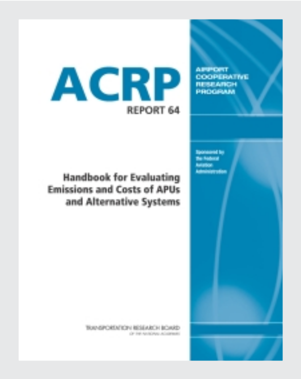

Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems

DETAILS

244 pages | 8.5 x 11 | null
ISBN null | DOI 10.17226/22797

AUTHORS

Environmental Science Ass ociates

AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP REPORT 64

Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems

Environmental Science Associates
San Francisco, CA

with

AERO Systems Engineering, Inc.
Atlanta, GA

Synergy Consultants, Inc.
Seattle, WA

Wyle, Inc.
Arlington, VA

Subscriber Categories
Aviation

Research sponsored by the Federal Aviation Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2012
www.TRB.org

AIRPORT COOPERATIVE RESEARCH PROGRAM

Airports are vital national resources. They serve a key role in transportation of people and goods and in regional, national, and international commerce. They are where the nation's aviation system connects with other modes of transportation and where federal responsibility for managing and regulating air traffic operations intersects with the role of state and local governments that own and operate most airports. Research is necessary to solve common operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the airport industry. The Airport Cooperative Research Program (ACRP) serves as one of the principal means by which the airport industry can develop innovative near-term solutions to meet demands placed on it.

The need for ACRP was identified in *TRB Special Report 272: Airport Research Needs: Cooperative Solutions* in 2003, based on a study sponsored by the Federal Aviation Administration (FAA). The ACRP carries out applied research on problems that are shared by airport operating agencies and are not being adequately addressed by existing federal research programs. It is modeled after the successful National Cooperative Highway Research Program and Transit Cooperative Research Program. The ACRP undertakes research and other technical activities in a variety of airport subject areas, including design, construction, maintenance, operations, safety, security, policy, planning, human resources, and administration. The ACRP provides a forum where airport operators can cooperatively address common operational problems.

The ACRP was authorized in December 2003 as part of the Vision 100-Century of Aviation Reauthorization Act. The primary participants in the ACRP are (1) an independent governing board, the ACRP Oversight Committee (AOC), appointed by the Secretary of the U.S. Department of Transportation with representation from airport operating agencies, other stakeholders, and relevant industry organizations such as the Airports Council International-North America (ACI-NA), the American Association of Airport Executives (AAAE), the National Association of State Aviation Officials (NASAO), Airlines for America (A4A), and the Airport Consultants Council (ACC) as vital links to the airport community; (2) the TRB as program manager and secretariat for the governing board; and (3) the FAA as program sponsor. In October 2005, the FAA executed a contract with the National Academies formally initiating the program.

The ACRP benefits from the cooperation and participation of airport professionals, air carriers, shippers, state and local government officials, equipment and service suppliers, other airport users, and research organizations. Each of these participants has different interests and responsibilities, and each is an integral part of this cooperative research effort.

Research problem statements for the ACRP are solicited periodically but may be submitted to the TRB by anyone at any time. It is the responsibility of the AOC to formulate the research program by identifying the highest priority projects and defining funding levels and expected products.

Once selected, each ACRP project is assigned to an expert panel, appointed by the TRB. Panels include experienced practitioners and research specialists; heavy emphasis is placed on including airport professionals, the intended users of the research products. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, ACRP project panels serve voluntarily without compensation.

Primary emphasis is placed on disseminating ACRP results to the intended end-users of the research: airport operating agencies, service providers, and suppliers. The ACRP produces a series of research reports for use by airport operators, local agencies, the FAA, and other interested parties, and industry associations may arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by airport-industry practitioners.

ACRP REPORT 64

Project 02-25
ISSN 1935-9802
ISBN 978-0-309-21402-5
Library of Congress Control Number 2012936817

Published reports of the

AIRPORT COOPERATIVE RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR ACRP REPORT 64

Christopher W. Jenks, *Director, Cooperative Research Programs*
Crawford F. Jencks, *Deputy Director, Cooperative Research Programs*
Michael R. Salamone, *ACRP Manager*
Marci A. Greenberger, *Senior Program Officer*
Joseph J. Brown-Snell, *Program Associate*
Eileen P. Delaney, *Director of Publications*
Maria Sabin Crawford, *Assistant Editor*

ACRP PROJECT 02-25 PANEL
Field of Environment

Samuel J. Hartsfield, *Port of Portland (OR) Aviation Division, Portland, OR* (Chair)
Kim Marie Berry, *General Mitchell International Airport - Milwaukee County (WI), Milwaukee, WI*
Kane Carpenter, PG, *Austin-Bergstrom International Airport, Austin, TX*
Rudolph Dudebout, *Honeywell Aerospace, Phoenix, AZ*
Tiffany Goebel, *We Energies, Milwaukee, WI*
Brian L. Sprenger, *Gallatin Airport Authority, Belgrade, MT*
Lindsay Guttilla, *FAA Liaison*
Rhett Jefferies, *FAA Liaison*
Christine Gerencher, *TRB Liaison*

FOREWORD

By Marci A. Greenberger
Staff Officer
Transportation Research Board

ACRP Report 64: Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems provides a handbook to help airports evaluate different alternatives to aircraft auxiliary power units (APUs). The handbook addresses environmental impacts, costs, infrastructure and maintenance requirements, as well as funding options. The accompanying *ACRP CD-113: Tool for Evaluating Emissions and Costs of APUs and Alternative Systems (TEECAAS)* provides a user-friendly software tool that can be used to quantify emissions from APUs and alternative systems, while also providing quantitative analysis of the financial implications of implementing and operating the systems. While the handbook provides the overall evaluation guidance including step-by-step details of the quantification process, the tool facilitates the quantification work.

