energy for transportation, and as a consequence of some industrial processes. Although aviation CO_2 emissions only make up approximately 2.0 to 2.5 percent of total global annual CO_2 emissions, research to reduce CO_2 emissions is urgent (1) because such reductions may be legislated even as commercial air travel grows, (2) because it takes new technology a long time to propagate into and through the aviation fleet, and (3) because of the ongoing impact of global CO_2 emissions.

The purpose of this report is to examine propulsion and energy technologies; it does not cover research in other areas, such as airframe design or air traffic management systems (e.g., optimizing flight descent paths to save fuel). The report also excludes nontechnology policy approaches, such as the imposition of carbon taxes, the use of carbon offsets, or legislative limits on carbon emissions.

This report focuses on large commercial aircraft—single-aisle and twin-aisle aircraft that carry 100 or more passengers—because such aircraft are the source of more than 90 percent of global CO_2 emissions from commercial aircraft operations. Moreover, while smaller aircraft also emit CO_2, they make only a minor contribution to global emissions, and many technologies that reduce CO_2 emissions for large aircraft also apply to smaller aircraft.

Recommendation. *High-Priority Approaches.* Agencies and organizations in government, industry, and academia with an interest in developing propulsion and energy system technologies that could reduce CO_2 emissions from global civil aviation and that could be introduced into service during the next 10 to 30 years should execute a national research agenda that places the highest priority on four approaches:

- **Advances in aircraft–propulsion integration,**
- **Improvements in gas turbine engines,**
- **Development of turboelectric propulsion systems,[1] and**

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[1] Turboelectric propulsion systems use gas turbines to drive electrical generators that power electric motors that drive propulsors (fans or propellers). A partial-turboelectric system is a promising variant of the full turboelectric system that uses electric propulsion to provide part of the propulsive power, the rest being provided by a turbofan driven by a gas turbine. In contrast, hybrid electric systems use high-capacity batteries to provide some or all of the propulsive power during one or more phases of flight, and all-electric systems rely solely on batteries for propulsive power. The term "electric propulsion" encompasses all of these concepts.

- **Advances in sustainable alternative jet fuels.[2]**

Finding. *Rationales*. The rationales for investing in each of the four recommended high-priority approaches are as follows:

- *Aircraft–propulsion integration research*. Advances in the integration of aircraft and propulsion are needed to enable many aspects of low carbon aviation that are not achievable with the incorporation of discrete improvements in individual component technologies. Areas of interest include evolutionary configurations such as lower fan pressure ratio engines in nacelles on standard tube-and-wing aircraft as well as significant departures from standard configurations, including modified aircraft platforms, distributed propulsion concepts, and boundary layer ingestion configurations.
- *Gas turbine engine research*. Gas turbine engines have considerable room for improvement, with a potential to reach overall efficiencies perhaps 30 percent higher than the best engines in service today, with a concomitant reduction in CO_2 emissions. This magnitude of gain requires investment in a host of technologies to improve thermodynamic and propulsive efficiency of engines, with each discrete technology contributing only a few percent or less.
- *Turboelectric propulsion research*. Turboelectric propulsion systems are probably the only approach for developing electric propulsion systems for a single-aisle passenger aircraft that is feasible in the time frame considered by the committee. System studies indicate that turboelectric propulsion systems, in concert with distributed propulsion and boundary layer ingestion, have the potential to ultimately reduce fuel burn up to 20 percent or more compared to the current state of the art for large commercial aircraft.
- *Sustainable alternative jet fuels research. S*ustainable alternative jet fuels (SAJF) will be able to reduce life-cycle CO_2 emissions, and in some cases the reductions may be substantial. SAJF have the potential for immediate impact on lowering net global CO_2 emissions from commercial aviation because, as drop-in fuels, they are compatible with existing aircraft and infrastructure. Thus, their widespread use will not be limited by the rate at which new aircraft replace existing aircraft. The combustion of SAJF will likely also produce lesser amounts of other harmful emissions, such as oxides of sulfur and particulate matter, than the combustion of equivalent amounts of conventional jet fuel. SAJF are also compatible with and complementary to the three other high-priority approaches recommended in this report for reducing carbon emissions.

Many potential approaches and technologies for reducing CO_2 emissions through the use of advanced propulsion and energy systems are not included here in the four high-priority approaches or their associated high-priority research projects. These include all-electric and hybrid-electric propulsion systems, high-power batteries and fuel cells for propulsion, superconducting motors and generators, hybrid compound engines (which combine a gas turbine and another internal combustion engine such as a diesel), engines that use thermodynamic cycles other than the simple Brayton cycle that is used by conventional gas turbine engines, and alternative fuels such as hydrogen or liquefied natural gas. This does not mean that the committee is recommending that all research to support these other approaches should be discontinued, nor does it imply that the committee believes it can predict with certainty how far the state of the art may advance in any of these areas over the next 30 years. Over the long term, only time will tell where and when breakthroughs in various technologies will revolutionize approaches for reducing CO_2 emissions for commercial aviation, and a broad-based program of basic research is more likely to

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[2] This report uses the term sustainable alternative jet fuels (SAJF) to characterize a family of drop-in fuels that are intended to lower the net life-cycle carbon emissions of commercial aviation. First and foremost, SAJF must meet current specifications for jet fuel, either on their own or when blended with conventional jet fuel. As such, SAJF (blended as necessary) are drop-in replacements for conventional jet fuel. SAJF are alternative in that they are produced primarily from nonpetroleum sources of hydrocarbons using a potentially broad range of biochemical and thermochemical conversion processes. To date, four pathways have been approved for producing alternative fuels that meet the specifications necessary to be considered jet fuel, while others are pending. To be successful over the long term, alternate fuels must be sustainable both in terms of their ability to reduce net life-cycle carbon emissions relative to conventional jet fuel and in terms of environmental, societal, and economic factors. Not all alternative fuels will result in a net reduction in life cycle carbon depending, for example, on their source materials.

make breakthroughs than one that is narrowly focused. On the other hand, the approaches and research projects detailed in this report are necessarily focused on a very particular goal: identifying the most promising propulsion and energy system technologies for reducing CO_2 emissions that could be introduced into service during the next 10 to 30 years, and the committee has concluded that the four high-priority approaches are indeed the most promising approaches, insofar as the other approaches are less likely to be matured to the point that products satisfying Federal Aviation Administration (FAA) certification requirements can be developed for a regional jet or larger commercial aircraft within the 30-year time frame addressed by this report. Also, the national research agenda recommended by the committee could lower the priority assigned to research programs that are developing high-power batteries, fuel cells, and superconducting motors for the purpose of incorporating them in the propulsion systems of large commercial aircraft. Even if that happens, however, a substantial national research investment in each of these technologies is certain to continue because of their potential to benefit a wide array of other applications. Aircraft-specific research in these areas may then take on a higher priority as the general state of the art advances.

HIGH-PRIORITY RESEARCH PROJECTS

The committee identified 12 high-priority research projects that it recommended for consideration by agencies and organizations in government, industry, and academia with an interest in developing propulsion and energy system technologies that could reduce CO_2 emissions from global civil aviation and could be introduced into service during the next 10 to 30 years. As indicated below, two of the high-priority research projects address aircraft–propulsion integration, three address gas turbine engines, three address turboelectric propulsion, and four address SAJF.

Aircraft–Propulsion Integration

Nacelles for Ultrahigh-Bypass-Ratio Gas Turbines

This project would develop nacelle and integration technologies to enable ultrahigh-bypass-ratio propulsors. It is closely related to the gas turbine research project on low-pressure ratio fan propulsors, and work on the two projects should be closely coordinated.

Aircraft–propulsion integration refers to the aerodynamic, structural, and subsystem (fuel, pneumatic, hydraulic, electrical, control, etc.) interfaces between engines and airframe. Today, commercial aircraft share a configuration known as “tube and wing,” characterized by thin wings mounted to a roughly circular cross-section tubular body. Engines on current turbofan-powered commercial aircraft are mounted on pylons, which isolate the engine and airframe aerodynamic characteristics. The engines are enclosed by fairings known as nacelles, which contain many of the subsystems important to the operation of the aircraft such as the electrical generators. The aerodynamic, structural, and subsystem integration of the engine and nacelle with the airframe is a technology important to determining aircraft performance and optimum engine characteristics such as propulsor diameter and fan pressure ratio. Achieving the goal of this research project will require compact nacelles with lighter weight and lower drag to increase propulsive efficiencies. Key research topics for this project include internal and external aerodynamics, acoustics, thrust reversing, operability, manufacturing, and overall weight.

Boundary Layer Ingestion

This project would pursue technologies that can enable boundary layer ingestion (BLI) to reduce the velocity defect in the aircraft wake (also known as wake cancellation) and thus reduce cruise energy consumption.

Several proposed advanced aircraft designs include configurations in which the boundary layer developing along the aircraft is ingested into the propulsor resulting in wake cancellation, which reduces the power needed to propel the aircraft and so reduces energy consumption and CO_2 emissions. BLI requires a much higher level of aircraft–propulsion integration than is common today and imposes new constraints and requirements on both the airframe and the propulsion system.

BLI configurations have been proposed using a variety of propulsor drive systems, including direct-drive turbofan engines, geared mechanical drives, and electrical drives. BLI holds a theoretical promise to significantly reduce aircraft fuel consumption, all else being equal. Most proposed BLI configurations with respect to the propulsor–aircraft integration, are significantly different than conventional designs, so all else is not equal. For example, BLI configurations bring a very high distortion level into the fan, which impacts efficiency, fatigue life, and noise, at least partially offsetting potential gains from wake cancellation. The benefits and costs of BLI are also confounded by many other significant aircraft and propulsion changes in advanced designs. Therefore, careful, detailed aircraft design studies are needed to guide investments in component and subsystem technologies.

Key research topics for this project include (1) exploring the aerodynamic, structural, subsystem, control, and safety implications of BLI configurations, including detailed systems analyses of alternative approaches such as various advanced propulsion system options and (2) developing technologies for propulsion fans for operation in highly distorted flow fields characteristic of BLI configurations, including detailed assessment of the penalties inherent to current technology as well as pursuing design and technology approaches that mitigate such penalties. This research project requires both analysis and testing at representative Mach numbers.

Gas Turbine Engines

Low-Pressure-Ratio Fan Propulsors

This project would develop low-pressure-ratio fan propulsors to improve turbofan propulsive efficiency. It is closely related to the aircraft–propulsion integration research project on nacelles for ultrahigh-bypass-ratio gas turbines, and work on these two projects should be closely coordinated.

However it is produced, shaft power is converted to propulsive power with a “propulsor,” which is either a fan in a duct or a propeller. All else being equal, the lower the pressure across the propulsor, the lower the exhaust velocity will be and, hence, the higher the propulsive efficiency. The relevant design parameter for turbofan engines is the fan pressure ratio. At constant thrust, as fan pressure ratio is reduced, more airflow and thus a larger fan or more fans are needed.

The penalty for encasing the propulsor in a duct is an increase in weight and drag. As the duct diameter grows, the propulsor efficiency increases, but at some point the increased weight and drag of the fan, duct, and nacelle cancel the efficiency gain. As a result, further increasing the size of the fan reduces efficiency. Also, larger diameter fans and nacelles may require longer and thus heavier landing gear. Therefore, at a given level of engine, nacelle, and aircraft technology, there is an optimum fan diameter for minimum fuel burn. Key research topics for this project include turbomachinery design, duct losses, acoustics, aeromechanics, nacelle aerodynamics and weight, manufacturing, and aircraft integration.

Engine Materials and Coatings

This project would develop materials and coatings that will enable higher engine operating temperatures. Advanced materials for gas turbine engines have been a particularly fruitful investment area because a successful material can often be used to improve existing engines as well as to enable new concepts. The system-level benefits of new materials may come from reduced weight, higher temperature capability, or reduced cooling requirements and thus higher thermodynamic efficiency. For example, advanced materials for compressors can enable the higher compression ratios needed to improve engine thermal efficiency.

Advanced materials for combustors and turbines can also improve engine power-to-weight ratios and can improve part durability to keep fuel burn from increasing as an engine ages. Key research topics for this project include advanced materials that provide viable approaches to greatly reducing or eliminating turbine film cooling as well as compatible coatings for environmental protection, erosion prevention, ice rejection, and thermal barriers.

Small Engine Cores

This project would develop technologies to improve the efficiency of engines with small cores so as to reach efficiency levels comparable to or better than engines with large cores.

Improved aircraft efficiency means that smaller engine cores would be needed since less power would be required for the same mission. Historically, engines with cores having a small physical size are less efficient than large engines, and new technologies are needed to overcome this disparity. Key research topics for this project include improvements in turbomachinery aerodynamic performance, manufacturing, tip clearance control, secondary flow losses, combustion, and the operational life of turbine airfoils.[3]

Turboelectric Propulsion

Turboelectric Aircraft System Studies

This project would conduct more encompassing studies of aircraft powered by turboelectric systems in order to better understand the benefits, component performance sensitivities, certification issues, and trade-offs related to key aircraft systems, such as thermal management and energy storage.

Motors, generators, and electrical distribution systems lie at the heart of electrical systems, and most electric propulsion research is understandably focused on these key elements. As these electric propulsion technologies advance, it is essential that research to advance capabilities in related aircraft systems is properly directed. Studies to date of the benefits and challenges of turboelectric propulsion have paid insufficient attention to all contributing aircraft systems. One key research topic is thermal management, because thermal management systems are essential to the performance of the electric propulsion system and because they may affect aircraft flight performance. Other key research topics include aircraft structure and optimized aerodynamic integration. Establishing cost targets, thermal management targets, and reliability targets at an early stage in the research and development (R&D) process would help define the research plan. In addition, certification plans would be most effective if established in active collaboration with the U.S. Federal Aviation Administration and other certification authorities such as the U.K. Civil Aviation Authority and the European Aviation Safety Agency.

Core Turboelectric Technologies

This project would develop the core technologies that are required for megawatt (MW)-class turboelectric propulsion systems: motors, generators, inverters, power distribution, and circuit protection.

Turboelectric propulsion concepts are heavily dependent on the advancement of aircraft electrical power system technologies. These technologies include generator systems for electrical power generation; power electronics for power conversion, conditioning, and distribution; high-power aircraft distribution that includes circuit protection; motors; and energy storage. A key issue is how to address higher distribution voltages designed for operation at altitude.

Requirements for electrical system components are beyond the current state of the art, especially for large commercial aircraft. The committee's projection of the state of the art in 20 years is that requirements for specific power[4] of motors and generators can be met for single-aisle aircraft, and projected power capability is expected to cover the lowest end of the projected range of requirements for regional or single-aisle aircraft. Circuit protection and high-power distribution cabling for MW-class aircraft power systems will also need to be developed. Research for this project could initially focus on technologies for 1 MW systems, with a long-term focus on 1 to 5 MW systems.

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[3] "Airfoil" refers to both the stationary vanes and the stators in a turbine as well as the rotating blades.

[4] In this report, specific power and specific energy refer to power and energy per unit mass, respectively, and power density and energy density refer to power and energy per unit volume.

Megawatt-Class Research Facilities

This project would develop research facilities for MW-class electric power and thermal management systems suitable for testing turboelectric aircraft propulsion systems.

The research and development of MW-class machines for aircraft applications are hampered by the lack of facilities. Existing facilities for the development of motors, generators, and other electrical equipment for aircraft were generally designed to support nonpropulsion power for the vehicle. Electric propulsion systems will need to have much higher power capacities than electrical systems currently on aircraft. Facilities to meet these higher power levels have not been developed. No capability for proper simulation of a turboelectric propulsion system for a large aircraft exists at this time. After initially focusing on ground-based facilities, a flight demonstration program for a turboelectric system could be considered to support advanced development of MW-class systems.

Sustainable Alternative Jet Fuels

SAJF Industry Modeling and Analysis

This project would undertake research to enable detailed and comprehensive modeling and analysis of SAJF development efforts and impacts at microscale (individual projects) and macroscale (nationwide or worldwide) levels to support the needs of policymakers and industry practitioners.

The variability in the many different sustainability frameworks relevant to SAJF complicates the process of developing SAJF that can be widely marketed as meeting sustainability needs, and it increases uncertainty about the economic feasibility of SAJF. The variability and uncertainty might also influence policy or decisions that have established relatively high hurdles for various metrics. For example, the U.S. Renewable Fuel Standard program and the Roundtable on Sustainable Biomaterials have established the need for advanced fuels to achieve at least a 50 percent reduction in life-cycle CO_2 emissions. This 50 percent minimum reduction disincentivizes the potential of some synthetic fuel production pathways that could produce lesser but still substantial life-cycle reductions in carbon emissions. Key research topics for this project include conducting comprehensive comparative technoeconomic assessments of potential SAJF feedstocks and conversion processes; enhancing system modeling and analysis capabilities for micro (individual project) and macro (nationwide or worldwide) evaluations of the potential impacts and benefits of SAJF development and commercialization (for policy and business decision support); and advancing the science, application, and harmonization of sustainability analysis, starting with life-cycle CO_2 modeling and then progressing to additional topics of interest.

Low-Cost Feedstocks

This project would support continued development of sustainable, low-cost feedstocks and associated systems that have the potential to enable the large-scale production of economically viable SAJF.

Several processes have been demonstrated to produce SAJF that can be qualified as drop-in fuels, and others are envisioned. The development of feedstocks is one of several technical challenges that must still be overcome to enable economically competitive production of SAJF at scales of significance. Despite progress to date in developing feedstocks, in many cases SAJF feedstocks are widely dispersed, they are unwieldy (e.g., they may have low bulk density, small seed size, and/or high moisture content), and/or they are not easily collected, transported, stored, or preprocessed with existing equipment. Key research topics for this project include (1) identifying and developing feedstocks that could enable economically viable and sustainable production of SAJF; (2) developing strategic approaches for the use of several waste streams that could be used as SAJF; and (3) using the results of past feedstock evaluations to inform and prioritize current feedstock development activities. Waste streams of potential interest include municipal solid waste, human waste and sanitary waste treatment, animal waste, animal processing waste, and gaseous waste.

Conversion Processes, Fuel Production, and Scale-Up

This project would develop technologies and processes for cost-effective feedstock conversion, fuel production, and scale-up from pilot and demonstration facilities to enable full-scale production of SAJF.

Cost-effective conversion technologies are not available for some promising feedstocks. Key research topics for this project include creating additional process development facilities to enhance the ability of SAJF conversion technology developers to move expeditiously from benchtop to pilot scale with minimal capital and operating expenses; developing fuel conversion and finishing processes and equipment, focusing first on processes common to multiple conversion processes; and fostering the development of lower-cost hydrogen production to deal with the fundamental hydrogen deficit in converting many biofeedstocks to finished fuels.

SAJF Fuel Testing, Evaluation, and Qualification

This project would improve fuel testing, evaluation, and qualification efforts to lower testing costs, increase throughput, and enhance understanding of fuel properties. It takes longer than it should to commercialize new SAJF production methods, in part because of the cost and time required to complete fuel qualification and certification processes. These processes are costly; fuels required for testing are difficult to produce in sufficient quantities in reasonable amounts of time; and the entities undertaking qualification are typically small, underfunded start-up organizations that also must deal with the many other technical and economic challenges usually encountered by start-up companies.

An industry process has been established using standard specifications and qualification practices established by ASTM International to qualify processes for producing drop-in SAJF. The ASTM qualification process has limited throughput, it is highly dependent on physical testing for validation, and is insufficiently based on chemistry and combustion science.

Key research topics for this project include (1) eliminating or reducing time-consuming and costly physical testing by developing a low-cost, high-throughput approach to meeting ASTM specifications and qualification standards relevant to SAJF; this will likely require determining which molecular components in the family of molecules present in the jet fuel are cause for concern with respect to material compatibility; (2) improving the ability to characterize combustion attributes of properties of various SAJF constituents using analysis and simpler testing; (3) assessing the environmental effects (nearer term) and turbomachinery health and performance benefits (longer term) of potential SAJF pathways; and (4) developing a database, to be made broadly available to members of the SAJF community, of fuel feedstocks, processes, fuel properties, and combustion emission characteristics to facilitate the use of alternative jet fuels.

CHALLENGES TO IMPLEMENTING ADVANCED LOW-CARBON TECHNOLOGIES FOR COMMERCIAL AIRCRAFT

Many challenges need to be overcome to implement the proposed research agenda. Some are systemic—being issues for all of the approaches considered—and others are technical, economic, and policy challenges related to the high-priority approaches recommended by the committee.

Systemic Challenges

- *Economic competitiveness*. Commercial aviation is a highly competitive industry for which reduction in fuel burn (and, thus, CO_2) is a major technology driver. Cost considerations can be a challenge and have to be taken into account as new systems are proposed for commercial development.
- *Aircraft systems complexity and integration*. Commercial aircraft are composed of many distinct systems that are carefully integrated and regulated to maximize performance and safety. Disciplined system integration is required to introduce new technologies so that the improvement of one system does not adversely impact the performance of other systems or the performance of the aircraft as a whole.

Technical Challenges

- *Propulsive efficiency*. Low fan pressure ratios are needed to reduce exhaust velocities and thereby improve propulsive efficiency, regardless of whether the fan is driven by a gas turbine or an electrical motor. For a constant level of thrust, this requires that the effective fan area increase so as to avoid commensurate increases in weight, drag, and integration losses.
- *Thermodynamic efficiency*. Enabling higher operating temperatures is a prerequisite to achieving significant improvement in gas turbine engine thermodynamic efficiency, and a major impediment to achieving higher operating temperatures is the difficulty of developing advanced materials and coatings that can withstand higher engine operating temperatures.
- *Boundary layer ingestion*. To use boundary layer ingestion and wake cancellation to reduce aircraft cruise energy requirements, an aircraft configuration integrated with a propulsor design is needed in which the overall benefits of wake cancellation outweigh the costs in terms of propulsor efficiency, noise, and weight.
- *Small engine cores*. Activities being pursued to either improve the thermodynamic efficiency of gas turbine cores or improve overall aircraft efficiency result in smaller core sizes. For single-aisle aircraft, this tendency to core size reduction creates multiple challenges for maintaining and improving efficiencies of the overall engine and engine–aircraft integration.
- *Electrical technologies*. The state of the art of electrical technologies for motors, generators, power distribution, and power electronics (for example, inverters, converters, and circuit protection) will need to advance to enable turboelectric propulsion concepts for large commercial aircraft.
- *Aircraft systems*. Turboelectric aircraft propulsion systems present a number of challenges related to other aircraft systems (e.g., thermal management systems). More structurally and aerodynamically efficient configurations can help address these challenges.
- *Research infrastructure for electrical technologies*. The research and development of megawatt-class turboelectric aircraft propulsion systems is hampered by the lack of development testing facilities.
- *Feedstock development*. Despite progress to date in developing feedstocks, in many cases SAJF feedstocks are widely dispersed, they are unwieldy (e.g., they may have low bulk density, small seed size, and/or high moisture content), and/or they are not easily collected, transported, stored, or preprocessed with existing equipment.
- *Feedstock conversion technologies*. Cost-effective conversion technologies are not available for some promising feedstocks.
- *SAJF fuel testing, qualification, and certification*. It takes longer than it should to commercialize new SAJF production methods, in part because of the cost and time required to complete current fuel qualification and certification processes. Improvements to the qualification process are also needed to enable compositionally based evaluation of additional SAJF production pathways.

Economic Challenges

- *Relative economic value*. A balanced technology investment portfolio in aircraft–propulsion integration research is needed to ensure that economic uncertainties arising from changes in net fuel price do not slow continued reductions in emissions by commercial aircraft.
- *Feedstock price and availability*. Currently achievable refinery-gate feedstock prices are expensive relative to the final product, which is driven in part by immature or nonexistent feedstock supply chains.
- *Industrial sector collaboration*. The nascent SAJF industry lacks the inherent elements of collaboration of a fully developed industrial sector; these elements are required for initial matching of supply and demand signals and for subsequent system optimization.

- *Technoeconomic factors*. Lack of technoeconomic assessments and a comparative understanding of various approaches impede the ability of industry and the researchers and agencies that support SAJF R&D to make practical decisions about the prioritization of R&D and demonstration and deployment efforts.
- *Hydrogen price and availability*. Hydrogen is needed for almost all SAJF production, and in several conversion processes (those with potentially the lowest feedstock costs) it represents a significant portion of operating cost.
- *SAJF development and demonstration projects*. Additional, affordable SAJF demonstration and deployment efforts are needed to adequately address economic and technical risks.
- *Funding for SAJF capital investments*. Uncertainty about economic viability of SAJF production has impeded engagement from the petroleum industry or other large industrial entities that could bring appropriate resources to bear on addressing economic challenges.
- *Challenges for small SAJF start-ups*. Start-ups are unable to explore and leverage the full range of technical and economic opportunities that might provide sufficient economic benefit to facilitate commercialization.

Policy Challenges

- *Certification*. Technical and policy issues surrounding certification of aircraft and propulsion concepts and technologies not covered by current certification procedures are important for guiding technology development. In addition, manufacturers must have confidence that these issues will be resolved in a timely fashion before they are likely to begin advanced development of the relevant aircraft and propulsion systems.
- *Renewable Fuel Standard*. Uncertainties about the long-term impact of the U.S. Renewable Fuel Standard, which provides indirect incentives for the production of SAJF, limit its effectiveness in fostering the development of an SAJF industry.
- *Sustainability assessment models and requirements*. There is no well-defined, internationally adopted framework for sustainability analysis of alternative jet fuels.

COORDINATION OF RESEARCH AND DEVELOPMENT

It will not be possible to execute the recommended research agenda without commitment, resources, leadership, and focus from relevant agencies and organizations in government, industry, and academia. Within the government, key players include the Department of Defense (DOD), the Department of Energy (DOE), the FAA, NASA, the Department of Agriculture, the Department of Transportation, the Environmental Protection Agency, and the National Science Foundation. A coordinated approach would make the best use of the available resources.

The research projects within each high-priority approach would rely on academia and industry to play the same role that they normally play in the development of new technologies and products. In particular, academia would generally participate in the projects at lower levels of technology readiness, while industry would focus on more advanced research and product development.

Many federal organizations and agencies have important roles to play in reducing CO_2 emissions. The FAA would be most directly engaged in the development of certification standards and methodologies for technologies not well covered by current practices. DOD would have an interest in all four of the high-priority approaches to the extent that they could improve the capability of military aircraft or, in the case of SAJF, address the larger goal of reducing the environmental impact of defense operations. NASA would contribute primarily by supporting basic and applied research in all four approaches, though it would likely play a lesser role in SAJF development given that much of the research (e.g., on feedstocks and fuel conversion processes) does not concern a NASA mission area. DOE and its national laboratories would contribute to the development of batteries, fuel cells, and SAJF feedstocks and conversion processes. The primary contributions of the Department of Agriculture, Environmental Protection Agency, Department of Transportation, Department of Commerce, and National Science Foundation would be to SAJF research.

Recommendation. *Organizational Research Priorities*. The relative priority that various agencies and organizations assign to the four recommended high-priority approaches and research projects within each approach should be guided by (1) the importance a given organization attaches to the rationales associated with each approach, (2) the resident expertise and mission objectives of the organization, and (3) the desired mix of a given organization's research portfolio in terms of risk, technical maturity, and economic potential.

CONCLUDING REMARKS

Four high-priority approaches were identified throughout the course of study that have the potential to reduce CO_2 emissions from commercial aviation, particularly from those aircraft that produce the bulk of the emissions: large single- and twin-aisle aircraft. However, developing new technology for large commercial aircraft requires substantial time and resources. Aircraft–propulsion integration and gas turbine engines are both well-established approaches that need to be pursued. In contrast, the funding situation for the other two approaches, turboelectric propulsion and SAJF, is somewhat problematic. It is not clear when turboelectric propulsion technology will advance to the point that it provides the performance needed for practical application in commercial aircraft. It is also uncertain when SAJF will be able to compete economically with petroleum-based fuels, especially considering the capital costs of founding a new industry and the fluctuating prices of conventional jet fuel. Given the immediacy of the issues, however, research supporting all four approaches is prudent both to reduce current CO_2 emissions and to alleviate the potential adverse consequences of future aviation growth worldwide.

1

Introduction

The primary human activities that release carbon dioxide (CO_2) into the atmosphere are the combustion of fossil fuels (coal, natural gas, and oil) to generate electricity, the provision of energy for transportation, and as a consequence of some industrial processes. This report focuses on reducing life-cycle CO_2 emissions from commercial aviation.

Human activities also produce or release additional greenhouse gases other than CO_2, most importantly methane, nitrous oxide, and fluorinated gases such as hydrofluorocarbons and perfluorocarbons. The physical mechanisms by which greenhouse gases cause climate change are well understood.[1] Since 1750, CO_2 has contributed more to global warming than any other greenhouse gas, and there is growing recognition of the need for aviation to reduce its CO_2 emissions.[2] One manifestation of this is the recent agreement at the International Civil Aviation Organization, a United Nations standards organization, on a fuel economy standard for new aircraft. It will apply to new aircraft designs starting in 2020 and to in-production types in 2023. As has been the case for standards on aircraft emissions and noise, it is expected that national governments will incorporate the new fuel economy standard into their national rules. If the CO_2 rules follow the precedent of other aviation emissions regulations, they will be periodically reviewed and tightened, necessitating an ongoing investment to reduce the net CO_2 emitted by aircraft.

CARBON DIOXIDE EMISSIONS FROM COMMERCIAL AVIATION

This report is focused on propulsion and energy technologies that have the potential to start reducing global emissions from commercial aviation within the next 20-30 years.[3] Aviation CO_2 emissions presently make up

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[1] Intergovernmental Panel on Climate Change, 2007, Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007). https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4_wg1_full_report.pdf (accessed June 29, 2016).

[2] Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, N.Y., p. 135.

[3] Both propulsion and energy technologies are of interest to cover the entire process from energy storage (e.g., using jet fuel, alternative fuels, or batteries) to the generation of propulsive power (e.g., using gas turbines, generators, and/or motors).

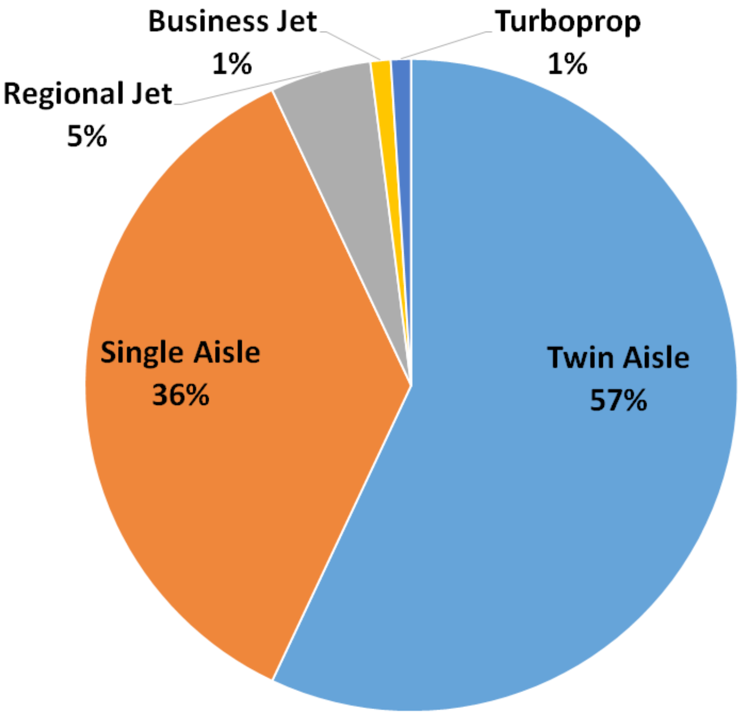

FIGURE 1.1 Global civil aviation fuel consumption. SOURCE: Data from B. Yutko and J. Hansman, 2011, *Approaches to Representing Aircraft Fuel Efficiency Performance for the Purpose of a Commercial Aircraft Certification Standard*, MIT International Center for Air Transportation, Cambridge, Mass.

approximately 2.0 to 2.5 percent of total global annual CO_2 emissions.[4] In the United States, the aviation sector contributes about 11 percent of transportation greenhouse gases, with commercial aviation contributing 9 percent of total transportation emissions.[5]

As commercial aviation continues to grow in terms of revenue-passenger miles and cargo ton miles, CO_2 emissions are expected to increase. To reduce the contribution of aviation to climate change, it is essential to improve the effectiveness of ongoing efforts to reduce emissions and initiate research into new approaches. Although aviation CO_2 emissions are a small part of total CO_2 emissions, action to reduce them is urgent for the reasons stated above and because it takes new technology a long time to propagate into and through the aviation fleet.

This report classifies commercial aircraft as indicated below based on typical passenger capacity (all figures approximate):

- General aviation: fewer than 6 passengers
- Commuter: fewer than 20 passengers
- Regional: 30-100 passengers
- Single-aisle: 100-200 passengers
- Twin-aisle: more than 200 passengers

In general, the range of each class of aircraft is greater than that of the class that precedes it, but there are

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[4] D.S. Lee, D.W. Fahey, P.M. Forster, PJ. Newton, R.C. Wit, L.L. Lim, B. Owen, R. Sausen, 2009, Aviation and global climate change in the 21st century, *Atmospheric Environment* 43:3520-3537.

[5] EPA, 2015, *EPA Inventory of US Greenhouse Gas Emissions*, EPA-430-R-15-004, Washington, D.C.

some exceptions given the wide array of aircraft designs within each class. This report focuses on large commercial aircraft—that is, single-aisle and twin-aisle subsonic transport aircraft—because they are the source of the bulk of aviation emissions (see Figure 1.1). Smaller aircraft also emit CO_2; however, they make only a minor contribution to global emissions, and in any case many technologies that reduce CO_2 emissions for larger aircraft are also applicable to smaller jet aircraft.

> **Finding.** *CO_2 Emissions from Commercial Aircraft*. More than 90 percent of CO_2 emissions from global commercial aircraft operations are generated by large aircraft (twin-aisle and single-aisle airplanes with more than100 passengers), so research to reduce commercial aircraft emissions will be most useful if it focuses on technology applicable to these large commercial aircraft.

SYSTEMIC CHALLENGES TO LOWERING GLOBAL EMISSIONS FROM COMMERCIAL AVIATION

Each year, about 20,000 commercial aircraft carry 3 billion passengers over 3 trillion passenger-miles, connecting 35,000 city pairs with 30 million aircraft movements. These aircraft also carry more than $6 trillion in air cargo, about 35 percent of world trade by value. Commercial aircraft now consume more than 70 billion gallons of jet fuel per year. Thus, any discussion of reducing the carbon emission from commercial aircraft will need to be applicable to and effective at this scale.

CO_2 emissions from a commercial aircraft can be reduced in the following ways:

- Reduce the energy required to fly the aircraft by reducing its weight and/or drag.
- Improve the efficiency with which the energy is converted from fuel into thrust—in other words, improve the propulsion system efficiency.
- Reduce the carbon intensity of the energy required—in other words, reduce the net amount of carbon that is emitted into the atmosphere for each joule of energy that is generated. This includes total life-cycle carbon emissions during production of the fuel. For electric aircraft, this would also include carbon emissions produced by the source of electricity, either on the ground (for battery-powered aircraft) or on the aircraft (for generator-equipped electric aircraft).

Making additional progress in any of these areas is challenging, but there are also many promising approaches, as discussed in more detail in the next section and in subsequent chapters. In addition to the technical, economic, and policy challenges identified in Chapters 2-5 for specific approaches, there are also two systemic challenges that all approaches need to overcome.

Economic Competitiveness

Commercial aviation is a highly competitive industry for which reduction in fuel burn (and, thus, CO_2) is a major technology driver. Cost considerations can be a challenge and have to be taken into account as new systems are proposed for commercial development.

Individual aircraft can be in service for more than 30 years. Airlines and aircraft manufacturers are constantly seeking ways to increase efficiency, and in particular fuel burn efficiency. Decisions by airlines to invest in new aircraft—and in which kind—are driven by complex assessments involving many considerations, including near- and long-term projections of economic conditions; fuel costs; societal expectations regarding the environmental impact of aviation in terms of noise and emissions; the cost of retraining operational or maintenance personnel and of acquiring new facilities for maintenance and fuel distribution and other potential operational and capital costs; and national and international policies and regulations that impact aviation, and so on. These considerations are also important to aircraft and engine manufacturers as they try to anticipate the factors that will drive future purchase decisions by airlines.

Aircraft Systems Complexity and Integration

Commercial aircraft are composed of many distinct systems that are carefully integrated and regulated to maximize performance and safety. Disciplined system integration is required to introduce new technologies so that the improvement of one system does not adversely impact the performance of other systems or the performance of the aircraft as a whole.

Transitioning new aircraft propulsion technologies into an operational aircraft is a complex systems engineering task. For example, the motors, generators, and other electrical components of an electric aircraft propulsion system will generate heat that must be dissipated by a robust thermal management system, which may affect aircraft flight performance. Even after engineering solutions to such problems are developed, it usually takes a long time to build the confidence needed to introduce new technologies into commercial aviation. Because safety is essential to the commercial aviation industry's success, new technologies and designs need to also go through extensive certification processes that can take up to a decade. In addition, airlines expect new aircraft to have at least the same level of operational reliability as the aircraft they are replacing.

REPORT ORGANIZATION AND PRIORITIZATION PROCESS

After considering various potential prioritization methodologies, the committee came up with the following two-step process for developing a national research agenda on propulsion and energy systems for reducing CO_2 emissions from commercial aircraft:[6]

High-Priority Approaches

In the first step, the committee examined several potential high-priority approaches to CO_2 reduction based on three considerations:

1. *Improvement potential*. This criterion considers the level of CO_2 reduction per passenger mile or stored power energy in the fuel that a given approach may help achieve.
2. *Timeline*. This criterion considers the nominal time for relevant technologies to substantially reduce global aviation emissions. To meet the 30-year time frame considered by this study, the new technology needs to have reached at least technology readiness level 6 (TRL 6)[7] within 20 to 25 years from now.
3. *Risk*. This criterion considers the levels of technical and economic and policy risk associated with achieving projected improvements within the time frame of interest.

Next, the committee identified the four top-level approaches that are most likely to meet the goal of developing low-carbon propulsion and energy system technologies that could be introduced into service during the next 10 to 30 years. These approaches—and the rationales for investing in them—are as follows:

- *Aircraft–propulsion integration research*. Advances in the integration of aircraft and propulsion are needed to enable many aspects of low carbon aviation that are not achievable with the incorporation of discrete improvements into individual component technologies. Areas of interest include evolutionary configurations such as lower fan pressure ratio engines in nacelles on standard tube-and-wing aircraft as well as significant

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[6] As described in the study statement of task (see Appendix A), the committee's deliberations focused on research related to propulsion and energy systems. This report does not include recommendations concerning other avenues for reducing carbon emission, such as operational improvements, changes to airport ground equipment (e.g., electric airport shuttles), airframe improvements not related to advanced propulsion concepts, and nontechnology policy approaches such as the imposition of carbon taxes, the use of carbon offsets, or legislative limits on carbon emissions.

[7] NASA uses technology readiness levels (TRLs) to track the maturity of a new technology under development. TRL 6 is achieved when a system or subsystem model or prototype has been verified in a relevant environment.

departures from standard configurations including modified aircraft platforms, distributed propulsion concepts, and boundary layer ingestion configurations.

- *Gas turbine engine research*. Gas turbine engines have considerable room for improvement, with a potential to reach overall efficiencies perhaps 30 percent higher than the best engines in service today, with a concomitant reduction in CO_2 emissions. This magnitude of gain requires investment in a host of technologies to improve thermodynamic and propulsive efficiency of engines, with each discrete technology contributing only a few percent or less.
- *Turboelectric propulsion research*.[8] Turboelectric propulsion systems are likely the only approach for developing electric propulsion systems for a single-aisle passenger aircraft that is feasible in the time frame considered by this study. System studies indicate that turboelectric propulsion systems, in concert with distributed propulsion and boundary layer ingestion, have the potential to ultimately reduce fuel burn up to 20 percent or more compared to the current state of the art for large commercial aircraft.
- *Sustainable alternative jet fuels research*.[9] *S*ustainable alternative jet fuels (SAJF) will be able to reduce life-cycle CO_2, emissions, and in some cases the reductions may be substantial. SAJF have the potential for immediate impact on lowering net global CO_2 emissions from commercial aviation because, as drop-in fuels, they are compatible with existing aircraft and infrastructure. Thus, their widespread use will not be limited by the rate at which new aircraft replace existing aircraft. The combustion of SAJF will likely also produce lesser amounts of other harmful emissions, such as oxides of sulfur and particulate matter, than the combustion of equivalent amounts of conventional jet fuel. SAJF are also compatible with and complementary to the three other high-priority approaches recommended in this report for reducing carbon emissions.

More information on each of the four approaches appears in Chapters 2, 3, 4, and 5, respectively.[10]

High-Priority Research Projects

As a second step, after identifying the high-priority approaches above, the committee examined potential research projects for each approach based on four considerations:

1. *Breadth of applicability*. This criterion considers the range of aircraft to which a particular improvement could be applied. For example, drop-in fuels can be used in all aircraft, by definition. In contrast, electrical propulsion systems are currently limited to small aircraft.
2. *Ease of integration*. This criterion considers how easily a particular improvement could be incorporated into an aircraft or the air transportation system. For example, fuels that are not drop-in would require changes to aircraft engines, aircraft architecture, and to the fuel manufacturing and distribution systems.
3. *Technical and economic risk*. This criterion considers the extent to which a research project could mitigate

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[8] Turboelectric propulsion systems use gas turbines to drive electrical generators that power electric motors that drive propulsors (fans or propellers). A partial-turboelectric system is a promising variant of the full turboelectric system that uses electric propulsion to provide part of the propulsive power; the rest is provided by a turbofan driven by a gas turbine. In contrast, hybrid electric systems use high-capacity batteries to provide some or all of the propulsive power during one or more phases of flight, and all-electric systems rely solely on batteries for propulsive power. The term "electric propulsion" encompasses all of these concepts.

[9] This report uses the term sustainable alternative jet fuels (SAJF) to characterize a family of drop-in fuels that are intended to lower the net life-cycle carbon emissions of commercial aviation. First and foremost, SAJF must meet current specifications for jet fuel, either on their own or when blended with conventional jet fuel. As such, SAJF (blended as necessary) are drop-in replacements for conventional jet fuel. SAJF are alternative in that they are produced primarily from nonpetroleum sources of hydrocarbons using a potentially broad range of biochemical and thermochemical conversion processes. To date, four pathways have been approved for producing alternative fuels that meet the specifications necessary to be considered jet fuel while others are pending. To be successful over the long term, alternate fuels must be sustainable both in terms of their ability to reduce net life-cycle carbon emissions relative to conventional jet fuel and in terms of environmental, societal, and economic factors. Not all alternative fuels will result in a net reduction in life cycle carbon depending, for example, on their source materials.

[10] The approaches on aircraft and propulsion integration, gas turbine engines, and turboelectric propulsion focus on propulsion research. The SAJF approach focuses on energy.

the technical and economic risk and/or shorten the timeline for relevant CO_2 technology to become operational within the time frame of interest.

4. *Improvement potential*. This criterion considers the level of CO_2 reduction per passenger mile or stored power energy in the fuel that a technology may help achieve.

The high-priority research projects identified for each approach are detailed in Chapters 2-5 and summarized in Chapter 6, which also includes a list of all findings, the challenges, high-priority research projects, and recommendations.

Other Potential Approaches and Research Projects

Many potential approaches and technologies for reducing CO_2 emissions by means of advanced propulsion and energy systems are not included with the four high-priority approaches recommended here or the associated high-priority research projects. This does not mean that the committee is recommending that all research to support other approaches should be discontinued, nor does it imply that the committee believes it can predict with certainty how far the state of the art may advance in any of these areas over the next 30 years. Over the long term, only time will tell which breakthroughs in which technologies will revolutionize approaches for reducing CO_2 emissions for commercial aviation, and a broad-based program of basic research is more likely to make breakthroughs than one that is narrowly focused. On the other hand, the approaches and research projects detailed in this report are necessarily focused on a very particular goal: identifying the most promising propulsion and energy system technologies for reducing CO_2 emissions that could be introduced into service during the next 10 to 30 years.

Many approaches other than the four recommended as a high priority show some promise for reducing CO_2 emissions, but 30 years is not a particularly long time when it comes to developing and introducing new technologies into commercial aviation, and 10 years is almost no time at all. Even after new technologies are well understood, and even after they have been demonstrated in full-scale prototypes, it can take a decade or more to accomplish both of the following:

- Ensure that the components and systems that incorporate these technologies meet expectations with respect to reliability, safety, performance, economic return, and so on.
- Develop and validate certification standards to enable their use on commercial aircraft.

The timeline for inserting new technology into commercial aviation generally increases as the approaches and technologies differ more from those currently in use. For example, the design of any electric propulsion system will depart substantially from the design of current systems. One option would be to pursue a broad research program that supports a wide array of electric propulsion concepts. The committee concluded, however, that batteries with the power capacity and specific power[11] required by all-electric or hybrid-electric systems for aircraft at least as large as a regional jet are unlikely to be matured to the point that products satisfying FAA certification requirements can be developed within the 30-year time frame addressed by this report. The design of turboelectric electric propulsion systems, however, does not include high-power batteries, thereby eliminating a major technical risk. Accordingly, turboelectric systems are recommended as the highest-priority approach to achieving electric propulsion for large commercial aircraft. Of course, turboelectric systems still face substantial technology challenges associated with generators, inverters, power distribution, and so on. However, all of these components are also included in various other electric propulsion concepts, so advances in turboelectric technologies will also enhance the feasibility of other concepts.

It may seem counterintuitive to pass over all-electric and hybrid-electric propulsion concepts as high-priority approaches given that small general-aviation aircraft using these concepts are already flying. Indeed, small aircraft can be useful to conduct flight tests of new technology, and in some cases technologies developed for use in large

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[11] In this report, specific power and specific energy refer to power and energy per unit mass, respectively, and power density and energy density refer to power and energy per unit volume.

aircraft have later migrated to small aircraft. Even so, not all technologies that are suitable for general aviation aircraft are scalable to the large sizes, long flight distances, and high operational tempos that are key characteristics of large commercial aircraft. This is the case for all-electric and for hybrid-electric systems given the time frame of interest for this study. In addition, the committee is not aware of any system studies showing that hybrid systems, including variants such as series/parallel partial hybrid systems, would reduce CO_2 emissions more than turboelectric systems (including a partial turboelectric system), which are recommended as a high-priority approach.

Advances in superconducting materials could eventually result in high-power superconducting motors and generators suitable for use on aircraft. Superconducting components could greatly reduce the weight of a wide array of electric propulsion concepts. However, the committee does not anticipate that the technical and certification challenges to developing such devices will be overcome during the next 20 to 30 years.

Another approach for electric propulsion would be to use fuel cells to convert hydrocarbon or hydrogen to electricity. If fueled by hydrocarbons, the amount of CO_2 reduction becomes problematic. In any case, fuel cells are unlikely to be able to provide the power needed for propulsion of a regional jet or larger commercial aircraft in the foreseeable future. Advanced fuel cells will likely be able to replace the gas turbine auxiliary power units that aircraft use to produce electrical power when the main engines are shut down. If fueled by hydrogen, this application of fuel cells would reduce total CO_2 emissions from commercial aviation, but only by a relatively small amount. Therefore, even though fuel cell auxiliary power units should be considered as part of the process for reducing CO_2 emissions, the committee did not classify them as a high priority.

The national research agenda recommended by this report could lower the priority assigned to research programs that are developing high-power batteries, fuel cells, and superconducting motors for the purpose of incorporating them in the propulsion systems of large commercial aircraft. Even if that happens, however, a substantial national research investment in each of these technologies is certain to continue because of their potential to benefit a wide array of other applications. Aircraft-specific research in these areas may then take on a higher priority as the general state of the art advances.

Many different types of internal combustion engines have been used to power commercial aviation, and even more types of engines have been studied. This includes piston engines, hybrid compound engines (which combine a gas turbine with another internal combustion engine such as a diesel), and engines that use thermodynamic cycles other than the simple Brayton cycle used by conventional gas turbine engines. Gas turbines dominate the current fleet of commercial aviation aircraft because their inherent characteristics, combined with decades of research, development, and operational experience, have resulted in very high levels of safety, reliability, performance, and efficiency. In addition, ongoing investments in gas turbine research have produced a steady trend of increasing efficiency, lower fuel consumption, and reduced emissions per passenger mile. Accordingly, the committee concluded that continued research in gas turbines should be the highest priority approach for developing advanced internal combustion engines for commercial aviation. Some specific areas of research, such as acoustics and open rotors, could contribute to reducing CO_2 emissions from gas turbine engines, but the committee concluded that they are unlikely to reduce CO_2 emissions by commercial aviation as much as research in the areas that are identified as a high priority.

There are many options other than conventional jet fuel to use as sources of energy to drive aircraft propulsion systems. Potential alternatives include hydrogen, blending of ethanol and biodiesel with conventional jet fuel, nuclear power, and compressed or liquefied natural gas. All of these have been studied, and some are more feasible than others. Unlike all of these options, however, SAJF is well suited as a drop-in aviation fuel that can reduce CO_2 emissions throughout the existing fleet of commercial aircraft, and that is why SAJF is the committee's highest-priority approach for energy systems.

2

Aircraft–Propulsion Integration

INTRODUCTION

This chapter reviews relevant background to commercial aircraft propulsion and aircraft–propulsion integration in general, describes the current state of the art, and suggests promising research directions for integrating aircraft and propulsion technologies in order to reduce energy consumption and thus aircraft CO_2 emissions. The discussion is focused on subsonic airliner propulsion. Considerations particular to other types of aircraft such as general aviation, supersonic transports, or military vehicles are outside the committee's purview and are thus not covered.

The power needed to propel an aircraft increases at more than the airspeed squared. Thus, high powers and large energies are needed to fly at high speeds over long distances. Relative to ground vehicles, it takes an enormous amount of energy and power to move a large commercial aircraft at high speeds across a continent or ocean (see Figure 2.1).[1] Thus, the value of high efficiency and high specific energy increases with speed and range.

The maximum power required for an aircraft is the power at takeoff; it scales with aircraft weight. The interrelated requirements that determine the power levels are too complex to discuss here, but they include considerations of runway length, airport elevation and ambient temperatures,[2] climb rate, and cruise efficiency.

The energy use and power required during different segments of a flight are illustrated in Figure 2.2 for a current single-aisle aircraft with seating for 150-180 passengers. The particular mission shown is for a load of 150 passengers with fuel on board to fly a 1,000 nautical mile (nm) mission. The maximum range of this aircraft is over 3,000 nm. At the maximum range, the total energy required for cruise is about three times that required for a 1,000 nm flight. Future improvements in aircraft, engines, and air traffic management could reduce the power and energy requirements noticeably, but the trends and order of magnitude will remain similar.

Fuel efficiency has always been a primary design criterion for commercial aircraft since it is an important determinant of aircraft range, size, and economics. Overall, the fuel burn per seat mile of gas turbine–powered commercial aircraft has been reduced by 70 percent since service started in the 1950s, at an average rate of about

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[1] The power and energy needs of aircraft are driven by their size, speed, and range. Compared to an automobile, a large commercial aircraft has a much greater passenger capacity (100-400 passengers), traveling at perhaps 10 times an automobile's speed and at up to 20 times the range while still delivering a fuel efficiency per passenger mile that is comparable to automobiles at average passenger loads.

[2] Airports at high elevations and high ambient temperatures are more challenging.

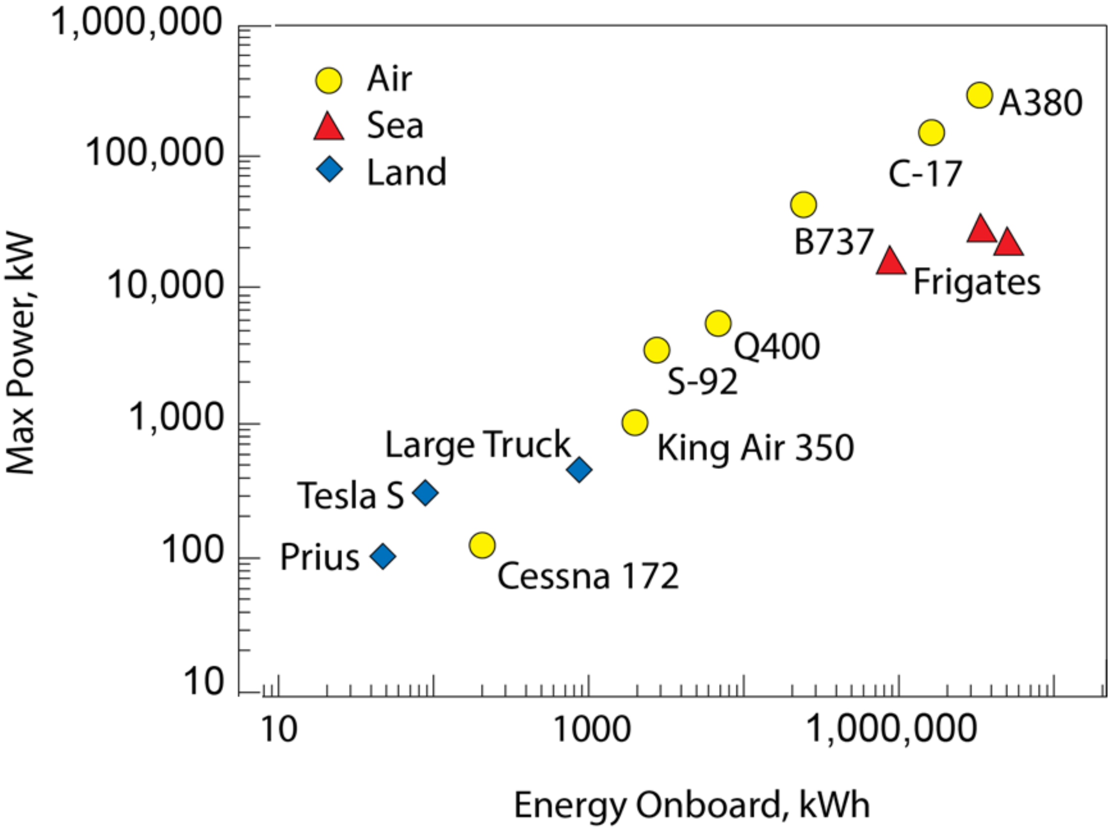

FIGURE 2.1 Power and energy required for vehicles ranging from small cars to large commercial aircraft. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

2 percent per year since 1970 (see Figure 2.3). About half the gain has been the result of improvements to the airplane, the rest to the engine.

BASIC CONSIDERATIONS

For the purposes of this study, it is useful to consider aircraft propulsion as consisting of three interdependent elements: an energy storage system, a motor to produce shaft power from that stored energy, and a propulsor to convert shaft power to propulsive power. Each is discussed briefly below.

Energy Storage

In current aircraft, energy is stored in the form of a liquid hydrocarbon fuel, which is burned with air in the engines. Other liquid or gaseous fuels such as hydrogen or natural gas can be considered, but they are not in use at this time and, as discussed in Chapter 5, they are not likely to be ready for operational use within the 30-year time frame addressed by this report. Fuels that are gases at room temperature incur relatively high penalties in terms of required volume and tank weight that may offset their potential technical advantages, not considering issues of infrastructure, production, and distribution.

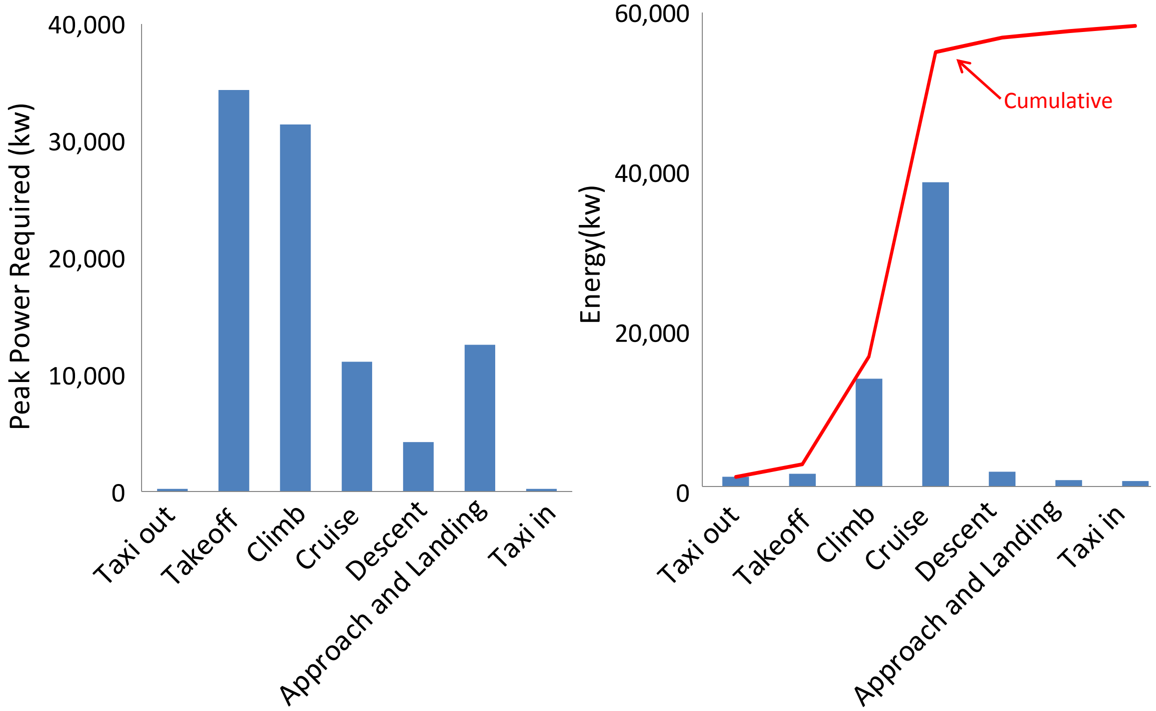

FIGURE 2.2 Mission segment energy and power required for a representative 150-passenger single-aisle aircraft with 3,000 nm design range flying a 1,000 nm mission. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

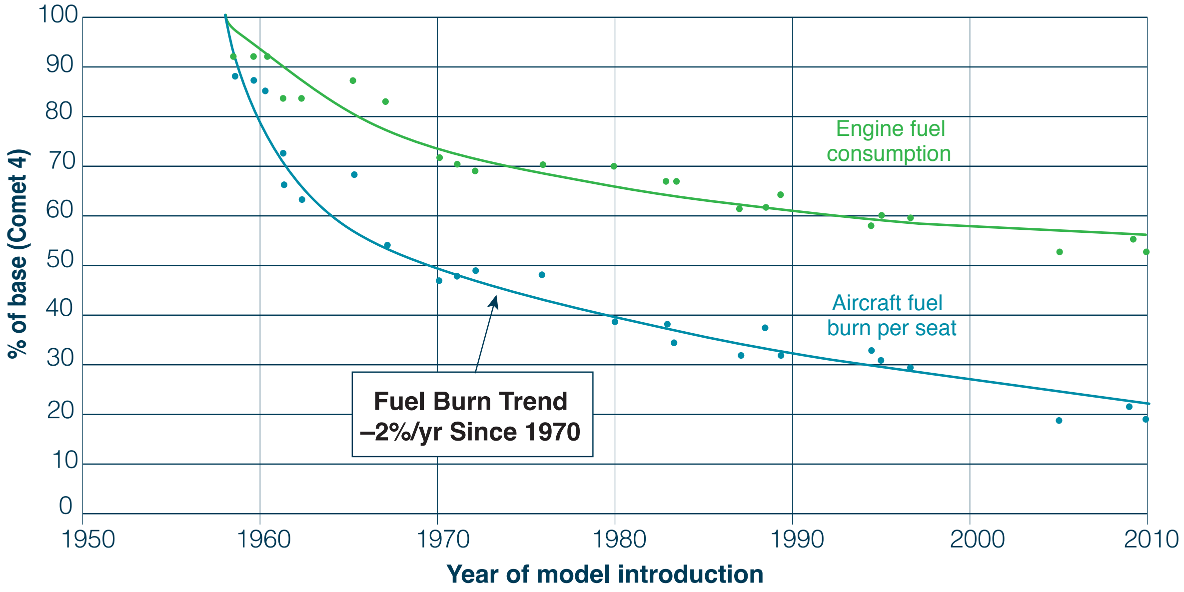

FIGURE 2.3 History of commercial aircraft fuel burn per seat-mile. SOURCE: Derived from Air Transport Action Group.

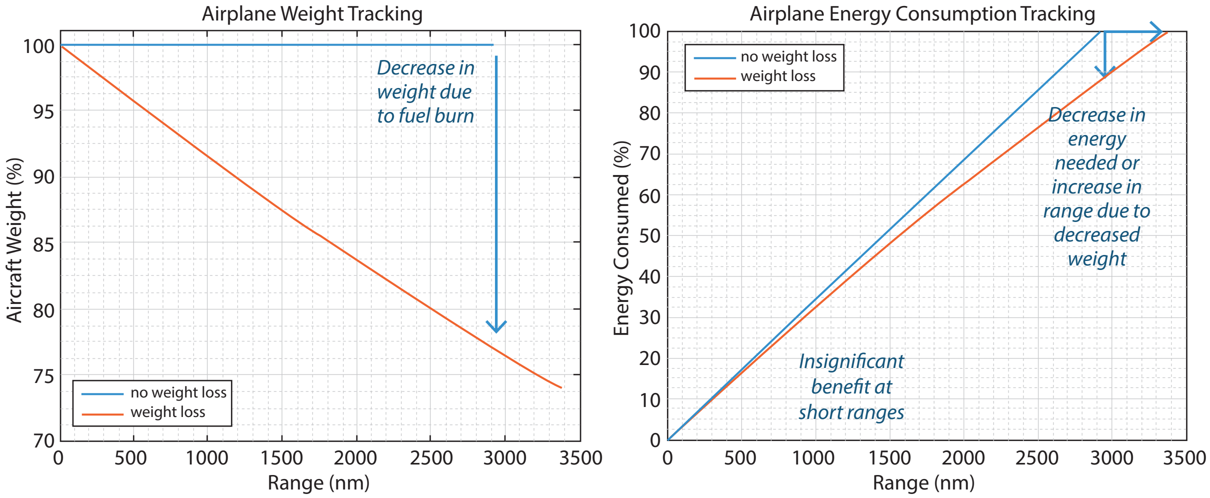

FIGURE 2.4 Benefit of fuel burn weight decrease on net propulsive energy needed to fly a particular range in a single-aisle aircraft. SOURCE: Marty K. Bradley, Boeing Commercial Airplanes.

The energy storage system on current commercial aircraft typically consists of fuel tanks, valves, sensors, and transfer pumps and piping to move fuel to the engines. Most fuel is stored in the wings. This arrangement has several advantages: (1) the fuel is located at about the center of gravity of the aircraft to minimize the shift in center of gravity as fuel is burned, (2) the wing's structural weight is reduced because the fuel weight partially offsets the bending moment produced by wing lift, and (3) no space useful for payload is lost to fuel. Also, the wings are "wet," that is the skin of the wings is also the wall of the fuel tanks, so that little additional weight is needed to contain the liquid fuel. Very long-range aircraft, in which the fuel weight may comprise more than 40 percent of the gross takeoff weight, may require additional tanks in the fuselage or tail.

Aircraft weight and drag penalties incurred by energy sources less dense than jet fuel (e.g., hydrogen and natural gas) will need to be accounted for when comparing designs using alternative energy sources. For example, given the low density of hydrogen, the drag and weight increase from the tanks needed for cryogenic liquid H_2 offset the gain in energy density for high-speed aircraft. Similarly, battery-powered concepts in which the batteries occupy the freight compartment need to be compared with aircraft having similar net payload capabilities.

Fueled energy system weight change during flight is another important consideration, strongly influencing aircraft range or the takeoff weight needed to achieve a fixed range. Because current aircraft typically lose 10-40 percent of the initial weight as fuel is burned, the net propulsive energy (i.e., the energy supplied to the vehicle by the propulsor) that is needed to keep the vehicle aloft decreases during a mission, allowing flight at higher altitude, which further reduces drag. By contrast, the weight of a closed battery system such as Li-ion stays constant during a flight, so the system would require more total energy than a fueled system all else being equal. An air battery system such as Li-air would actually gain weight during a mission, requiring additional energy. The impact of the aircraft weight change increases with aircraft range, as illustrated in Figure 2.4 for a generic single-aisle aircraft. At approximately 3,000 nm range, a non-weight-changing (battery-powered) aircraft with the same starting weight uses 12-13 percent more energy than one that reduces weight when burning fuel to supply the energy. This difference is much less significant for short ranges than for long-range aircraft.[3]

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[3] The efficiency of gas turbine and electric propulsion aircraft is discussed in more detail in Chapters 3 and 4, respectively.

Motors

The choice of motor to convert energy into shaft power must be compatible with the form of the energy stored. Energy may be stored electrochemically as in a battery, in which case an electric motor is an obvious device to convert that energy to shaft power. An electric motor would also be used if a fuel cell were employed to provide electrical power from fuel. Flight-weight, reliable, electric motors and the requisite drive electronics, cabling, and cooling do not currently exist in the sizes required for commercial aircraft propulsion. The prospects for these technologies are discussed in Chapter 4.

Gas turbine engines now power essentially all commercial aircraft. While light aircraft may use spark-ignition or diesel motors to reduce cost, commercial aircraft all use gas turbine engines owing to the combination of low weight, high efficiency, and very high reliability. Current aircraft gas turbines are optimized for fossil fuel, but alternative synthetic fuels from a variety of sustainable feedstock have recently been certified for commercial use. Turbines are also capable of burning gaseous fuels, given suitable modifications to the fuel and combustion systems. Fuels are discussed at length in Chapter 5. Aircraft gas turbine engines certified for crewed aircraft are available in sizes from about 300 to 90,000 kilowatt (kW).

The engineering metrics most important for the motor driving the propulsor are the specific weight and the efficiency. The specific weights of aircraft gas turbines up to the shaft driving the propulsor (thus comparable to an electric motor) range from about 12 to 23 kW/kg when accessories such as fuel pumps and controls are included. Certified, flight-weight electric drives at the size required for large commercial aircraft (larger than 1 MW) do not now exist; 250 kW size drives and power electronics have been demonstrated with specific weights of 1.5-2 kW/kg. The motor efficiency of large commercial aircraft gas turbines in service (defined as shaft power produced divided by fuel energy flow in) is now about 55 percent. With a typical propulsor efficiency of 80 percent, total fuel-to-propulsor efficiency is about 45 percent. As discussed in Chapter 4, the propulsive power for a turboelectric system would also flow through a generator, motor, power electronics, cabling, and cooling, which have a combined efficiency of about 80 percent, resulting in a net turboelectric motor efficiency of about 45 percent and a total fuel-to-propulsor efficiency of about 35 percent. Thus, reductions in CO_2 emissions for a turboelectric propulsion system will depend on factors other than motor efficiency. This is also discussed in Chapter 4.

Propulsors

However it is produced, shaft power is converted to propulsive power with a “propulsor” having either a ducted or an unducted configuration. When the propulsor consists of two contra-rotating propellers in tandem, it is sometimes referred to as an “open rotor.” Propulsive efficiency is defined as the propulsive power delivered to the aircraft (which is equal to thrust times airspeed) divided by the shaft power input to the propulsor. All else being equal, reducing the pressure across the propulsor reduces the exhaust velocity, which therefore increases propulsive efficiency. The relevant design parameter is the fan (or propulsor) pressure ratio, Figure 2.5. At constant thrust, as fan pressure ratio is reduced, more airflow and thus a larger propulsor area are needed. This requires either a larger fan (or propeller) diameter or more fans (or propellers). Either approach will have important design implications for an airplane, ranging from landing gear height to overall airframe configuration.

Turbofan engines mount the fan in a duct to serve several purposes: Doing so isolates the fan aerodynamics from aircraft speed, thereby facilitating higher airspeeds; it attenuates fan noise; and, in the case of a catastrophic engine failure, it improves safety by containing debris from the fan blades exiting radially and potentially striking the aircraft. The penalty paid for the duct is an increase in weight and drag. As the duct diameter grows, the propulsor efficiency increases, but at some point the increased weight and drag of the fan, duct, and nacelle cancel the efficiency gain, so that further increasing the size of the fan and its duct would increase the fuel burn of the aircraft. Also, larger diameter fans and nacelles may require longer and thus heavier landing gear. Therefore, at a given level of engine, nacelle, and aircraft technology, there is an optimum fan diameter for minimum fuel burn (see Figure 2.6). Moving the optimum fan pressure to lower values requires improving some combination of engine weight, engine inlet and duct length, nacelle weight and drag, landing gear weight, and nacelle–wing interface technologies.

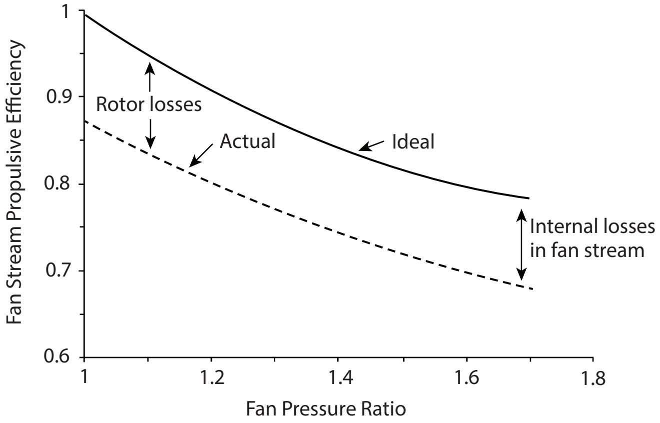

FIGURE 2.5 Propulsive efficiency can increase as fan pressure ratio drops. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

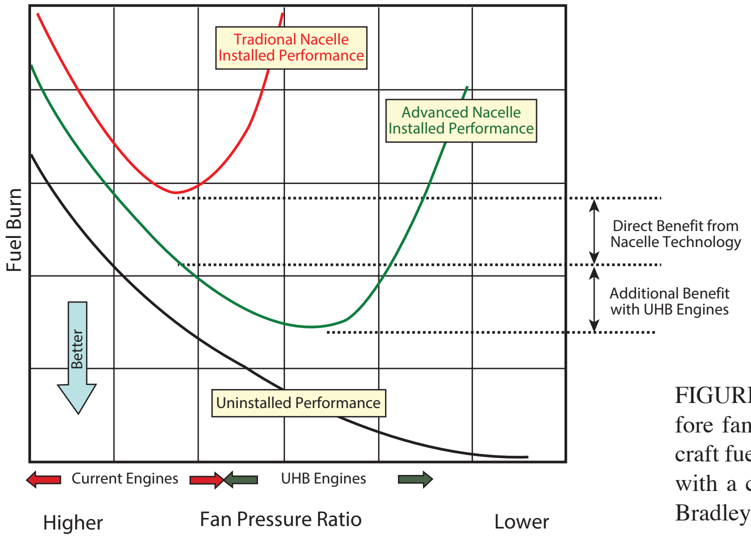

FIGURE 2.6 Influence of fan pressure ratio (and therefore fan area at constant thrust) and installation on aircraft fuel burn for a sample ultrahigh bypass ratio engine with a compact advanced nacelle. SOURCE: Marty K. Bradley, Boeing Commercial Airplanes.

Propellers and other unducted propulsors avoid the weight and drag penalties of a fan duct but also miss the advantages of ducted fans in terms of noise attenuation, safety, and high speed. While current turbofan aircraft mount engines on pylons standing off from the wing or fuselage, most commercial propeller aircraft in service today use a wing-mounted, tractor configuration in which the engines are cantilevered forward of the wing. Currently, large commercial aircraft, which are powered exclusively by turbofans, are designed for cruise speeds of Mach 0.78-0.86. Commercial propeller aircraft can cruise at speeds up to about Mach 0.68. Advanced propellers have been designed and demonstrated capable of flying in the Mach 0.7-0.78 range, although efficiency decreases as design airspeed is increased. At lower speeds, aircraft optimized for propellers can offer better efficiency than ducted approaches. Major impediments to the fielding of such aircraft at larger sizes include those associated with airframe integration, especially noise reduction and safety, and longer flight times.

The engineering metrics relevant to propulsors are propulsive efficiency, weight, and drag. Isolated (from the airframe) propulsor efficiencies are shown in Figure 2.5. State-of-the-art commercial turbofan aircraft in service today have propulsive efficiencies of 70-80 percent. Overall fuel burn must consider weight and installation aerodynamic effects, so that direct comparisons are best done at the aircraft level. It is the installed performance of the propulsion system that is important, not that of the engine or propulsor alone.

Distributed propulsion, which is discussed below in the section on advanced aircraft–propulsion integration concepts, uses multiple, relatively small motors and fans. Distributed propulsion may overcome the integration challenges of finding room for larger diameter fans by instead increasing the number of fans, though this has its own integration challenges.

Other Aircraft-Level Metrics

Safety is essential for aeronautical systems, especially those used in commercial aircraft. One key to achieving the current extraordinary low accident rate of airliners is an empirically based, stringent set of design requirements for aircraft and their propulsion systems. The requirements for specific design functionalities, material properties, and redundancy are significant factors in the cost and complexity of current propulsion systems. In addition, if existing certification standards cannot assure the safety of new technologies, then new standards must be developed and validated. Any consideration of changes or innovations proposed to reduce energy consumption need to be mindful of such requirements since aircraft safety cannot be compromised. For example, the high volatility and low temperatures of cryogenic fuels introduce significant safety challenges, especially in the area of crashworthiness, though much can be learned from the utilization of cryogenics in space platforms and their associated design requirements.

Since commercial aviation is a business, the cost of the aircraft propulsion system is always an important design consideration and directly relevant to reducing energy consumption. Roughly speaking, current engines account for about 20 percent of the purchase cost of a commercial airplane. Propulsion system concepts that are significantly more costly will not be implemented unless they offer clear value in the eyes of the airline customer or are necessary to satisfy a regulatory requirement. The designs of current engines often reflect this as a constraint on the economics of propulsion. At a given level of technology, gas turbine performance can be traded for cost as represented by such factors as material choice, design complexity, and maintenance intervals. In other words, turbofan engines could be designed to consume less energy if engine purchase price and maintenance cost constraints were relaxed. Thus, it would be appropriate for comparative analyses of alternative approaches that raise the overall purchase and operating cost of the propulsion system and airplane to consider the performance of a gas turbine solution at the same overall purchase and operating costs.

The value of reducing carbon emissions (i.e., increasing aircraft efficiency) is strongly dependent on the price of energy/fuel/carbon. At the historical average price of jet fuel of less than $1/gal (2012 U.S. dollars), fuel represented about 20 percent of the direct operating cost of a twin-aisle airliner, not including aircraft depreciation. At that price, fuel is less than an airplane's depreciation, so even a 5 percent fuel burn deficit did not render a product uncompetitive or eliminate it from the market. The historic high fuel price in 2008 was close to $5/gal, at which point fuel represented 60 percent of the aircraft's operating cost. At that level, a 5 percent reduction in fuel burn had immense economic impact. As of April 2016, with the spot price of crude oil at $36, the spot price of jet fuel was about $1 per gallon. The U.S. Energy Information Administration projects that the spot price of crude oil in 2040 will be 2 to 7 times as much as current prices (in constant dollars), and it also projects that the cost of jet fuel will track the cost of crude oil.[4,5] The economic viability of technologies that significantly increase the cost of propulsion systems and aircraft but reduce energy cost is very strongly dependent on the value placed on carbon emissions relative to other aircraft properties such as economy, speed, noise, and so on.

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[4] Energy Information Agency, 2016, Petroleum and Other Liquids: Spot Prices, Washington, D.C. https://www.eia.gov/dnav/pet/xls/PET_PRI_SPT_S1_D.xls.

[5] Energy Information Agency, 2015, *Annual Energy Outlook 2015 with Projections to 2040*, DOE/EIA-0383(2015), Washington, D.C., http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf.

ADVANCED AIRCRAFT–PROPULSION INTEGRATION CONCEPTS

In all cases, the propulsor and motor must be mounted to the aircraft in order to react against the aircraft and transmit the thrust forces and torque produced. The manner of this mounting, which is one aspect of propulsion integration, has many important aerodynamic, structural, and safety implications for the aircraft. Aircraft–propulsion integration considerations are a function of many details of both the aircraft configuration and the propulsion system. Such considerations are extremely important in selecting the best propulsion system and in optimizing an aircraft for low energy consumption.

Aircraft–propulsion integration refers to the aerodynamic, structural, and subsystem (fuel, pneumatic, hydraulic, electrical, control, etc.) interfaces between engines and airframe. These subsystems are important to the operation of the airplane, are in many cases safety critical, and consume on the order of 5-8 percent or more of the energy required for flight. Safety-critical examples include wing and inlet anti-icing and cabin environmental control. These functions are all required independent of the energy or propulsion system powering the aircraft. To a large degree, they are also independent of aircraft efficiency in that their power and energy requirements do not necessarily decrease as aircraft and propulsion systems improve. In fact, the electrical power demand of aircraft subsystems will likely increase as more utility functions are powered by electricity. Thus, one would expect that subsystem power and energy needs may grow as a fraction of total aircraft load unless technology is advanced in this area.

Today, all commercial aircraft share a configuration known as tube and wing. This configuration is characterized by thin wings, swept for efficiency at high subsonic speeds, which are mounted to a roughly circular cross-section tubular body. Engines on current turbofan-powered commercial aircraft are mounted on pylons, which stand the engines off the wings or fuselage in order to isolate the engine and airframe aerodynamic characteristics. The pylons must transmit the thrust loads from the engine to the airframe as well as convey all fluid and electrical interconnections. The engines are enclosed by fairings known as nacelles, which contain many of the subsystems important to the operation of the aircraft such as the electrical generators. The nacelles also serve other purposes, including aerodynamic fairing of the engine, conditioning of airflow into the engine, thrust reversing, and noise attenuation. The aerodynamic, structural, and subsystem integration of the engine and nacelle with the airframe is important to determining aircraft performance and optimum engine characteristics such as propulsor diameter and fan pressure ratio. Whatever the propulsor, either a fan or a propeller, virtually all engines today require nacelles.

It is also possible to embed engines within the wings as was done on the Comet airliner in the 1950s, or within the airframe, as was done on the B-2 bomber, which has an unusual blended wing/body configuration. To date, embedded configurations have not proven advantageous compared to the pylon mount common to airliners today. One major challenge is that these installations required relatively long ducts to move air to and from the engines. Such duct lengths, with relatively large viscous losses due to large surface area, are not compatible with the low fan pressure ratios used to improve propulsive efficiency on modern commercial airliners.

There has been much study of various commercial blended wing/body configurations over the past several decades, including configurations with engines on pylons and ones with embedded engines. To date no such commercial aircraft has been developed. Indeed, refinements of pylon-mounted engine, tube-and-wing configurations have made a contribution to the 70 percent fuel efficiency gain illustrated in Figure 2.3.