The handbook and software tool can be used by airports of all sizes, whether or not they have collected airport-specific data. Such specific information includes airport temperature ranges, operations by aircraft category, the amount of time aircraft spend at gates, power requirements, and various other datasets. In those cases where airport-specific data are not available, the included set of default data can be used. The resulting emissions, power requirements, and costs can be used to analyze various airport scenarios. The handbook and tool are intended to be used for planning purposes only, and should not be used to replace or supersede the use of the Federal Aviation Administration's (FAA's) Aviation Environmental Design Tool (AEDT).

As airports have strategized to improve local air quality, APUs have increasingly served as a well-known source of reducing airport-related emissions. APUs provide beneficial power, heating, and air conditioning to the aircraft cabin, but because of their fuel use, can result in considerable emissions. As a replacement for APU usage at gate areas, various alternative ground-based systems have been developed to help reduce emissions. These alternative systems include mobile units, bridge or ramp-based units, and centrally located systems. Each alternative has different operating and capital costs as well as different energy usage and emissions. Since each airport is different, there is no single solution that works for all airports. Airports differ in many aspects such as local climatology, terminal and ramp infrastructures, and airline fleet mix and operations, all of which influences the choice of which alternative systems to implement.

Many airports are aware of the range of alternative systems available, but they need more information on the environmental benefits as well as the operational and capital cost considerations for selecting and implementing such systems. A team led by Environmental Science Associates (ESA) was retained under ACRP Project 02-25 to conduct the research necessary for this project. The work included both qualitative and quantitative assessments including case studies comparing APUs with alternative systems. This research culminated in the guidance provided in the handbook and the software tool.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

CHAPTER 1

Introduction and Background

Amid growing concerns regarding airport-related emissions, and in light of rising fuel costs, airport operators and airlines have been investigating various options for reducing aircraft-related emissions and fuel consumption. Aircraft are one of the primary sources of emissions at airports, and thus, there is widespread interest in identifying methods to reduce aircraft-related emissions. One of the options that has been implemented at commercial service airports throughout the United States is the provision of ground-based power, heating, and cooling systems to reduce the use of aircraft auxiliary power units (APUs) which combust jet fuel and hence are a source of pollutant emissions. This Handbook will aid the practitioner to better understand the types of alternative systems available and the associated emissions, energy consumption, and cost implications of implementing these alternative systems at airports.

1.1 Background

An APU is an engine located on a vehicle that provides energy for functions other than propulsion or movement. APUs are found on most large commercial service aircraft, as well as some trucks. Most commercial aircraft engines have large, heavy rotors that must be accelerated to a high rotational speed to provide sufficient air compression for self-sustaining operation. The primary purpose of an aircraft APU is to provide power to start the main engines. Over time, aircraft APUs have evolved to also provide air conditioning or heat for cabin comfort, and electric power for cabin lights and avionics.

APUs were first used on piston-powered aircraft in the early 1900s. Beginning in the 1960s, most commercial service aircraft were equipped with an APU. The invention of the APU has independently from ground facilities (i.e., by providing power to start the main aircraft engines). Widespread adoption of APUs has allowed aircraft to fly to remote areas and to serve remote communities where ground power is not readily available.

An aircraft APU is essentially a turbine engine that uses the same fuel as the main aircraft engines. In general, the APU consists of a compressor section, a turbine section, and an accessory drive section. The APU is located in the tail section of most aircraft (Figure 1), but the APU can also be located elsewhere on the aircraft.

The APU supplies electric power to the aircraft systems and cooled/heated air for the cabin when the aircraft is parked. APU use times can range from approximately 20–25 minutes for quick-turn passenger aircraft to several hours for cargo aircraft when ground infrastructure systems (i.e., ground power and pre-conditioned air systems) are not available. During the winter at

SOURCE: Aerospaceweb, 2010

Figure 1. Typical aircraft APU.

cold-temperature airports, pilots will often operate APUs for extended periods to prevent water onboard the aircraft from freezing.

In order to reduce aircraft APU usage, and hence emissions of both criteria pollutants and greenhouse gases, some form of ground-based power must be available. In most climatic conditions, the ground-based power system must also be coupled with heating, ventilation, and air conditioning (HVAC) capabilities to reduce aircraft APU use. It is important to note that even in those situations when ground-based power and HVAC infrastructure are available at an airport, aircraft pilots will typically use APUs upon arriving at an aircraft parking position and before departing the aircraft parking position. It is estimated that APUs are used for approximately 2 minutes when aircraft first arrive at a parking position and for approximately 5 minutes prior to push-back.

The HVAC portion of a ground-based alternative system is referred to as pre-conditioned air (PCA). The power requirements of aircraft are primarily 400 hertz, but some smaller aircraft require 28.5 volts direct current (VDC) power. Thus, some ground power systems at airport terminals are capable of providing both 400 hertz and 28.5 VDC power.

When new passenger boarding bridges (commonly referred to as gates) are constructed, they often include some form of an alternative system to provide electric power and PCA to parked aircraft. Similarly, in response to airline needs, some airport operators are retrofitting existing gates with these alternative systems, or assisting the airlines with the installation of such systems at the gates. As discussed in Chapter 3 of this Handbook, alternative systems generally have less pronounced effects on local air quality and global emissions of greenhouse gases when compared with aircraft APUs.

1.2 APUs and Types of Alternative Ground Infrastructure Systems

When evaluating different ground-based power and PCA systems, the following types of information are needed:

- The temperatures at which heated or cooled air is needed (i.e., ambient temperatures);
- Aircraft types that would be using the ground-based power and PCA systems; and
- The characteristics and conditions of the electrical and HVAC systems at the airport.

The first two items form the basis for examining the capabilities of the alternative system while the later is used to determine which category of alternative system (i.e., central or point of use) is most cost effective. The approach to determining the cost effectiveness of various alternative systems will vary based on the specific conditions at an airport and thus is beyond the scope of this Handbook; users should consult their asset management and facility managers to understand the cost effectiveness of these alternative systems relative to their specific conditions. Some limited information regarding costs and operational issues associated with alternative systems is presented in Chapter 4.