The National Aeronautics and Space Administration (NASA) has promulgated a set of goals known as N + 3 for aircraft entering service 20 or 30 years or so from now aimed at reducing noise, fuel burn, and emissions.[6] Depending on the reference, the energy reduction goal is 60-70 percent better than the reference 1990s design aircraft for similar missions. Several organizations and teams have published designs that they claim have the potential to meet these goals given sufficient investment. All require innovation in aircraft design (which is beyond the scope of this committee), in propulsion, and in aircraft–propulsion integration. The propulsion approaches under consideration include ultrahigh bypass ratio turbofans, turboprops, distributed propulsion, and hybrid-electric schemes.

Several proposed advanced aircraft designs include configurations in which the boundary layer developing along the aircraft is ingested into the propulsor to reduce the velocity defect in the aircraft wake (also known as

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[6] NASA, "ARMD NRA: Advanced Concept Studies Awards," last update October 6, 2008, http://www.aeronautics.nasa.gov/nra_awardees_10_06_08.htm.

wake cancellation), thus reducing the thrust needed to propel the aircraft and so reducing energy consumption. While it can be debated whether the effect of boundary layer ingestion (BLI) should be considered one of increased propulsive efficiency or decreased aircraft drag, it is clear that it requires a much higher level of propulsion–aircraft integration than is common today and imposes new constraints and requirements on both the airframe and the propulsion system. BLI configurations have been proposed using a variety of propulsor drive systems, including direct-drive turbofan engines, geared mechanical drives, and electrical drives. In some approaches, distributed propulsion may be synergistic with BLI, but this is not necessary.

BLI can be used in designs where a propulsor is integrated into the aft fuselage to capture the fuselage boundary level or on an upper surface to capture part of the fuselage or wing boundary layer. Theoretical designs of several configurations have been documented in the literature, including three that pass the boundary layer of the top surface of the flattened fuselage through propulsors (e.g., the MIT/NASA D8, NASA N3-X, and Cambridge/MIT SAX-40 aircraft concepts) and two with circumferential ingestion at the rear of a circular fuselage (i.e., the Bauhaus Luftfahrt Ce-Liner[7] and Boeing SUGAR Freeze [8] aircraft concepts). Figure 2.7 illustrates four concept aircraft proposed by different organizations. The D8 (A) and the Propulsive Fuselage (B) ingest the boundary layer directly into the fans of turbofan engines.[9] The SAX-40 (C) uses a gear drive system to power three fans from each of its three gas turbines,[10] while the N3-X (D) uses a turboelectric configuration in which two gas turbines drive electric generators that in turn power 13 electric motor–driven fans.[11] Not shown is the Boeing SUGAR Freeze, which has an aft fuselage BLI configuration for an aircraft powered by cryogenic fuel (liquefied natural gas).[12] BLI configurations also can benefit from using the larger number of fans with low fan pressure ratio to produce a higher propulsive efficiency (same trend as in Figure 2.5). Alternatively, a fan pressure ratio benefit can also be obtained with distributed propulsion that does not use BLI. Some boundary layer ingestion configurations use a small number of relative large fans (1, 2, or 3); others use more (10-15) smaller ones. In either case the fans can conceptually be driven by electric or gas turbine motors, either directly, through shafts and gear trains,[13] or electrically through power extracted from the gas turbines and distributed via electrical cables.

Boundary layer ingesting configurations have been proposed using a variety of propulsor drive systems, including direct-drive turbofan engines, geared mechanical drives, and electrical drives.

Low-speed wind tunnel tests of the D8 configuration documented a 6 to 8 percent reduction in cruise power requirement with BLI.[14] Other studies have claimed a potential reduction of more than 20 percent if the entire vehicle boundary layer is cancelled. BLI configurations bring a very high distortion level into the fan, which impacts efficiency, fatigue life, and noise—at least partially offsetting potential gains from wake cancellation.

It should be emphasized that all of the configurations shown in Figure 2.7 are advanced concepts only, with significant uncertainty surrounding the performance of an operational aircraft based on these concepts. Considerable detailed study is required to assess their viability and

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[7] M. Bradley, 2012, "NASA N+3 Subsonic Ultra Green Aircraft Research SUGAR Final Review," Boeing, http://aviationweek.typepad.com/files/boeing_sugar_phase_i_final_review_v5.pdf.

[8] Boeing's Subsonic Ultra Green Aircraft Research (SUGAR) Program had multiple elements, including SUGAR Freeze, which focused on cryogenic fuels and superconducting electrical components, and SUGAR Volt, which focused on nonsuperconducting electric propulsion.

[9] S.A. Pandya, 2012, "External Aerodynamics Simulations for the MIT D8 'Double-Bubble' Aircraft Design," presented at the Seventh International Conference on Computational Fluid Dynamics, https://www.nas.nasa.gov/assets/pdf/papers/ICCFD7-4304_paper.pdf.

[10] The Cambridge-MIT Institute, "Silent Aircraft Initiative," last update 2008, http://silentaircraft.org.

[11] J.L. Felder, 2014, "NASA N3-X with Turboelectric Distributed Propulsion," NASA Glenn Research Center, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150002081.pdf.

[12] M. Bradley, 2012, "NASA N+3 Subsonic Ultra Green Aircraft Research SUGAR Final Review," Boeing, http://aviationweek.typepad.com/files/boeing_sugar_phase_i_final_review_v5.pdf.

[13] J. Whurr, 2013, "Future Civil Aeroengine Architectures and Technologies," presented at the 10th European Turbomachinery Conference, http://www.etc10.eu/mat/Whurr.pdf.

[14] A. Uranga, M. Drela, E.M. Greitzer, N.A. Titchener, M.K. Lieu, N.M. Siu, A.C. Huangk, G.M. Gatlin, and J.A. Hannon, 2014, "Preliminary Experimental Assessment of the Boundary Layer Ingestion Benefit for the D8 Aircraft," presented at the 52nd Aerospace Sciences Meeting, AIAA SciTech, AIAA Paper No. 2014-0906, http://web.mit.edu/drela/Public/N+3/Uranga2014_compressed.pdf.

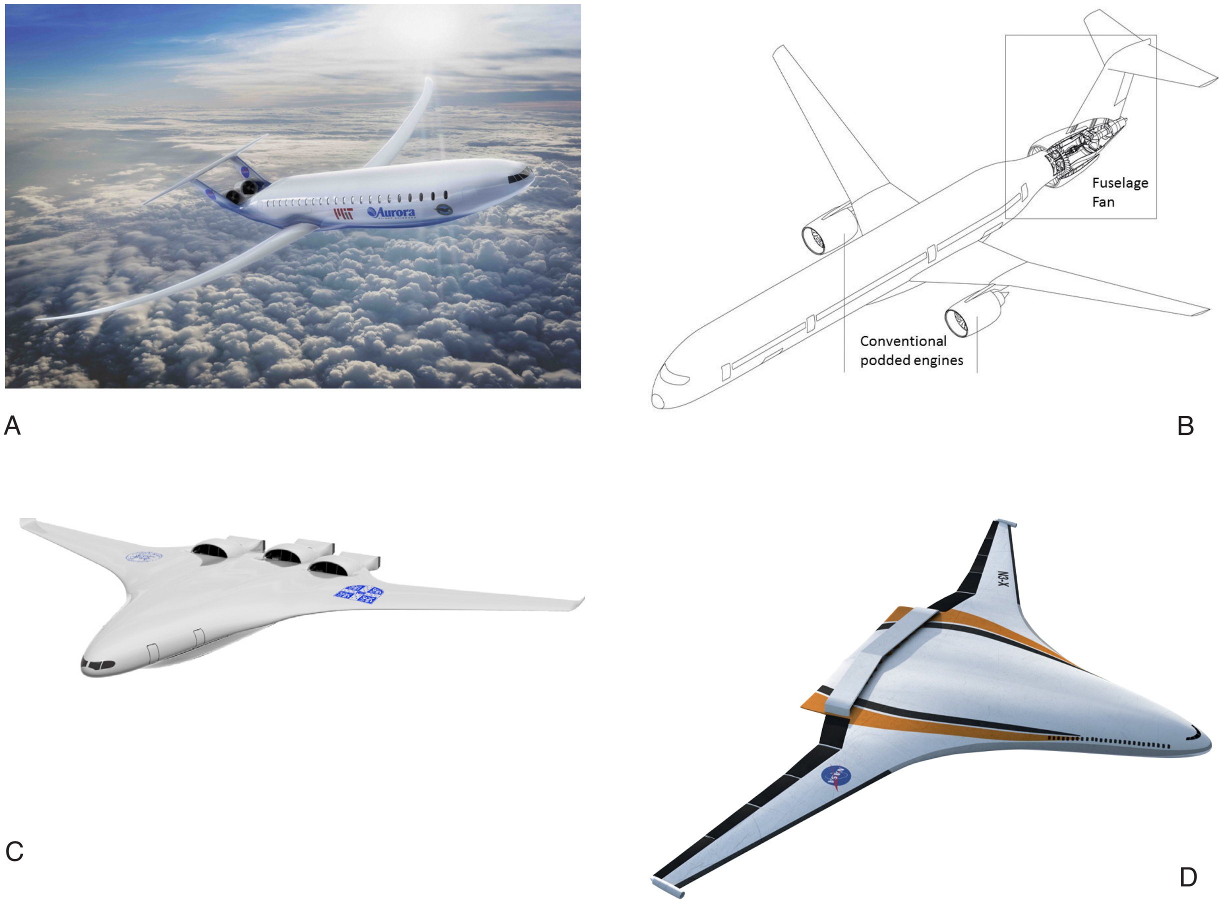

FIGURE 2.7 Some proposed boundary layer ingestion configurations: (A) D8, (B) Propulsive Fuselage, (C) SAX-40, and (D) N3-X. A and B are 150-180 passenger aircraft; C and D are about twice that size and range. SOURCE: Courtesy of Aurora Flight Sciences (A), Bauhaus Luftfahrt (B), Cambridge-MIT (C), and NASA (D).

their value relative to more conventional approaches at the same level of technology. The studies reviewed by the committee focused on the propulsion and some aerodynamic considerations of wake cancellation; many more disciplines will need to be explored to turn these ideas from advanced concepts into promising design approaches. Questions of aerodynamic performance, weight, subsystem requirements, and safety all need to be addressed to arrive at an overall integrated airplane assessment.

Considerable research will be required to establish the net energy reduction benefit of practical BLI configurations and to identify any impacts on other aircraft requirements such as noise, safety, and reliability. All things considered, boundary layer ingestion configurations may be a productive research path for reducing aircraft fuel burn.

INTEGRATION OF AIRCRAFT PROPULSION AND POWER SYSTEMS

Aircraft require power for a variety of functions such as electric power for avionics, cabin air supply and conditioning, deicing, and actuators for flight controls and landing gear. On most aircraft these functions are supplied by a variety of propulsion engine–derived sources including electrical generators, pneumatic bleeds, and hydraulic pumps. Together they constitute the engine offtake. It is also possible to use electrical power only, in which case the aircraft is known as a more- or all-electric aircraft. Aircraft variation in power demand does not match the variation of power output of the engines. At takeoff the offtake needed represents less than 1 percent of engine power. During descent, it represents effectively 100 percent. In other words, during descent the engine power setting is determined by the need to provide offtake power rather than to propel the aircraft. Currently, about 6 to 8 percent of the fuel consumed during cruise is to supply engine offtake functions. As aircraft have become more efficient, engine offtake requirements as a fraction of propulsion system output have grown because the propulsive power needed drops but the power needed to support passengers and crew or to deice the aircraft have not changed dramatically. At the same time as fan pressure ratios have dropped and bypass ratios have increased to improve propulsive efficiency, there is even less power available in the engine to supply offtake requirements. This mismatch between needs and capabilities now results in designs that are not optimized for overall fuel burn. There are significant opportunities to improve aircraft fuel burn by more tightly integrating these now distinct aircraft systems. New architectures for these future integrated systems could consider energy storage, load leveling, auxiliary power unit (APU) utilization or elimination, higher distribution voltage, thermal management, safety, and redundancy.

Integrated propulsion and power systems include more electric or all-electric power systems that use little or no engine bleed. These power systems require significant changes to aircraft systems compared to the more typical approaches that utilize significant engine bleed for heating, cooling, and environmental control systems in the aircraft. There are significant opportunities to improve aircraft fuel burn by more tightly integrating these now distinct aircraft and engine power systems.

Rationale for Aircraft–Propulsion Integration

Finding. *Rationale for Aircraft–Propulsion Integration*. Advances in integrating aircraft and propulsion are needed to enable many aspects of low-carbon aviation that are not achievable by incorporating discrete improvements in individual component technologies. Areas of interest include both evolutionary configurations such as lower fan pressure ratio engines in nacelles on standard tube-and-wing aircraft and significant departures from standard configurations, including modified aircraft platforms, distributed propulsion concepts, and boundary layer ingestion configurations.

CHALLENGES

Technical Challenges

Propulsive Efficiency

Low fan pressure ratios are needed to reduce exhaust velocities and thereby improve propulsive efficiency, regardless of whether the fan is driven by a gas turbine or an electrical motor. For a constant level of thrust, this requires that the effective fan area increase so as to avoid commensurate increases in weight, drag, and integration losses.

At constant thrust, lowering the fan pressure ratio requires increasing the fan area. The typical approach is to increase fan and nacelle diameter, which increases aircraft weight and drag. At the same time, lower pressure rise across the fan means that internal flow wall drag and nozzle losses become more important, driving designs toward shorter ducts, in turn reducing the duct area available for noise attenuation. Because slower fan speed also lowers fan noise frequencies, noise attenuation requires duct liners of greater volume. Rather than making a single fan larger, multiple fans (distributed propulsion) can also be used to increase total fan area, but the power must be distributed to the multiple fans by an electrical system or mechanical shafting, which adds weight and reduces transfer efficiency. Overall, the low pressure ratio fans needed to improve propulsive efficiency present installation challenges so that the performance penalties caused by higher noise, weight, and drag and lower transfer efficiencies do not cancel out the gain of lower exhaust velocity.

Boundary Layer Ingestion

To use boundary layer ingestion and wake cancellation to reduce aircraft cruise energy requirements, an aircraft configuration integrated with a propulsor design is needed in which the overall benefits of wake cancellation outweigh the costs in terms of propulsor efficiency, noise, and weight.

The potential for wake cancellation to reduce aircraft cruise energy requirements, which could be considered as either drag reduction or improved propulsive efficiency, has long been recognized. Many implementations have been proposed, but none have been realized; all represent significant departures from legacy conventional aircraft configurations. All also result in the propulsor—fan or propeller—operating in significantly distorted inflow, which is known to reduce propulsor efficiency, threaten rotor mechanical integrity, and generate significant noise.

Economic Challenge

Relative Economic Value

A balanced technology investment portfolio in aircraft–propulsion integration research is needed to ensure that economic uncertainties arising from changes in net fuel price do not slow continued reductions in emissions by commercial aircraft.

The relative economic value of different aircraft configurations and propulsion systems can change dramatically as fuel prices change, so the relative value of technology approaches can change as well. Currently, the price of jet fuel is well within the range of historic norms, so aircraft depreciation is a larger cost than fuel. Thus technical approaches to reducing fuel burn that significantly increase the purchase price of an airplane are not favored commercially. The future net cost of jet fuel is highly uncertain and could rise dramatically due to economic factors and policy responses to climate change. In this case the relative balance could change between, on the one hand, operators' cost and, on the other, the value society places on the importance of carbon emissions and other aircraft environmental effects such as oxides of nitrogen (NO_x), particulates, and noise. The challenge is to construct a balanced technology investment portfolio that is robust to a key economic uncertainty of commercial aviation—namely, net fuel price.

Policy Challenge

Certification

Technical and policy issues surrounding certification of aircraft and propulsion concepts and technologies not covered by current certification procedures are important for guiding technology development. In addition, manufacturers must have confidence that these issues will be resolved in a timely fashion before they are likely to begin advanced development of the relevant aircraft and propulsion systems.

Rules for certification of new aircraft and engines are intended to establish that aircraft are in compliance with standards for safety and environmental impact. Existing certification rules and procedures have evolved over many decades, benefiting from aviation's vast experience. These rules are a major factor in the extraordinary safety record of commercial aviation. This experience, however, is based on a narrow range of possible commercial aircraft and propulsion configurations, namely tube-and-wing aircraft powered by pylon-mounted jet engines. Novel aircraft and propulsion proposals often contain features that are not consistent with current regulations or are not addressed by them. Inappropriate or inadequate certification regulations and procedures can impede the development of new approaches. Important questions include these: Is a new aircraft propulsion system approach sufficiently safe? What design approaches and technologies are needed to generate the required safety level? Which procedures are needed to demonstrate safety? Answers to these questions are important for guiding basic technology and for maturing aircraft designs. They need to be addressed on both a technical and policy basis well before aircraft development is started.

RECOMMENDED HIGH-PRIORITY RESEARCH PROJECTS

The two most promising technical directions in gas turbine research are (1) nacelle and integration technologies to enable ultrahigh bypass ratio propulsors so as to realize high propulsive efficiencies and (2) technologies that enable boundary layer ingestion. Power systems that are highly integrated on the aircraft level may reduce fuel burn, but the possible gain is estimated to be less than items (1) and (2), so a power system research project is not recommended as a high priority. While not called out explicitly, simulation and modeling improvement are important to all three of these projects.

Nacelles for Ultrahigh-Bypass-Ratio Gas Turbines

Develop nacelle and integration technologies to enable ultrahigh bypass ratio propulsors.

Improving propulsive efficiency requires reducing fan pressure ratios. Fan pressure ratios at least as low as 1.25 are of interest over the 30-year timeframe addressed by this report. Realizing such low pressure ratios means that technologies and design approaches will need to be developed to address challenges in all the areas relevant to installation of such fans. This includes internal and external aerodynamics, acoustics, thrust reversing, operability, manufacturing, and, of course, overall weight. The goal is to enable compact nacelles, including their installation, that are lighter and have less drag than today's nacelles in order to optimize propulsive efficiency. Many of the technologies for reducing internal propulsor flow path losses are relevant to conventional configurations with engines podded in nacelles and to configurations in which the propulsion system is imbedded within the airframe. This research project is closely related to the gas turbine research project on low pressure ratio fan propulsors, and work on the two should be closely coordinated.

Boundary Layer Ingestion

Pursue technologies that can enable boundary layer ingestion to reduce the velocity defect in the aircraft wake (also known as wake cancellation) and thus reduce cruise energy consumption.

BLI promises at least theoretically to significantly reduce aircraft fuel consumption, all else being equal. The propulsor–aircraft integration of most proposed BLI configurations, however, is significantly different than conventional designs, so all else is not equal. The benefits and costs of BLI are confounded by many other significant aircraft and propulsion changes in these advanced designs, necessitating careful, detailed aircraft design studies to guide investment in component and subsystem technologies. The highest priorities are as follows:

- *Design approaches*. Explore the aerodynamic, structural, subsystem, control, and safety implications of BLI configurations, including detailed systems analyses of alternative approaches such as various advanced propulsion system options. The value of these studies would be greatly enhanced if they include careful, apples-to-apples comparisons with more conventional configurations using similar levels of technology.
- *Fans in distorted flow fields*. Develop technologies for propulsion fans and their installation consistent with operating in the highly distorted flow fields that are characteristic of BLI configurations. One central technical challenge to the realization of BLI is overcoming the penalties associated with fan efficiency, noise, operability, and life that would accrue if BLI were implemented at the current state-of-the art fan and fan installation. Overcoming this challenge will require detailed assessment of penalties inherent in current technology, as well as pursuing design and technology approaches that mitigate such penalties. Progress in this area requires both analysis and testing at representative Mach numbers.

3

Aircraft Gas Turbine Engines

INTRODUCTION

All commercial aircraft designed in the last 40 years (other than aircraft with fewer than a dozen passengers) are powered by gas turbine engines, either turbofan or turboprop. Thus, any discussion of reducing carbon emissions from commercial aircraft will need to consider the potential for improvement of gas turbine engines. To that end, this chapter will delineate the current state of the art of aircraft engines, discuss the potential for and constraints on gas turbine improvement over the next three decades, and suggest research directions to achieve such improvement. Unless otherwise noted, the discussion in this chapter refers to gas turbine engines for large commercial aircraft, as discussed in Chapter 1.

BACKGROUND

Engine Metrics

For this discussion, engine refers to the device that converts the energy in fuel into shaft power and the shaft power into propulsive power. In current implementations, engines are highly integrated and take the form of a turbofan engine or a turboprop engine with propeller. With a modern turbofan (see Figure 3.1), the fan draws air through the inlet, 80-90 percent of which is exhausted through the fan nozzle to provide most of the thrust produced by the engine. The rest of the fan air is pressurized in the compressor and is either (1) used for cooling or (2) mixed with fuel and burned in the combustor. Exhaust gases from the combustor pass through the turbine, generating the mechanical energy that turns the shaft that drives the fan and compressor. The gases exiting the turbine pass through the exhaust nozzle at high speed, which provides additional thrust. A turboprop is simpler in design though similar in concept to a turbofan, the primary difference being that a turboprop uses a propeller in free air to produce thrust rather than a fan in a nacelle.

For gas turbine engines, the primary engineering metrics are overall efficiency, weight, additional drag, and reliability. Overall efficiency here refers to the efficiency with which the engine converts the power in the fuel flow to propulsive power. It is the product of thermodynamic efficiency of the process that converts fuel flow power to shaft power (herein called motor thermodynamic efficiency) and propulsive efficiency (the conversion

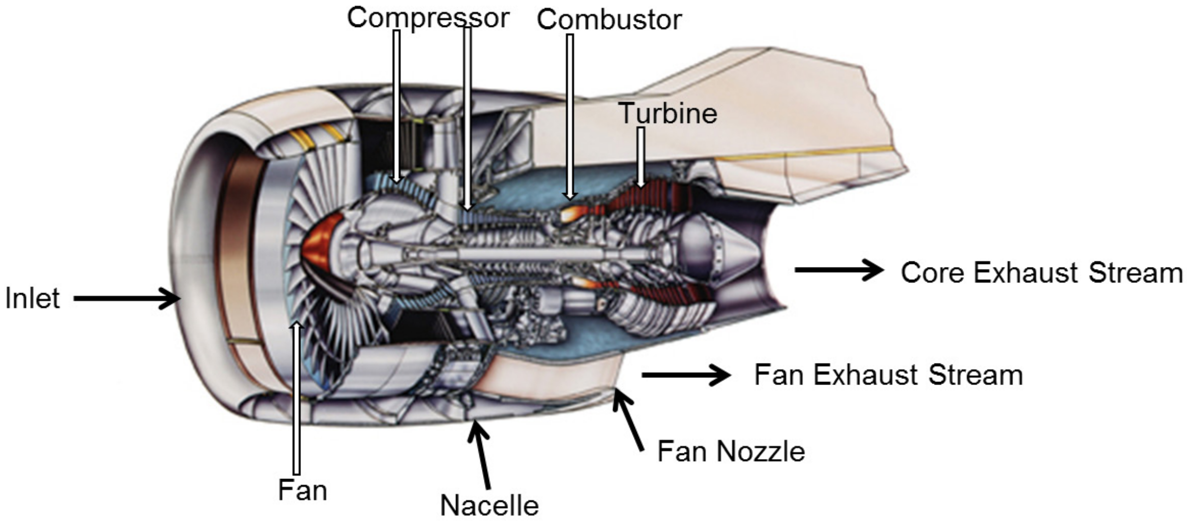

FIGURE 3.1 Airliner high bypass–ratio turbofan engine in its nacelle. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

of shaft power to propulsive power[1]). The most efficient commercial aircraft gas turbines in service or entering service in this decade have takeoff thrusts of 20,000 lb and above. These turbines operate at cruise, with motor thermodynamic efficiencies of up to 55 percent and propulsive efficiencies of well over 70 percent, yielding an overall efficiency (the product of the two) of about 40 percent (see Figure 3.2). The total cost of ownership is also an important metric that influences design efficiency and weight. This cost includes manufacturing cost, maintenance cost (mainly overhaul), and fuel. A combination of these costs appropriate to each application is used to assess best value. Generally, at a given level of available technology, gas turbine weight can be traded for efficiency and maintenance cost. Thus, engines for longer range aircraft (now all twin aisle) optimize to higher efficiency levels since the weight and cost trades between the engine and the fuel weight favor increased efficiency as range increases.

Motor thermodynamic efficiency of commercial aircraft engines has improved from about 30 percent to over 50 percent over the past 50 years, as shown in Figure 3.3. Most commercial airline engines are designed to maximize efficiency at cruise, since that is where most fuel is burned. The ultimate cruise thermodynamic efficiency is constrained by thermodynamics to somewhat above 80 percent for an ideal cycle consisting of lossless components. Of course, this is not realizable in a practical sense since real components have losses. Where the practical limit lies given aviation's important constraints of safety, weight, reliability, and cost is a matter of some speculation. However, several estimates have placed it at between 65 and 70 percent, given the development of new materials, architectures, and component technologies, as is discussed in the sections that follow.

Propulsive efficiency is defined here as the propulsive power delivered to the aircraft (which is equal to thrust times airspeed) divided by the shaft power input to the propulsor. For turbofan aircraft in service now, propulsive efficiency is 70-80 percent (Figure 3.4). Turboprops are about 10 percent more efficient at their current cruise Mach numbers. As noted in Chapter 2, as propulsors increase in size to increase propulsive efficiency, care needs be taken to distinguish and account for aircraft installation effects that may contribute to overall aircraft weight and increase drag but that are not normally attributed to engine efficiency.

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[1] Care must be taken since "efficiency" may be defined differently depending on the reference or organization. In this report the definition is chosen to allow consistent comparisons among alternative propulsion approaches.

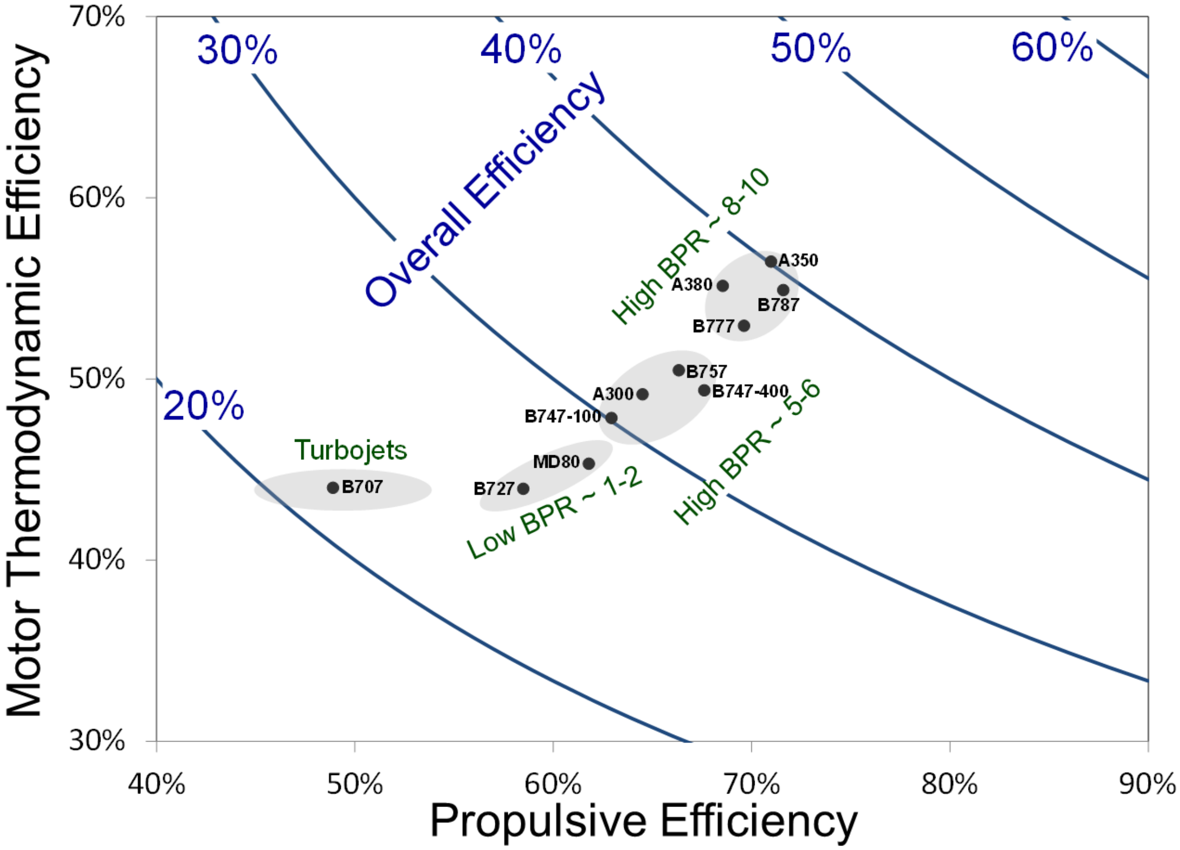

FIGURE 3.2 Commercial aircraft gas turbine engine efficiency trend. BPR, bypass ratio. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

Gas Turbine Characteristics

Gas turbine engines have several characteristics that distinguish them in important ways from other power plants such as internal combustion engines or electric drives. All engines produce waste heat that must be rejected. The penalties associated with such heat rejection increase with airspeed. One distinguishing characteristic of a gas turbine that is especially relevant to high-speed aircraft is that the heat from the fuel lost to inefficiency in gas turbines for the most part travels out as the exhaust and, indeed, produces positive thrust. This is in contrast to other power plants such as piston engines, Rankine and Sterling cycles, and electric drives. These power plants must explicitly reject waste heat, and their necessary cooling systems can add considerably to complexity, weight, and drag. Such penalties can be substantial. For example, the committee estimates that the drag increase (or net thrust decrease) to reject 10 percent of the propulsion power as heat may be on the order of 5 percent.

A second relevant characteristic is that at constant throttle settings, a modern turbofan engine's thrust varies with speed and altitude in a way that matches the variation in thrust required by a commercial subsonic airliner. Specifically, current subsonic airliners require about three to five times more thrust to take off than they do to cruise, and the power produced by a high bypass ratio turbofan engine at constant throttle setting varies in much the same way. Thus, turbofan engines are well suited to current airliners. This is illustrated in Figure 3.5 for a

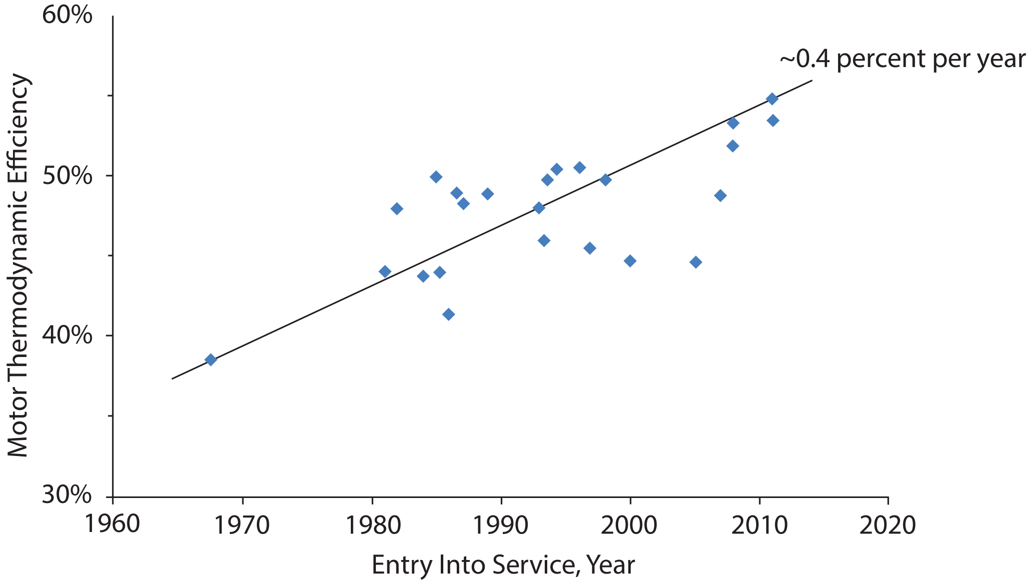

FIGURE 3.3 Trend with time of the thermodynamic efficiency of commercial aircraft turbofan motors at cruise. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

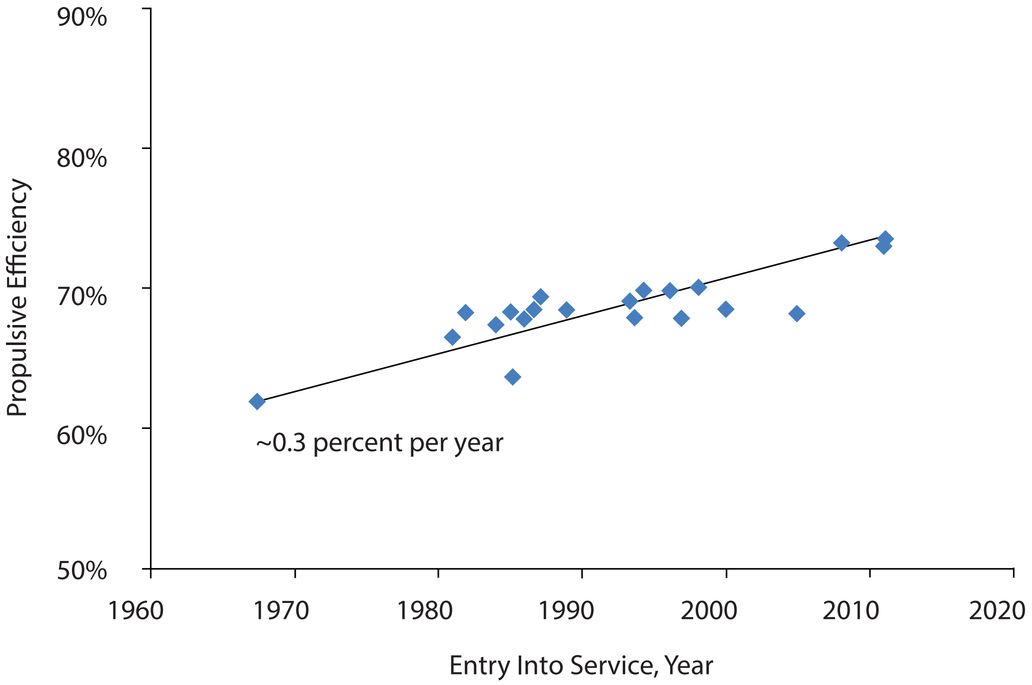

FIGURE 3.4 Trend with time of commercial aircraft turbofan propulsive efficiency at cruise. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

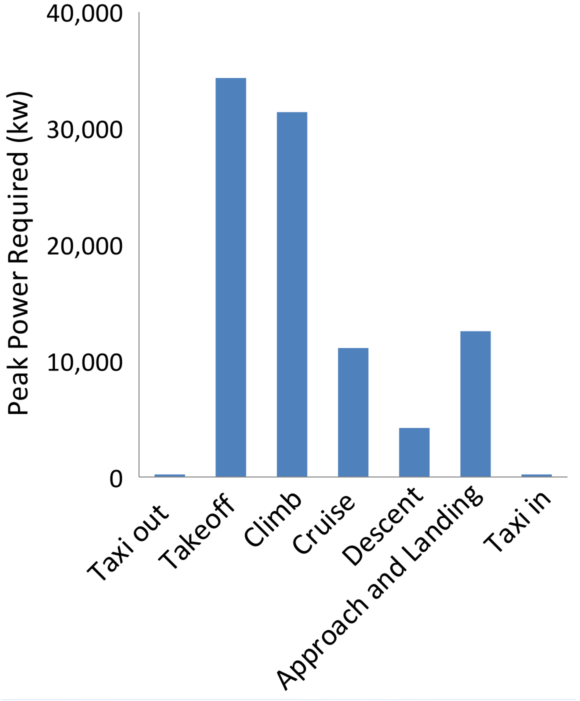

FIGURE 3.5 Single-aisle aircraft power by mission segment; dimensional and percent available powers are shown. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

single-aisle, 150-180 passenger aircraft fueled for a 1,000 nautical mile (nm) mission. This means that compared to requirements at cruise, extra propulsion weight need not be carried nor drag incurred for an airliner to be able to take off. Also, since most gas turbine engines are already optimized for minimum fuel burn during cruise, there is little to be gained by better matching of the engine to the airplane characteristics. In addition, because of the combined effects of ram air compression at cruise speed and low ambient temperature at cruise altitude, a gas turbine's motor efficiency is 6 to 8 percent greater at cruise than it is at takeoff.

Role of Engine Size

When considering the role of gas turbine size (thrust) on efficiency, one needs to distinguish between economic and physical factors. In general, current larger engines have better efficiency than smaller engines. Much of this difference is design intent. Large commercial engines are designed for long-range aircraft, for which fuel consumption is the overriding consideration. This is due to overall life-cycle cost considerations and reflects that the trade-off between engine weight and fuel consumption is more favorable the longer an aircraft's range. That is, higher efficiency is advantageous, even if it comes at the cost of some increased engine weight, because more efficient engines allow aircraft to carry less fuel, and the reduced fuel loading becomes more and more significant for long-haul routes. Engine overhaul is another major operating cost for airlines. The number of on-off flight cycles is a major determinant of how frequently engines must be overhauled. Smaller engines designed for shorter-range commercial aircraft will have, on average, many more daily flight cycles than larger engines designed for large transports that are more likely to be flying long-haul routes. Therefore, it is particularly important for smaller engines to be able to execute a large number of flight cycles between overhauls. So, for the same level of technology, larger engines tend to be optimized for higher efficiency, while smaller engines tend to be optimized for lighter weight and more flight cycles between overhauls. (The even smaller engines designed for business and general aviation aircraft are principally constrained by purchase price, which is a much more important consideration for these relatively lightly used aircraft than is fuel or overhaul cost.) In other words, for economic reasons, small engines are not designed to the same efficiency as large engines.

Figure 3.6, which complements the historical evolution shown in Figure 3.3, shows the variation of motor thermodynamic efficiency with engine size in terms of takeoff power for existing turboprop and commercial turbofan engines. High-power turbofans generally have higher efficiency than turbofans designed for lower power, and all turbofans have higher efficiency than lower-power turboprops. The N + 3 region on the figure refers to NASA terminology for engines that may enter service beyond 2035. As discussed above, the differences between turboprops and commercial turbofans reflect market-driven design intent, different design operating altitudes and airspeeds, and the date of design and therefore the technology level of the engines (in general new commercial turbofans have entered the market more frequently than have new turboprops).

The efficiency of small gas turbines can be improved to the extent that high-efficiency technologies used in large engines can be incorporated in small engines, although that could result in prices that are too high for current small engine markets. Investment in technology specifically aimed at small engines is needed for engine cores having a small physical size to reach efficiency levels comparable to (or better than) large core engines. Physical limitations to such improvements have not been well established and could be an area of fruitful research. Such research addressing the specific needs of small engines intended for commercial transports could enable some distributed propulsion concepts. Perhaps most importantly, since as airplane and engine efficiency improves, less power is needed for flight, the engine size and power required at constant airplane capability will decrease in the

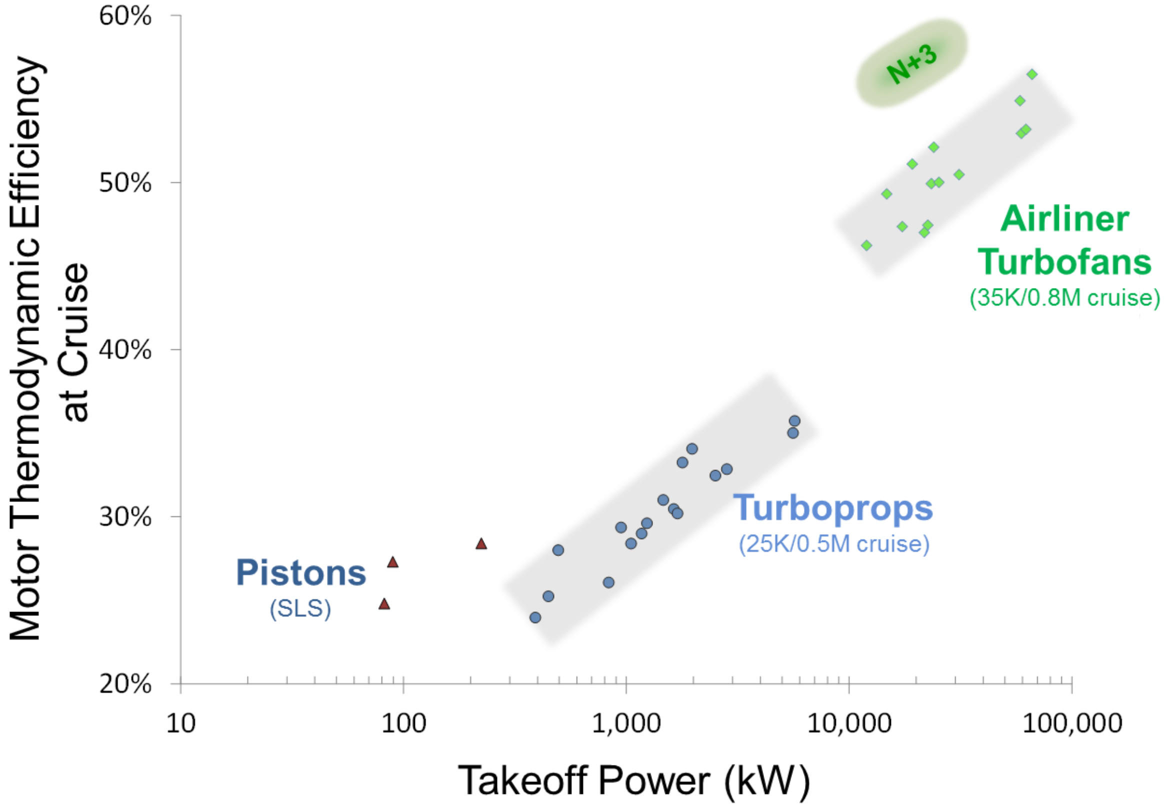

FIGURE 3.6 Variation of motor thermodynamic efficiency at cruise with engine size (in terms of sea level power) for existing aircraft turbine engines. NOTE: SLS, sea level static. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

future. Also, the overall pressure ratio[2] of gas turbines has increased over time to improve thermodynamic efficiency. At the same time, however, the size of the high-pressure compressor, the combustor, and the turbine have decreased, exacerbating the challenges of smaller size.

As airplane and engine efficiencies improve, less power is needed for flight, so that the engine size and power required at constant airplane capability will decrease in the future.

Potential for Improvement

Since the first aircraft gas turbines were built in the late 1940s, overall efficiency—fuel flow to propulsive power—has improved from about 10 percent to its current value, approaching 40 percent (see Figure 3.2). It is likely that the rate of improvement of these engines can continue at about 7 percent per decade for the next several decades given sufficient investment in technology. The potential for overall improvement is best considered in terms of the constituent efficiencies: thermodynamic efficiency of the motor and propulsive efficiency of the propulsor.

As noted above, it is not clear how close to the theoretical limits it may be possible to come with a gas turbine for commercial aircraft given aviation's important constraints of safety, weight, reliability, and cost. Several authors have considered the question of the practical limits for simple cycle gas turbines given the potential for new materials, engine architectures, and component technologies. Their estimates of the individual limits of thermodynamic and propulsive efficiency differ somewhat (and may divide losses differently between thermodynamic and propulsive efficiency), but they agree that an improvement of 30-35 percent in overall efficiency compared with the best engines today may be achievable. As shown in Figure 3.7, motor thermodynamic efficiencies of 65-70 percent and propulsive efficiencies of 90-95 percent may be possible.

Gas turbine engines have considerable room for improvement, with overall efficiencies improving by 30 percent or more compared to the best engines in service today. Improvements will come from many relatively small increments rather than a single breakthrough technology.

Some studies suggest that improvements in turbomachinery performance and reduction in cooling losses could improve thermodynamic efficiency by 19 percent and 6 percent, respectively.[3] This magnitude of gain is not achieved by simply inserting new technology in existing engines. Rather it requires optimization of the cycle given specific levels of component performance characteristics, temperature capability, and cooling. Practical intercooled or recuperated cycles could increase efficiency by another 4.[4] Improved fans and propellers could also increase propulsive efficiency by 10 percent.[5] Of course, the practical limits to propulsive efficiency cannot be addressed at the engine level alone without reference to airplane configuration and propulsion integration, as discussed in Chapter 2.

To summarize, aircraft gas turbine engines have considerable room for improvement, with a potential to improve overall efficiencies by 30 percent or more over the best engines in service today, with the potential for improvement of propulsive efficiency being about twice that of thermodynamic efficiency. This level of performance will require many technology improvements and come in the form of a number of relatively small increments, a few percent or less, rather than through a single breakthrough technology. The following section discusses many of these technologies.

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[2] The overall pressure ratio is the ratio of the compressor outlet pressure to the compressor inlet pressure.

[3] D.K. Hall, 2011, "Performance Limits of Axial Turbomachine Stages," M.S. thesis, Massachusetts Institute of Technology, Cambridge, Mass.

[4] J. Whurr, 2013, "Future Civil Aeroengine Architectures and Technologies," presented at the 10th European Turbomachinery Conference, http://www.etc10.eu/mat/Whurr.pdf.

[5] D. Carlson, 2009, "A Propulsion Renaissance: New Cycles, New Architectures and the Opportunity for Workforce Development," presented at the 19th International Society for Air Breathing Engines ISABE Conference, Montreal, Canada.

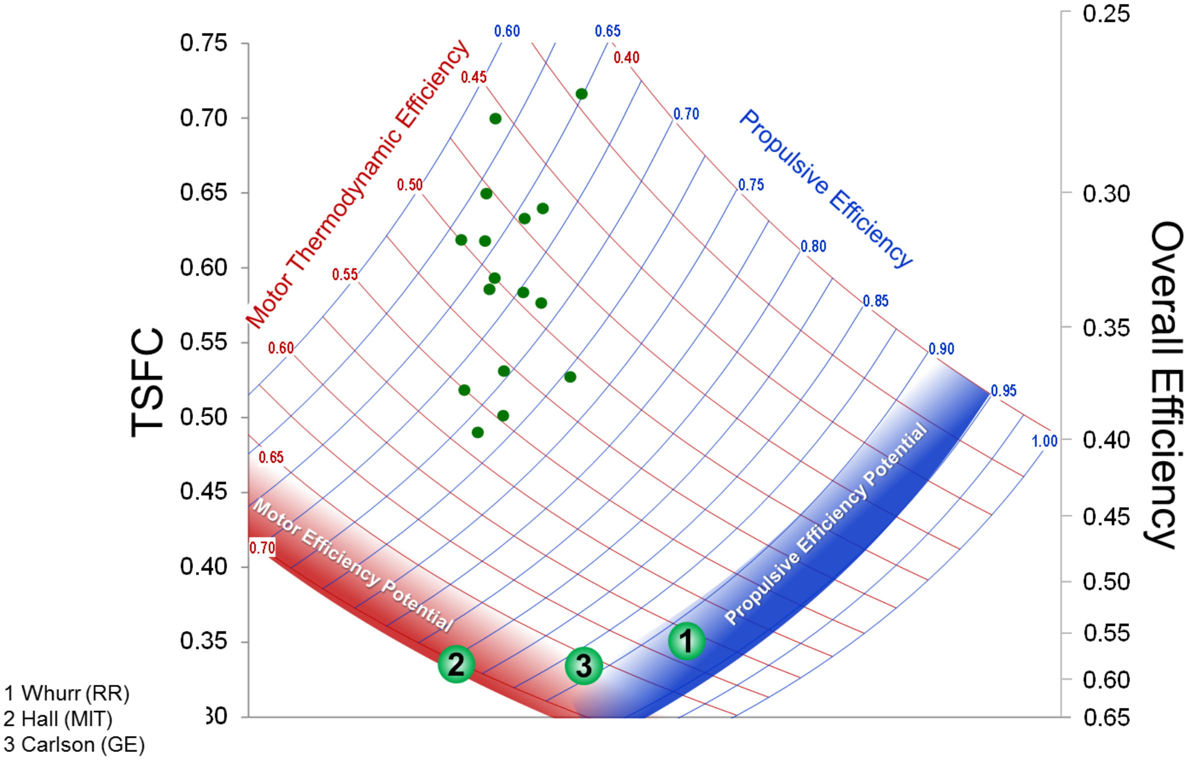

FIGURE 3.7 Motor thermodynamic and propulsive efficiencies at cruise of some in-service engines (dots) along with literature projections of practical limitations for a simple cycle gas turbine. Also shown are thrust specific fuel consumption (TSFC) and overall efficiency. Numbered symbols refer to specific references: (1) Whurr, 2013; (2) Hall, 2011; and (3) Carlson, 2009. SOURCE: A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed, *AIAA Journal* 52(5):901-911, doi:10.2514/1.J052713. Reproduced by permission of United Technologies Corporation, Pratt & Whitney.

OPPORTUNITIES FOR REDUCING CARBON DIOXIDE

Improving aircraft fuel efficiency can be considered in two parts. The first is increasing propulsive efficiency. Work in this area is important no matter the choice of motor to power the propulsor. The second part is improving the motor thermodynamic efficiency of an aircraft gas turbine engine. The following sections discuss areas of technology investments that could yield substantial gains in aircraft fuel burn. The general categories listed are not new; the same list would have been appropriate for the past several decades. What are new are many of the particulars of specific investment opportunities. Each advanced technology might offer only a percent or so in improvement, or even less. In aircraft engine development, progress has been made through the development of many relatively small technology steps that together amount to steady improvement.

The relative value of a new technology may very much depend on engine architecture. In other words, a new technology might be very valuable for a particular engine design approach but be much less so for others. Furthermore, newly designed engines are highly optimized at the system level to realize the benefits the incorporated technologies provide. Therefore, a new technology might offer less benefit when applied to an existing engine design than it would when applied to a new design.

Improving Propulsive Efficiency

Independent of the source of shaft power, aircraft are dependent on propulsors (that is, either fans or propellers) to convert the shaft power to thrust. With very few exceptions, large commercial aircraft use turbofan engines. Some regional commercial aircraft with a capacity of fewer than 80 passengers are powered by turboprop engines.

Propellers

Propellers can offer superior efficiency to fans at lower flight Mach numbers at the cost of noise. Such lower speeds are not economically significant at relatively short stage lengths such as 300 nm. Propellers optimized for higher Mach numbers than are currently being flown by propeller aircraft have been demonstrated in flight. At the current state of the art, high flight-speed, unducted propulsors, such as open rotors, face significant noise, mechanical complexity, and installation safety concerns that need to be overcome before they can be considered attractive alternatives to ducted fans, and the committee concluded that they should not be pursued as a high priority for the purpose of reducing CO_2 emissions from large commercial aircraft. Therefore, the discussion of propulsors in the rest of this chapter will focus on the performance of ducted fans used in the turbofan engines of large commercial aircraft.

Turbofan Propulsor

Here, "turbofan" refers to the entire internal flow path of the fan stream, comprising inlet, fan, fan duct, and fan exhaust nozzle, which together comprise the propulsor of a turbofan engine. Improving propulsive efficiency requires dropping the fan exhaust velocity by reducing the fan pressure ratio[6] as well as the pressure losses along the internal flow path. The fan rotor adds energy to the flow. Some of this energy is then lost to drag along the inlet and duct walls, the fan stators, and imperfect fan nozzle expansion. Thus technology will need to be developed to reduce pressure loss within the fan stream flow path taking into account overall system weight and noise. (Unlike early jet aircraft, for which exhaust jet noise dominated, the noise of most modern large commercial aircraft is dominated by fan noise. Fan duct walls include acoustic treatment, which attenuates this noise but adds weight and pressure loss.) Thus, significant payoffs can arise from advances in technologies such as high efficiency, low noise, low fan pressure ratio (1.35:1 and below), fan turbomachinery with improved acoustic, aeromechanical and stability behavior, fan duct acoustic liners with improved acoustic damping and pressure loss characteristics, as well as lighter blading and containment systems. Advancements in exhaust nozzles, fixed and variable, also fall under this topic. For boundary layer ingestion to become a viable aircraft design approach (see Chapter 2), propulsor-duct solutions must be found that are acoustically and aeromechanically acceptable and in which the losses due to distortion are small compared to the gains from wake cancellation.

Improving Thermodynamic Efficiency

There is a vast literature on aircraft gas turbine engines and the improvements needed to reduce fuel burn. The specifics of which approaches offer the most promise evolve as progress is made and new engine designs are developed. The thermodynamic constraints and current mechanical limitations on improving efficiency are very well understood. Simply put, increasing efficiency requires increasing compressor exit and turbine inlet temperatures while concomitantly reducing aerodynamic losses and structural weight.[7] Large aircraft gas turbines are now constrained as much by limitations on compressor temperatures as by turbine temperatures. Engineering approaches that permit higher temperatures while reducing or eliminating cooling air are especially valuable. Technologies

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[6] Fan pressure ratio is the ratio of the pressure at the fan exit to that at the fan inlet.

[7] Higher temperatures will be accompanied by higher pressures, but accommodating higher pressures is primarily an engineering design task. Developing the ability to accommodate higher temperatures is a much more difficult challenge that can only be overcome through a program of research and technology development.

that allow engines to retain "like new" efficiency would also reduce fuel burn. Now engines lose several percent in efficiency as they age between overhauls, and they do not recover their original performance after overhauls.

Improved overall aircraft efficiency will mean that reduced engine core size will challenge engine efficiency for single-aisle aircraft.

Improved aircraft efficiency means that engine cores will shrink since less power will be needed for the same mission. This implies that reduced engine core size will challenge engine efficiency for single-aisle aircraft.[8] One element of increasing engine thermal efficiency is increasing the overall pressure ratio, which increases the density of the air in the core. The combination of increased thermal efficiency and reduced airplane power requirements means that core size (usually measured in terms of compressor exit area) shrinks. For the same mission aircraft, it has shrunk by a factor of 10 since 1972 and will continue to do so in the future. Also, as discussed above, gas turbine engines for smaller aircraft are less efficient than engines for larger aircraft.

Materials and Manufacturing

The history of the aircraft gas turbine engines is the history of advanced material development specifically aimed at improving gas turbines; some highly successful examples include forged titanium alloys (now widely used in aircraft structure as well), several nickel superalloys, single-crystal turbine airfoils,[9] forged high-temperature powder metal alloys, coatings for environmental protection and for thermal barriers, and, most recently, titanium aluminides. There are few applications other than gas turbines that can justify the cost of developing these specialty materials, which tend to be expensive to use as well as develop and require decades to move from lab bench to commercial service. Nevertheless, advanced materials have been a particularly fruitful investment area because a successful material can often be used to improve existing engines as well as enable new concepts. There is no reason to believe that this cannot continue to be the case. The system-level benefits from new materials come from reduced weight, higher temperature capability, or reduced cooling, each of which increase efficiency. Even though an aircraft engine application may justify material costs of hundreds or even thousands of dollars per kilogram, cost-benefit is still a major consideration. For example, a large national investment in metal-matrix composites in the 1980s and 1990s resulted in both a technically viable manufacturing process and several successful demonstrations of metal matrix components in engines. Nevertheless, when projected to wide-scale adoption, the parts appeared to be too expensive to be viable.

Even at a conceptual level, it is often difficult to distinguish between materials development and the manufacturing technology required to fabricate parts from that material. This is especially true for many high-temperature materials (such as single-crystal turbine airfoils, powder metal disks, and high-temperature coatings) as well as some polymer composites. This is not the case for materials adopted from other applications such as steel, aluminum, and some nickel alloys, where the material manufacturing is distinct from the part fabrication. New manufacturing methods such as the additive manufacture of high-temperature materials like titanium and nickel superalloys can be considered either an innovation or a confluence of the additive manufacture of plastics (in use since the early 1990s) with the powder metal processing long used for disks. In either case, it represents an alternative path to the realization of complex parts and new materials. It offers intriguing possibilities to realize structures or properties that would otherwise be prohibitively expensive. This technology is in its infancy in terms of dimensional control, surface finish, and material properties, so significant progress should be possible. Manufacturing technology advances such as this may be a significant contributor to improving engine performance, weight, and perhaps cost.

While advanced materials can reduce fuel burn by reducing weight, they can be especially valuable when they improve temperature capability and reduce cooling requirements. This is true for compressor materials to

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[8] Current engines for twin-engine, twin-aisle aircraft have twice the core size of engines for single-aisle aircraft, so thrust requirements of twin-aisle aircraft would need to drop by more than a factor of two before core size would become an issue for them.

[9] "Airfoil" refers to the stationary vanes, or stators, in a turbine and the rotating blades.

enable higher compression ratios needed to improve engine thermal efficiency (a capability of 1300°F to 1500°F is desired in the near term) as well as for combustors and turbines to improve engine power-to-weight ratios (where long lives at material temperatures of 2200°F to 3000°F are needed). Materials can also improve part durability to retain rather than increase fuel burn as an engine ages.

The most fruitful areas of materials research at this time appear to be in advanced high-temperature metals, ceramics, and coatings:

- *High-temperature ceramics*. This is an area that may see considerable progress over the next decades. This includes ceramic matrix composites (CMCs) as well as monolithic ceramics. Some CMCs are already entering commercial service. Additional CMCs and monolithics may enter commercial service in the next few years, and, should they prove viable and cost effective at large scale, will see widespread use. The advantage of these materials is their high-temperature capability and low density. Challenges include low fracture toughness, low thermal conductivity, and manufacturing cost. The materials, which could enter service in the next few years, are capable of service at 2200°F -2400°F. Of particular research interest are less developed high-temperature materials, ones with capability up to about 2700°F, which would dramatically reduce or eliminate cooling in many parts of an engine and thus boost efficiency and lower weight.
- *High-temperature metallic alloys*. Advances in these alloys will arise from further development of nickel-based alloys as well as new materials classes such as niobium and molybdenum. Nickel-based materials can be improved by moving to disks constructed from dual or graded alloys or even single crystals. While denser than the ceramics, niobium and molybdenum have temperature capability approaching that of CMCs and much higher fracture toughness and thermal conductivity. This combination of properties makes them potentially attractive for static, internally cooled parts such as turbine vanes or combustors. Work is needed on fabrication technologies and coatings for environmental protection.
- *Coatings*. Coatings can add value to many engine parts. They are required at high temperature for environmental protection. For cooled parts, thermal barrier coating can significantly increase the temperature capability and reduce cooling requirements. Erosion coating can extend part life and retain performance. Ice-phobic coating can reduce the threats posed by ice formation. Further progress in coatings of all types can be expected given sufficient investment.

Turbomachinery

The state of the art in compressor and turbine turbomachinery efficiency is about 90 percent, while studies suggest that efficiencies of better than 95 percent may be possible.[10] Thus, there is considerable room for improvement. Applications of interest include aerodynamics, aeromechanics, and the mechanical arrangements of complete components, especially those that enable higher compressor discharge temperatures. Improved analysis tools and emerging manufacturing technologies may open new approaches or make old ideas feasible. Historically, turbomachinery efficiency improved as machine size increased, all else remaining equal. As engine and airplane efficiency improves, less thrust is needed for a given mission, so the size of engine turbomachinery shrinks. Also, as the overall pressure ratios (OPRs) of engines have been increased to improve thermodynamic efficiency, the flow areas and thus the dimensions of airfoils in the core, especially at the rear of the compressor and in the high-pressure turbine, have shrunk dramatically. Indeed, the newest engines entering service at the 30,000 lb thrust level have the same core diameter as older designs that are still in production and deliver only one-fifth the thrust. Current turbomachinery design trades between size and efficiency are based on empirical practice rather than first principles limitations.[11] This implies that research to realize higher efficiency at small sizes could reduce the fuel burn of advanced aircraft. Obvious areas of concern include sensitivity to geometry variations such as tip clear-

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[10] D.K. Hall, 2011, "Performance Limits of Axial Turbomachine Stages," M.S. thesis, Massachusetts Institute of Technology, Cambridge, Mass.

[11] A.H. Epstein, 2014, Aeropropulsion for commercial aircraft in the 21st century and research directions needed, *AIAA Journal* 52(5):901-911.

ance and airfoil shape, which become more challenging as size is reduced. Manufacturing technology investments could assist here.

Work on analytical tools can help progress in this area. Significant investments over 40 years have yielded complex computer simulations that analyze turbomachinery aerodynamics at the design point. These tools are inadequate at important operating conditions away from the design point, such as idle. Mechanical analysis tools suffer from inadequate models of nonlinear mechanical interactions such as friction, sliding interactions, and plastic deformation. Aeromechanics is another turbomachinery discipline in which physics-based simulations are not yet capable of adequately predicting engine behavior over the entire operating regime. Overall, the advancement in the accuracy and speed of simulation tools so that they can be better used to optimize the overall engine system in a timely manner during design may add several percentage points of improvement in fuel burn and certainly reduce development cost and time.

In conclusion, although there have been substantial investments in turbomachinery over many decades, efficiency, weight, and cost could still be improved significantly.

Cooling and Secondary Flow Reduction

A modern engine uses 20-30 percent of the compressor core flow for hot section cooling and purging. This is a direct debit to engine efficiency since the work that must be done to compress this air is only partially recovered as thrust. Turbine cooling is another area that has received considerable attention over decades. Improved methods have reduced the amount of cooling air required and enabled longer engine life even at higher temperatures. Manufacturing technologies to realize sophisticated cooling schemes have been one area of progress, but more can be done here, especially for nonmetallic materials. Another constraint on cooling is the clogging of small passages and holes over time by dirt ingested by the engine.[12] Currently, cooling hole sizes are dictated by clogging concerns rather than by cooling efficiency—that is, the holes are oversized to keep them from clogging. Thus, technologies that improve dirt separation and rejection could contribute to a reduction in fuel burn. These challenges are exacerbated as engine size is reduced.

Combustion Systems

Current combustion systems are better than 99 percent efficient in converting the chemical energy in fuel to heat.[13] The design challenges are mainly ones of retaining this level of performance and the reliability needed for commercial airline service while reducing regulated emissions. Both lean burn and rich burn approaches have proven competitive to date. Continued emissions work will be needed given the expected tightening of emissions requirements coupled with the increase in engine pressure ratio that will be needed to further reduce fuel burn. As engine overall pressure ratios are increased to improve thermodynamic efficiency and reduce CO_2, combustor design will be further challenged to meet both emissions and mechanical integrity goals. Areas that may be helpful include new design concepts and improved modeling tools, especially physics-based approaches capable of accurate prediction of regulated emissions. Alternative fuels to date are compatible with existing combustor technology. New approaches to combustor design may be able to significantly shorten combustor length, thus reducing engine weight and CO_2 emissions.

Controls, Accessories, and Mechanical Components

Overcoming the limitations and constraints of existing engine controls and accessories such as generators, pumps, and heat exchangers offers the potential to improve fuel consumption, reduce weight, and reduce cost. This

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[12] Fuel consumption degrades as an engine is operated because deposits (a.k.a. dirt) accumulate on airfoils and reduce their aerodynamic efficiency, as evidenced by the fact that semiannual engine washing can improve fuel burn by about 1 percent. Dirt can also cause erosion that increases tip clearance, which increases fuel burn, and dirt can clog cooling holes in the turbine. These effects are much worse in places with poor air quality.

[13] Arthur H. Lefebvre, 1998, *Gas Turbine Combustion*, second ed., CRC Press, Boca Raton, Fla.

is an area in which there has been little research over the past few decades. While many advanced engine control architectures have been proposed and analyzed, the lack of enabling hardware, including processors, sensors, and actuators with the needed temperature capabilities, has inhibited practical application. As aircraft subsystems become more electrical and as fan pressure ratios drop to improve propulsive efficiency, this challenge will be exacerbated. The inefficiency of current fuel pumps consumes much of the heat capacity of the fuel flow that would otherwise be available for the cooling needed by other aircraft heat sources. Therefore, improving fuel pump efficiency, especially at low fuel flows, would reduce the size and pressure drops associated with other engine and aircraft cooling requirements. Heat exchangers, which are addressed in more detail below, are far from their theoretical maximum performance.

Taken together, engine accessories occupy a significant portion of the propulsion system volume, especially on smaller engines; this problem becomes more challenging as fan pressure ratio is lowered to improve propulsive efficiency. Reducing the volume of these accessories could lead to lower fan pressure ratios by enabling better nacelle designs. Overall, improving the performance, efficiency, and size of external components such as pumps, heat exchangers, and controls would help to reduce CO_2 emissions.

Gas turbine mechanical components such as bearings and seals offer many opportunities for improvement. Bearings and their need for cooling and lubrication add considerable complexity to an engine. The bearings in a midsized gas turbine dissipate about 100 kW into the oil, heat that must be rejected to the fuel or the environment. The oil system of a modern gas turbine is exceedingly complex. One reason is that bearings are located where the ambient temperatures exceed the autoignition temperature of the oils. Thus the bearing compartments must be cooled with seals to inhibit oil leakage. Efforts to replace oil-lubricated, rolling-element bearings have not been successful to date, but the combination of smaller engine cores, advanced analytical techniques, and new materials may permit the use of either air bearings or magnetic bearings on smaller commercial aircraft. Air bearings have been used for decades on aircraft environmental control systems and some auxiliary power units, so safe, long-term service has already been demonstrated, albeit in less thermally demanding environments. Modeling and materials work could help here. Industrial magnetic bearings are used on some ground-based power turbines and on industrial pumps and compressors. In addition to elimination of oil and the oil system, they offer the potential advantage of active control of rotor dynamics, a serious issue for aircraft engines. Challenges in the past include the weight and volume of the power electronics needed, as well as high-temperature capabilities of the magnets themselves. There has been much progress here in the past two decades, especially in power electronics, so this may be another area that could contribute significantly to improving aircraft engines.[14]

Alternative Thermodynamic Cycles

Engines in commercial service today use simple Brayton cycles. There are many variations of the Brayton cycle that could theoretically offer improvement. Regenerative cycles capture heat from the exhaust and move it to the compressor to improve engine performance when operating off the design point. Intercooled cycles cool the air during compression to improve compressor efficiency while reducing compressor discharge temperature. Combined cycles capture some of the exhaust heat, which is then routed to a Rankine cycle to produce additional power for a given fuel burn. These cycles all require large (relative to the motor) heat exchangers, which add considerable weight, volume, cost, and maintenance burdens. While prevalent in ground power plants, to date they have not been used in aircraft engine applications because these cycles have not appeared attractive given the current state of the art of components. (Intercooled and combined cycle gas turbines are extensively used in ground-based power generation, where size, weight, and on-off cycling are lesser issues.) Significant improvements in heat exchanger technology would be required to make such approaches viable for low-carbon propulsion of commercial transport aircraft. These advanced engine cycle concepts are constrained by the capabilities of current heat exchanger technology.

Intermittent combustion approaches and those that use shock waves have been studied for many decades and in some cases have been brought to the point of laboratory demonstration. For example, the Humphrey cycle uses

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[14] Power electronics are discussed in detail in Chapter 4.

unsteady processes to realize a pressure gain in the combustor rather than the pressure drop of a Brayton cycle, but it does so at a loss in combustion efficiency. The Humphrey cycle poses several engineering challenges, including the mechanical integrity of the system with large pressure pulses. The potential value of various hybrid cycles to commercial aircraft propulsion for fuel burn reduction has yet to be clearly established. The committee determined that hybrid cycles should not currently be considered a high-priority research area for subsonic commercial aircraft compared to other investment opportunities.

Heat Exchangers

Heat exchangers are an important part of any propulsion system, air-breathing or electric. Their temperature capability, life, volume, and weight are limiting in many applications. Current turbofan engines use heat exchangers to cool engine oil, generator coolant, and bleed air to the aircraft. In the near future, some engines will soon use heat exchanges to produce cooling air for the turbines. As cores get smaller and electrical demands grow, more heat must be rejected to the fan stream. At the same time, as fan pressure ratios drop, this heat rejection becomes increasingly expensive in terms of fuel burn, weight, and volume. Some advanced cycle concepts are even more dependent on heat exchanger technology. Indeed, the viability of airborne intercooled and regenerative cycles is constrained by heat exchanger penalties. This may be an even larger constraint on electric and hybrid-electric approaches in which the heat is of low quality, exacerbating heat rejection penalties. Airborne heat exchangers have not seen much progress over many decades. Heat exchangers used on ground-based engines are often the largest and most expensive component and the one requiring the most maintenance. Airborne concepts are needed that reduce pressure drop, weight, and volume per unit heat transferred; work at high temperatures; and have longer life and lower cost. New manufacturing technology, such as additive manufacturing, may enable new concepts.

> Advanced engine cycle concepts are constrained by the capabilities of current heat exchanger technology.

RATIONALE FOR GAS TURBINE ENGINE RESEARCH

The overall efficiency of commercial aircraft engines has been improving at a rate of about 7 percent per decade since 1970 (see Figures 3.3 and 3.4). Today, the overall efficiency of commercial aircraft propulsion is approaching 40 percent. Aircraft engines are not mature: Given sufficient investment, there is a potential to continue this rate of improvement for the next several decades. Additional benefit may be realized by innovative propulsion–airframe integration technologies, discussed in Chapter 2.

> **Finding.** *Rationale for Gas Turbine Engine Research*. Gas turbine engines have considerable room for improvement, with a potential to reach overall efficiencies perhaps 30 percent better than the best engines in service today, with a concomitant reduction in CO_2 emissions. This magnitude of gain requires investment in a host of technologies to improve thermodynamic and propulsive efficiency of engines, with each discrete technology contributing only a few percent or less.

CHALLENGES

Aircraft gas turbine challenges were discussed above to elucidate some of the many opportunities available to improve engine performance. These opportunities are often presented in a traditional, disciplinary sense:

- Materials and manufacturing,
- Turbomachinery—aerodynamics and structural concepts,
- Heat exchangers,
- Low-emissions combustion systems operating at very high pressure ratios,
- Controls and accessories,

- Manufacturing, and
- Improved simulation capability.

To focus on improving efficiency and CO_2 as fast as possible at given levels of investment, it is useful to consider the challenges and research opportunities by topical area. Overcoming the challenges will require a mix of disciplines to become an engineering reality and will involve work on both scientific advances and design concepts. Balanced investments in simulation and experimental capabilities are needed. In each area, research is needed not only for the advancement of methods and materials, but also to provide explicit resources for the exploration of new concepts. As discussed above, many gas turbine propulsion technologies could be advanced to reduce aviation's CO_2 emissions. The areas whose promise for reducing CO_2 emissions over the next three decades justifies the most investment are summarized in the following challenges:

Technical Challenges

Propulsive Efficiency

Low fan pressure ratios are needed to reduce exhaust velocities and thereby improve propulsive efficiency, regardless of whether the fan is driven by a gas turbine or an electrical motor. For a constant level of thrust, this requires that the effective fan area increase so as to avoid commensurate increases in weight, drag, and integration losses.[15]

Thermodynamic Efficiency

Enabling higher operating temperatures is a prerequisite to achieving significant improvement in gas turbine engine thermodynamic efficiency, and a major impediment to achieving higher operating temperatures is the difficulty of developing advanced materials and coatings that can withstand higher engine operating temperatures.

Small Engine Cores

Activities being pursued to either improve the thermodynamic efficiency of gas turbine cores or improve overall aircraft efficiency result in smaller core sizes. For single-aisle aircraft, this tendency to core size reduction creates multiple challenges for maintaining and improving efficiencies of the overall engine and engine-aircraft integration.

Improvements in overall aircraft efficiency from better airframe and engines design will reduce the engine power needed and thus the physical size of the engine core for a given aircraft. This trend to smaller cores will be exacerbated by the need to increase engine overall pressure ratios to improve thermodynamic efficiency. Efficient small cores can also be an enabling factor for distributed propulsion architectures with gas turbine engines.

RECOMMENDED HIGH-PRIORITY RESEARCH PROJECTS

Low-Pressure-Ratio Fan Propulsors

Develop low-pressure-ratio fan propulsors to improve turbofan propulsive efficiency.

Key research topics for this project are turbomachinery design, duct losses, acoustics, aeromechanics, nacelle aerodynamics and weight, manufacturing, and aircraft integration. The degree to which propulsive efficiency can be improved will reflect design optimizations for all of these factors. A less certain investment would be in research

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[15] This challenge, which also appears as a challenge for aircraft–propulsion integration, is listed as a challenge for gas turbine research because it is a prerequisite for achieving significant improvement in gas turbine engine propulsive efficiency.

aimed at both loss and noise reduction for fans in the presence of the distorted inflow characteristic of BLI-wake cancellation schemes, which are attractive only if the losses and noise incurred by the distorted propulsor are relatively small. This research project is closely related to the aircraft–propulsion integration research project on nacelles for ultrahigh-bypass-ratio gas turbines, and work on these two projects should be closely coordinated.

Engine Materials and Coatings

Develop materials and coatings that will enable higher engine operating temperatures.

Key research topics for this project are advanced materials that could lead to the reduction or elimination of turbine film cooling as well as to compatible coatings for environmental protection, erosion prevention, ice rejection, and thermal barriers.

Small Engine Cores

Develop technologies to improve the efficiency of engines with small cores so as to reach efficiency levels comparable to or better than engines with large cores.

Key research topics for this project are turbomachinery aerodynamic performance, manufacturing, tip clearance control, secondary flow losses, thermal management, combustion, and the life span of turbine airfoils.

4

Electric Propulsion

INTRODUCTION

Electrical propulsion in commercial aircraft may be able to reduce carbon emissions, but only if new technologies attain the specific power,[1] weight, and reliability required for a successful commercial fleet. The committee considered six different electric propulsion architectures. As shown in Figure 4.1, one is all-electric, three are hybrid electric, and two are turboelectric:

- All electric
- Hybrid electric
  - Parallel hybrid
  - Series hybrid
  - Series/parallel partial hybrid
- Turboelectric
  - Full turboelectric
  - Partial turboelectric

These six architectures, which are shown in Figure 4.1, rely on different electric technologies (batteries, motors, generators, etc.) The levels of CO_2 reduction associated with the different architectures are a function of the configuration, component performances, and missions. The results of system studies on various architectures are summarized in the following section.

All-electric systems use batteries as the only source of propulsion power on the aircraft.

The hybrid systems use gas turbine engines for propulsion and to charge batteries; the batteries also provide energy for propulsion during one or more phases of flight. As shown in Figure 4.1, with a parallel hybrid system, a battery-powered motor and a turbine engine are both mounted on a shaft that drives a fan, so that either or both can provide propulsion at any given time. With a series hybrid system, only the electric motors are mechanically connected to the fans; the gas turbine is used to drive an electrical generator, the output of which drives the motors and/or charges the batteries. Series hybrid systems are compatible with distributed propulsion concepts, which

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[1] In this report, "specific power" and "specific energy" refer to power and energy per unit mass, respectively, and "power density" and "energy density" refer to power and energy per unit volume.

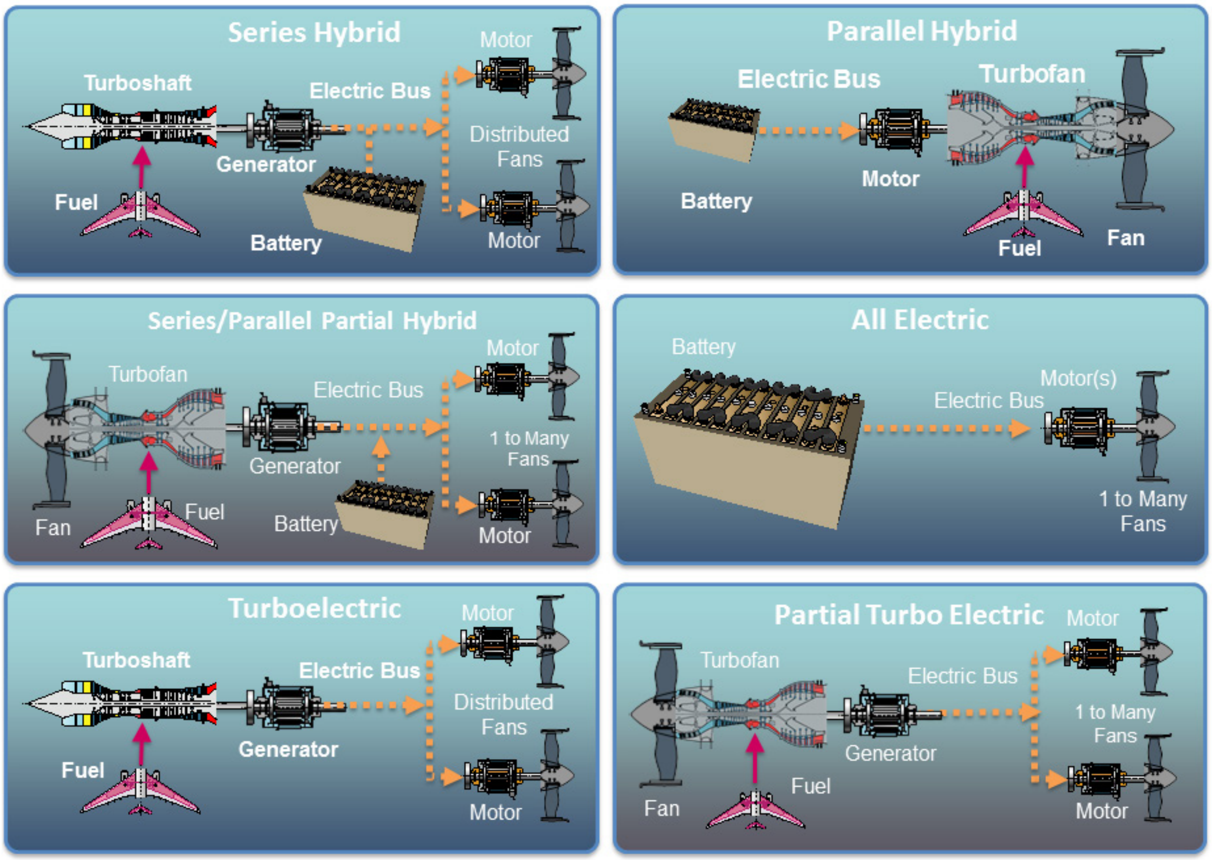

FIGURE 4.1 Electric propulsion architectures. SOURCE: Modified from James L. Felder, NASA Glenn Research Center, “NASA Hybrid Electric Propulsion Systems Structures,” presentation to the committee on September 1, 2015.

use multiple relatively small motors and fans. The series/parallel partial hybrid system has one or more fans that can be driven directly by a gas turbine as well as other fans that are driven exclusively by electrical motors; these motors can be powered by a battery or by a turbine-driven generator.

Full and partial turboelectric configurations do not rely on batteries for propulsion energy during any phase of flight. Rather, they use gas turbines to drive electric generators, which power inverters and eventually individual direct current (DC) motors that drive the individual distributed electric fans. A partial turboelectric system is a variant of the full turboelectric system that uses electric propulsion to provide part of the propulsive power; the rest is provided by a turbofan driven by a gas turbine. As a result, the electrical components for a partial turboelectric system can be developed with smaller advances beyond the state of the art than are required for a full turboelectric system. Because it is relatively easy to transmit power electrically to multiple widely spaced motors, turboelectric and other electric propulsion concepts are well-suited to distributed propulsion for higher bypass ratios, and they provide aircraft design options for maximizing the benefits of boundary layer ingestion (BLI) in the fans.