As noted earlier, APUs supply cooled and heated air to the aircraft cabin. Thus, when considering alternative systems, airport operators need to identify the ambient temperatures at which aircraft require heated or cooled air. Airport operators should consider guidance developed by the FAA in support of the Voluntary Airport Low Emissions (VALE) grant program, which specifies the following climatic conditions related to aircraft APUs and alternative systems (FAA 2010a; FAA 2010b):

- Cold conditions (e.g., under 45°F)—aircraft requires heating and electric power
- Neutral conditions (the FAA's VALE program specifies 45 to 50°F)—aircraft requires only electric power (no heating or cooling)
- Hot conditions (e.g., greater than 50°F)—aircraft requires cooling and electric power

Although there are different manufacturers of APUs (e.g., Honeywell, Hamilton Sundstrand, etc.), each with different technical specifications, the overall technology is similar from manufacturer to manufacturer. The main differences between the various APUs are related to their load ratings for electric power and PCA which are dependent on the type and size of aircraft serviced by the APU. Some APUs are built specifically for certain aircraft types, while others can be installed in different aircraft types within the same size category. Table 1 provides a summary of selected APUs and associated aircraft types grouped by aircraft category. Since ACRP Project 02-25 is focused on the commercial aircraft fleet in the United States, Table 1 does not include military aircraft or general aviation aircraft.

In lieu of the use of APUs, alternative ground infrastructure systems can be used to supply electric power and PCA to parked aircraft. However, as discussed previously, APUs are still commonly used for short periods of time at airports that have alternative systems in place (e.g., to start the main aircraft engines). Unlike individual APU models, alternative systems[1] are better described by their overall system categories:

- Ground power providing 400 hertz, 28.5v, or both power levels:
  - Portable diesel-powered systems;
  - Point of Use (POU) systems that are mounted either on the loading bridge or on the ground; and
  - Central systems.

[1]Although this Handbook discusses each system separately, it is important to note that airport operators can mix and match the ground power and PCA components associated with each system.

Table 1. Aircraft types and auxiliary power units grouped by aircraft category.

Aircraft Category	Example Aircraft Types	Representative APUs
Narrow Body	Boeing 737-700 Series, Boeing MD-80 Series, Airbus A320 Series, Boeing 757-200 Series, Airbus A319-100 Series, Boeing 737-800 Series, Boeing 737-300 Series, Boeing 717-200 Series, Embraer ERJ170, Embraer ERJ175.	GTCP 36-300 (80 HP), GTCP 85 (200 HP), GTCP85-98 (200 HP), GTCP85-129 (200 HP), GTCP-129H, GTCP 331-9B, GTCP 331-200, GTCP 85-98, GTCP 36-150, GTCP 36-4A.
Wide Body	Boeing 767-300 Series, Boeing 777-200 Series, Airbus A300B/C/F-600 Series, Boeing 767-200 Series, Boeing 767-400, Airbus A310-200 Series, Boeing 777-300 Series, Airbus A300B/C/F Series, Airbus A310-300 Series, Boeing 787-300 Series.	TSCP700-4B, GTCP331-200ER, GTCP331-500, APS 5000.
Jumbo - Wide Body	Boeing 747-400 Series, Airbus A330-200 Series, Airbus A340-200 Series, Boeing 747-200/300 Series, Airbus A330-300 Series, Airbus A340-600 Series, Airbus A340-300 Series, Airbus A340-500 Series, Boeing 747-100 Series, Airbus A380 Series.	GTCP 331-350, PW-980, GTCP 660, APU PW901A.
Regional Jet	Bombardier CRJ-200/400, Embraer ERJ145, Bombardier CRJ-700, Bombardier CRJ-900, Embraer ERJ140, Bombardier CRJ-100, Embraer ERJ135, Dornier 328 Jet, BAE 146-100, BAE 146-200.	GTCP 36-100, GTCP 36-150, GTCP 85.
Turbo Prop	DeHavilland DHC-8-400, DeHavilland DHC-8-100, Embraer EMB120 Brasilia, DeHavilland DHC-8-300, DeHavilland DHC-8-200, Shorts 360-100 Series, DeHavilland DHC-7 Dash 7, Embraer EMB110 Bandeirante, Fokker F27-100 Series, Fokker F27-200 Series.	T-62T-40C7, APS 1000 T-62T-46C12, GTCP 36-150, GTCP 30-54.

SOURCE: Developed from the FAA's Emissions and Dispersion Modeling System (EDMS) fleet database (FAA 2010a).

- PCA (heated or cooled air):
  - Portable diesel-powered systems;
  - POU systems that are mounted either on the loading bridge or on the ground; and
  - Central systems.

Point of Use (POU) systems provide the primary infrastructure needed for the power/HVAC capability at the use location. In contrast, central systems provide their primary function at a central location. For the PCA element, central systems are often integrated into the airport's overall HVAC system.

As each alternative system type can be used to satisfy the power and PCA load requirements for multiple aircraft types, the choice of which alternative system to implement is based on various factors related to costs, infrastructure requirements, and operational considerations. The three types of alternative systems have their advantages and disadvantages.[2]

A portable diesel-powered system, often referred to as a Ground Power Unit (GPU), is shown in Figure 2. These systems can be mounted on the back of a truck or they can be trailer/cart mounted for greater mobility. While a GPU provides for flexibility of movement and has a relatively low initial capital cost, local emissions are not avoided when most GPUs are in operation

[2]The focus of this Handbook is on the tradeoffs between the two alternative systems (Point of Use and central) that can be bridge- or ramp-based.

Figure 2. Typical diesel-powered portable system.

(i.e., diesel emissions). It is important to note that some battery based GPUs have been developed, but these battery based systems are primarily used to provide power to small general aviation aircraft and thus are not used at most commercial service airports.

Commercial service airports have a large number of vehicles and activities that are conducted on the ramp and adjacent to aircraft parking positions. Ramp traffic congestion and vehicle storage can also be an issue with mobile units.