Turboelectric propulsion research is one of the four high-priority approaches identified in this report for developing advanced propulsion and energy system technologies that could be introduced into service during the next 10 to 30 years to reduce CO_2 emissions. As detailed in the section Technology Needs, below, hybrid-electric and all-electric systems are not recommended as a high-priority approach because the committee determined that batteries with the power capacity and specific power required for commercial aircraft at least as large as a regional jet are unlikely to be matured to the point that products satisfying FAA certification requirements can be developed within the 30-year time frame addressed by this report. The same situation applies to technologies associated with superconducting motors and generators, fuel cells, and cryogenic fuels. All-electric battery-powered airplane configurations will be limited to small aircraft (general aviation and commuter aircraft), which are not a significant source of CO_2 emissions compared to larger commercial aircraft. For large commercial aircraft it is likely that fuel cell applications will be limited to secondary systems such as auxiliary power units and starter systems. Considerable improvements in the specific power of batteries and fuel cells will have to be attained before these power sources would be considered for large aircraft. In addition, the net reduction in CO_2 emissions from using all-electric or fuel-cell systems is greatly minimized unless the electrical power used to (1) charge the batteries or (2) produce the hydrogen used to power the fuel cells is generated using renewable or low-carbon-emission technologies.

SYSTEM STUDIES CONDUCTED BY INDUSTRY, GOVERNMENT, AND ACADEMIA

The committee drew upon an extensive list of recent electric and hybrid electric aircraft system studies conducted by industry, government, and academia. The experts who conducted many of the studies briefed the committee, and several committee members directly participated in or monitored some of the studies.

The studies considered by the committee are listed and summarized in Table 4.1. These studies can be categorized in different ways. Most were aircraft conceptual studies where advanced electrical components were assumed to be available in the future, but they varied widely in assumed aircraft size, range, electrical architecture,

TABLE 4.1 System Studies of Aircraft with Electric Propulsion

Name and Organization	Aircraft	Time Frame	Electric Architecture	Components	Component Performance
Boeing SUGAR[a,b,c]	Single-aisle	N + 3	Parallel hybrid	Motor (1.3-5.3 MW) Batteries	3-5 kW/kg 750 Wh/kg
		N + 4	Parallel hybrid (fuel cells, superconducting, cryogenic fuels, BLI, open fan)	Motor Batteries	8-10 kW/kg 1,000 Wh/kg
Bauhaus[d,e]	Regional and single-aisle	N + 3 N + 4	Parallel hybrid All-electric	Batteries Batteries	1,000-1,500 Wh/kg 1,780-2,000 Wh/kg
NASA N3X[f]	Twin-aisle	N + 3 (N + 4)	Turboelectric (distributed propulsion, BLI, superconducting, cryogenic fuels)	Generator (30 MW), motor (4 MW)	>10 kW/kg @ 98% efficiency (and other combinations)
ESAero[f]	Single-aisle	N + 2 (N + 4)	Turboelectric (distributed propulsion, superconducting)	Generator Motor	8 kW/kg 4.5 kW/kg
NASA small aircraft[g]	General aviation	N + 1	Turboelectric (distributed propulsion with powered lift)	Generator (<1 MW), motor (<1 MW)	6.5 kW/kg
			All-electric	Batteries	>400 Wh/kg

TABLE 4.1 Continued

Name and Organization	Aircraft	Time Frame	Electric Architecture	Components	Component Performance
UTRC[h]	Single-aisle	N + 3	Parallel hybrid	Motor, batteries	Not specified
	Any airliner	N + 3	Auxiliary power unit (fuel cell, cryogenic fuel)	Generator	3-10 kW/kg
Airbus[i]	General aviation	N + 1	All-electric	Batteries	250-400 Wh/kg
			Hybrid	Motor, generator	Not specified
	Single-aisle	N + 3	Series hybrid (dist. prop., BLI)	Batteries	800 Wh/kg
Cambridge[j]	General aviation	N + 1	Parallel hybrid	Batteries	150-750 Wh/kg
	Single-aisle	N + 3	Parallel hybrid	Batteries	750 Wh/kg
NASA[f] STARC-ABL	Single-aisle	N + 3	Partial turboelectric (BLI)	Generator (1.45 MW), motor (2.6 MW)	13 kW/kg
Georgia Tech[k]	Single-aisle	N + 3	Parallel hybrid	Motor (1 MW)	3-5 kW/kg
				Batteries	750 Wh/kg

[a] M.K. Bradley, and C.K. Droney, 2011, *Subsonic Ultra Green Aircraft Research: Phase I Final Report*, s.l, NASA CR-2011-216847.

[b] M. Bradley and C.K. Droney, 2012, *SUGAR Phase II: N+4 Advanced Concept Development*, s.l, NASA. NASA/CR-2012-217556.

[c] M.K. Bradley and C.K. Droney, *Subsonic Ultra Green Aircraft Research: Phase II. Volume II: Hybrid Electric Design Exploration*, NASA/CR–2015-218704/Volume II, Boeing Research and Technology, Huntington Beach, Calif.

[d] C. Pornet, C. Gologan, P.C. Vratny, A. Seitz, O. Schmitz, A.T. Isikveren, and M. Hornung, 2015, Methodology for sizing and performance assessment of hybrid energy aircraft, *AIAA Journal of Aircraft* 52(1):341-352.

[e] H. Kuhn, Bauhaus Luftfahrt, Ottobrunn, Germany, Future Technologies and Ecology of Aviation, "Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions: Long-Term Perspectives," presentation to the committee on September 2, 2015.

[f] James L. Felder, NASA Glenn Research Center, "Systems Analysis and Integration, Advanced Air Transport Technology Project," presentation to the committee on December 7, 2015.

[g] Mark D. Moore, NASA Langley Research Center, "Distributed Electric Propulsion (DEP) Vehicles," presentation to the committee on September 1, 2015.

[h] Chuck Lents, United Technologies Research Center, "UTRC Presentation to the Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions," presentation to the committee on September 1, 2015.

[i] Peter Rostek, Project Leader Hybrid Electric Propulsion, Hybrid Electric Propulsion—A European Initiative for Technology Development," presentation at Electric and Hybrid Aerospace Technology Symposium (E&H ATS), Bremen, November 17, 2015.

[j] C. Friedrich and P.A. Robertson, 2015, Hybrid-electric propulsion for aircraft, *AIAA Journal of Aircraft* 52(1):176-189.

[k] Dimitri Mavris, Georgia Tech Aerospace Systems Design Laboratory, "Briefing to the NRC Low Carbon Aviation Committee," presentation to the committee, December 10, 2015.

electrical performance, time frame, whether cost and environmental impact were considered, and overall level of detail. Each of these studies contributes to the body of knowledge for electric aircraft and has been used by the committee to identify overall trends and establish electric component performance levels that could enable various types of electric aircraft.

The time frame of each study in Table 4.1 is described using NASA's N + 1 to N + 4 nomenclature to predict when a given concept will achieve a specified level of technology readiness (TRL 6[2]) and, subsequently, initial operational capability (IOC), which occurs when the first aircraft of a given type is placed in service. The specific time frames are defined as follows:

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[2] NASA uses technology readiness levels (TRLs) to track the maturity of a new technology under development. TRL 6 is achieved when a system or subsystem model or prototype has been verified in a relevant environment.

- N + 1 = TRL 6 achieved in 2010-2015 and IOC achieved in 2015-2025
- N + 2 = TRL 6 achieved in 2015-2020 and IOC achieved in 2025-2030
- N + 3 = TRL 6 achieved in 2025-2030 and IOC achieved in 2030-2040
- N + 4 = TRL 6 achieved in 2035-2040 and IOC achieved in 2040-2050

These studies often assume optimistic and aggressive technology development that is not currently supported by budgetary commitments. Slower development of key energy storage or electric system components can make the N + 3 time frames slide into N + 4 or beyond. For example, in Table 4.1, N3X technologies are reported as N + 3, but the committee believes it is more likely that these advanced cryogenic electric components belong in the N + 4 time frame. Similarly, one version of the ESAero Turboelectric concept relies on superconducting components and likewise belongs in the N + 4 time frame.

The design and usage optimization of electric propulsion architectures over a range of aircraft designs and series of missions is complex and has been only partially investigated by most of the listed studies. The investigation of highly integrated power systems is a continuation of the trend to more electric power systems, such as the one used in the Boeing 787. The possibilities for improved peak power management, running turbines and generators at optimum efficiency, energy storage, safety through redundancy, and possibly eliminating a separate auxiliary power unit (APU) or emergency ram-air driven turbine are just starting to be investigated.

The studies assumed different levels of electrical energy storage and component performance depending on their time frame of interest and on the assumed rate of technology development. The most important parameters for aircraft systems are specific energy (Wh/kg) for energy storage and specific power (kW/kg) for electrical components.

The studies generally assume that energy storage would be provided by advanced secondary (rechargeable) batteries. Calculations of specific energy take into account assumed depth of discharge, efficiency losses, and the weight of the installed system, including structure to support the cells, battery thermal management, and possibly safety containment measures. For any given battery type, it is likely that such considerations will result in a value for specific energy that is much lower than the specific energy for a battery of that type that has not been adapted for use in aviation. The system studies attempted to account for this, so most of the numbers in Table 4.1 are the effective installed performance levels. However, there are likely to be some inconsistencies between the various studies in the installation assumptions and calculation methods. Energy storage performance is discussed in more detail in the next section. Most studies did not look at energy cost, battery replacement cost, system operating cost, or life-cycle carbon emissions.

Electrical component specific power is not evaluated in a consistent fashion in all the studies in Table 4.1. Components of interest include motors, generators, inverters, controllers, conductors, switches, and thermal management. Most studies include the weight of generators, inverters, and their thermal management components in total power system weight, while separately aggregating motors, controllers, and their thermal management components. There may be different assumptions concerning redundancy and safety in each study. Therefore, deducing needed component specific power (for a motor alone for example) may be difficult. Component performance will be discussed in more detail in the next section.

By reviewing, comparing, and discussing the results from the studies, the committee was able to make a series of general observations and establish representative technology challenges and recommendations for component performance requirements to enable various types of electric and hybrid electric systems.

The potential reduction in CO_2 possible with all-electric, hybrid electric, and turboelectric aircraft is generally much less than some of the “headline” numbers claimed in the studies. Many studies compare their projected reductions to different baselines. Often the large numbers quoted (for example, 70 percent fuel burn reduction) include postulated performance improvements arising from improvements in other areas, including aerodynamics, structures, operations, and gas turbines. In addition, the improvements arising from electric propulsion are often in comparison to current aircraft, not to future conventional aircraft of the same time period that could also benefit from many of the improvements from these other areas.

Tables 4.2 and 4.3 were created to relate levels of electrical power component performance requirements to various propulsion architectures and aircraft types. The values in Tables 4.2 and 4.3 can be used to help establish

TABLE 4.2 Electrical System Component Performance Requirements for Parallel Hybrid, All-Electric, and Turboelectric Propulsion Systems

	Electric System[a]		Battery[b]
Aircraft Requirements	Power Capability (MW)	Specific Power (kW/kg)[c]	Specific Energy (Wh/kg)
General aviation and commuter			
Parallel hybrid	Motor <1	>3	>250
All-electric	Motor <1	>6.5	>400
Turboelectric	Motor and generator <1	>6.5	n/a
Regional and single-aisle			
Parallel hybrid	Motor 1-6	>3	>800
All-electric[b]	Motor 1-11	>6.5	>1,800
Turboelectric	Motor 1.5-3; generator 1-11	>6.5	n/a
Twin-aisle			
Parallel hybrid	Not studied		
All-electric	Not feasible		
Turboelectric	Motor 4; generator 30	>10	n/a
APU for large aircraft	Generator 0.5-1	>3	Not studied

[a] Includes power electronics.

[b] Total battery system and usable energy for discharge durations that are relevant to commercial aviation flight times, nominally 1-10 hours. Values shown are for rechargeable batteries; primary (nonrechargeable) batteries are not considered relevant to commercial aviation.

[c] Conversion factors: 1 kW/kg = 0.61 HP/lb; 1 kg/kW = 2.2 lb/kW = 1.64 lb/HP.

technology targets for technology development planning and to predict the sequential progress of aircraft development as technologies improve. Integrated aircraft propulsion and power systems are enabled relatively early compared to all-electric and turboelectric architectures, and turboelectric architectures are enabled before parallel hybrid and all-electric architectures. Specific technology projections and research targets are discussed in more detail in the next section.

Potential applications (and time frames) for all-electric and parallel-hybrid concepts are based largely on projected advances in energy storage technology. Jet fuel is an excellent way to store energy, with an equivalent specific energy of approximately 13,000 Wh/kg. As shown in Tables 4.2 and 4.3, a regional or single-aisle aircraft is conceivable with batteries having a specific energy of "only" 800 Wh/kg for a parallel hybrid system (or 1,800 Wh/kg for an all-electric system). Even so, these levels far exceed both the current state of the art (200-250 Wh/kg) and the committee's projection of how far the state of the art will advance during the next 20 years (400-600 Wh/kg). Of course, smaller general aviation aircraft designed for short-range missions can and have been designed with less-advanced batteries. However, the committee is unaware of any systems studies that show that any electric propulsion system that relies on less-advanced batteries to augment the propulsion system of large commercial aircraft will reduce CO_2 emissions more than would a partial turboelectric or conventional propulsion system.

Turboelectric concepts are not dependent on advances in energy storage technologies. However, to be successful they need to take advantage of synergistic benefits achieved through aircraft–propulsion integration, using BLI and distributed propulsion. Turboelectric architectures inherently have lower efficiency than conventional gas turbine propulsion owing to energy conversion and transmission losses, but they can be more readily adapted for boundary layer ingestion and distributed propulsion, which are discussed in detail in Chapter 2. A key benefit of distributed propulsion is the drop in motor size and power required as there are many more motors. This means that smaller (and easier to develop) 1 megawatt (MW) and 2 MW electric motors can be put into service earlier than if fewer larger motors were used. The potential applications (and time frame) for turboelectric concepts will be based largely on projected advances in the specific power of components.

A partial turboelectric architecture (or some other variant of a turboelectric system) is likely to provide the first opportunity for an electric propulsion system to be incorporated in a regional or single-aisle aircraft configuration and is the first application likely to begin having a significant impact on reducing aviation carbon. Areas

TABLE 4.3 Electrical System Components: (A) Current State of the Art of Electric Components for Aircraft Applications, (B) Stated Research Goals for Some Current Research Programs, and (C) the Committee's 20-Year Projection of the Performance of Electric Components Configured for Aircraft Applications

	Motor and Generator		Power Electronics		Battery[a]
	Power Capability (MW)	Specific Power (kW/kg)[b]	Power Capability (MW)	Specific Power (kW/kg)	Specific Energy (Wh/kg)
A. Current state of the art					
Noncryogenic[c]	0.25	2.2	0.25	2.2	200-250
Cryogenic power[d]	1.5	0.2			
B. Research goals[e]					
NASA 10-year goals[f]	1-3	13	1-3	15	
NASA 15-year goals	5-10	16	5-10	19	
U.S. Air Force 20-year goals[g]	1	5	1	5	400-600
Ohio State Univ. 3-year goals	0.3	15			
Ohio State Univ. 5-year goals	2	15	2	23	
Airbus 15-year goal		10-15			
McLaren automotive projection[h]			0.25	50	
C. Committee's projection of the state of the art in 20 years (noncryogenic)[i]	~1-3	~9	~1-3	~9	~400-600

[a] Total battery system and usable energy for discharge durations that are relevant to commercial aviation flight times, nominally 1-10 hours. Values shown are for rechargeable batteries; primary (nonrechargeable) batteries are not considered relevant to commercial aviation.

[b] Conversion factors: 1 kW/kg = 0.61 HP/lb; 1 kg/kW = 2.2 lb/kW = 1.64 lb/HP.

[c] Values shown are for systems currently operational in aircraft.

[d] Specific power only considers the mass of the motor or generator, not the mass of additional systems required to maintain cryogenic operation. State of the art is for a DC superconductor. Ultimately, a 1.0-1.5 kHz superconductor will be needed.

[e] Values shown do not necessarily include packaging needed for use on aircraft. For the same level of technology, values of specific power and specific energy that include the weight of required packaging will be lower than those that do not.

[f] NASA generally matures technology no further than technology readiness level (TRL) 6, meaning that a system or subsystem model or prototype has been verified in a relevant environment. Efforts to achieve the10-year goal are currently targeting TRL 4, meaning that a component and/or breadboard has been validated in a laboratory environment, and the goals for specific power and energy do not include packaging.

[g] Goals for specific power and energy include packaging needed for use on an aircraft.

[h] McLaren is a race car producer in the United Kingdom, and these goals are for automotive applications.

[i] This projection assumes TRL 6 is achieved in 20 years, with advanced systems entering service in 30 years.

for further investigation include determining the sensitivity of partial turboelectric system designs to the specific power of motors and components and trade studies between different conceptual designs. More structurally and aerodynamically efficient configurations, such as those with advanced materials, more laminar flow, higher aspect ratio wings (e.g., truss-braced wing), or hybrid wing–body configurations could reduce energy requirements, thereby making electric propulsion architectures more practical and practical sooner.

TECHNOLOGY NEEDS: STATUS AND PROJECTIONS

Electric Machines and Power Conditioning

Introduction

Turboelectric propulsion concepts are heavily dependent on advances in aircraft electrical power system technologies. These technologies include generator systems for electrical power generation; power electronics for power conversion, conditioning, and distribution; high power aircraft distribution that includes circuit protection;

motors; and energy storage. A key issue is how to address higher distribution voltages designed for operation at altitude. It is also important to address total aircraft design impacts when assessing different turboelectric propulsion concepts. Limiting analysis to the propulsion system is not a valid approach to comparing different turboelectric propulsion concepts. It is imperative to include subsystems such as thermal management and other aircraft housekeeping electrical power requirements. The Boeing 787 provides the most relevant baseline for a total power system rating of 1 MW with understood size and weight metrics. The Boeing 787 also provides an appreciation of housekeeping (nonpropulsive) power requirements that, when applied to a single-aisle aircraft, will add 500 kW-1 MW of electrical power demand that the turboelectric propulsion system must satisfy.[3]

Turboelectric propulsion concepts for aircraft are described in the introduction to this chapter. This section includes a discussion of aircraft electrical power technologies and challenges that are critical to enabling turboelectric propulsion concepts. The state of the art and 20-year projections for these electrical power system technologies are summarized in Table 4.3. As indicated there, the goals of many organizations exceed the committee's projections of how far the state of the art is likely to advance in the next 20 years.

Requirements for electrical system components are beyond the current state of the art, especially for the large aircraft that account for more than 90 percent of global CO_2 commercial aircraft emissions. The committee predicts that the state of the art in 20 years will allow requirements for specific power of motors and generators to be met for the lowest end of regional and single-aisle aircraft.

Electric Machines for Aircraft Motors and Generators (Noncryogenic)

Figure 4.2 illustrates the progression of the state of the art for aircraft generators in service and under development with ratings from tens of kW up to MW-class, including wound-field synchronous, permanent magnet, and wire-wound superconducting synchronous machines. Note that power densities for aircraft applications lag the densities of other industrial applications such as automotive and ships, mainly because the stringent operating environment and safety certification requirements unique to aircraft add size and weight to electrical power system components. As indicated, some of the generators depicted were built and tested, but others were not. The generators shown span the range from the current state of the art (2.2 kW/kg) to a future vision with a specific power increased by a factor of ten (22 kW/kg). Many figures of merit are relevant to the selection of aircraft generators. These include dynamic and transient electrical performance, size, weight, efficiency, and reliability. These figures of merit lead to design considerations such as high and variable speeds that result in smaller and lighter machines compatible with variable speed turbine engines. Machine thermal management is also a consideration and must be compatible with aircraft thermal management systems (i.e., excessive demand for cooling fluid/oil to minimize machine size at the expense of an excessive thermal system size will not work).

Hybrid-electric propulsion concepts use generators to make electrical power. These machines deliver torque to perform electric engine start and then become primary sources of electrical secondary (non-propulsive) power once engines are burning fuel. Starter/generator systems will be larger than motor systems due to larger power electronics requirements to provide torque and generate electrical power. Each Boeing 787 has a total of four state-of-the-art generators on the main engines, providing a total of 1 MW of electrical power. The specific power of the generators alone is roughly 2.2 kW/kg. Including associated electronics roughly doubles the weight for a system specific power of 1.1 kW/kg.

Rather than use just one large generator, aircraft use multiple, smaller generators to increase power system reliability for flight-critical systems. For example, the Boeing 787 uses four 250 kW generators, and the F-35 uses two 80 kW generators.

As shown in Table 4.3, the committee projects that the specific power of motors and generators could increase to approximately 9 kW/kg in 20 years, with power levels of approximately 1-3 MW. This could be achieved by increasing machine speed (overcoming today's limits imposed by mechanical stress), increasing power conversion efficiency (limited by the performance of silicon-based power electronics), and increasing power generation and

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[3] For more information, see the discussion of power offtake in Chapter 2.

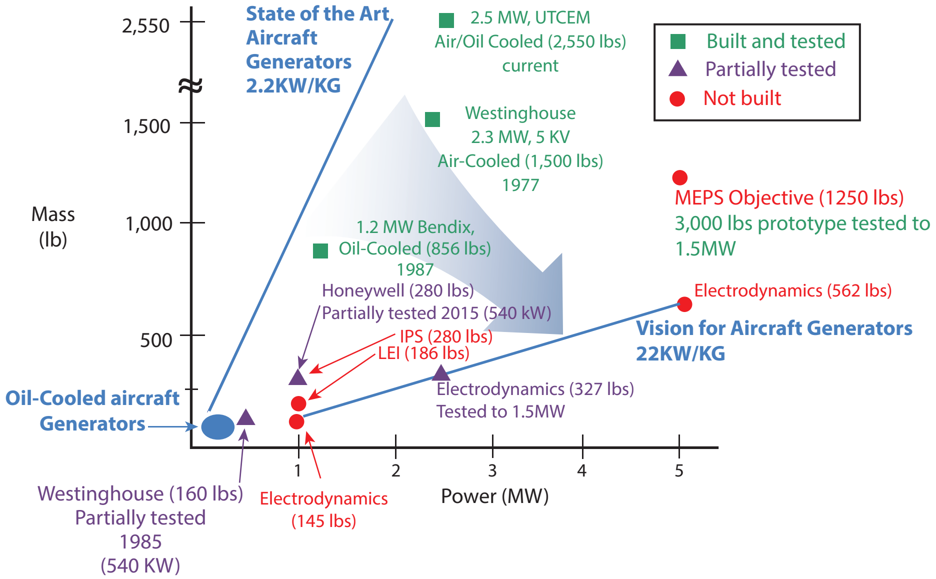

FIGURE 4.2 Aircraft megawatt generator research and development history and vision. SOURCE: William Borger, W.U. Borger Consulting, “HE/E Technologies for Low Carbon Propulsion,” presentation to the committee on September 1, 2015. Courtesy of Air Force Research Laboratory, Electrodynamics, Honeywell, et al.

distribution voltage (limited by breakdown voltage at altitude). Figure 4.2 depicts many attempts to build MW-class aircraft generators, and the ability to break through this barrier is critical to enabling turboelectric propulsion.

To properly characterize the performance of advanced generators, they must be tested as part of a system that is representative of how they will be used on aircraft. Testing infrastructure available today is limited in its capability to conduct MW-class research and development testing for aircraft applications at both the component and system level.

Power Electronics

Power electronics already play a key role for aircraft electrical power systems and that role becomes more critical as those power systems become part of MW-class flight critical turboelectric propulsion systems. Power electronics are used for power conversion (including motor drives) and power distribution (circuit protection). Silicon carbide (SiC) power electronics are enabling for MW-class aircraft power due to their improved efficiency and high voltage performance characteristics compared to today’s silicon-based power electronics. SiC is also a more reliable technology than silicon in commercial aircraft environments. Specific power for silicon-based power electronics systems today is approximately 2.2 kW/kg for aircraft applications, and their use for circuit protection is limited to 25 A at 270 V DC (7kW). Higher powered circuit protection is provided by mechanical breakers and relays up to about 500 A at 270 V DC (135kW) using state-of-the-art equipment. It is envisioned that in 20 years SiC-based power electronics systems for aircraft applications will have a specific power of 9 kW/kg for power conversion and circuit protection using electronic components up to 200 A at ±270 V (essentially 540 V, for a power capacity of 108 kW) or using mechanical breakers up to 1,000 A at ±270 V (540 kW).[4] High specific powers will be facilitated by advances in components that make power electronics heavy: switching components,

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[4] To provide circuit protection, circuit breakers that are rated for a system with these nominal operating parameters will actually need to be able to withstand much higher values of current and voltage to accommodate transients.

materials, switching topologies, passive filter components such as transformers, packaging, and thermal management components.

High Power Distribution

A power distribution system voltage of ±270 V (or 540 V) seems to be the limit for the foreseeable future due to physics-based limits referred to as Paschen curve limits. This voltage is used on the Boeing 787 today, and the U.S. Air Force is investigating the use of ±270 V for future high power aircraft. Many high power turboelectric system concepts include kilovolt-class power distribution systems. Such high voltages would require new types of insulation systems and electrical conductor spacing rules and practices.

Circuit protection and high-power distribution cabling for MW-class aircraft power systems also need to be developed. Every electrical circuit on an airplane must have circuit protection. MW-class circuit breakers may exist for power plants in ground and marine applications, but it should not be assumed that the technology incorporated in these breakers is applicable to aviation unless and until it has been verified that aircraft requirements related to weight, volume, voltage, etc. can be resolved. The committee is not aware of any ongoing circuit protection development for MW-class aircraft power systems. The preceding section, Power Electronics, describes current and future projected capabilities of circuit protection components.

Cryogenic/superconducting power distribution is discussed in a later section, Cryogenic Electric Aircraft Power Systems. Efforts have been made to develop other types of conductors for power transmission (e.g., polymers and nanotubes/graphene), but without any notable successes relevant to aircraft applications in the near- to mid-term.

Power System Efficiency

Electrical power system efficiency claims for many hybrid-electric propulsion concepts are more than 95 percent, but they are for machines only and do not include any type of power conversion. In addition, electrical power efficiencies are generally given for full load conditions. Efficiencies drop off when not at full load due to inherent losses in the system that exist independent of load. Figure 4.3 depicts an example of power system efficiency. Assuming 95 or 99 percent conversion efficiency at each step, as shown, the electrical power drive system (i.e., the components between the gas turbine engine and the propulsor) will have a combined efficiency of about 80 percent ($0.95 \times 0.95 \times 0.99 \times 0.95 \times 0.95 = 0.8$). When this efficiency is combined with turbine engine and propulsor efficiencies, as illustrated in Figure 4.3, total fuel to propulsor efficiency is 35 percent ($0.55 \times 0.8 \times 0.8 = 0.35$).[5] If benefits assessments of turboelectric systems account for actual electrical system efficiency along with the size and weight of the electrical power system components, then they can be compared with similar analyses of conventional and other propulsion concepts. Some literature has suggested eliminating conversion and control electronics to have the generators directly drive the propulsor motors, but this concept has not yet been demonstrated for applicability to turboelectric propulsion. If successful, this approach would eliminate two power conversion stages in Figure 4.3 (the converter controller and the motor drive).

Thermal Management

The ability of aircraft to manage heat will be a limiting factor for the high-power electrical power systems needed for turboelectric propulsion. The thermal management system itself will require electrical power to operate, and that power demand will need to be accounted for along with the demands of other nonpropulsive (secondary)

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[5] The estimated component efficiencies are intended to be illustrative. Even if ongoing efforts to improve these efficiencies are successful (for example, by improving the efficiency of motor/generators and propulsor motors from 95 percent to 98 percent, total system efficiency would increase from 35 percent to 38 percent. In addition, the estimated efficiency shown here does not account for energy required to operate thermal management systems to remove waste heat resulting from system inefficiencies.

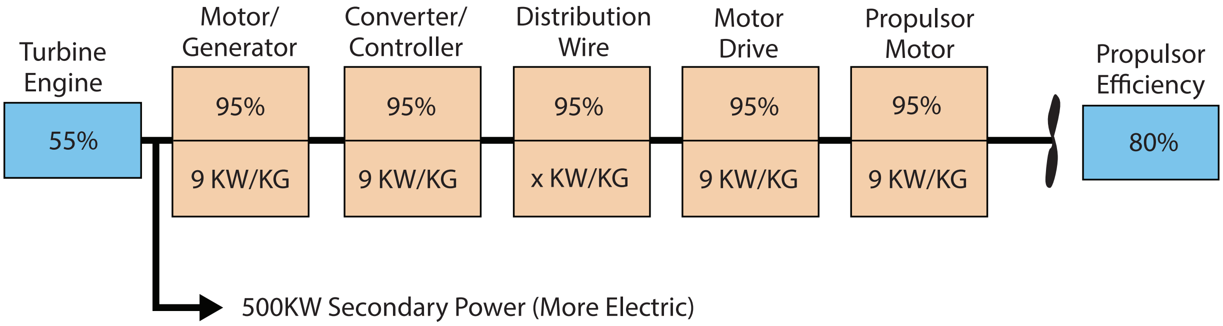

FIGURE 4.3 Turboelectric propulsion system: component efficiency and specific power.

power systems. Approaches for thermal management of MW-class turboelectric aircraft propulsion systems have not been addressed in detail in system trade studies to date.

Batteries

Batteries have been proposed for powering electric aircraft, either as stand-alone systems or hybridized with other power generation systems. Batteries offer modular building blocks for a wide variety of operational concepts in centralized or distributed power systems. They can respond very quickly to changing power demands and could be used to meet peaking or load-leveling requirements. Batteries provide electrical power with no direct carbon emissions, but the indirect emissions from the power source used to charge the batteries must be taken in account. Electricity generated using fossil fuels has substantial CO_2 emissions, but these emissions can be mitigated more effectively on the ground than at altitude. The power industry has access to increasingly efficient and effective means of limiting the release of ground-based CO_2 emissions, and if the electricity source is powered by solar, wind, or nuclear power, the indirect emissions are nearly carbon-free.

Many organizations have developed and demonstrated short-range, one- or two-passenger, battery-powered electric aircraft using commercially available batteries. A smaller number of similarly sized hybrid-electric aircraft have also flown. A battery system with specific energy greater than 800 Wh/kg is required to enable parallel hybrid propulsion systems on regional and single-aisle aircraft (see Table 4.2). All-electric regional and single-aisle aircraft would be suitable only for short-range operations, and even then they would require a battery system specific energy of 1,800 Wh/kg. This far exceeds the committee's 20-year projection for battery specific energy (400-600 Wh/kg).

Lithium-ion batteries currently dominate the market in both consumer electronics and electric vehicles. Batteries can be scaled to meet power and energy requirements for aviation, as lithium-ion battery systems with power capability greater than 10 MW and energy storage capacity greater than 10 MWh have already been demonstrated in stationary energy storage for electric utility applications. The key challenge to battery-powered propulsion systems for aviation is to increase battery specific energy. Current lithium-ion battery cells typically achieve 150-250 Wh/kg, while commercial lithium-sulfur cells currently achieve over 350 Wh/kg.

Advances in cathode materials, anode materials, and electrolytes have the potential to perhaps double the specific energy of lithium-ion batteries. Even higher specific energies may be possible in the longer term through the use of advanced battery concepts, such as lithium-sulfur, aluminum-air, and lithium-air.

The theoretical specific energies, based on the active materials, for lithium-sulfur (2,680 Wh/kg), aluminum-air (8,140 Wh/kg), and lithium-air batteries (11,000 Wh/kg in the charged state; 3,500 Wh/kg in the discharged state) are quite impressive. Practical specific energies are significantly lower, however, due to the added weight of current collectors, electrolytes, separators, battery cases, and terminals. Thus, while batteries with specific energies of 1,500 Wh/kg may be achievable, such high specific energies will require major breakthroughs.[6] Furthermore,

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[6] P.G. Bruce, S.A. Freunberger, L.J. Hardwick, and J. Tarascon, 2012, Li-O_2 and Li-S batteries with high energy storage, *Nature Materials* 11(1):19–29, doi:10.1038/nmat3191.

the requirement to simultaneously achieve long cycle life, low cost, and acceptable safety greatly increases the complexity of the overall challenge.

Major technological innovation in "beyond lithium-ion" battery systems will be required to achieve the range of acceptable specific energies needed for commercial introduction of battery-powered electric and hybrid aircraft propulsion systems before these systems can make a significant contribution to reducing carbon emissions in commercial aviation.

The environmental benefits of all-electric aircraft will be offset by CO_2 emissions from the source of electricity used to charge their batteries. In addition, the economic viability of all-electric aircraft will depend, in part, on the cost of new infrastructure, including infrastructure on site at airports to charge aircraft propulsion batteries. In addition, a fleet of large commercial all-electric aircraft would only be possible with new or upgraded power transmission lines to airports and, potentially, new generating capacity.

Fuel Cells

Fuel cells convert the chemical energy in a fuel into electrical power without any combustion. The exhaust from fuel cells is totally carbon-free if hydrogen is used as the fuel. However, if a hydrocarbon fuel is used, the exhaust still contains CO_2 in direct proportion to the amount of fuel consumed, but there are no NO_x or particulate emissions.

Two types of fuel cells that have been developed for automobile transportation and stationary power generation applications can be considered for aviation. The proton exchange membrane (PEM) fuel cells operate at 80°C to 120°C and require pure hydrogen as the fuel; if a hydrocarbon fuel is used for them, it will have to be first reformed to produce pure hydrogen without any CO, which easily poisons PEM fuel cells. Solid oxide fuel cells (SOFCs) operate at 750°C to 1000°C and can use a variety of hydrocarbon fuels, including jet fuels.

Fuel cells have been investigated for a variety of aviation applications, including these:

- Auxiliary power units (APUs),
- Low-altitude aircraft propulsive power,
- High-altitude long-endurance aircraft,
- Airport applications,
- Ground support equipment,
- Mobile lighting,
- Mobile generators, and
- Unmanned air vehicles.

Sandia National Laboratories analyzed the use of PEM fuel cells in a commercial aircraft (Boeing 787 Dreamliner) to assess the feasibility of having a fuel cell system on the airplane and the impact on other airplane systems and flight performance. They concluded that a fuel cell system onboard a commercial airplane is technically feasible, that it would perform well electrically, that it would be a flexible power source, and that recovery of heat and/or water would allow the fuel cell system to pay for itself and reduce the consumption of jet fuel.

Pacific Northwest National Laboratory evaluated the use of SOFC APUs in a more electric aircraft; again, the Boeing 787 Dreamliner was chosen for the study. The researchers concluded that the weight of the existing SOFCs would have to be reduced by a factor of 2 or 3 in order to compete on the basis of total fuel consumption during flight, and significant increases in specific power would be required to achieve fuel savings during flight.

A collaboration between Protonex and the Naval Research Laboratory (the Ion Tiger Fuel Cell UAV Demonstration), showed the use of PEM fuel cells in an unmanned air vehicle (UAV) for 26 hr of flight on gaseous hydrogen fuel and 48 hr on liquid hydrogen fuel. The Air Force Research Laboratory demonstrated the use of a SOFC power system utilizing JP-8 logistic fuel in Air Force UAV applications; it concluded that the key challenges are to achieve power system efficiency greater than 30 percent while operating on logistic fuels for extended mission durations (more than 50 hrs) and to integrate the fuel cell system into a package with high specific power (more than 150 W/kg). The U.S. Air Force is developing SOFCs with high specific power (more than 500 W/

kg); current SOFC power systems have a specific power of less than 100 W/kg compared to about 1,000 W/kg for internal combustion engines.

Boeing, with General Electric, has investigated concepts including fuel cell/turbine and fuel cell/battery hybrids (SUGAR N + 4 concepts) to reduce airliner fuel consumption and emissions. Boeing conducted fuel cell demonstrator airplane flight tests in 2007 and 2008, and in 2012 it conducted 737 ecoDemonstrator flight tests with a high-temperature PEM fuel cell with Japan's Ishikawajima-Harima Heavy Industries. Other organizations (Bauhaus Luftfahrt and DLR, both of Germany) are also exploring similar fuel cell hybrid systems for aviation.

The success of the above efforts notwithstanding, daunting challenges will need to be overcome to use fuel cells as part of an electric propulsion system.

PEM fuel cells are presently being designed and built for automotive and APU applications, generally in 1 to 100 kW sizes; the feasibility of commercial scale-up to the sizes necessary for MW-class commercial aircraft needs to be established. Hydrogen (fuel) storage, either as compressed hydrogen gas or as liquid hydrogen, operation at high altitudes, and transient operating conditions are key challenges and concerns.

Hydrogen storage for hydrogen-fueled fuel cells is a problem in terms of size, weight, thermal management, and airport infrastructure. The weight of the storage systems affects both the specific power and the energy of a fuel cell system, and the size affects both power and energy density. Regenerative fuel cells that make, store, and then consume hydrogen could conceptually be used as an energy storage system for hybrid electric propulsion systems. Regenerative fuel cells, however, are more complex than other fuel cells, and they have low round-trip energy efficiency.

SOFCs are being developed for both large-scale stationary power applications (more than 100 kW) and small-scale (1 to 10 kW) APUs and residential applications. SOFCs work better under consistent, steady power conditions; for aviation applications, transient response times, and on/off thermal cycles need to be improved. A key challenge is to increase specific power from less than 100 W/kg presently to over 500 W/kg for potential aviation applications.

There are no currently certified fuel cell systems on a commercial aircraft. The current technology readiness level for PEM fuel cells and SOFCs is TRL 4/TRL 5.[7]

Because of the challenges and concerns outlined here, while fuel cells may contribute as a power source for auxiliary power units, the committee does not foresee their contribution as an aircraft propulsion source in the timeline of this study. To be considered as a propulsion source, vast improvements in specific power would have to be achieved.

Cryogenic Electric Aircraft Power Systems

The development of cryogenic electrical power generation has been pursued for aircraft applications for several decades, and much progress has been made. Even so, there is still work to be done, and it is difficult to assess realizable specific powers of cryogenic generator systems for aircraft applications. Cryogenic machines have been built and tested, but without the power conditioning required for an aircraft generator system; the cryogenic machines as tested are not able to handle any type of transient load. Machine testing typically evaluates only open and short circuit performance to evaluate machine electromagnetics, and this type of testing is not sufficient to demonstrate the suitability of cryogenic generators for high-power aircraft applications.

One of the persistent long-term challenges for cryogenic electric aircraft power systems is the lack of superconducting material suitable for alternating current (AC) applications; AC-tolerant superconductors have the potential to reduce the mass and weight of wires by orders of magnitude compared to copper. However, even direct current (%) distribution systems experience transients that will present problems for non-AC compatible material. Without high-frequency AC superconductors available, only the machine field winding, which uses a DC current, is superconducting. To get machines to sizes appropriate for aircraft installation, a 1000-1500 Hz compatible superconductor is required for a full cryogenic generator. Another challenge with superconductors is the need

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[7] NASA TRL 4 and 5 mean that a component and/or breadboard has been validated in a laboratory environment (for TRL 4) or in a relevant environment (for TRL 5).

to perform voltage regulation; conventional approaches to voltage regulation will not work with a conductor that has zero electrical resistance.

Cryogenic system operating temperature is an important consideration. The more powerful the magnetic field in which a superconducting material operates, the lower the required cryogenic temperature will be. For example, superconducting materials being developed today for operation at 77 kelvin (K) do not function as superconductors in a 10 tesla magnetic field until the material is cooled down to 20 K. Cryocoolers able to cool to 20 K are four times the size and weight of 77 K cryocoolers. Even for an aircraft powered by liquefied natural gas (LNG), given that LNG is stored at 112 K, cryocoolers would be required for cooling from 112 K to 20 K. Any cryocoolers used on aircraft will have to be very robust, with redundant capability on board, to meet safety requirements in the event of a cryogenic component failure.

The minimum capacity of cryocoolers is determined by the thermal load on the cryogenic systems the cooler is designed to support. This may be just a few watts, but cryocoolers sized to meet this minimum requirement will take days to cool an aircraft system from ambient to operating cryogenic temperature, during which time the aircraft would be out of service. Faster cooling methods can be employed, but only if the system is designed to withstand the resulting thermal shock.

In summary, cryogenic technologies have the ability to greatly reduce the specific power of electrical systems for a wide variety of applications, including aviation. However, there are substantial barriers to the implementation of these technologies in the challenging operational environment of a commercial aircraft, and it is not envisioned that technology for cryogenic power generation or power distribution will be ready for incorporation in an aircraft propulsion system within the 30-year time frame addressed by this report.

APPLICATION TO GENERAL AVIATION AND COMMERCIAL AIRCRAFT

As discussed in Chapter 1, reductions in carbon emissions from general aviation and commuter airline operations will not make a significant difference in total carbon emissions from global commercial aviation. However, these aircraft types can serve as technology development platforms and will help define an application pathway to regional and larger aircraft. So even though all aircraft categories are described in this section, the focus for significant carbon reductions in the future will have to be on single- and twin-aisle aircraft, but with some consideration also given to regional aircraft.

As shown in Table 4.2, the electrical system requirements for aircraft of a given class will vary according to the type of propulsion system (e.g., parallel hybrid, all-electric, and turboelectric). Of these three, turboelectric systems permit the use of the smallest electrical machines, which reduces technology development risk and schedule. A series/parallel partial hybrid system could also be developed with relatively small electrical machines and batteries, but commercial aircraft studies to date have not shown that such a system is preferable to either a conventional propulsion system or a partial turboelectric system.

Application to General Aviation

All-electric technology aircraft have been operating as technology demonstrators and are starting to enter production. Some examples of these aircraft, which represent the state of the art as of 2015, are shown in Figure 4.4. They use relatively small electric motor systems, on the order of 60-80 kW.

Application to Commuter Aircraft

In April 2015, Siemens announced the development of a direct-drive (2,500 rpm), 260 kW aircraft electric motor weighing a little over 100 lb. The motor specific power is on the order of 5 kW/kg, and it is capable of powering aircraft with a maximum takeoff gross weight of 4,000 lb. The potential availability of such an engine suggests that twin-engine commuter aircraft could be powered by electric motors using current technology. Of course, the question remains regarding the weight and performance of the power source, be it batteries or some hybrid system, as these will determine the potential range of such aircraft and hence their economic viability.

Notwithstanding the potential availability of the Siemens electric motor, NASA has been studying an advanced nine-passenger aircraft concept with distributed electric propulsion that could replace aircraft like the nine-passenger Cessna 402. Cape Air operates 84 Cessna 402s in the Northeast, Midwest, Montana, and the Caribbean. Figure 4.5 shows the Cessna 402 alongside an advanced distributed propulsion concept. Arguably, this eight-motor concept could be powered by 60 kW motors, which are already used in the emerging general aviation industry for two-place trainer aircraft.

Application of Electric Propulsion to Regional and Single-Aisle Aircraft

In 2010, NASA studies were completed on a range N + 3 aircraft with capacities ranging from 20 to 180 passengers. Study teams were led by General Electric, the Massachusetts Institute of Technology, Northrop Grumman, and the Boeing Company. Probably the most thoroughly investigated concept since that initial study is the Boeing SUGAR (Subsonic Ultra Green Aircraft Research) family of aircraft with various electric propulsion architectures. The SUGAR Volt concept features a twin-engine aircraft (see Figure 4.6) and relies upon projected advances in battery technology to enable a parallel hybrid electric propulsion system. The aircraft's concept engines were provided by General Electric and used a large electric motor attached to the low pressure shaft of a gas turbine. This allowed the turbofan to run conventionally, burning aviation fuel, or it could use the electric motor to augment the power supplied to the low pressure shaft (and hence the fan). The motor could also provide exclusive power

FIGURE 4.4 Examples of all-electric-powered general aviation aircraft. SOURCE: Courtesy of Pipistrel (www.pipistrel.si), (*top left*); Jean-Marie Urlacher (http://www.urlachair.com) (*top right*); Wikimedia Commons user Adambro, "Boeing Fuel Cell Demonstrator_AB1," https://commons.wikimedia.org/wiki/File: Boeing_Fuel_Cell_Demonstrator_AB1.JPG, Creative Commons Attribution-Share Alike 3.0 Unported (*bottom left*); Airbus, "Airbus-E-Fan-close-up," http://www.gaoperator.com/airbus-e-fan-close-up/, © Airbus Group (*bottom right*).

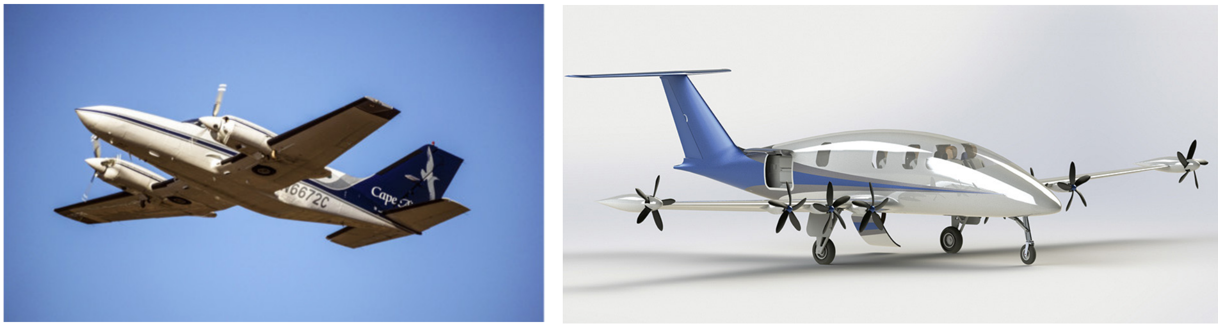

FIGURE 4.5 A nine-passenger Cape Air Cessna 402 and an advanced nine-passenger distributed electric propulsion conceptual aircraft. SOURCE: Courtesy of Cape Air (*left*) and NASA (*right*).

to the fan when the core of the gas turbine is shut down during portions of the cruise mission, thereby significantly reducing emissions. Figure 4.6 shows the primary SUGAR Volt airframe architecture. Another element of the SUGAR project, the SUGAR Freeze, considered the viability of using fuel cells, cryogenic technologies, and boundary layer ingestion (using a propulsor in the aft fuselage).

Empirical Systems Aerospace has developed the ECO-150 concept aircraft in two variants, one that would

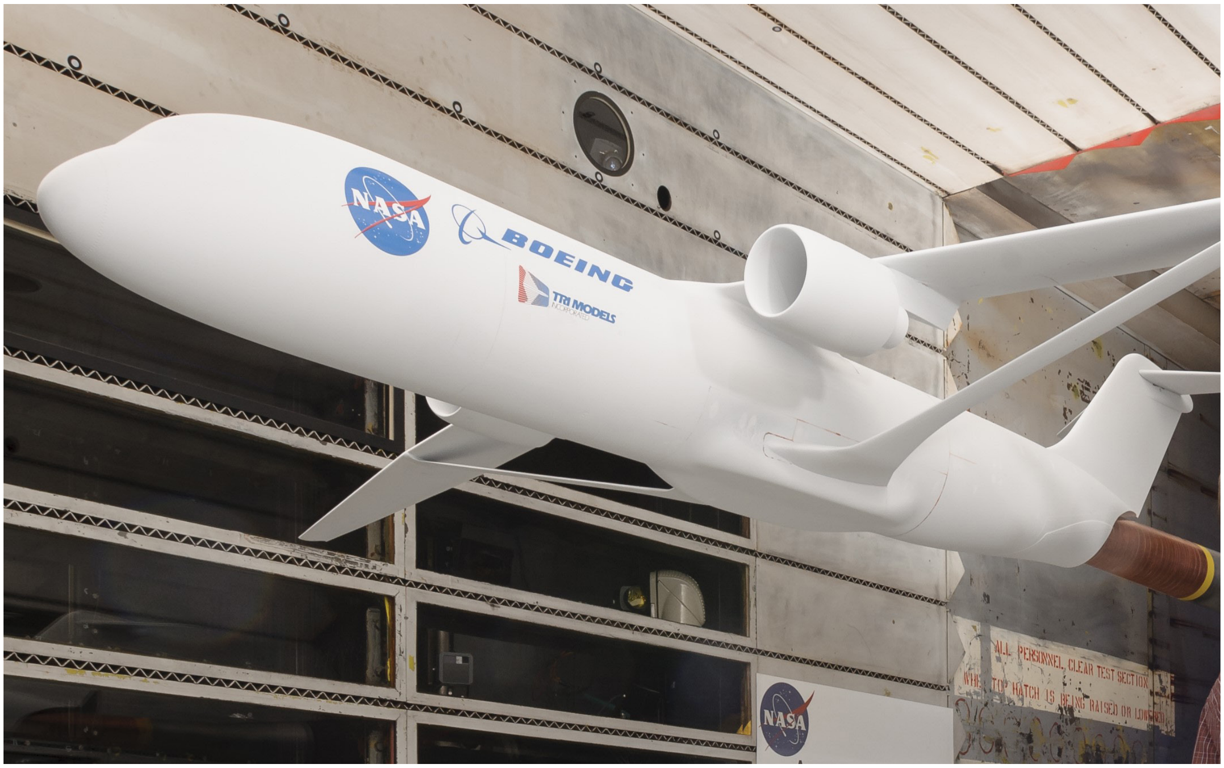

FIGURE 4.6 Boeing SUGAR concept. SOURCE: NASA, "Slimmed Down Aircraft Wing Expected to Reduce Fuel and Emissions by 50%," April 4, 2016, http://www.nasa.gov/image-feature/ames/slimmed-down-aircraft-wing-expected-to-reduce-fuel-and-emissions-by-50.

FIGURE 4.7 Rolls-Royce Distributed Open Rotor Aircraft concept for regional aircraft. SOURCE: © 2016 Rolls-Royce, plc.

use cooled, superconducting technology, and another that would use nonsuperconducting electrical systems. Both concepts would use a turboelectric system with distributed propulsion.

Figure 4.7 shows the Distributed Open Rotor Aircraft electric propulsion concept that has been studied by Rolls-Royce in the United Kingdom. This concept uses multiple propulsors distributed across a significant portion of the wing. These propulsors could be either electrically powered by turbogenerators mounted on the wings or shaft driven. The study evaluated an electrical power distribution system based on electrical technologies available at TRL 4 today. Regardless of the power distribution mechanism used for this concept, the slipstream of the propulsors significantly increases the wing lift coefficient at takeoff, allowing the wing area to be reduced and enabling the wing to be designed with a very high aspect ratio, optimized for highly efficient cruise performance. A key feature of this concept is its use of distributed propulsion (described in Chapter 2). For an electric propulsion system, the use of many fans lowers the power required of each motor. This potentially makes the aircraft practical sooner, as smaller motors can be used instead of waiting for the development of larger motors.

Partial turboelectric systems are also being studied. The NASA STARC-ABL (single-aisle turboelectric aircraft–aft boundary layer) is an example of a partial turboelectric system (see Figure 4.8).

Airbus and Rolls-Royce are studying the e-Thrust concept (see Figure 4.9), which relies on cryogenically cooled superconducting technology that is unlikely to be ready for operational use within the 30-year time frame addressed by this report.

Applications of Electric Propulsion to Twin-Aisle Aircraft

As noted above, no electric propulsion concepts will mature to the point that they can meet the needs of twin-aisle aircraft within the 30-year time frame addressed by this report.

FIGURE 4.8 STARC-ABL (150 passenger) concept being developed by NASA. SOURCE: NASA.

FIGURE 4.9 Airbus/Rolls-Royce e-Thrust concept. SOURCE: © Airbus Group.

RATIONALE FOR TURBOELECTRIC PROPULSION RESEARCH

> **Finding.** *Rationale for Turboelectric Propulsion Research.* Turboelectric propulsion systems are likely the only approach for developing electric propulsion systems for a single-aisle passenger aircraft that is feasible in the time frame considered by this study. System studies indicate that turboelectric propulsion systems, in concert with distributed propulsion and boundary layer ingestion, have the potential to ultimately reduce fuel burn up to 20 percent or more compared to the current state of the art for large commercial aircraft.

Batteries could be a propulsion power source for a small all-electric aircraft (not a subject of this study) within the timeline of this study. To be considered a propulsion source, significant improvements in specific power will have to be achieved and advanced batteries will need to meet economic, safety, and reliability requirements. In particular, the benefits of all-electric aircraft could be offset by CO_2 emissions from the source of electricity and the cost of new infrastructure.

While fuel cells may contribute as a power source for auxiliary power units, the committee does not foresee their contribution as a source of aircraft propulsion in the timeline of this study. To be considered as a propulsion source, vast improvements in specific power would have to be achieved.

CHALLENGES

Technical Challenges

Electrical Technologies

The state of the art of electrical technologies for motors, generators, power distribution, and power electronics (for example, inverters, converters, and circuit protection) will need to advance to enable turboelectric propulsion concepts for large commercial aircraft.

Electrical machines (motors, generators, inverters) need to be developed to attain specific power, weight, and reliability for commercial aircraft application. Specific power will have to be improved by a factor of between 5 and 10 from the current state of the art. Machine thermal management targets will have to be compatible with aircraft thermal management systems. Electrical machine efficiencies will have to be improved from 95 percent to 97 or 98 percent. It remains to be seen if the voltage of the aircraft power distribution system should be increased as part of the effort to reduce weight and increase specific power.

Circuit protection and high-power distribution cabling for MW-class aircraft power systems will need to be developed.

Advanced materials will likely play a key role in advancing the state of the art of electrical machines and power electronics. Motor efficiencies and power density, for example, can be improved through the use of better conductors, insulators, magnets, bearings, thermally conductive materials, polymer composites, and composites reinforced with nanofibers and carbon nanotubes.

Aircraft Systems

Turboelectric aircraft propulsion systems present a number of challenges related to other aircraft systems (e.g., thermal management systems). More structurally and aerodynamically efficient configurations can help address these challenges.

Aircraft turboelectric propulsion requires advances in many system capabilities. Motors, generators, and electrical distribution systems lie at the heart of electrical systems, and most electric propulsion research is understandably focused on these key elements. As these electric propulsion technologies advance, it is essential that research to advance capabilities in related aircraft systems is properly directed. Studies to date of the benefits and challenges of turboelectric propulsion, however, have paid insufficient attention to all contributing aircraft systems. This is particularly true with regard to thermal management systems, because they are essential to the performance of the electric propulsion system and because they may affect flight performance of the aircraft. Other systems of particular interest include aircraft structure and optimized aerodynamic integration.

Research Infrastructure for Electrical Technologies

The research and development of megawatt-class turboelectric aircraft propulsion systems is hampered by the lack of development testing facilities.

Existing facilities for the development of motors, generators, and other electrical equipment for aircraft have been generally designed to provide nonpropulsive power. Electric propulsion systems will need to have much higher power capacities than electrical systems currently on aircraft. Facilities to meet these higher power levels have not been developed. No capability for proper simulation of a turboelectric propulsion system for a large aircraft exists at this time.

RECOMMENDED HIGH-PRIORITY RESEARCH PROJECTS

Turboelectric Aircraft System Studies

Conduct more encompassing studies of aircraft powered by turboelectric systems in order to better understand the benefits, component performance sensitivities, certification issues, and trade-offs related to key aircraft systems, such as thermal management and energy storage.

Establishing cost targets, thermal management targets, and reliability targets at an early stage would help define the research plan. In addition, certification plans would be most effective if established in active collaboration with the U.S. Federal Aviation Administration or other certification authorities such as the U.K. Civil Aviation Authority and the European Aviation Safety Agency.

Core Turboelectric Technologies

Develop the core technologies that are required for megawatt-class turboelectric propulsion systems: motors, generators, inverters, power distribution, and circuit protection.

It would be appropriate for research to address 1 to 5 MW systems, with an initial focus on 1 MW systems.

Megawatt-Class Research Facilities

Develop research facilities for megawatt-class electric power and thermal management systems suitable for testing turboelectric aircraft propulsion systems.

After initially focusing on ground-based facilities, a flight demonstration program for a turboelectric system could be considered in order to support advanced development of MW-class systems.

5

Sustainable Alternative Jet Fuels

INTRODUCTION

This chapter looks at alternative jet fuels that have lower carbon emissions than conventional petroleum-based fuels over the entire life cycle of the fuels. It discusses the challenges associated with their development and commercialization and outlines key needs for achieving significant production and use of drop-in sustainable jet fuels produced from feedstocks other than petroleum (see Box 5.1). If such commercialization takes place, aviation has the opportunity to significantly lower the net carbon emissions from aviation, potentially in a more aggressive and timely fashion than can be reasonably achieved with improved operations, infrastructure, and aircraft. This reduction can also be achieved without impacting the time frame or suitability of other potential carbon-lowering approaches.

Much has been accomplished over the last decade to validate the qualification, production, and usage of lower net carbon fuels. Some versions of these fuels are on the cusp of commercialization. However, many research, development, demonstration, and deployment challenges remain in moving these fuels to significant production and mainstream usage. This chapter addresses those challenges and related research projects.

It is not feasible for the aviation industry to switch from conventional jet fuel to a different fuel type, nor are

BOX 5.1
Drop-in Jet Fuel

Drop-in jet fuels have aggregate properties that are essentially equivalent to those of conventional (petroleum-based) jet fuels. As such, drop-in fuels are fully miscible with conventional jet fuels, and they are fully compatible with existing aircraft and the existing fuel infrastructure (tanks, pipelines, equipment, etc.). A reasonable level of variation in certain properties of jet fuel is acceptable to accommodate the variation in sources of petroleum and refining around the world. The ability to tolerate this variability enables the introduction of fuel components produced from nonpetroleum feedstocks, while still delivering the final physical and fit-for-purpose attributes demanded of jet fuel.

BOX 5.2
Sustainable Alternative Jet Fuels

This report uses the term sustainable alternative jet fuels (SAJF) to characterize a family of drop-in fuels that are intended to lower the net life-cycle carbon emissions of commercial aviation.

Jet Fuels. First and foremost, SAJF will need to meet current specifications for jet fuel, either on their own or when blended with conventional jet fuel. As such, SAJF (blended as necessary) are "drop-in" replacements for conventional jet fuel.

Alternative. SAJF are alternative in that they are produced primarily from nonpetroleum sources of hydrocarbons using a potentially broad range of biochemical and thermochemical conversion processes. To date, four pathways have been approved for producing alternative fuels that meet the specifications necessary to be considered jet fuel while others are pending.

Sustainable. To be successful over the long term, alternate fuels will need to be sustainable both in terms of their ability to reduce net life-cycle carbon emissions relative to conventional jet fuel and in terms of environmental, societal, and economic factors. Not all alternative fuels will result in a net reduction in life cycle carbon depending, for example, on their source materials.

there readily identifiable, feasible, lower-carbon alternative fuel types that could be introduced in a reasonable time frame. Many entities have validated the technical viability of producing synthetic jet fuel (or jet fuel blending components) from a wide range of hydrocarbon sources other than petroleum, using a broad range of biochemical and thermochemical conversion processes. Several approaches to producing synthetic drop-in jet fuels have demonstrated not only a lower life-cycle carbon footprint than conventional petroleum-based jet fuel, but also other elements of sustainability—for example, social, environmental, or economic. This report refers to such fuels as sustainable alternative jet fuels (SAJF, see Box 5.2).

A wide array of organizations has been working for the last decade to support the development of SAJF and to create a framework by which such fuels can enter the marketplace. The SAJF community in the United States now includes a broad coalition federal agencies, state and local constituents, operators of aircraft powered by gas turbines (commercial, military, business, and general aviation), engine and aircraft manufacturers, some members of the petroleum industry, academia, nongovernmental organizations, and various public–private partnership efforts.

Civil and military users of jet fuel have engaged in several technical and commercial demonstrations of the production and use of SAJF and continue to do so worldwide. Even so, bringing SAJF to market at competitive prices remains an elusive goal for many reasons related to technological maturity, feedstock production and distribution systems, production infrastructure, conflicting market signals, policy issues, and depressed oil prices.

In the absence of government policies that mandate or strongly incentivize the use of SAJF, research and development (R&D) efforts continue on ways to lower the capital and operating costs of SAJF production, both for conversion processes that have already been developed and for entirely new conversion processes under development. A few SAJF producers have found unique ways to approach initial commercialization, for instance by using very inexpensive feedstocks (e.g., municipal solid waste, forestry residues, and other industrial waste streams). Initial production contracts and offtake commitments are in place for some of these processes, albeit for very modest quantities of SAJF. A new industrial sector with requisite supply-chain resources is needed to bring significant quantities of SAJF to the marketplace. Large commercial entities (e.g., existing jet fuel producers) could undertake such industrial development, but at present there are no large commercial entities driving SAJF development.

Policy elements are sometimes used to address the challenges of introducing new technologies, especially for products that deliver societal value (e.g., aviation safety and environmental protection) but are sold at a higher price than competing products. Several government agencies in the United States and elsewhere have been aiding the development of this new industrial sector. Much has been accomplished, but much remains to be done.

This committee, mirroring similar evaluations from others affiliated with the above developments, has identified high-priority research projects that could help facilitate the accelerated introduction and broad commercialization of SAJF. These projects are focused on four areas:

- Modeling and analysis of SAJF development,
- Feedstock development, production, and logistics,
- Conversion processes, fuel production, and scale-up, and
- Fuel testing, qualification, and certification.

Evidence suggests that efforts are needed in all these areas to truly enable a vibrant SAJF industry that might deliver significant quantities of appropriately priced fuel for the aviation enterprise in a timely fashion. Further, the work being done individually by multiple U.S. government agencies and SAJF developers could be made more effective through greater collaboration and alignment of efforts, as well as through increased engagement on the part of several agencies that have not had significant engagement to date.

BACKGROUND

Aircraft engines are designed to burn only a narrow range of fuels, and using fuels with characteristics that fall outside this range will detract from safety, efficiency, and/or operability. Operators of aircraft powered by gas turbines will continue to demand the use of hydrocarbon jet fuel for the foreseeable future. While burning SAJF will produce nearly the same amount of CO_2 per unit of fuel as conventional jet fuel, the use of SAJF reduces net life-cycle carbon emissions because SAJF enable reusing or recycling carbon that is already in the biosphere to create the fuel.

Potential Alternative Drop-In Jet Fuels

Jet fuel comprises a distribution of hydrocarbons with typically 7 to 18 carbon atoms per molecule. Jet fuel is referred to as a middle distillate, or kerosene-type, fuel. It is typically produced by the distillation of petroleum in a refinery, falling between the products gasoline, on the higher end of the volatility range, and diesel, on the lower end. Jet fuel is often characterized as a pure hydrocarbon with an aggregate composition of $C_{12}H_{23}$.[1]

There is broad consensus in the aviation industry—and in the committee—that drop-in jet fuels are far superior to other alternative fuels based on five considerations: certification; lack of technically feasible alternatives; infrastructure; the existing and pending fleet; and SAJF specifications and qualification practices.

Certification

Gas turbine engines are certified to meet stringent performance and operability criteria to ensure safety. Engine manufacturers define what fuel types satisfy these criteria using fuel specifications. For already-certified aircraft types, using a different fuel type would require recertification of the aircraft to demonstrate that performance, operability, and safety are not compromised by the new fuel. Recertification may require modifications to the aircraft or engine, which would likely be prohibitively expensive. In contrast, a drop-in fuel that meets appropriate fuel specifications obviates the need for recertification or a large investment in aircraft or engine modifications.

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[1] Jet fuel is a generic term that encompasses many specific variants, such as Jet A, Jet A-1, JP-5, and JP-8. In most cases, the other names imply specific variants of the fuel, as often detailed in the specifications themselves. Jet A is the most common form of jet fuel used by commercial aviation in the United States, while Jet A-1 predominates in the rest of the world.

Lack of Technically Feasible Alternatives

Jet fuel helps meet the need for safe, efficient, and economic high-speed travel because it has a balance of appropriate fuel properties, such as high energy per unit mass, high energy per unit volume, stability, nonvolatility, low freezing point, low vapor pressure, materials compatibility, and low toxicity. Since the dawn of aviation, aviation equipment manufacturers, in conjunction with research institutions, academia, and other technology developers, have evaluated options for future fuels, engines, and vehicle configurations in an effort to improve efficiency, productivity, and economic returns. Many alternatives have been considered—including nuclear power, hydrogen, and compressed or liquefied natural gas—but not one has proved feasible for commercial aviation. Ethanol and biodiesel blending components have dominated consideration as alternative fuels for ground vehicles, but these fuels are not suitable for aviation due to issues with safety, operability, and/or performance. As discussed in Chapter 4, neither fuel cells nor batteries will advance enough to power large commercial aircraft within the 30-year time frame addressed by this report. Liquefied natural gas and liquid hydrogen both have higher energy content per unit mass than conventional jet fuel, but they require two to four times as much volume to hold the same amount of energy as jet fuel. In addition, liquefied natural gas and liquid hydrogen both introduce unique aircraft integration and substantial new safety challenges. Aircraft designed to use such fuels would have significantly larger fuels tanks and engine fuel systems, resulting in higher drag, weight, and complexity; much shorter range; and/or reductions in other operational capabilities, such as speed, payload, or altitude capability. Also, the net reduction in carbon emissions arising from the adoption of hydrogen-fueled aircraft, for example, could be quite small unless the hydrogen is produced with electricity generated by renewable or low-carbon-emission technologies or if it is produced from hydrocarbons such as methane.

Infrastructure

Given the global nature of aviation and the tremendous investment in and long life span of aircraft and aviation infrastructure, switching fuel types would require significant modifications to the air transportation system and supporting services, including aircraft, airports, airport fuel delivery systems, and national pipeline systems. All this would be in addition to creating a new industrial sector for the production of the new fuel. There would also be a lengthy transition period, during which both the old and new fuel systems would need to operate, resulting in greater system complexity, higher costs, and longer time to completion.

Existing and Pending Fleet

New aircraft typically have production runs that last for 10-15 years, and then they remain in service for perhaps 25-30 years. This means that even with the introduction of a new engine or aircraft type with a new fuel or power source 15-20 years from now (to allow time for technology maturation and product development), conventional jet fuel would remain the primary source of aviation fuel perhaps through 2050 or longer, until aircraft using the new fuel became dominant in the fleet.

SAJF Specifications and Qualification Practices

ASTM International is a not-for-profit organization that develops voluntary, consensus standards for industrial processes, materials, and products. Two ASTM documents are of particular relevance to SAJF:

- ASTM D7566. Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.
- ASTM D4054. Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives.

Not every synthetic fuel production process creates the full range of molecules that are present in conventional jet fuel and are required to meet jet fuel specifications. This is the case for the five synthetic fuel production

TABLE 5.1 Approved Alternative Fuel Production Pathways

Name (from ASTM D7566 Annex)	Description	Qualification Date	Blend Limitation (%)
A1: FT-SPK[a]	Fischer-Tropsch conversion of syngas to synthetic paraffinic kerosene	September 2009	50
A2: HEFA-SPK[b]	Hydroprocessed esters and fatty acids (lipids from plant and animal sources) to synthetic paraffinic kerosene	July 2011	50
A3: HFS-SIP[c]	Hydroprocessed fermented sugars to synthesized isoparaffins	June 2014	10
A4: FT-SPK/A[d]	Fischer-Tropsch conversion of syngas to synthetic paraffinic kerosene and aromatics	November 2015	50
A5: ATJ-SPK[e]	Thermochemical conversion of alcohols (isobutanol only initially) to paraffinic kerosene	April 2016	30

[a] In this process, syngas (a mixture of carbon monoxide and hydrogen) is processed in a Fischer-Tropsch catalytic reactor to produce a mix of longer-chain paraffinic hydrocarbons which are subsequently converted into jet fuel with typical refinery finishing processes. Common methods of producing syngas include gasification of solid forms of hydrocarbons (e.g., biomass residues, municipal solid waste, coal, or combinations thereof) and the conversion of natural gas or biogas into syngas (e.g., via steam methane reforming). Gasification entails processing feedstock in a high-energy, reduced-oxygen environment such that the feedstock does not combust but is thermally deconstructed into its constituent elements (hydrogen, carbon monoxide, nitrogen, water, methane, hydrogen sulfide, carbon dioxide, and other compounds). The gasifier output must be cleaned of particulate matter, sulfur, and other impurities. Syngas is also produced as a byproduct of various industrial processes.

[b] Waste fats, oils, and greases or plant-derived oils can be cleaned and treated with hydrogen to produce jet fuel. Some sources of plant-derived oils, such as soybeans, are so expensive that they exacerbate the challenge of producing cost-competitive SAJF. Other options are potentially more competitive. Examples include waste fats, oils, and grease and nonfood crops, especially those grown on land that is not suitable for growing food crops, are potentially more competitive.

[c] Biomass feedstocks can be converted to sugars using a variety of pretreatment technologies. Microorganisms have been developed that will convert the sugars directly into an isoparaffin for blending with jet fuel.

[d] This process is similar to FT-SPK, but it includes the addition of production methods that also produce aromatic hydrocarbons.

[e] Alcohols can be converted to pure hydrocarbons in the jet fuel range through a process of dehydration, oligomerization, hydrogenation, and fractionation.

pathways that have been approved to date under ASTM D7566 (see Table 5.1). Accordingly, as indicated in the table, they must be blended with conventional jet fuel, up to maximum allowable blending levels, for the synthetic blend to be considered a drop-in alternative jet fuel.

Synthetic fuels produced from feedstocks other than petroleum do not necessarily guarantee sustainable, nor will they necessarily achieve the net carbon reduction required by policy measures targeting sustainability. For example, both of the Fischer-Tropsch pathways in Table 5.1 (FT-SPK and FT-SPK/A) use synthesis gas (syngas) which can be produced from various feedstocks including biomass, coal, natural gas, or waste gaseous streams from various industrial processes. To be considered sustainable, the input feedstocks for the syngas production would themselves need to be viewed as sustainable, and thus some sources of syngas (e.g., coal gasification with or without carbon capture and sequestration) could be precluded from use for the production of SAJF.

In the future some alternative fuels may qualify as drop-in fuels without blending, but that has not been the case to date.

SAJF State of Development

Although SAJF have been produced, the oil and transportation fuel industry is very competitive, increasingly so given low crude oil prices, making it very difficult for producers of SAJF to be economically competitive, especially given the capital costs of building large production facilities, the difficulty of establishing new supply chains, and the projected operating costs associated with proven feedstocks and conversion processes. In addition, the petroleum industry has been conservative in its engagement and support of alternative fuel development generally.

The U.S. aviation enterprise has demonstrated significant interest and engagement in the development, production, and use of SAJF over the past several decades. More than 20 airlines have flown more than 1,600 demonstration and proving flights using SAJF produced in limited production runs from pilot production facilities and facilities temporarily configured for SAJF production.[2] The U.S. Navy and Air Force have been active in the testing of fuels in support of qualification activities, for both previous and pending qualification efforts.[3] Even so, the Defense Logistics Agency has announced that it will purchase biofuel blends only if they are cost competitive with conventional fuels. Similarly, airlines have expressed interest in acquiring significant quantities of SAJF at petroleum parity pricing. Offers to purchase SAJF at higher prices will be evaluated subject to strategic interests of the airline. For example, the AltAir Biofuels facility in Paramount, California, is the first commercial production facility for SAJF (and for renewable hydrocarbon diesel, which is not a jet fuel).[4] This facility, which was commissioned in late 2015, is now delivering SAJF to customers such as United Airlines and World Fuel Services, a jet fuel distributor.

The state of the art in sustainable fuels is advancing rapidly. In addition to the five qualified fuel production pathways listed in Table 5.1, three additional pathways could be approved before the end of 2017. Several additional pathways are also being developed by task forces within the ASTM community, while more than 10 additional pathways may be pursued based on comments by their technology developers.[5,6,7,8] As each new pathway is approved, ASTM D7566 will be expanded to provide specifications that encompass all of the feedstocks and conversion processes approved for use in that pathway.

Several other producers, using a range of feedstocks and processes, are currently involved in the development of initial production facilities, including three companies with funding from the Defense Production Act: Fulcrum BioEnergy, Red Rock Biofuels, and Emerald Biofuels. These companies are targeting start of production in the 2017-2018 time frame, and two of them have agreements with major airlines to use the SAJF they produce. Altogether, these three facilities will likely produce no more than 50-100 million gallons of middle distillate (diesel and jet fuel blending components) per year, which would constitute perhaps 0.3 percent of the total U.S. demand for jet fuel. If U.S. commercial aviation consumes 20 billion gallons of jet fuel in 2020, 308 million gallons of conventional jet fuel would need to be replaced by SAJF with a 65 percent reduction in life-cycle carbon emissions to lower the total net carbon emissions of U.S. commercial aviation by 1 percent.

Life-Cycle Carbon Emissions

Any SAJF, by definition of it being a drop-in fuel, is expected to have an aggregate chemical composition that is essentially equivalent to petroleum-based jet fuel (i.e., $C_{12}H_{23}$). As such, the CO_2 emissions from an engine burning SAJF will be practically equivalent to those from combustion of petroleum-based jet fuel.

Life-cycle analyses of alternative fuels determine the extent to which their production and use would reduce carbon emissions on a life-cycle basis compared to conventional jet fuel. Life-cycle analyses take into account all emissions associated with producing the final fuel from its initial form (e.g., an oil well, planting of oil seed crops, or conversion of municipal solid waste), as well as aircraft emissions. Biomass-derived alternative jet fuels have the potential to reduce life-cycle emissions compared to conventional jet fuel, since biomass-based hydrocarbons

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[2] IATA, "Alternative Fuels," http://www.iata.org/whatwedo/environment/Pages/alternative-fuels.aspx, accessed May 14, 2016.

[3] U.S. Government Accountability Office, 2015, *Observations on DOD's Investments in Alternative Fuels*, GAO-15-674, Washington, D.C.

[4] Because this facility is located in California, it benefits from the incentives provided by California's low-carbon fuel standard.

[5] Direct sugars to hydrocarbons. This pathway involves the direct catalytic conversion of sugars into hydrocarbons without the use of microorganisms.

[6] Coprocessing of biocrudes at petroleum refineries. Biomass can be minimally treated to produce a biocrude that can be mixed with crude oil to form the input into an oil refinery. Depending on the quality of the biocrude it can also be inserted at the entry of the fluid catalytic cracker and/or the hydrotreater of a refinery. The refinery then produces the usual slate of gasoline, diesel, jet, and other products. The portion of biomass-based carbon molecules that constitute the jet fuel cut can be considered as an alternative fuel.

[7] Renewable diesel blending with jet fuel.

[8] The qualification of a production pathway in accordance with ASTM D7566 does not imply that commercialization will follow soon or at all. It took 4 years and 6 months from the qualification of HEFA-SPK to begin using this method to produce commercial volumes of fuel (at the AltAir refinery).

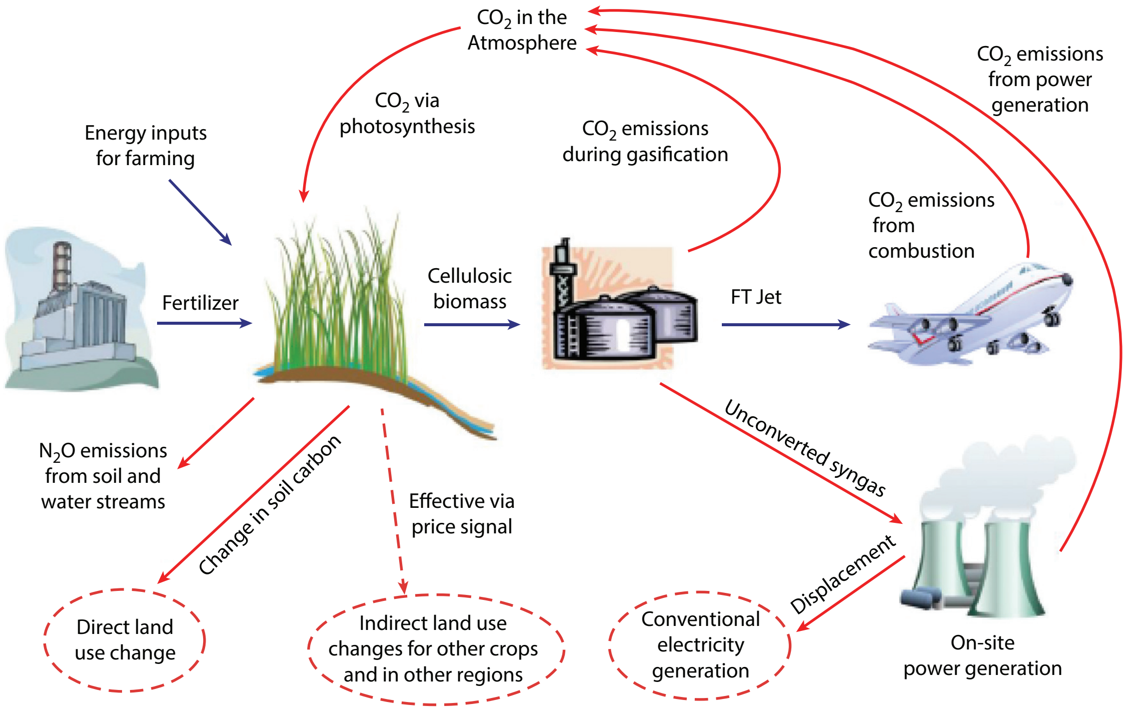

FIGURE 5.1 Jet fuel production using cellulosic biomass. SOURCE: Argonne National Laboratory, *Life Cycle Analysis of Alternative Aviation Fuels in GREET*, ANL/ESD/12-8, U.S. Department of Energy, Oak Ridge, Tenn., June 2012, http://www.energiasustentables.com.ar/bioenergia-en/fundamentos%20adicionales-en.html. Argonne National Laboratory is managed and operated by UChicago Argonne, LLC, for the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

absorbed CO_2 from the atmosphere when they grew and the CO_2 emitted during fuel combustion is equal to that absorbed during its growth (see Figure 5.1). The uptake of CO_2 by the biomass is assumed to be “credit” that offsets (at least in part) the combustion CO_2 in the life-cycle analysis. This biomass credit is the primary difference between biomass and fossil fuels in terms of their carbon emissions. However, a biofuel does not necessarily have life-cycle emissions that are below a petroleum-based baseline, since there can be emissions associated with acquiring a feedstock, with fuel production, with feedstock and fuel transportation, as well as with land-use change attributable to the production of biomass-based feedstocks. Similar CO_2 emissions are also associated with the production of fossil fuels.[9]

SAJF produced from nonpetroleum hydrocarbon sources (feedstocks) can significantly reduce life-cycle emissions compared to conventional petroleum-derived jet fuel. Argonne National Laboratory has conducted life-cycle analysis of bio-based aviation fuel pathways and compared them with petroleum-based jet fuels (see Figure 5.2). The first column shows that for an alternative fuel that uses coal rather than biomass as the dominant raw material, CO_2 emissions are 71 percent higher than with conventional jet fuel. For SAJF (that is, for alternative fuels derived entirely from biomass), depending upon the feedstock and conversion process, reductions in CO_2 emissions relative to conventional jet fuel range from 41 to 89 percent. On a sector-wide basis, total reductions in life-cycle emissions will depend on rates of production and utilization, which are functions of the fuel’s commercial viability.