Self-contained, stationary, power, and PCA systems, also referred to as POU systems, run as single units (i.e., self-contained units—located at their POU) using airport electricity. As a result, their use does not produce emissions at the airport, although off-airport emissions associated with electricity generation at a power plant do occur. POU systems have lower up-front capital costs than central systems, but operating and maintenance costs can be substantial over time as discussed in Chapter 3. POU infrastructure also provides flexibility in modularity-of-use (can be purchased one at a time) and can be installed a few at a time, minimizing the required capital outlay. POU systems are typically bridge- or ramp-based. A typical passenger boarding bridge based POU system is depicted in Figure 3. The images depict a self-contained PCA unit and a power converter (frequency converter) unit.

Note: The image on the left shows a bridge-mounted PCA unit; the image on the right shows a bridge-mounted power converter unit

Figure 3. Typical bridge-mounted POU system.

Central systems use a main, centralized set of chiller and boiler units to provide pre-conditioned air to air handling units (AHUs) located at each gate. AHUs are simple devices consisting primarily of a blower, coil, and the associated actuators and controls. Unlike a POU system, a central ground power system has its power converters located at a central location, and the resulting power is distributed to gate electrical boxes at various gate locations. Power (solid state frequency) converters are typically comprised of four sections—the converter section, the direct current (DC) link, the inverter section, and a controls section—that work to convert DC voltage to an alternating current (AC) 400 Hz power at the required voltage. POU units typically provide 115/200V, 3 phase, and 4—wire service for direct connection to the aircraft. In contrast, a central system can operate at many different voltages with final transformation to the required voltage in a gate box at the aircraft parking position. Central systems are typically 115/200V, 3 phase, and 4 wire (requires no transformation) or 575V, 3 phase, and 3 wire (requires transformation). Figure 4 depicts the main components of a central system.

Because central power and PCA systems use grid electricity and natural gas, their operation results in little or no direct emissions of criteria pollutants. However, since these systems draw power from the electric grid, they are an indirect source of greenhouse gas emissions. Although the initial capital investment for a central system is greater than for a POU system, they generally require less maintenance, and their operating costs tend to be lower than POU systems (AERO Systems Engineering 2011). Central systems are usually housed in the central plant or another facility within the terminal building complex with utility equipment (i.e., AHUs and gate boxes).

1.3 Purpose of the Handbook and Reasons for the Research

As discussed previously, the use of alternative ground-based infrastructure systems (hereinafter referred to as alternative systems) to reduce the use of aircraft APUs has been identified as an effective method to reduce fuel burn and air pollution. While airport operators generally understand that implementation of alternative systems can result in reduced APU-related emissions and fuel consumption, there is little information regarding the relative benefits and costs associated with the primary types of alternative systems. Because size, layout, fleet makeup, and climatic conditions vary by airport, the same alternative system cannot be implemented at all airports. There is no one-size-fits-all solution—alternative system specifications must be tailored to the conditions at each individual airport.

The Transportation Research Board (TRB) initiated ACRP Project 02-25 in July 2010. The Handbook, one of the primary products of the ACRP Project 02-25, contains information regarding the types of alternative systems available, and potential emission reduction benefits associated with reducing aircraft APU usage through the implementation of an alternative system. The Handbook also contains guidance that facilitates comparisons between different types of alternative systems across several parameters (e.g., energy use, emissions, infrastructure requirements, and cost). The Handbook is intended to present technical data for APUs and alternative systems in a clear and easy-to-understand manner using methodical step-by-step instructions and example calculations.

This Handbook also provides information regarding tradeoffs associated with different alternative systems as well as information regarding operational efficiencies and limitations. The Handbook is intended to provide general guidance and to facilitate decision-making regarding the implementation of alternative systems.

The Handbook is geared toward planning-level analyses and assessments, and data contained in the Handbook and the associated Software Tool are not intended to support engineering or

Note: The photo on the upper-left shows a bridge-mounted gate box. The photo on the upper-right shows a bridge-mounted AHU. The photo on the lower-left represents a centrally located power converter unit. The photo on the lower-right shows centrally located chiller and boiler units.

Figure 4. Typical components of a central system.

design processes. Similarly, the information contained in this Handbook regarding emissions associated with APUs and alternative systems should not be used for regulatory compliance purposes or in support of federal or state environmental impact documentation. Information contained in the Handbook is not intended to replace or supersede in any way the required use of the FAA's Emissions and Dispersion Modeling System (EDMS) and Aviation Environmental Design Tool (AEDT) (FAA 2010a; FAA 2011b).

1.4 Software Tool Overview

The Handbook is accompanied by ACRP-CD-113 which contains a Software Tool, the Tool for Evaluating Emissions and Costs of APUs and Alternative Systems (TEECAAS), which automates the calculation of fuel/energy use, emissions, and costs using methodologies specified in the Handbook. While the Handbook provides overall guidance to allow the user to make informed decisions regarding alternative systems, TEECAAS strictly focuses on the quantification of emissions and costs. As with the Handbook, the tool is intended for planning-level assessments only and should not be used for regulatory compliance purposes. It is not intended to replace or supersede in any way the required use of the FAA's EDMS or AEDT.

TEECAAS was designed as a single window containing tabbed sheets with various datasets. The default data provided on each sheet have been grouped based on data category (e.g., APU use times, emissions indices, etc.). It is anticipated that most users of TEECAAS will use some of the default datasets to perform emission and cost calculations. **It should be noted that TEECAAS results may not match results calculated using the guidance provided in Chapter 3 of the Handbook due to rounding errors. Emission factor values, energy consumption rate values and other information provided in Chapter 3 have been rounded to improve the readability of the Handbook. In contrast, the TEECAAS software makes use of unrounded emission factors and energy consumption rate values in its calculations to improve the fidelity of the results/output.**

TEECAAS is a Microsoft Windows-only tool that works on all versions of Windows starting with XP.

1.5 Organization of the Handbook and Intended Users

The Handbook has been organized to separate information for first-time users from the information for more experienced users (See Figure 5). Chapters 1 and 2 present primer-type information for individuals who are less familiar with the different types of equipment and the issues involved with their usage. Chapters 3 and 4 present information that can be used to calculate emissions and costs for POU and central systems. Chapters 3 and 4 also present qualitative information regarding other important considerations relative to the design and implementation of alternative systems. Individuals who are not familiar with emission and cost characteristics associated with APUs and alternative systems should review Chapter 2, while those who are more familiar with the subject matter can jump ahead to Chapter 3. A consolidated list of key assumptions, an acronym list, a list of helpful websites, and a list of Frequently Asked Questions (FAQs) have been included in the Handbook (see appendices) to provide relatively quick answers to common questions.

The intended users of both the Handbook and the Software Tool (TEECAAS) are airport operators and consultants wishing to conduct planning-level assessments involving implementation of alternative ground power, heating, and air conditioning systems. Although

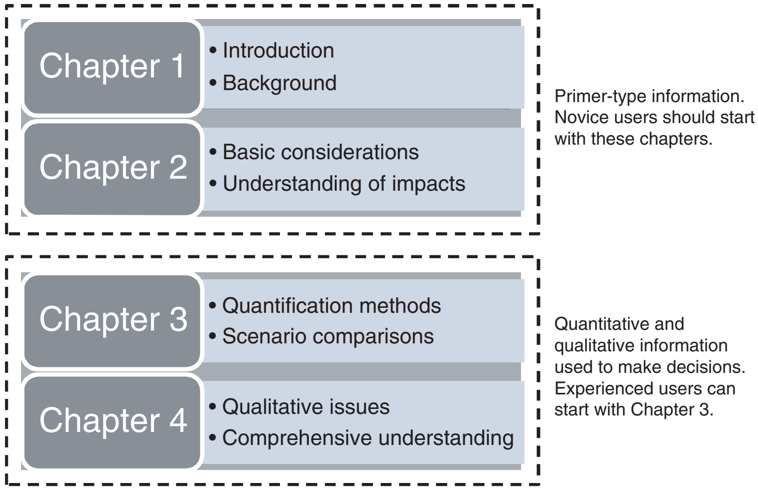

Figure 5. Handbook organization and utilization tips.

TEECAAS strictly focuses on calculations, the Handbook provides both primer-level information as well as detailed discussions of issues and methods. Therefore, the Handbook can potentially be used by airport management personnel wishing to gain a better understanding of the issues involved with alternative systems and by technical personnel to conduct quantitative assessments.

CHAPTER 2

Considerations for Planning the Implementation of an Alternative System

This chapter expands on the background information presented in Chapter 1. The information presented herein provides a broad overview of the major issues and considerations associated with planning and implementing alternative systems at airports. Information contained in this chapter is intended to provide a solid basis from which to conduct the quantitative and qualitative assessments described in Chapters 3 and 4. The considerations described in this chapter are grouped into the following categories:

- Implementation and operation,
- Regulations,
- Environmental,
- Costs, and
- Funding.

2.1 Implementation and Operation

Airport capital improvement projects are increasingly being challenged by agencies and individuals on environmental grounds. Noise and air pollution are often listed as concerns by airport neighbors. Criteria pollutant emissions (e.g., carbon monoxide [CO], nitrogen oxides [NO_x], and sulfur oxides [SO_x], etc.) and, more recently, greenhouse gas emissions (e.g., carbon dioxide [CO_2], methane [CH_4], etc.) associated with airport operations are being targeted and/or scrutinized by state and regional air quality management agencies. Airport operators have been working with airlines and other stakeholders to identify opportunities to reduce emissions from airport sources. Some airport operators have replaced gasoline- and diesel-powered on-airport vehicles and equipment with electric or alternative fuel vehicles and equipment. Similarly, the provision of alternative ground power and PCA systems at airports is a tested method of reducing APU fuel burn and related pollutant emissions.

As discussed previously, POU units are usually mounted on the underside of the Passenger Boarding Bridge (PBB). The POU gate equipment is generally much larger than the central systems' individual gate equipment. However, central systems also require space within the airport terminal facility and/or central plant, and therefore, central systems have greater total space requirements. While some central system components such as AHUs and 400 Hz gate boxes may be mounted on the PBB, a dedicated facility needs to be built to serve as the central plant to house the chillers and frequency converters for a central system. This, coupled with the need for distribution systems between the central plant(s) and the gate utilization equipment, is why central systems have significantly higher capital costs than POU systems. It should be noted, however, that central systems also allow for the use of existing airport boilers for heat energy (i.e., for supplying heated air to aircraft cabins). The lower cost of natural gas relative to grid electricity makes the central system with airport boilers an attractive option. As explained in Chapter 4, central systems are also more energy efficient than POU systems, as a result of efficiencies gained by centralizing the core equipment. Central systems also have lower maintenance costs, on average, than POU systems (ASE 2011).

The implementation of alternative systems typically requires infrastructure support/upgrades. Both central and POU systems require electrical infrastructure including components such as electrical feeders, breakers, and bus taps. Typically, POU-style systems require significantly more electrical power related upgrades than central systems (ASE 2011).

Once a central system is built, it is fixed and cannot be easily moved, except for some of its PBB-located components (e.g., AHUs and gate boxes). In contrast, a POU system can be detached from its mounting location on a PBB and relocated to another location fairly readily (e.g., another gate, terminal, etc.). The modular nature of POU systems makes them attractive from a flexibility-of-use standpoint. Since each POU unit is independent, it can be replaced, moved, or upgraded without concern for impacts on other POU units.

In order to ensure proper use of alternative systems, airport operators need to work closely with the airlines and their ground handling companies. While securing buy-in from airlines regarding the use of alternative systems is virtually guaranteed at the corporate level, since the systems represent a win-win situation for the airlines (i.e., reduces fuel usage and emissions usually at the expense of the airport operator), it is often more difficult to secure cooperation from airline personnel based at airports and pilots. Airlines play an important role in ensuring the proper use of alternative systems. Airlines need to ensure that their personnel and contractors are both trained and willing to use the alternative systems. Although airlines can potentially fund the construction of alternative systems (either in-part or in-whole), airport operators typically fund and take ownership of alternative systems since they are difficult to relocate to another facility (especially central systems).