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[9] A. Elgowainy, J. Han, H. Cai, M. Wang, G.S. Forman, and V.B. DiVita, 2014, Energy efficiency and greenhouse gas emissions intensity of petroleum products at U.S. refineries, *Environmental Science and Technology* 48:7612-7624.

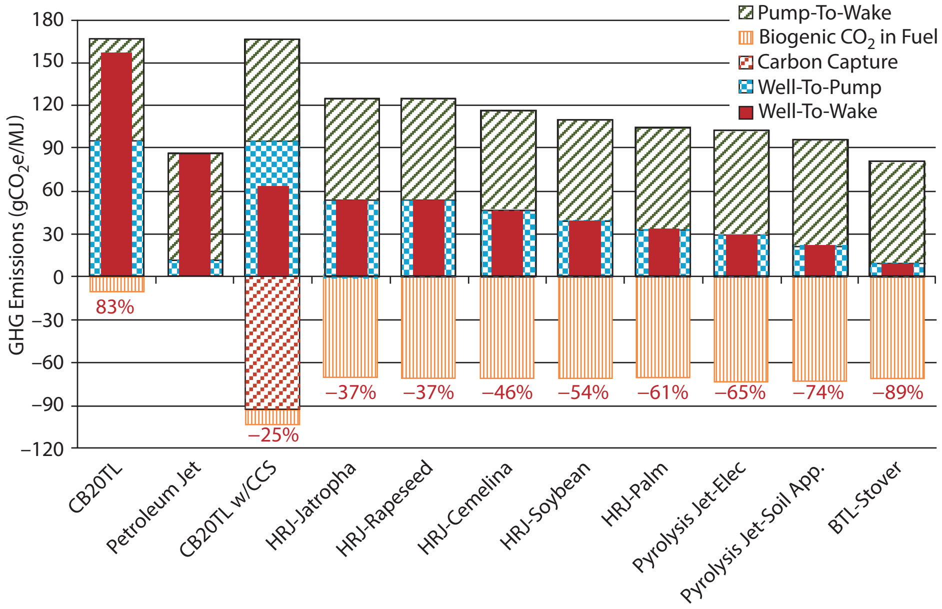

FIGURE 5.2 Life-cycle (well-to-wake) greenhouse gas emissions for alternative jet fuels compared to petroleum-based jet fuels. CB20TL, coal/biomass-to-liquid with 20 percent biomass in total inputs (by mass); CCS, carbon capture and storage; HRJ, hydroprocessed renewable jet; BTL, biomass to liquid. SOURCE: Reprinted from J. Han, A. Elgowainy, H. Cai, and M.Q. Wang, Life-cycle analysis of bio-based aviation fuels, *Bioresource Technology* 150:447-456, 2013. Copyright © 2013, with permission from Elsevier.

Additional Benefits

The commercialization of SAJF offers other potential societal benefits by expanding domestic energy sourcing; reducing greenhouse gases and other emissions that impact air quality; promoting economic development; promoting social welfare; and delivering other environmental services to the biosphere (e.g., improving water quality, reducing nutrient leaching, reducing erosion, restoring degraded soils, enhancing biodiversity, and assisting with reductions in pest and weed treatment for other crops). Many of these benefits arise from new agricultural opportunities in areas not amenable to the production of food crops. Given those potentials, SAJF development efforts are being supported by federal, state, and local government agencies that recognize the potential benefits:

- *Environmental benefits—Lowering emissions around airports*. SAJF blending components typically contain less sulfur than conventional jet fuel. As a result, their use will likely reduce emissions of oxides of sulfur (SO_x), and because SO_x is a precursor for secondary particulate matter, such emissions will also be reduced. SAJF blending components typically contain lower levels of aromatics (specifically, polycyclic aromatics), which improves combustion characteristics. Owing to this and other factors, SAJF tests have shown general reductions in aerosol emissions, particles, and black carbon.[10]
- *Societal benefits—Jobs and rural development*. Several examples of SAJF-focused feedstock development at various locations around the world are demonstrating the potential for growing feedstocks in ways that do not compete with food production, thereby providing societal benefits without unintended consequences such as food shortages. Examples include the use of family farming of a new type of tobacco in the South

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[10] Virent, Inc. "Virent Bio-Jet Provides more than 50% Reduction in Particulate Matter Emissions," last update January 6, 2016, http://www.virent.com/news/virent-bio-jet-provides-more-than-50-reduction-in-particulate-matter-emissions.

African Solaris project,[11] halophyte[12] usage in saline environments in the Middle East and Mexico,[13] and blighted citrus grove replacement in Florida.[14]

- *Noncommercial aviation*. SAJF developed for commercial aviation can also be used as a jet fuel for military, business, and general aviation. In fact, the Department of Defense is also supporting SAJF development, and the success of those efforts would also be broadly applicable.

INTERNATIONAL CONSIDERATIONS

The International Civil Aviation Organization has tasked its Committee on Aviation Environmental Protection to look at the feasibility of SAJF contributing significantly to the goals of capping net carbon emissions from 2020 onward and achieving a 50 percent reduction in net carbon emissions by 2050 from 2005 levels. In addition, the International Air Transport Association has examined issues related to SAJF and actions that national governments could take to address these issues.[15]

The majority of SAJF production could be distributed, with facilities geographically dispersed and located synergistically with feedstock supplies to keep costs and emissions to a minimum. Although the majority of efforts to date have been focused in the United States and Europe, there exist expectations that this production can proliferate around the world, with local governments attempting to capture some of the indirect benefits of such fuel production, as outlined previously. Recent announcements from Indonesia, Japan, China, and other countries provide support for these views.[16,17,18]

CHALLENGES

SAJF has the potential to provide commercial aviation with a low-carbon fuel with almost universal application. However, there are many economic, technical, and policy challenges that need to be overcome to achieve this vision. The economic challenges are taken up first because they constitute the largest barrier to the development and commercialization of SAJF.

The creation of a large-scale SAJF industrial sector will be difficult, especially given (1) the need to compete with producers of conventional jet fuel, (2) the barriers to entry, particularly for the production of a commodity product, and (3) the inability to capture sufficient value from the primary attribute of the new product, which is the inherent reduction in net carbon emissions resulting from the use of SAJF. The challenges associated with cost-competitiveness are illustrated in Figure 5.3, which shows that even with optimistic estimates of capital and operating expenses, SAJF costs more than conventional jet fuel, especially in the face of low crude oil prices. There are several SAJF technologies that can produce fuel for less than the price of conventional jet if the cost of crude oil is at least $120 per barrel. As of April 2016, however, the cost of crude oil was $36 per barrel and the cost of jet fuel was about $1 per gallon.[19] As discussed in Chapter 2, predictions of future costs of crude oil are

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[11] Project Solaris website, http://www.projectsolaris.co.za/, accessed May 10, 2016.

[12] Halophytes are plants that can grow in a salty environment such as areas exposed to salt spray, salt marches and mud flats, and other soils with high salt content.

[13] Masdar Institute, "Abu Dhabi's Innovative Bioenergy Project Highlighted at Leading Bioenergy Conference," last update October 31, 2015, http://www.masdar.ac.ae/component/k2/item/6594-abu-dhabi-s-innovative-bioenergy-project-highlighted-at-leading-bioenergy-conference.

[14] Treasure Coast Research Park, "Biofuel Feedstocks Research Takes Off in Fort Pierce," last update 2013, http://www.treasurecoastresearchpark.com/biofuel-research-takes-off-in-ft-pierce.

[15] International Air Transport Association (IATA), 2015, *Report on Alternative Fuels*, 10th Edition, Montreal, Canada, http://www.iata.org/publications/Documents/2015-report-alternative-fuels.pdf.

[16] Federal Aviation Administration, "U.S./Indonesia Agreement on Sustainable Air Transportation and Aviation Alternative Fuels," last update October 23, 2015, http://www.faa.gov/news/updates/?newsId=84086.

[17] Initiatives for Next-Generation Aviation Fuels (INAF), 2015, *Roadmap for Establishing Supply Chain for Next-Generation Avi*ation Fuels, Japan, http://aviation.u-tokyo.ac.jp/inaf/roadmap_en.pdf.

[18] Xinhua News Agency/China Finance Corporation (CFC), "China Grants 1st Bio Jet Fuel Airworthiness Certificate to Sinopec," last update February 13, 2014, http://en.xinhua08.com/a/20140213/1299111.shtml.

[19] Energy Information Agency, 2016, "Petroleum and Other Liquids: Spot Prices," Washington, D.C. https://www.eia.gov/dnav/pet/xls/PET_PRI_SPT_S1_D.xls.

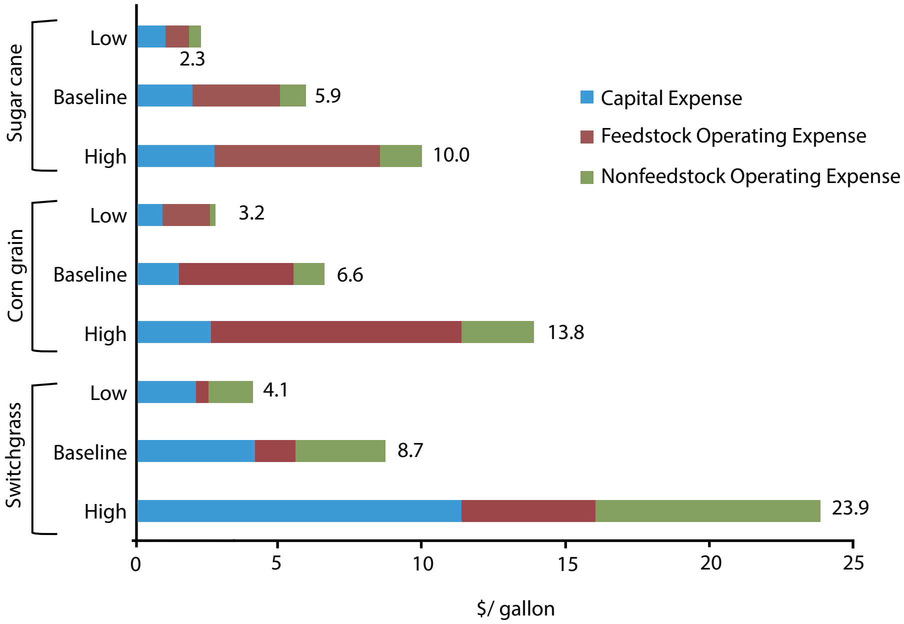

FIGURE 5.3 Minimum selling price of alternative jet fuels using a variety of feedstocks. SOURCE: Adapted from M.D. Staples, R. Malina, H. Olcay, M.N. Pearlson, J.I. Hileman, A. Boies, and S.R.H. Barrett, "Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies, *Energy and Environmental Science* 7:1545, 2014, http://dx.doi.org/10.1039/C3EE43655A, used with permission of the Royal Society of Chemistry.

highly uncertain: the U.S. Energy Information Administration projects that the spot price of crude oil in 2040 will be 2 to 7 times as much as current prices.[20]

Economic Challenges

The economic challenges to widespread use of SAJF are spread across the business model: high capital expense, high operating expense (including feedstock cost), and the relative immaturity of the systems, machinery, and processes required to enable robust supply chains for these processes. Research could address cost reductions for many of these elements, but demonstration and deployment efforts will also be needed to address fully all of the economic challenges.

Feedstock Price and Availability

Currently achievable refinery-gate feedstock prices are expensive relative to the final product, which is driven in part by immature or nonexistent feedstock supply chains.

Well-defined, well-established supply chains are needed for large-scale, dedicated production of SAJF feedstocks, particularly agricultural and wood products. Economies of scale are not yet achievable.

It remains questionable whether all feedstocks of interest (initial and envisioned) will be able to deliver enough energy per unit cost to the various conversion processes, especially for "first-unit" production, because much of the demonstration work completed to date for any specific feedstock has been done on a limited basis.

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[20] Energy Information Agency, 2015, *Annual Energy Outlook 2015 with Projections to 2040*, DOE/EIA-0383(2015), Washington, D.C., http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf, Figure 3.

Developing an SAJF enterprise that can provide fuel globally, throughout the year, will be extremely complex. Sustainable feedstocks are typically only applicable on a regional basis, so different types of feedstocks and conversion processes will be needed. Also, within an agricultural feedstock family, individual feedstocks are typically only available during certain times of the year. Thus, for any particular SAJF production facility to maintain operations throughout the year, either it will probably need to store large quantities of feedstock to sustain itself throughout the year, or it will need to access multiple feedstocks and/or import feedstocks from other regions with different growing seasons, using multiple supply chain concepts. This same issue applies to many nonagricultural feedstocks, too, where intermittency issues may be driven by factors other than harvest availability.

Many feedstocks are diverse and unique; harvest, handling, storage, and processing technologies are needed for multiple feedstock types, as well as for the manufacture of such equipment. Important advances are being made, for example, with the harvest, storage, and transport of cellulosic plants in support of pilot plants. Nonetheless, appropriately affordable, robust, and producible conversion equipment, and the facilities and systems to enable production of such equipment at sufficient scale, are not available, and future availability is uncertain at best.

There are varying models for the envisioned development of full-scale SAJF production capabilities, but because key technologies related to fuel conversion and associated infrastructure have not yet been optimized, models cannot be validated, and as a result research may not be targeting the best solutions.

With no large vertical integrator driving the overall development of the entire supply chain, it is proving tremendously difficult to manage the simultaneous and independent growth of the feedstock supply chains and conversion facilities at appropriate scales. This may prove particularly challenging for feedstock systems that take several years to achieve scale or maturity and have no other viable customers. If the feedstock is available prior to being needed in the conversion facility, who will buy it, and at what price? Can it be stored without degradation? Who will pay for the storage? And so on. Conversely, who will capitalize and build a production facility without the assurance that feedstocks will be available when needed? Some feedstocks (e.g., crop residues or municipal waste, which are a byproduct of other activity) may prove significantly easier to address than others (e.g., crops, such as oilseeds, that would be grown specifically as a feedstock).

Industrial Sector Collaboration

This nascent industry lacks the elements of collaboration that are inherent in a fully defined industrial sector which enable system optimization, or even the initial matching of supply and demand signals.

The establishment of a new industrial sector, with its requisite resources (e.g., supply chain, equipment, facilities, personnel, equity, etc.) entails the fostering and bringing together of organizations who have not worked with one another previously. Large producers of conventional jet fuel, who are perhaps in the best position to address this challenge, currently seem to have little motivation to do so, given that SAJF by design is interchangeable with their current products, but its production comes with uncertain margins, higher investment, and higher risk.

Technoeconomic Factors

Lack of technoeconomic assessments and comparative understanding of various approaches impedes the ability of industry and the researchers and agencies that support SAJF R&D to make practical decisions about the prioritization of R&D and demonstration and deployment efforts.

A comprehensive set of common-baseline, comparative technoeconomic assessments of current and projected pathways and feedstocks is needed to provide insights into the technical and economic feasibility of proposed SAJF production pathways. These assessments are not necessarily associated with “picking winner and losers” (an issue of some sensitivity among government agencies and policymakers). For a given pathway and feedstock, technoeconomic assessments of discrete technology elements can ascertain where the most gain might be achieved for a given level of research effort.

Hydrogen Price and Availability

Hydrogen is needed for almost all SAJF production, and in several conversion processes (those with potentially the lowest feedstock costs) it represents a significant portion of operating cost.

Hydrogen is needed for SAJF production because the ratio of hydrogen atoms to carbon atoms in jet fuel molecules is typically higher than the hydrogen-to-carbon ratio in feedstocks. Thus, in almost all cases, hydrogen is a key input to the feedstock conversion process. In many regions associated with abundant supplies of feedstock, hydrogen is not readily accessible, particularly at reasonable cost. In many cases, hydrogen can be supplied from the conversion of natural gas, but natural gas infrastructure is also limited. Biogas (e.g., from manure digesters, waste-water treatment plants, landfills, or other biomass conversion techniques) could facilitate production of the large amounts of hydrogen typically needed for SAJF production, and it could do so with minimal increase in life-cycle carbon emissions. Even in that case, however, infrastructure could still be an issue, for example, to transfer locally produced biogas from a very large number of broadly distributed sources into distribution pipelines.

SAJF Development and Demonstration Projects

Additional, affordable SAJF demonstration and deployment efforts are needed to adequately address economic and technical risks.

After several decades of on-again, off-again development of SAJF, coupled with some well-publicized commercialization failures, major SAJF economic and technical challenges persist. As a result, members of the investment and finance community are generally uncomfortable with the risk associated with development of commercial facilities. The engagement of large, well-respected commercial engineering and construction companies who could provide turnkey project development and performance guarantees would help to alleviate such concerns, but unresolved risks have likewise dissuaded these companies from taking on such a role, implying that demonstration and deployment efforts executed to date have not been successful enough to move to the next step.

Funding for SAJF Capital Investments

Uncertainty about economic viability of SAJF production has impeded engagement from the petroleum industry or other large industrial entities that could bring appropriate resources to bear on addressing economic challenges.

Some incremental capital costs are driven by perceptions of unabated high risk resulting from uncertainties about the economic viability of SAJF.

Challenges for Small SAJF Start-Ups

Start-ups are unable to explore and leverage the full range of technical and economic opportunities that might provide sufficient economic benefit to facilitate commercialization.

The likelihood that small, underresourced entrepreneurs will be able to successfully commercialize new SAJF technology would be greatly enhanced if R&D organizations had more insight into opportunities to minimize the risks and maximize the economic returns of a new SAJF endeavor. Mechanisms that could provide that insight (e.g., national databases of opportunities, foundational analytical work, and feasibility studies) are lacking. Areas of potential interest include the following:

- Use of idled brownfield or other distressed properties to lower capital requirements, receive favorable tax treatment, and/or reduce operating expense (e.g., through the use of excess hydrogen capacity from an adjacent industrial process).

- The pursuit of technology refinements and/or scale that would reduce capital and operating expenses (e.g., through less expensive catalysts, more efficient processes, or a reduced need for consumables such as water, chemical reagents, and catalysts).
- Use of lower cost feedstocks (e.g., municipal solid wastes, steel mill offgases, and other waste streams).
- Reducing the cost of more traditional feedstocks, either through commercial mechanisms (e.g., long-term contracting, vertical integration, and use of aggregators) or actual reduction in costs (e.g., improvements in agronomy).
- Development of new feedstocks that can be delivered to the refinery gate with more accessible energy content per unit cost by, for example, fostering the breeding or development of new species of biomass with more useful energy content per unit volume or mass.
- Development of high-value products that can be coproduced with SAJF.

Technical Challenges

Several SAJF production pathways have been demonstrated, and others are in varying stages of development. Even so, several remaining technical challenges need to be overcome to enable economically competitive large-scale production of SAJF using a wide range of promising feedstocks.

Feedstock Development

Despite progress to date in developing feedstocks, in many cases, SAJF feedstocks are widely dispersed, they are unwieldy (e.g., they may have low bulk density, small seed size, and/or high moisture content), and/or they are not easily collected, transported, stored, or pre-processed with existing equipment.

Feedstock Conversion Technologies

Cost-effective conversion technologies are not available for some promising feedstocks.

SAJF Fuel Testing, Qualification, and Certification Processes

It takes longer than it should to commercialize new SAJF production methods, in part because of the cost and time required to complete current fuel qualification and certification processes. Improvements to the qualification process are also needed to enable compositionally based evaluation of additional SAJF production pathways.

Fuel qualification and certification processes are costly, fuels required for testing are difficult to produce in sufficient quantities in reasonable amounts of time, and the entities pursuing qualification are typically small, underfunded start-up organizations that will also need to deal with the many other technical and economic challenges that a start-up company usually encounters.

An industry process has been established through the use of standard ASTM practices and specifications, and it is being used to qualify production pathways for alternative jet fuels. The ASTM testing and qualification process, however, has limited throughput, it is highly dependent on physical testing for validation, and it is insufficiently based on science (chemistry and combustion sciences). Progress is being made, but key shortfalls exist in several areas: (1) lack of testing facilities, (2) lack of fundamental understanding of the impact of chemical composition on physical properties, (3) uncertainties about the compatibility of various fuel molecules and combinations of molecules with materials generally used in aircraft fuel systems, gas turbines, and existing fuel supply and storage infrastructure, and (4) lack of pilot scale research and process demonstration facilities. These shortfalls are impeding the broad commercialization of such fuels. For example, equipment and infrastructure owners are uncertain about the direct impact of various SAJF compositions, so they typically request a full set of materials compatibility testing for each proposed fuel conversion process. Further, the industry would benefit from a more compositionally-based specification to allow for expedited consideration of fully synthetic fuels and to allow the blending of various synthetic blending components.

Policy Challenges

Policy elements (and subsequent rule making) can clearly impact the potential for SAJF development and commercialization, particularly if they are able to assist in closing any portion of an existing price gap between the price of petroleum-based jet fuel and SAJF. It is beyond the scope of this study to assess or recommend new policies that would incentivize the production of SAJF; however, the committee has identified two policy challenges to implementing SAJF technologies.

Renewable Fuel Standard

Uncertainties about the long-term impact of the U.S. Renewable Fuel Standard, which provides indirect incentives for the production of SAJF, limit its effectiveness in fostering the development of an SAJF industry.

As in any industry, investment and engagement are enhanced by long-term, well-defined policies that provide stability. Stability lowers risk, and gives investors, developers, and financiers the certainty that their business models are sound for the life of the project. This has proven to be problematic with the current U.S. Renewable Fuel Standard, which sets annual minimum requirements for the distribution of biofuels as a ground transportation fuel. (In 2022, the requirement amounts to about 7 percent the expected U.S. demand for gasoline and diesel fuel.[21]) Uncertainty has arisen because of delays to the implementation of the biofuel mandate, because of congressional debate about its value, and because of uncertainties about fuel standards for 2023 and beyond, which have yet to be defined.

Sustainability Assessment Models and Requirements

There is no well-defined, internationally adopted framework for sustainability analysis of alternative jet fuels.

The variability in the many different sustainability frameworks complicates the process of developing SAJF that can be widely marketed as meeting "sustainability needs," and it increases uncertainty about the economic feasibility of SAJF. The variability and uncertainty might also influence policy or decisions that have established relatively high hurdles for various metrics. For example, both the U.S. Renewable Fuel Standard and the independent Roundtable on Sustainable Biomaterials have established the need for advanced fuels to achieve at least a 50 percent reduction in life-cycle CO_2 emissions.[22] This disincentivizes the potential of some synthetic fuel production pathways that could produce lesser but still substantial reductions in life-cycle carbon emissions.

ONGOING EFFORTS TO DEFINE A FEDERAL ALTERNATIVE JET FUEL R&D STRATEGY

In 2013 several government agencies and their public–private partnerships involved in the development and commercialization of SAJF recognized the need to further coordinate the broad range of activities occurring in the public and private sectors to improve the focus, effectiveness, and timeliness of such efforts. Discussions among involved federal agencies[23] led to an agreement to develop and initiate a Federal Alternative Jet Fuel R&D Strategy

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[21] In the United States, there is no mandate for the production of SAJF. The Renewable Fuel Standard provides a mechanism that allows the production of SAJF to indirectly contribute to a fuel producer's obligations under the Standard to produce biofuel for ground transportation.

[22] For cellulosic biofuel pathways, the minimum acceptable reduction is 60 percent.

[23] Department of Commerce, Department of Defense, Department of Energy, Department of Transportation, Environmental Protection Agency, NASA, National Science Foundation, and the Department of Agriculture.

under the leadership of the White House Office of Science and Technology Policy (OSTP).[24] This new strategy will target the following objectives:

- Identify key scientific and technical barriers to development of SAJF.
- Provide federal agencies with detailed national goals and objectives to inform their R&D program decisions, including budgeting and prioritization.
- Promote crosscutting and collaborative R&D activities by both federal and nonfederal stakeholders.

The process of developing the strategy has included workshops, meetings, and other interactions with stakeholders from industry, nongovernmental organizations, academia, state and local governments, and potential producers of SAJF. The strategy is intended to be a comprehensive document that provides a shared and actionable SAJF R&D plan that mobilizes public and private stakeholders to address key scientific and technical challenges over the near-, mid-, and far-terms.

RATIONALE FOR SUSTAINABLE ALTERNATIVE JET FUELS

Finding. *Rationale for Sustainable Alternative Jet Fuels. S*ustainable alternative jet fuels (SAJF) will be able to reduce life-cycle CO_2, emissions, and in some cases the reductions may be substantial. SAJF have the potential to immediately lower net global CO_2 emissions from commercial aviation because, as drop-in fuels, they are compatible with existing aircraft and infrastructure. Thus, their widespread use will not be limited by the rate at which new aircraft replace existing aircraft. The combustion of SAJF will likely also produce lesser amounts of other harmful emissions, such as oxides of sulfur and particulate matter, than the combustion of equivalent amounts of conventional jet fuel. SAJF are also compatible with and complementary to the three other high-priority approaches recommended in this report for reducing carbon emissions.

RECOMMENDED HIGH-PRIORITY RESEARCH PROJECTS

The high-priority research projects described below are necessary but not sufficient to enable broad development, commercialization, and use of SAJF; sustained progress is required over a wide range of interrelated efforts. Furthermore, the recommended research projects will not address all of the economic and policy challenges discussed above, because not all of them can be overcome solely through typical R&D.

SAJF Industry Modeling and Analysis

This project would undertake research to enable detailed and comprehensive modeling and analysis of SAJF development efforts and impacts at microscale (individual projects) and macroscale (nationwide or worldwide) levels to support the needs of policymakers and industry practitioners.

Key tasks to execute this research project are listed below. Relevant federal agencies include the U.S. Department of Energy (DOE), Department of Transportation (DOT), Federal Aviation Administration (FAA), and U.S. Department of Agriculture (USDA).

- Conduct comprehensive comparative technoeconomic assessments of potential SAJF feedstocks and conversion processes.
  - —Develop models for, and conduct comparative technoeconomic assessments of, SAJF feedstocks and conversion processes.
  - —Use these models, along with existing frameworks and databases, to create a comprehensive database

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[24] Committee on Technology, National Science and Technology Council, OSTP.

  of relevant SAJF feedstocks and conversion processes. Use the results of technoeconomic assessments to inform R&D prioritization to improve the effectiveness of integrated R&D efforts.
  - Institute a process to periodically refresh technoeconomic assessments and to evaluate new SAJF production pathways of interest as they are identified, for example, through interactions with organizations such as the ASTM International Committee on Petroleum Products, Liquid Fuels, and Lubricants, the Coordinating Research Council, the Commercial Aviation Alternative Fuels Initiative, and the Federal Aviation Administration's Center of Excellence for Alternative Jet Fuels and Environment.
- Enhance system modeling and analysis capabilities for microscale (individual projects) and macroscale (nationwide or worldwide) evaluations of potential impacts and benefits of SAJF development and commercialization to support for policy and business decision making.
- Advance the science, application, and harmonization of sustainability analysis, particularly with regard to life-cycle CO_2 modeling.

Low-Cost Feedstocks

Support continued development of sustainable, low-cost feedstocks and associated systems that have the potential to enable the large-scale production of economically viable SAJF.

Key tasks to execute this research project are listed below. Relevant federal agencies include DOE, DOT, the Environmental Protection Agency (EPA), and USDA.

- Identify and develop feedstocks that could enable economically viable and sustainable production of SAJF. For example, efforts to develop feedstocks from agricultural and wood products could target reductions in input requirements, enhancements in recoverable energy content, or those with attributes that enable lower cost processing.[25]
- Develop strategic approaches to more fully explore viable usage of waste streams that are large in volume, relatively constant in supply, ubiquitous in availability, low in cost, and have established production and/or collection systems in place. Waste streams of potential interest include:
  - Municipal solid waste, including a comprehensive approach to utilization of nonrecyclables (organics, plastics, tires, etc.).
- Human waste and sanitary waste treatment (e.g., gasification or other conversion of sludge, and use of biogas from digesters).
  - Animal waste, especially since waste disposal, groundwater contamination, and nutrient leaching are becoming significant issues that could negatively impact the availability of low-cost food production.
  - Food processing waste.
  - Gaseous waste such as carbon monoxide, hydrogen, CO_2, and methane, which in some cases arise from the above sources.
- Use the results of feedstock evaluations performed under the SAJF Industry Modeling research project, above, to inform and prioritize feedstock development activities, within existing programs.

Conversion Processes, Fuel Production, and Scale-Up

Develop technologies and processes for cost-effective feedstock conversion, fuel production, and scale-up from pilot and demonstration facilities to enable full-scale production of SAJF.

Key tasks to execute this research project are listed below. Relevant federal agencies include the Department of Defense (DOD) and DOE.

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[25] U.S. Department of Energy, 2015, *Advanced Feedstock Supply System Validation Workshop Summary Report: Mobilizing the Billion Tons*, INL/EXT-10-18930, Washington, D.C., https://www.bioenergykdf.net/system/files/1/15-50315-R3_Summary_Report_Only_ONLINE.PDF.

- Create additional process development facilities[26] to enhance the ability of SAJF conversion technology developers to move expeditiously from bench-top to pilot scale with minimal capital and operating expenses.
    - —Design facilities to be of sufficient flexibility and complexity to enable R&D (fundamental and applied) on an extremely broad range of thermochemical and biochemical conversion, and fuel finishing processes.
    - —Design facilities of sufficient scale to allow for production of sufficient quantities of SAJF to complete qualification processes in accordance with relevant ASTM standards (i.e., ASTM D4054 and D7566).
    - —Enhance the ability of facilities to access applicable human and technical resources from the National Labs, from a broad range of disciplines.
- Pursue development of fuel conversion and finishing processes and equipment, focusing first on processes common to multiple conversion processes.
- Foster the development of lower-cost hydrogen production to provide the hydrogen that is needed for almost all SAJF production.

SAJF Fuel Testing, Qualification, and Certification

Improve fuel testing, qualification, and certification processes to lower testing costs, increase throughput, and enhance understanding of fuel properties.

Key tasks to execute this research project are listed below. Relevant federal agencies include the Department of Commerce, DOD, DOE, DOT, NASA, the National Science Foundation.

- Eliminate or reduce time-consuming and costly physical testing by developing a low-cost, high throughput approach to meeting ASTM specifications and qualifications standards relevant to SAJF (i.e., ASTM D4054 and D7566). This will likely require determining which molecular components in the family of molecules in SAJF are causes for concern with respect to material compatibility.
- Bolster current efforts, such as those by the FAA Aviation Sustainability Center's National Jet Fuels Combustion Program, to develop a research program to improve the ability to characterize combustion attributes of properties of various SAJF constituents using analysis and simpler testing. Similar work could focus on qualification and quantification of environmental effects (nearer term) and turbomachinery health and performance benefits (longer term) of potential SAJF pathways. This would likely enable the SAJF community to move away from a reliance of rote physical testing, which is costly and timely, to more of an analytical approach, and better optimize the type of engine, auxiliary power unit, and/or rig testing that is needed to resolve any outstanding issues. This would also support the development of a more-compositionally based specification, and facilitate the development of concepts for 100 percent drop-in fuels from single SAJF sources, as well as blends from multiple SAJF sources.
- Assess the environmental effects (nearer term) and turbomachinery performance benefits (longer term) of potential SAJF pathways.
- Develop a database, made broadly available to the members of the SAJF community, of fuel feedstocks, processes, fuel properties, and combustion emission characteristics to facilitate utilization of alternative jet fuels.

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[26] This is envisioned as enabling similar success to what has been previously demonstrated (e.g., what the Assured Aerospace Fuels Research Facility at Wright Patterson Air Force Base has done for HEFA-SPK development, and what the Alternative Fuels User Facility and Thermochemical Pilot and Users Facility at the Department of Energy's National Renewable Energy Laboratory and the Advanced Biofuels Process Demonstration Unit at Lawrence Berkeley National Lab have done for biologic conversion development.

6

Findings, Recommendations, Roles, and Resources

APPROACHES FOR REDUCING CO_2 EMISSIONS

Finding. *CO_2 Emissions from Commercial Aircraft*. More than 90 percent of CO_2 emissions from global commercial aircraft operations are generated by large aircraft (i.e., twin-aisle and single-aisle airplanes with more than100 passengers), so research to reduce commercial aircraft emissions will be most useful if it focuses on technology applicable to these large commercial aircraft.

Recommendation. *High-Priority Approaches.* Agencies and organizations in government, industry, and academia with an interest in developing propulsion and energy system technologies that could reduce CO_2 emissions from global civil aviation and that could be introduced into service during the next 10 to 30 years should execute a national research agenda that places the highest priority on four approaches:

- **Advances in aircraft–propulsion integration,**
- **Improvements in gas turbine engines,**
- **Development of turboelectric propulsion systems,[1] and**
- **Advances in sustainable alternative jet fuels.**

Finding. *Rationales*. The rationales for investing in each of the four recommended high-priority approaches are as follows:

- *Aircraft–propulsion integration research*. Advances in the integration of aircraft and propulsion are needed to enable many aspects of low-carbon aviation that are not achievable with the incorporation of discrete improvements in individual component technologies. Areas of interest include both evolutionary

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[1] Turboelectric propulsion systems use gas turbines to drive electrical generators that power electric motors that drive propulsors (fans or propellers). A partial-turboelectric system is a promising variant of the full turboelectric system that uses electric propulsion to provide part of the propulsive power; the rest is provided by a turbofan driven by a gas turbine. In contrast, hybrid electric systems use high-capacity batteries to provide some or all of the propulsive power during one or more phases of flight, and all-electric systems rely solely on batteries for propulsive power. The term "electric propulsion" encompasses all of these concepts.

configurations such as lower fan pressure ratio engines in nacelles on standard tube-and-wing aircraft as well as significant departures from standard configurations including modified aircraft platforms, distributed propulsion concepts, and boundary layer ingestion configurations.

- *Gas turbine engine research*. Gas turbine engines have considerable room for improvement, with a potential to reach overall efficiencies perhaps 30 percent higher than the best engines in service today, with a concomitant reduction in CO_2 emissions. This magnitude of gain requires investment in a host of technologies to improve thermodynamic and propulsive efficiency of engines, with each discrete technology contributing only a few percent or less.
- *Turboelectric propulsion research*. Turboelectric propulsion systems are likely the only approach for developing electric propulsion systems for a single-aisle passenger aircraft that is feasible in the time frame considered by this study. System studies indicate that turboelectric propulsion systems, in concert with distributed propulsion and boundary layer ingestion, have the potential to ultimately reduce fuel burn up to 20 percent or more compared to the current state of the art for large commercial aircraft.[2]
- *Sustainable alternative jet fuels research. S*ustainable alternative jet fuels (SAJF) will be able to reduce life-cycle CO_2 emissions, and in some cases the reductions may be substantial. SAJF have the potential for immediate impact on lowering net global CO_2 emissions from commercial aviation because, as drop-in fuels, they are compatible with existing aircraft and infrastructure. Thus, their widespread use will not be limited by the rate at which new aircraft replace existing aircraft. The combustion of SAJF will likely also produce lesser amounts of other harmful emissions, such as oxides of sulfur and particulate matter, than the combustion of equivalent amounts of conventional jet fuel. SAJF are also compatible with and complementary to the three other high-priority approaches recommended in this report for reducing carbon emissions.

Hybrid-electric and all-electric systems were considered but are not recommended as a high priority because the committee determined that batteries with the power capacity and specific power[3] required for commercial aircraft at least as large as a regional jet are unlikely to be matured to the point that products satisfying FAA certification requirements can be developed within the 30-year time frame addressed by this report. The same situation applies to technologies associated with superconducting motors and generators, fuel cells, and cryogenic fuels, and other potential approaches and technologies that are not included in the list of high-priority approaches above or the list of high-priority research projects described below.

CHALLENGES

Finding. *Systemic Challenges*. To be successful, any approach to reducing CO_2 emissions from commercial aviation must overcome two systemic challenges:

- *Economic competitiveness*. Aviation is a highly competitive industry for which reduction in fuel burn (and, thus, CO_2) is a major technology driver. Cost considerations can be a challenge and have to be taken into account as new systems are proposed for commercial development.
- *Aircraft systems complexity and integration*. Commercial aircraft are composed of many distinct systems that are carefully integrated and regulated to maximize performance and safety. Disciplined system integration is required to introduce new technologies so that the improvement of one system does not adversely impact the performance of other systems or the performance of the aircraft as a whole.

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[2] Although turboelectric concepts include a gas turbine, the potential improvements resulting from research in gas turbine engine research (potentially up to 30 percent) and turboelectric propulsion (potentially up to 20 percent) do not together imply that future aircraft have the potential for improvements up to 50 percent.

[3] In this report, "specific power" and "specific energy" refer to power and energy per unit mass, respectively, and "power density" and "energy density" refer to power and energy per unit volume.

Finding. *Technical, Economic, and Policy Challenges*. The success of each individual approach to reducing CO_2 emissions from commercial aviation requires overcoming technical, economic, and/or policy challenges.

Aircraft–Propulsion Integration Research

Technical Challenges

- *Propulsive efficiency*. Low fan pressure ratios are needed to reduce exhaust velocities and thereby improve propulsive efficiency, regardless of whether the fan is driven by a gas turbine or an electrical motor. For a constant level of thrust, this requires that the effective fan area increase so as to avoid commensurate increases in weight, drag, and integration losses.
- *Boundary layer ingestion*. To use boundary layer ingestion and wake cancellation to reduce aircraft cruise energy requirements, an aircraft configuration integrated with a propulsor design is needed in which the overall benefits of wake cancellation outweigh the costs in terms of propulsor efficiency, noise, and weight.

Economic Challenge

- *Relative economic value*. A balanced technology investment portfolio in aircraft–propulsion integration research is needed to ensure that economic uncertainties arising from changes in net fuel price do not slow continued reductions in emissions by commercial aircraft.

Policy Challenge

- *Certification*. Technical and policy issues surrounding certification of aircraft and propulsion concepts and technologies not covered by current certification procedures are important for guiding technology development. In addition, manufacturers must have confidence that these issues will be resolved in a timely fashion before they are likely to begin advanced development of the relevant aircraft and propulsion systems.

Gas Turbine Engine Research

Technical Challenges

- *Propulsive efficiency*. Low fan pressure ratios are needed to reduce exhaust velocities and thereby improve propulsive efficiency, regardless of whether the fan is driven by a gas turbine or an electrical motor. For a constant level of thrust, this requires that the effective fan area increase so as to avoid commensurate increases in weight, drag, and integration losses.[4]
- *Thermodynamic efficiency*. Enabling higher operating temperatures is a prerequisite to achieving significant improvement in gas turbine engine thermodynamic efficiency, and a major impediment to achieving higher operating temperatures is the difficulty of developing advanced materials and coatings that can withstand higher engine operating temperatures.
- *Small engine cores*. Activities being pursued to either improve the thermodynamic efficiency of gas turbine cores or improve overall aircraft efficiency result in smaller core sizes. For single-aisle aircraft, this tendency to core size reduction creates multiple challenges for maintaining and improving efficiencies of the overall engine and engine-aircraft integration.

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[4] This challenge, which also appears as a challenge for aircraft–propulsion integration, is listed as a challenge for gas turbine research because it is a prerequisite for achieving significant improvement in gas turbine engine propulsive efficiency.