2.2 Regulations

This section provides some context for regulations that directly or indirectly govern either the use of APUs or alternative systems at airports. Regulations and policies discussed in this section encompass the following:

- Airport Rules and Regulations/Policies,
- Clean Air Act and General Conformity Requirements,
- The National Environmental Policy Act (NEPA), and
- The FAA's VALE Program.

The following sections briefly discuss these regulations and policies.

2.2.1 Airport Rules and Regulations/Policies

Airport operators enact formal rules and regulations that apply to their tenants across a number of administrative and operational areas. These regulations and/or policies are often reflected in airport lease and use agreements. Such policies can be implemented to reduce emissions as well as to reduce noise exposure. As these policies can vary from airport to airport, users of this Handbook are advised to review the individual policies of their airport. According to the Boeing Commercial Airplane website (Boeing 2011), 25 US airports have restrictions on the use of APUs. These restrictions range from limits on the duration of APU use, to conditions on when the APU can be used (e.g., restriction on APU use during nighttime hours).

2.2.2 Clean Air Act and General Conformity Requirements

Airport activity is subject to compliance with many federal regulations, including the federal Clean Air Act of 1977 (CAA), as amended. Under the Clean Air Act, the United States Environmental Protection Agency (USEPA) has established National Ambient Air Quality Standards (NAAQS) for a series of criteria pollutants, including carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter (PM—coarse and fine particles), sulfur dioxide (SO_2), lead (Pb), and ozone (O_3). Geographic areas in which concentrations of these pollutants are determined to be in excess of the NAAQS are designated as nonattainment areas (NAAs) and are subject to controls enacted by the state to achieve attainment. While many regions of the United States have achieved attainment of the NAAQS, many are still subject to control plans (called maintenance plans) to ensure continued compliance. These plans (and plans developed to bring the nonattainment areas into compliance of the NAAQS) are referred to as State Implementation Plans (SIPs).

The CAA Amendments of 1990 require federal agencies to ensure that their actions conform to the appropriate SIP. Conformity is defined as demonstrating that a project conforms to the SIP's purpose of eliminating or reducing the severity and number of violations of the ambient air quality standards and achieving expeditious attainment of such standards. Most federally-funded and approved actions or projects at an airport are subject to the "General Conformity" regulations (40 Code of Federal Regulations [CFR] Part 93, Subpart B). General Conformity applies to federal actions occurring in nonattainment and maintenance areas for any of the criteria pollutants.

A conformity determination is required for a project/action proposed to be located in a maintenance or nonattainment area if the project's total direct and indirect emissions would equal or exceed the annual *de minimis* emissions levels specified in 40 CFR 93.153. Project-related emissions for airport projects are often found to be *de minimis,* but projects involving a substantial increase in aircraft operations or notable construction activity often require a conformity determination.

2.2.3 National Environmental Policy Act (NEPA)

In addition to the requirements of the Clean Air Act, before undertaking a federal action, the federal agency must first comply with the provisions of the NEPA. Federal actions undertaken by the FAA range from providing federal funding to airport operators to approving airport layout plans. The purpose of NEPA is to consider early in the decision-making process the probable environmental effects of a federal action and to enable decision makers to have this information before making their decision. Two FAA Orders provide guidance regarding airport projects and compliance with the NEPA. FAA Order 1050.1E *Environmental Impacts: Policies and Procedures* provides overall NEPA guidance for all FAA divisions. FAA Order 5050.4B *National Environmental Policy Act (NEPA) Implementing Instructions for Airport Projects* provides guidance to the Airports Division of the FAA which oversees the review of airport development projects.

FAA guidance identifies three paths toward compliance with the NEPA. Certain projects as defined in FAA Orders 1050.1E or 5050.4B, which are shown not to create significant effects (i.e., no extraordinary circumstances), may be categorically excluded from detailed environmental evaluation. For other projects, an Environmental Assessment (EA) is required to determine if significant impacts, as defined in the FAA Orders, would occur. If significant impacts would occur, the FAA is required to prepare an Environmental Impact Statement (EIS). If no significant impacts would occur, the FAA can issue a Finding of No Significant Impact (FONSI).

The use of APUs does not constitute a federal action. However, approval of the installation of PCA or gate based ground power at an airport might be a federal action since the project might necessitate a change in the footprint of the passenger terminal facilities and a revision of the airport layout plan. Installation of PCA and/or ground power is not specifically listed as being categorically excluded from NEPA review in FAA Order 1050.1E. However, installation of alternative systems is similar to other actions that are categorically excluded, and thus, that approach is often used to comply with the requirement of the NEPA.

2.2.4 The FAA's VALE Program

The VALE program was established in 2004 through the Century of Aviation Reauthorization Act legislation (VISION 100) to help commercial service airports in designated nonattainment and maintenance areas implement emission reduction actions. The VALE program allows airport sponsors to use the Airport Improvement Program (AIP) and Passenger Facility Charges (PFCs) to finance the purchase of low emission vehicles, refueling and recharging stations, gate electrification, and other airport air quality improvement projects. As of March 2011, the FAA had funded the installation of PCA and/or ground power at 11 airports through the VALE program (FAA 2011b).

As a condition to obtaining a VALE grant, the state in which the airport is located must agree to issuance of Airport Emission Reduction Credits (AERCs). To be AERC eligible, the project/emissions must meet the following criteria:

- **Quantifiable—**Emission reductions are quantifiable if they can be measured in a reliable manner and the method of calculation can be replicated using a publicly available model.
- **Surplus—**Emission reductions are considered surplus if they are not otherwise required by federal, state, or local regulations or relied on to meet other applicable air quality attainment or maintenance requirements for a particular NAAQS. The emission reductions associated with the use of PCA and/or ground power are considered surplus if there are no applicable federal, state, or local regulations requiring the emission reductions.
- **Permanent—**Emission reductions must be permanent throughout the lifetime of the equipment. Since ground power and PCA systems are infrastructure, emission reductions associated with those systems are usually considered permanent by design.
- **Adequately Supported—**The sponsor of the project must have adequate funding, personnel, and resources to implement and verify the approved low emission measures on schedule.
- **Federally Enforceable**

Emission reduction measures are generally considered to be federally enforceable if they meet the following criteria:

- The measures are independently verifiable.
- A complete schedule to implement and verify the measures has been adopted by the airport sponsor.
- Violations of the emission reduction credit (ERC) requirements are practicably enforceable in accordance with the Clean Air Act, USEPA and state regulations, and FAA grant assurances.
- Liability for violations can be identified.
- Required airport emissions-related information is publicly available.

The emission reductions are enforceable through FAA's grant assurance provisions and through the four VALE program special conditions (i.e., tracking, labeling, keeping equipment for its useful life, and replacing equipment in kind).

2.3 Environmental Considerations

The main environmental issue driving the implementation of alternative systems at airports is emissions of criteria pollutants and greenhouse gases. Criteria pollutants such as CO, NO_x and SO_x impact local/regional air quality whereas greenhouse gases such as CO_2 potentially have global impacts (i.e., climate change).

Many airports have recommended controls on the use of APUs or the implementation of ground-based infrastructure to reduce the use of APUs while aircraft are parked. In general, aircraft APUs generate higher noise levels than components of alternative systems (see Chapter 4). APUs and alternative systems are generally not associated with water quality or hazardous waste issues at airports, except possibly in the context of maintenance activities.

Aircraft are often the most significant source of criteria pollutant and greenhouse gas emissions at airports. While the majority of aircraft-related emissions correspond to the operation of the main engines, APU-related emissions can also be notable. The use of alternative systems can reduce direct/local emissions from APUs, but since alternative systems use grid electricity, there are indirect emissions to consider (i.e., emissions are essentially transferred to the power plants where electricity is generated). Local air quality can potentially be improved by employing alternative systems at airports since their use results in localized reductions of criteria pollutant emissions. The positive effects of alternative systems with respect to global climate change are less pronounced since it does not matter where greenhouse gas emissions occur—unlike criteria pollutants, greenhouse gases are significant at a global level. As discussed later in this Handbook, potential reductions in APU-related emissions of criteria pollutants and greenhouse gases are generally not identical to the increase in emissions at power plants associated with the use of an alternative system at an airport. A variety of factors explain these differences in emissions including the chemical composition and combustion characteristics of jet fuel and coal as well as various other factors including inefficiencies associated with electric power transmission (e.g., energy loss through electric power transmission lines).

Although accounting for greenhouse gas emissions at off-site locations may give the appearance of life-cycle emissions, only the end-state emissions are addressed in this Handbook. Upstream emissions associated with the manufacture and handling of fuels and equipment are outside the scope of the planning-level assessments described in this Handbook. In addition, data contained in this Handbook regarding emissions associated with electricity production reflect national averages in terms of utility mix (e.g., percent coal-fired power plants vs. hydroelectric, natural gas, etc.). Users with access to higher fidelity (e.g., regionally-specific) data can use that information to compute emissions instead of the national average data presented in the Handbook.

2.4 Costs

Airport operators need to carefully consider costs associated with implementing and operating alternative systems since they involve major up-front capital investments and potentially significant operating costs and maintenance expenditures:

- Capital costs refer to costs associated with base equipment, installation, and utility infrastructure upgrades necessary to support alternative systems. Typically, POU-style systems have lower initial installed costs, whereas due to the construction costs of the central plant as well as the electrical and mechanical distribution systems required, central systems generally have larger initial capital costs. The modularity of POU systems also provides flexibility in staging the roll-out of these systems since the airport operator has the option to implement the POU systems at a few gates over time. This flexibility allows airport operators and tenants who will use the alternative systems time to adjust to their usage and, in the case of some airports, more options if funding is limited.
- Operating costs refer to costs associated with using the alternative systems to supply electric power and heated or cooled air to aircraft. Typically, the largest operational cost is related to purchasing electricity from the local utility company. Central systems typically have lower operating costs due to certain efficiencies that are specific to central systems including thermal

storage. The use of a thermal storage system by central systems allows electrical consumption to be transferred to off-peak billing times. In contrast, POU systems are typically less efficient than central systems and have higher operating costs than central systems.

- Maintenance costs refer to costs associated with fixing or upgrading alternative system components to keep the systems operating properly. Typically, central systems have lower maintenance costs than POU systems. The differences in maintenance costs between POU and central systems become more pronounced as the quantity of aircraft gates served by the alternative system is increased. This is due primarily to the fact that in a central system, as the gate count increases, the central plant does not necessarily need to be expanded to accommodate the extra load. That is, the number of chillers and frequency converters at the central plant generally stays the same as the number of serviced gates increases. It is also generally understood that central systems tend to use more durable components—industrial-type equipment rather than the commercial type equipment used for POU systems (ASE 2011). Hence, the failure rate for central system components is often less than that for POU systems.

To properly compare these systems on a cost basis, life-cycle cost assessments should be conducted taking into account varying ranges of numbers of gates expected to be serviced by the alternative systems and the years of expected service. To conduct such assessments, the following variables need to be considered:

- Aircraft types or categories expected to be serviced;
- Aircraft/APU operations or number of Landing and Takeoff (LTO) cycles;
- APU times in mode (TIM) values that the alternative systems will duplicate;
- Electric utility costs (both consumption and demand costs);
- Natural gas costs (i.e., cost of natural gas used by airport boilers); and
- Annual average and seasonal ambient conditions.

Life-cycle cost assessments should be completed keeping in mind the life spans for each type of alternative system. For example, POU systems have a life span of approximately 15 years and central systems are considered to have a life span of 20 years or more (ASE 2011). The FAA's VALE program guidance suggests that POU PCA units have a life span of about 13 years, and POU ground power equipment is expected to have a life span of about 20 years (FAA 2010b).