Turboelectric Propulsion Research

Technical Challenges

- *Electrical technologies*. The state of the art of electrical technologies for motors, generators, power distribution, and power electronics (for example, inverters, converters, and circuit protection) will need to advance to enable turboelectric propulsion concepts for large commercial aircraft.
- *Aircraft systems*. Turboelectric aircraft propulsion systems present a number of challenges related to other aircraft systems (e.g., thermal management systems). More structurally and aerodynamically efficient configurations can help address these challenges.
- *Research infrastructure for electrical technologies*. The research and development of megawatt-class turboelectric aircraft propulsion systems is hampered by the lack of development testing facilities.

Sustainable Alternative Jet Fuels Research

Economic Challenges

- *Feedstock price and availability.* Currently achievable refinery-gate feedstock prices are expensive relative to the final product, which is driven in part by immature or nonexistent feedstock supply chains.
- *Industrial sector collaboration*. The nascent SAJF industry lacks the inherent elements of collaboration of a fully developed industrial sector; these elements are required for initial matching of supply and demand signals and for subsequent system optimization.
- *Technoeconomic factors*. Lack of technoeconomic assessments and comparative understanding of various approaches impedes the ability of industry and the researchers and agencies that support SAJF R&D to make practical decisions about the prioritization of R&D and demonstration and deployment efforts.
- *Hydrogen price and availability*. Hydrogen is needed for almost all SAJF production, and in several conversion processes (those with potentially the lowest feedstock costs) it represents a significant portion of operating cost.
- *SAJF development and demonstration projects*. Additional, affordable SAJF demonstration and deployment efforts are needed to adequately address economic and technical risks.
- *Funding for SAJF capital investments*. Uncertainty about economic viability of SAJF production has impeded engagement from the petroleum industry or other large industrial entities that could bring appropriate resources to bear on addressing economic challenges.
- *Challenges for small SAJF start-ups*. Start-ups are unable to explore and leverage the full range of technical and economic opportunities that might provide sufficient economic benefit to facilitate commercialization.

Technical Challenges

- *Feedstock development*. Despite progress to date in developing feedstocks, in many cases, SAJF feedstocks are widely dispersed, they are unwieldy (e.g., they may have low bulk density, small seed size, and/or high moisture content), and/or they are not easily collected, transported, stored, or preprocessed with existing equipment.
- *Feedstock conversion technologies*. Cost-effective conversion technologies are not available for some promising feedstocks.
- *SAJF fuel testing, qualification, and certification*. It takes longer than it should to commercialize new SAJF production methods, in part because of the cost and time required to complete current fuel qualification and certification processes. Improvements to the qualification process are also needed to enable compositionally based evaluation of additional SAJF production pathways.

Policy Challenges

- *Renewable fuel standard*. Uncertainties about the long-term impact of the U.S. Renewable Fuel Standard, which provides indirect incentives for the production of SAJF, limit its effectiveness in fostering the development of an SAJF industry.
- *Sustainability assessment models and requirements*. There is no well-defined, internationally adopted framework for sustainability analysis of alternative jet fuels.

HIGH-PRIORITY RESEARCH PROJECTS

Chapters 2-5 identified high-priority approaches and research projects for developing propulsion and energy systems to reduce commercial aviation carbon emissions globally. The research projects respond to all of the technical challenges, but some of the economic and policy challenges cannot be overcome by research and technology development.

Recommendation. *National Research Agenda.* Agencies and organizations in government, industry, and academia with an interest in developing propulsion and energy system technologies that could reduce CO_2 emissions from global civil aviation and could be introduced into service during the next 10 to 30 years should execute a national research agenda focused on high-priority research projects in the four recommended high-priority approaches, as follows:

- ***Aircraft–Propulsion Integration Research***
  - — ***Nacelles for ultrahigh bypass ratio gas turbines.* Develop nacelle and integration technologies to enable ultrahigh bypass ratio propulsors.[5]**
  - — ***Boundary layer ingestion.* Pursue technologies that can enable boundary layer ingestion to reduce the velocity defect in the aircraft wake (also known as wake cancellation) and thus reduce cruise energy consumption.**
- ***Gas Turbine Engine Research***
  - — ***Low pressure ratio fan propulsors.* Develop low pressure ratio fan propulsors to improve turbofan propulsive efficiency.**
  - — ***Engine materials and coatings.* Develop materials and coatings that will enable higher engine operating temperatures.**
  - — ***Small engine cores.* Develop technologies to improve the efficiency of engines with small cores so as to reach efficiency levels comparable to or better than engines with large cores.**
- ***Turboelectric Propulsion Research***
  - — ***Turboelectric aircraft system studies.* Conduct more encompassing studies of aircraft powered by turboelectric systems in order to better understand the benefits, component performance sensitivities, certification issues, and trade-offs related to key aircraft systems, such as thermal management and energy storage.**
  - — ***Core turboelectric technologies*. Develop the core technologies that are required for megawatt-class turboelectric propulsion systems: motors, generators, inverters, power distribution, and circuit protection.**
  - — ***Megawatt-class research facilities.* Develop research facilities for megawatt-class electric power and thermal management systems suitable for testing turboelectric aircraft propulsion systems.**
- ***Sustainable Alternative Jet Fuels Research***
  - — ***SAJF industry modeling and analysis.* Undertake research to enable detailed and comprehensive modeling and analysis of SAJF development efforts and impacts at microscale (individual projects)**

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[5] This research project is closely related to the gas turbine research project on low pressure ratio fan propulsors, and work on the two projects should be closely coordinated.

and macroscale (nationwide or worldwide) levels to support the needs of policymakers and industry practitioners.

- ***Low-cost feedstocks.*** **Support continued development of sustainable, low-cost feedstocks and associated systems that have the potential to enable the large-scale production of economically viable SAJF.**
- ***Conversion processes, fuel production, and scale-up.*** **Develop technologies and processes for cost-effective feedstock conversion, fuel production, and scale-up from pilot and demonstration facilities to enable full-scale production of SAJF.**
- ***SAJF fuel testing, qualification, and certification.*** **Improve fuel testing, qualification, and certification processes to lower testing costs, increase throughput, and enhance understanding of fuel properties.**

ROLES AND RESOURCES

It will not be possible to execute the recommended research agenda without commitment, resources, leadership, and focus from relevant agencies and organizations in government, industry, and academia. Within the government, key players include the Department of Defense (DOD), the Department of Energy (DOE), the Federal Aviation Administration (FAA), NASA, the Department of Agriculture, the Department of Transportation, the Environmental Protection Agency, and the National Science Foundation.

Roles

Supporting research in all four of the high-priority approaches is prudent both to reduce current CO_2 emissions and to alleviate the potential consequences of future aviation growth worldwide. The research projects within each high-priority approach would rely on academia and industry to play the same role that they normally play in the development of new technologies and products. In particular, academia would generally participate in the projects at lower levels of technology readiness, while industry would focus on more advanced research and product development.

The FAA would be most directly engaged in the development of certification standards and methodologies for technologies not well covered by current practices.

DOD would have an interest in all four of the high-priority approaches to the extent that they could improve the capability of military aircraft or, in the case of SAJF, address the larger goal of reducing the environmental impact of defense operations.

NASA would contribute primarily by supporting basic and applied research in all four approaches, though it would likely play a lesser role in SAJF development given that much of the research (e.g., on feedstocks and fuel conversion processes) does not concern a NASA mission area.

DOE and its national laboratories would contribute primarily to the development of batteries, fuel cells, gas turbines, and SAJF feedstocks and conversion processes.

The primary contributions of the Department of Agriculture and Environmental Protection Agency would be feedstock development and modeling of the SAJF industry, and the Department of Transportation would also make broad contributions to the SAJF research projects.

The Department of Commerce and National Science Foundation could help primarily in improving fuel testing, evaluation, and qualification processes for SAJF.

> **Recommendation. *Organizational Research Priorities*. The relative priority that various agencies and organizations assign to the four recommended high-priority approaches and research projects within each approach should be guided by (1) the importance a given organization attaches to the rationales associated with each approach, (2) the resident expertise and mission objectives of the organization, and (3) the desired mix of a given organization's research portfolio in terms of risk, technical maturity, and economic potential.**

Resources

Developing new technology for large commercial aircraft requires substantial time and resources, and there are well-established pathways for doing so, particularly with regard to improving gas turbine technology and aircraft–propulsion integration. Both of these approaches are well established and there are substantial motivations for four organizations with extensive research capabilities—the Department of Defense (and, in particular, its research laboratories), the Department of Energy (and its national laboratories), NASA (and its research centers), and the commercial aircraft industry (and its research centers)—to develop advanced technologies. In fact, these organizations, among others mentioned above, are already developing advanced technologies that are relevant to low carbon aviation. Although the missions of these organizations are very different, there are many points of commonality, and even greater progress could be accomplished by aligning relevant research programs in accordance with the recommended high-priority approaches and research projects.

In contrast, the funding situation for the other two approaches, turboelectric propulsion and SAJF, is somewhat problematic. It is not clear when turboelectric propulsion technology will advance to the point that it provides the performance needed for practical application in commercial aircraft. It is similarly uncertain when SAJF will be able to compete economically with conventional (petroleum-based) jet fuels, especially considering the capital costs of founding a new industry, and the fluctuating prices of conventional jet fuel. Currently available resources are making technological advances relevant to turboelectric propulsion and SAJF. Financial requirements, however, will increase substantially as the level of technology readiness increases and the next step requires, for example, flight tests of prototypes of high-power turboelectric systems or the development of full-scale SAJF production facilities. Even so, the turboelectric research projects will likely be able to maintain momentum as long as they achieve technological milestones for higher power systems. Options for sustaining SAJF research include leveraging the interest of multiple agencies with more focus on addressing global climate and energy concerns, such as the Department of Defense, the Department of Energy, the Department of Transportation, the Office of Science and Technology Policy, and entities interested in fostering rural and economic development, such as the Department of Agriculture, Department of Commerce, and state and local governments and public-private partnerships.

Appendixes

A

Statement of Task

The National Research Council will convene an ad hoc committee to develop a national research agenda with the objective of reducing life-cycle carbon emissions from commercial aviation globally, even if air traffic grows as expected. The recommended research agenda will consist of a prioritized set of research projects of importance to the national and international commercial aeronautics community, and it will focus on advances in technologies and capabilities that can only be achieved through substantial research and technology development. Specifically, the committee will focus on new or more highly efficient propulsion (such as hybrid-electric) and energy systems (such as biofuels, batteries, and fuel cells). This includes consideration of the opportunities and challenges that changes in propulsion and energy technologies have for aircraft configurations, airline operational models, and infrastructure integration. Other key considerations include economic, regulatory and other policy opportunities and challenges that would be associated with a potential major change in propulsion and/or energy systems. This study is focused on propulsion and energy systems research; it will not develop recommendations for research in other areas such as airframe designs or air traffic management systems. In addition, the scope of this study excludes non-technology, policy approaches such as the imposition of carbon taxes, the use of carbon offsets, or legislative limits on carbon emissions.

Carbon emissions should be considered over the entire life-cycle of the energy system (from source to use) as well as potential life-cycle environmental impacts of changes to the vehicle/propulsion system (from production to use to disposal/recycle).

In particular the committee will:

1. Consider the following:

    a. Current goals, guidance and plans by government, industry, and other relevant bodies to reduce carbon emissions globally from civil aviation in the face of increasing demand for air transportation.
    b. The current state of the art in lower-carbon propulsion and energy systems, lower-carbon propulsion and energy research efforts, and relevant research for other applications (for example, national defense, space, automotive, and marine applications) by industry, NASA, the Department of Defense, the Federal Aviation Administration, the Department of Energy, other federal agencies, academia, and non-U.S. research agencies and organizations.

2. Discuss the following:

   a. Research leading to advances in propulsion and energy system technologies that could be introduced into service during the next 10 to 30 years and that would reduce global carbon emissions by commercial aviation. Consider technologies that might contribute to (i) a steady pace of incremental advances and (ii) credible, step changes in advancing current capabilities.
   b. Synergistic opportunities and challenges for integration of advanced propulsion and energy systems with conventional and advanced airframe configurations, alternative airline concepts of operation, and with integration within the aviation and broader transportation and energy infrastructures.
   c. Other economic, technical, regulatory, and policy barriers, key challenges, and opportunities, both domestically and internationally, for implementing next-generation technologies for reducing global commercial aviation carbon emissions.

3. Outline a potential national research agenda to advance propulsion and energy systems to reduce global carbon emissions from commercial aviation, as follows:

   a. A broad vision for an aviation system powered by low-carbon propulsion and energy systems.
   b. A range of the most promising propulsion and energy system options to achieve the vision and the major technical, economic, and policy challenges associated with those major options.
   c. A research agenda consisting of a set of research projects, grouped by priority, that if successful could enable the most promising options.
   d. The agenda should be developed with due consideration of the resources and organizational partnerships required to complete the projects included in the agenda.
   e. The research agenda should, as appropriate, describe the potential contributions and role of U.S. research organizations, including NASA, other federal agencies, industry, and academia.

B

Committee and Staff Biographical Information

KAREN A. THOLE, *Co-Chair*, is professor and department head of mechanical and nuclear engineering at the Pennsylvania State University. Dr. Thole's scholarship in research has been focused on experimental fluid mechanics and heat transfer, particularly as applied to developing new cooling methods for gas turbine components. More recently, she has used advanced manufacturing methods to further develop new cooling methods for turbine airfoils. She founded two experimental research laboratories at Pennsylvania State University: the Experimental and Computational Convection Lab (ExCCL) and the Steady Thermal Aero Research Turbine (START) Lab, with both being selected as centers of excellence for one of the major gas turbine manufacturers. She has published nearly 200 archival journal papers and conference proceedings and holds three patents. Many of the cooling technologies she researched are now used on the engines that power the Joint Strike Fighter and commercial jets. She has served as the chair of the board of directors for the American Society of Mechanical Engineers' (ASME's) International Gas Turbine Institute, chair of the ASME Energy Conversion and Storage Segment, and a member of the NASA Advisory Council's Aeronautics Committee. Dr. Thole was a recipient of a National Science Foundation Career Award, was recognized by the White House as a 2011 Champion of Change in STEM, and as a Society of Women Engineers' 2014 Distinguished Engineering Educator. In 2015, she received ASME's George Westinghouse Gold Medal for her work in power generation, and in 2016 she received ASME's Edwin F. Church award for her contributions to mechanical engineering education. She holds a Ph.D. in mechanical engineering from the University of Texas, Austin.

WOODROW WHITLOW, JR., *Co-Chair*, is executive in residence in the Washkewicz College of Engineering at Cleveland State University (CSU). He assists the dean in strengthening the college, increasing enrollment and retention rates, adding new engineering education programs, and increasing the involvement of women and minorities in engineering studies. Prior to his appointment at CSU, Dr. Whitlow had a distinguished 34-year career with NASA. His areas of expertise include unsteady aerodynamics, computational fluid dynamics, and aeroelasticity. In his final NASA position of Associate Administrator for Mission Support, he managed a $3.8 billion budget to enable all program and institutional capabilities required to conduct NASA's aeronautics and space missions. Dr. Whitlow also served as the deputy director of Kennedy Space Center, director of Glenn Research Center, and director of the Critical Technologies Division in the Headquarters Office of Aeronautics. Dr. Whitlow was part of a team that drafted NASA's Aeronautics Blueprint, which included technology solutions for reducing carbon dioxide emissions while air traffic doubled over a 20-year period. Proposed concepts included alternative fuels, intelligent combustors, more fuel-efficient aircraft and propulsion systems, innovative vehicle concepts and propulsion cycles, and the use of advanced fuel cells and electric propulsion systems. Since 2006, Dr. Whitlow has served as chair of the U.S. National Committee for Airbreathing Engines and is the U.S. representative on the 29-nation International Society for Airbreathing Engines. He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA) and was chair of the 2010 AIAA Joint Propulsion Conference and a member of the executive steering committee for the 2014 and 2015 AIAA Propulsion and Energy Conference. Dr. Whitlow's awards include the Presidential Rank of Distinguished Executive, Presidential Rank of Meritorious Executive, NASA Distinguished Service Honor Medal, U.S. Black Engineer of the Year in Government, NASA Exceptional Service Honor Medal, NASA Equal Opportunity Honor Medal, the (British) Institution of Mechanical Engineers William Sweet Smith Prize, Minorities in Research Science Scientist-of-the-Year Award, and National Society of Black Engineers Distinguished Engineer of the Year Award. He also holds an honorary doctor of engineering degree from Cranfield University. He holds a Ph.D. in aeronautics and astronautics from MIT.

MEYER J. BENZAKEIN (NAE) is the Wright Brothers Institute Professor in the Aerospace Engineering Department and the assistant vice president for Aerospace and Aviation in the Office of Research at the Ohio State University. Previous positions at Ohio State University include director of the Propulsion and Power Center and chair of the Aerospace Engineering Department. He entered academia after retiring from General Electric Aircraft Engines, where for 10 years he was responsible for the research, technology development, and new product creation. At General Electric, he led the research effort in computational aerodynamics, aeroacoustics, aeromechanics, and combustion. Dr. Benzakein was responsible for the design and certification of all new commercial and military engines for 10 years at General Electric. He is a member of the National Academy of Engineering, a fellow of the AIAA, and a fellow of the Royal Aeronautical Society. In 2001 he received the Gold Medal of Honor from the Royal Aeronautical Society, and he is the recipient of the 2007 AIAA Reed Aeronautics Award. He has served on many industry and government advisory panels and received an honorary doctorate from the University of Poitiers, France, in 2006. He holds a Ph.D. in engineering mechanics from Wayne State University. He is a member of the Aeronautics and Space Engineering Board of the National Academies of Sciences, Engineering, and Medicine, and he has served on many other committees, including the Committee on Examination of the U.S. Air Force's Aircraft Sustainment Needs in the Future and Its Strategy to Meet Those Needs, the Panel on Air and Ground Vehicle Technology, and the Committee for the Evaluation of NASA's Fundamental Aeronautics Research Program.

R. STEPHEN BERRY (NAS) is the James Franck Distinguished Service Professor Emeritus of Chemistry at the University of Chicago and holds appointments at the college, the James Franck Institute, and the Department of Chemistry. He has also held an appointment in the School of Public Policy Studies at the university and has worked on a variety of subjects ranging from strictly scientific matters to a variety of topics in policy. His experimental research includes studies of negative ions, chemical reactions, detection of transient molecular species, photoionization, and other laser–matter interactions. Other research has involved interweaving thermodynamics with economics and resource policy, including efficient use of energy. Dr. Berry has chaired the Academies' Report Review Committee.

MARTY K. BRADLEY is a technical fellow at Boeing Commercial Airplanes in the Product Development Advanced Concepts Group. At Boeing he leads internally funded studies looking at advanced technologies and concepts for improved energy efficiency and reduced environmental impact. These include innovative configurations as well as improved aerodynamics, structures, systems, and advanced propulsion technologies, alternative fuels, and electric aircraft. He is chairman of the AIAA Green Engineering Program Committee, the focal point within the AIAA, bringing together environmental and aerospace technologies. His research interests include analysis of the life-cycle environmental impact of future Boeing products and environmental benefits and challenges of new aircraft technologies, new propulsion architectures, alternative fuels, and new energy technologies such as fuel cells, improved batteries, and hybrid systems. Previously, Dr. Bradley conducted similar research for Boeing Research and Technology and additionally was a leading researcher in the area of advanced high speed propulsion. He received a leadership award from the Commercial Aviation Alternative Fuels Initiative (CAAFI), an innovation award from Boeing for his work on the Subsonic Ultra Green Aircraft Research (SUGAR) program, and awards from NASA for his advanced propulsion projects. He holds a Ph.D. in aerospace engineering from the University of Southern California.

STEVEN J. CSONKA is the executive director of the Commercial Aviation Alternative Fuels Initiative (CAAFI), a public–private partnership involving the Federal Aviation Administration (FAA) Office of Environment and Energy; the Airports Council International-North America, representing airports; the Aerospace Industries Association, representing manufacturers; and Airlines for America (formerly the Air Transport Association), representing U.S. airlines. CAAFI is dedicated to the development and commercialization of renewable jet fuel for the jet-powered aviation enterprise. Mr. Csonka has a depth of knowledge on the current state of alternative jet fuel development, and extensive experience with deployment activities. His engagement with CAAFI working teams extends back to 2008 as he was working on behalf of GE Aviation on the development and execution of the Air Transport Action Group's comprehensive industry approach to mitigating the environmental impact of aviation, which includes use of biofuels. Mr. Csonka has broad experience from previous roles in the areas of business development, commercialization, technical evaluation, and advanced engineering. He is a commercial aviation professional with 29 years of experience with GE Aircraft Engines, American Airlines, GE Aviation, and CAAFI. Areas of expertise include conceptual analysis, design, manufacture, test, certification, operations, marketing, acquisition (seller and buyer) and support of propulsion systems. Mr. Csonka has received several managerial awards for innovation and performance from GE and American Airlines. He is a member of the Carbon War Room, the Technical Advisory Committee of the Department of Energy/U.S. Department of Agriculture Biomass Research and Development Board, and the FAA Aviation Sustainability Center Advisory Board. Previous advisory and steering appointments included the Department of Transportation's Future of Aviation Advisory Committee, the Air Transport Advisory Group, the General Aviation Manufacturers Association's Environmental Committee, and the Aerospace Industries Association's Environmental Committee. Mr. Csonka holds an M.S. in aerospace engineering and engineering mechanics from the University of Cincinnati, specializing in aircraft propulsion.

DAVID J. H. EAMES retired from Rolls-Royce North America as director of NASA Programs and Advanced System Studies. During his 34-year U.S. career with Rolls-Royce North America, Mr. Eames specialized in propulsion airframe integration for a variety of aircraft, including those studied for the U.S./U.K. Advanced Short Take-Off/Vertical Landing (ASTOVL) program; proprietary studies for Boeing, Lockheed Martin, Northrop Grumman, and Gulfstream; and various NASA N + 2 and N + 3 supersonic and subsonic aircraft conceptual designs. He has direct experience in most areas of propulsion system component research, including propulsion wind tunnel and flight testing. He has held several senior positions at Rolls-Royce North America, including chief of preliminary design; chief of product and technology strategy; chief of advanced engine business development; and chief systems engineer for early program development. Mr. Eames started his career at Rolls-Royce in the United Kingdom in the advanced projects department before leaving the company for 2 years, during which time he left the United Kingdom to work at the Boeing Commercial Airplane Company in Seattle, where he performed exhaust system design and rig testing for the B-737-300. He is a recipient of many AIAA and Society of Automotive Engineers (SAE) awards, including two Forest R. McFarland Awards, the SAE Aerospace Chair Award, and a NASA Group Achievement Award for his role in the Vertical/Short Take-Off and Landing (V/STOL) System Research Aircraft (VSRA) Flight Test Program. In 2015, Mr. Eames was named an AIAA fellow. He earned his M.S. in thermal power/gas turbine technology from Cranfield University.

DANIEL K. ELWELL is the president of Elwell and Associates, LLC, an aviation consulting firm. Previously, Mr. Elwell was senior vice president for safety, security, and operations at Airlines for America (A4A), where he was responsible for leading the U.S. airline industry's efforts to advance safety and security while improving operational efficiency. Before joining A4A, Mr. Elwell was vice president of civil aviation at the Aerospace Industries Association; assistant administrator for policy at the FAA; and a long-time U.S. Air Force and commercial airline pilot, with over 6,000 hours of flight time in more than 10 different aircraft types. For the last 7 years, Mr. Elwell has been a member of the technical subcommittee of the FAA's NextGen Advisory Committee. The subcommittee and its working groups (Business Case and Performance Working Group, Operations Working Group) collect data and examine actual and predicted operational benefits of performance-based navigation. As a long-time airline pilot, Mr. Elwell has extensive practical expertise in airline operations. He also understands the regulatory and policy challenges to improving airline (and general aviation) operations, as well as the technological enhancements to surveillance and navigation systems that are currently in use or will be in the next 10 to 20 years. He retired from the U.S. Air Force Reserve as a lieutenant colonel. He has numerous Air Force commendations and citations and worldwide operational experience, including service in Operation Desert Storm. Mr. Elwell earned his pilot wings at Williams Air Force Base in Arizona after graduating from the U.S. Air Force Academy with a B.S. in international affairs. He is currently a member of the Academies' Aeronautics Research and Technology Roundtable.

ALAN H. EPSTEIN (NAE) is the vice president of technology and environment at Pratt & Whitney. He is responsible for setting the direction for and coordinating technology across the company as it applies to product performance and environmental impact. He leads efforts to identify and evaluate new methods to improve engine performance and fuel efficiency for all new Pratt & Whitney products. He also provides strategic leadership in the investment, development, and incorporation of technologies that reduce the environmental impact of Pratt & Whitney's worldwide products and services. Before joining Pratt and Whitney, Dr. Epstein was the R.C. Maclaurin Professor of Aeronautics and Astronautics at the MIT, where he holds an appointment as professor emeritus. He was also the director of the MIT Gas Turbine Laboratory. His research at MIT was concerned with gas turbines, power and energy, aerospace propulsion, and micromechanical and electrical systems (MEMS). He has served on multiple government advisory committees, has authored or coauthored more than 140 technical publications, and has given more than 200 plenary, keynote, and invited lectures around the world. He has won several international awards for topics that include heat transfer, turbomachinery, instrumentation and controls, gas turbine technology, and MEMS. He was the ASME International Gas Turbine Institute's Gas Turbine Scholar in 2003. Dr. Epstein is a member of the National Academy of Engineering and a fellow of the AIAA and the ASME. He holds a Ph.D. from MIT in aeronautics and astronautics. Dr. Epstein was the chair of the Academies' Board on Army Science and Technology and has served on many previous committees of the Academies, most recently the Committee on Avoiding Technology Surprise for Tomorrow's Warfighter Symposium–2010; and the Committee for Technology Insight–Gauge, Evaluate, and Review. He is currently a member of the Aeronautics Research and Technology Roundtable and the Aeronautics and Space Engineering Board.

ZIA HAQ is a senior analyst at DOE in the Bioenergy Technologies Office. He is the DOE lead for the Defense Production Act Biofuels Initiative, and he manages the aviation and marine activities of the Bioenergy Technologies program. He has more than 20 years of experience in energy and the environment, with particular expertise in renewable energy, environmental regulations, and econometric analysis. Before joining DOE, Mr. Haq worked at Southern Company Services as a senior engineer in a coal gasification demonstration power plant. Mr. Haq holds an M.S. in chemical engineering from Johns Hopkins University.

KAREN MARAIS is an associate professor in the School of Aeronautics and Astronautics in the College of Engineering at Purdue University. At Purdue, Dr. Marais has worked on identifying and evaluating operational improvements to reduce the environmental impact of commercial aviation. Her research interests include modeling and mitigating aviation environmental impacts, improving aviation safety, and developing improved approaches to the engineering of complex systems. Recently, she investigated ways of improving the fuel efficiency of surface operations at commercial airports (through the FAA Partnership for Air Transportation Noise and Emissions Reduction, Center of Excellence), and of improving safety in general aviation fixed-wing and rotorcraft operations (through the FAA Center of Excellence Partnership to Enhance General Aviation Safety, Accessibility and Sustainability). Previously, Dr. Marais was on the faculty of Stellenbosch University (South Africa) in the Department of Industrial Engineering. She also held a postdoctoral appointment at MIT working with the Partnership for AiR Transportation Noise and Emissions Reduction. Before graduate school, she worked as an electronic engineer in South Africa. She is a recipient of a National Science Foundation (NSF) Faculty Early Career Development Award. She earned her Ph.D. in aerospace engineering from MIT.

JAMES F. MILLER is deputy director of the Energy Systems Division and senior electrochemical engineer at Argonne National Laboratory. Argonne's transportation-related activities include the Advanced Powertrain Research Facility, Engine Systems and Fuels Research, Electric Vehicle-Grid Interoperability Center, Battery Materials Engineering Research Facility, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation, Energy and Environment Modeling, and Autonomic Vehicle Simulation. He completed a 3-year assignment at DOE headquarters as a senior technical advisor, providing strategic planning support for DOE's Battery Program in the Vehicle Technologies Office, including the EV Everywhere Grand Challenge and transportation electrification in the DOE Quadrennial Technology Review. He previously served as director of Argonne's Electrochemical Technology Program, with major research efforts on advanced batteries and fuel cells, and as associate director of Argonne's Chemical Technology Division. He is a recipient of the 1998 DOE Fuel Cell Program Award, the 2011 DOE Vehicle Technologies Special Recognition Award, and the SAE 2014 Forest McFarland Award. Dr. Miller holds a Ph.D. in physics from the University of Illinois, Urbana-Champaign, and an M.B.A. from the University of Chicago. He has served on several committees of the Academies, including the Committee to Review NASA's Exploration Technology Development Programs, the Committee for the State of Ohio Wright Centers of Innovation, and the Committee for Review of Proposals of NASA's Low Emissions Alternative Power (LEAP) Project.

JOHN G. NAIRUS is the chief engineer of the Power and Control Division in the Air Force Research Laboratory's Aerospace Systems Directorate. He has 28 years of experience in various capacities beginning as research engineer and program manager in the area of power electronics and aircraft electrical power systems for the Power Division's Electrical Technology Branch in support of the More Electric Aircraft Initiative. Mr. Nairus also served as chief of the Mechanical Energy Conversion and Thermal and Electrochemical Branches before becoming the division's chief engineer. Mr. Nairus also is spearheading a tri-service initiative to integrate more-electric aircraft technologies and architectures with emerging advanced turbine engines. Technical areas of expertise include hybrid-electric propulsion, batteries, fuel cells, electrical power generation and distribution, thermal management, power electronics, and motor drives. He also continues to serve as an electrical power and thermal management subject matter expert in the Joint Strike Fighter Program Office. Mr. Nairus is a registered professional engineer in the state of Ohio, an AIAA associate fellow, and a recipient of the U.S. Air Force Exemplary Civilian Service Award. Mr. Nairus leads the Interagency Advanced Power Group, the membership of which includes the U.S. Air Force, U.S. Army, DOE, NASA, the National Institute of Standards and Technology (NIST), and the U.S. Navy and serves as the U.S. Air Force aircraft power and thermal lead for Office of the Secretary of Defense's Communities of Interest. Mr. Nairus is also deputy chair of the AIAA Energy Optimized Aircraft and Equipment Systems Program Committee. He holds an M.S. in electrical engineering from the University of Dayton.

STEPHEN M. RUFFIN is a professor of aerospace engineering at the Georgia Institute of Technology. He is also the director of the Georgia Space Grant Consortium. He is a specialist in high-temperature gas dynamics, compressible flow aerodynamics, and aircraft–propulsion integration. He is leading development of a 3-D Cartesian-grid based Navier-Stokes solver for design applications and development of Cartesian-grid approaches for complex vehicles and chemically reacting flows. The Aerothermodynamics Research and Technology Laboratory he directs has applied these techniques to applications as diverse as hypersonic planetary entry vehicles and flow physics, rotorcraft airframe interaction flows, transonic and supersonic missiles, and unsteady store separation problems. Previously, Dr. Ruffin worked in the Thermosciences Division at the NASA Ames Research Center. He holds a Ph.D. in aeronautics and astronautics from Stanford University. He served as a member of the Academies' NASA Technology Roadmap: Entry, Descent, and Landing Panel; and the Decadal Survey of Civil Aeronautics: Panel A, Aerodynamics and Aeroacoustics

HRATCH G. SEMERJIAN (NAE) is chief scientist emeritus at NIST. He recently served as the president and executive director of the Council for Chemical Research (CCR). Prior to joining CCR, Dr. Semerjian served as the director of NIST's Chemical Science and Technology Laboratory, NIST deputy director, NIST acting director, and NIST chief scientist. As NIST deputy director, he was responsible for overall operation of the Institute, the effectiveness of NIST's technical programs, and interactions with external and international organizations. His research interests have focused on combustion and reacting flow phenomena, and the formation and abatement of environmental pollutants in combustion processes, including gaseous pollutants such as carbon monoxide, nitrogen oxides, sulfur oxides, hydrocarbons, as well as particulates. His recent interests have focused on climate change, the impact of pollutants and combustion products, and their transport in the atmosphere. Dr. Semerjian is a member of the National Academy of Engineering and a fellow of ASME. He has also received the Brown Engineering Alumni Medal, the U.S. Department of Commerce Meritorious Federal Service (Silver Medal) Award, and the U.S. Department of Commerce Distinguished Achievement in Federal Service (Gold Medal) Award. He holds a Ph.D. in engineering from Brown University. He is a former member of the Academies' U.S. National Committee for the International Union of Pure and Applied Chemistry and a former ex-officio member of the Government-University-Industry Research Roundtable.

SUBHASH C. SINGHAL (NAE) is Battelle Fellow Emeritus at the Pacific Northwest National Laboratory (PNNL). At PNNL he worked in the Energy Science and Technology Directorate after having worked at Siemens Power Generation (formerly Westinghouse Electric Corporation) for more than 29 years. At PNNL, Dr. Singhal provided senior technical, managerial, and commercialization leadership to the Laboratory's extensive fuel cell program. At Siemens Westinghouse, he conducted and/or managed major research, development, and demonstration programs in the field of advanced materials for various energy conversion systems including steam and gas turbines, coal gasification, and fuel cells. He was manager of fuel cell technology there, responsible for the development of high-temperature solid oxide fuel cells (SOFCs) for stationary power generation. In this role, he led an internationally recognized group in the SOFC technology and brought this technology from a few-watt laboratory curiosity to fully integrated 200 kW size power generation systems. He has authored 100 scientific publications, edited 17 books, received 13 patents, and given numerous plenary, keynote, and other invited presentations worldwide. Dr. Singhal is a member of the National Academy of Engineering and a fellow of four professional societies: the American Ceramic Society, the Electrochemical Society, ASM International, and the American Association for the Advancement of Science. He is also a senior member of the Mineral, Metals and Materials Society. He received the Electrochemical Society's Outstanding Achievement Award in High Temperature Materials in 1994 and chairs its International Symposium on SOFCs. He is a former president of the International Society for Solid State Ionics and the Washington State Academy of Sciences. He is a recipient of the American Ceramic Society's Edward Orton Jr. Memorial Award; an Invited Professorship Award from the Japan Ministry of Science, Education and Culture; the Christian Friedrich Schoenbein Gold Medal from the European Fuel Cell Forum; and the prestigious Grove Medal. He serves on the editorial board of Elsevier's *Journal of Power Sources* and has been an associate editor of American Society of Mechanical Engineers' *Journal of Fuel Cell Science and Technology*. He has also served on many national and international advisory panels for the NSF, Materials Properties Council, DOE, NATO Advanced Study Institutes, NATO Science for Peace programs, United Nations Development Program, United Nations Industrial Development Organization, International Energy Agency, and the European Commission. He holds a Ph.D. in materials science and engineering from the University of Pennsylvania and an M.B.A. in technology management from the University of Pittsburgh. He has been a member of many committees of the Academies, most recently the Committee on Review of the 21st Century Truck Partnership, Phase 3; Planning Committee on International Comparative Study of High-Skilled Immigration Policy and the Global Competition for Talent; and the Planning Committee on International Comparative Study of High-Skilled Immigration Policy and the Global Competition for Talent. He is also a member of the Board on Higher Education and the Workforce.

Staff

ALAN C. ANGLEMAN, *Study Director*, has been a senior program officer for the Aeronautics and Space Engineering Board (ASEB) of the Academies since 1993, directing studies on the modernization of the U.S. air transportation system, system engineering and design systems, aviation weather systems, aircraft certification standards and procedures, commercial supersonic aircraft, the safety of space launch systems, radioisotope power systems, cost growth of NASA Earth and space science missions, autonomous systems, and other aspects of aeronautics and space research and technology. Previously, Mr. Angleman worked for consulting firms in the Washington, D.C., area, providing engineering support services to the Department of Defense and NASA Headquarters. His professional career began with the U.S. Navy, where he served for 9 years as a nuclear-trained submarine officer. He has a B.S. in engineering physics from the U.S. Naval Academy and an M.S. in applied physics from Johns Hopkins University.

CHARLES HARRIS is a research associate for the Space Studies Board (SSB) and the ASEB. He graduated from the University of North Carolina, Chapel Hill, in 2014 with a double major in public policy and communication studies and a minor in astronomy. He has served as an intern with NASA's Space Technology Mission Directorate at NASA Headquarters and with the Committee on Science, Space, and Technology in the U.S. House of Representatives. He has also worked as a junior associate with an independent policy firm focused on providing clients in the commercial space sector with government relations services and strategic consulting.

ANESIA WILKS joined the SSB as a program assistant in 2013. Ms. Wilks brings experience working in the Academies' conference management office as well as other administrative positions in the D.C. metropolitan area. She has a B.A. in psychology, magna cum laude, from Trinity University in Washington, D.C.

MICHAEL H. MOLONEY is the Director for Space and Aeronautics at the SSB and the ASEB of the Academies. Since joining the ASEB/SSB, Dr. Moloney has overseen the production of more than 60 reports, including five decadal surveys, in astronomy and astrophysics, Earth science and applications from space, planetary science, microgravity sciences, and solar and space physics. He has also been involved in reviewing of NASA's space technology roadmaps and oversaw a major report on the rationale for and future direction of the U.S. human spaceflight program, as well as reports on issues such as NASA's strategic direction; lessons learned from the decadal survey processes; the science promise of CubeSats; the challenge of orbital debris; the future of NASA's astronaut corps; NASA's aeronautical flight research program; and national research agendas for autonomy and low-carbon propulsion in civil aviation. Since joining the Academies in 2001, Dr. Moloney has also served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anti-counterfeiting technologies for currency, corrosion science, and nuclear fusion. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the BPA and study director for the 2010 decadal survey for astronomy and astrophysics (*New Worlds, New Horizons in Astronomy and Astrophysics*). In addition to his professional experience at the Academies, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government—including serving at Ireland's embassy in Washington and its mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics. Dr. Moloney is a corresponding member of the International Academy of Astronautics and a Senior Member of the American Institute of Aeronautics and Astronautics. He is also a recipient of a distinguished service award from the National Academies of Sciences, Engineering and Medicine.

C

Acronyms

AC	alternating current
APU	auxiliary power unit
BLI	boundary layer ingestion
CMC	ceramic matrix composite
CO_2	carbon dioxide
DC	direct current
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FT-SPK	Fischer-Tropsch conversion of syngas to synthetic paraffinic kerosene (an SAJF production pathway)
FT-SPK/A	Fischer-Tropsch conversion of syngas to synthetic paraffinic kerosene and aromatics (an SAJF production pathway)
HEFA-SPK	Hydroprocessed esters and fatty acids to synthetic paraffinic kerosene (an SAJF production pathway)
HFS-SIP	Hydroprocessed fermented sugars to synthesized isoparaffins (an SAJF production pathway)
IOC	initial operational capability
kW	kilowatt
kWh	kilowatt-hour

LNG	liquefied natural gas
MW	megawatt
NASA	National Aeronautics and Space Administration
nm	nautical mile
NO_x	oxides of nitrogen
NSF	National Science Foundation
OPR	overall press ratio
OSTP	Office of Science and Technology Policy
PEM	proton exchange membrane
R&D	research and development
SAJF	sustainable alternative jet fuel(s)
SiC	silicon carbide
SOFC	solid oxide fuel cell
SO_x	oxides of sulfur
SUGAR	subsonic ultra-green aircraft research
TRL	technology readiness level
UAV	unmanned air vehicle
USDA	U.S. Department of Agriculture
Wh	watt-hour