2.5 Funding

There are various potential sources for funding the implementation of alternative systems. These include:

- PFC Funds;
- AIP Grants;
- General Airport Revenue Bond (GARB) or Special Facility Bonds;
- VALE program grants; and
- Private initiatives (e.g., airline funding).

Currently, the PFC program allows commercial service airports controlled by public agencies to charge up to $4.50 per enplaned passenger. The money can be used for various purposes including safety, security, and environmental improvements. AIP funding is provided by the FAA to support various projects including programs designed to mitigate environmental impacts/concerns. The AIP program is a cost-share program where the FAA will fund 75% to 80% of eligible project costs for large- and medium-sized airports and 95% of eligible project costs for projects at general aviation airports. Bonds can be issued by an airport-owning or related entity to support various airport funding needs including initiatives and development plans. The VALE program is specifically aimed at reducing ground-level emissions from airport activities.

Although, the source of the funds for the VALE program are PFC and AIP monies (since the VALE program is specifically geared toward reducing airport-related criteria pollutant emissions), VALE funds are considered a separate funding source for the purposes of this research.

In addition to airport and FAA funding sources, the implementation of alternative systems can be cost-shared with the airlines; however, in most cases the airport operator or the airlines will invest in the systems alone. In those situations where an airline purchases the alternative system equipment, details regarding the ownership of the various pieces of equipment will need to be worked out between the airport and the airline.

An important consideration that may influence the choice of implementing POU or central systems has to do with the source of the funding. If the funding is a grant (e.g., through the VALE program) that cannot be used for other purposes, an airport operator may not care as much about the cost differences between different alternative systems and will focus on other aspects (e.g., flexibility of use). When an airport operator has more control over the source of funding (e.g., funds from the PFC program) it may be more difficult to commit significant capital resources to implementing a central system, when the capital outlay for a few modular POU systems is much lower.

CHAPTER 3

Quantitative Assessments

This chapter provides a step-by-step guide to calculating fuel (energy) consumption, emissions, and costs for various scenarios involving APUs and alternative systems. Fuel consumption and emissions can be computed for the following equipment:

- Aircraft APU,
- POU system,
- Central system, and
- Central system with airport boiler.

This guidance only presents cost calculations for alternative systems as cost data for APUs are generally not available. Emissions and cost data for diesel-powered portable alternative systems are also not addressed in this chapter due to a lack of reliable data.

This chapter begins with the data requirements associated with the emission calculation methodologies. The data requirements and sources discussion is followed by separate sections that identify the specific methods to calculate fuel burn/energy consumption and emissions for APUs and alternative systems and costs for alternative systems.

3.1 Data Requirements Overview and Data Sources

This section of the Handbook discusses the following:

- User Supplied Data—data that the user will need to supply to successfully use this Handbook or the associated Software Tool;
- Handbook Supplied Data—data collected in connection with this research effort. Handbook data includes default information that the user can use in lieu of certain user supplied information, as well as fuel consumption and emission factor data.

3.1.1 User Supplied Data

The Handbook and accompanying Software Tool provide default emission factors and, in some cases, default activity data. The results of the calculation methodology are greatly improved when users provide location-specific activity data. Activity can relate to the number of gates to be served by the alternative systems, the mix of aircraft operating at the aircraft parking positions that would be serviced by the alternative systems, and the amount of time an APU is used during a single landing takeoff (LTO) cycle. Users of the Handbook and Software Tool are encouraged to supply the following location-specific information (activity data) for their airport:

- **Number of LTO cycles by individual aircraft types—**aircraft operations and fleet mix are airport specific, and thus the user should assemble this information for the gates that would be served by the alternative systems. For the purposes of this Handbook, aircraft fleet mix is defined in terms of five (5) aircraft categories as shown in Table 1.

- **APU time of use (minutes) per aircraft LTO cycle—**APU use time will vary from airport to airport. Typically airports will collect gate block time and then note the amount of time on arrival and departure that the APU is in use.
- **Percent of the year that temperatures are cold, neutral, and hot—**using annual average weather data, the user is expected to define the percentage time that aircraft cooling is needed, the percentage time when no aircraft heating or cooling is needed, and the percentage time that aircraft heating is needed. As discussed previously, the technical report for the FAA's VALE program assumes that cooling is required when temperatures are above 50°F, and that heating is required when temperatures are below 45°F.

A wide variety of data sources exist concerning the number of LTOs performed at individual airports. Aircraft type data are also needed, so as to enable the proper identification of the APUs that are in use at the airport. Airport activity data, in terms of total aircraft operations by aircraft type, are available from several sources including:

- Commercially available data sources, such as OAGaviation.com or airlinedata.com;
- The Airport's Noise and Operations Monitoring Systems (ANOMS) or other data collected by the airport;
- The FAA's Enhanced Traffic Management Systems (ETMS) database;
- The FAA's Performance Data Analysis and Decision System (PDARS);
- Form T-100 Reports, available from the Bureau of Transportation Statistics (BTS); and
- Other FAA or airport-specific datasets.

It is important to remember that in order to apply the calculation methodologies presented in this Handbook the user needs to identify the number of LTOs by aircraft type/category. Therefore if total aircraft operations data are collected from these sources, these figures must be translated into LTOs, which is accomplished by dividing the operations by two.

Once the number of aircraft LTOs is defined, the user can begin the process of defining APU use times per LTO. This can be done by either using APU default information contained in the FAA's EDMS technical manual or by the use of actual gate block time. Gate block time can be estimated if the information collected shows flights (Aircraft X arrives at the gate at a time, and then departs at a time). The block time reflects the time the aircraft is at the gate. As noted earlier, there is a period while the aircraft is parked when most pilots will use the APU (assumed to be seven minutes on average). For example, if an aircraft is at the gate for 32 minutes, alternative systems could support that aircraft for 25 minutes, and the APU will be operated for 7 minutes. Instructions related to the format of user-specific APU TIM data and use of the methods employed in this Handbook are provided in Section 3.1.2.

As noted earlier, users should supply the percentage of the year that temperatures are in the ranges that necessitate aircraft heating or cooling. For those locations where data are not readily available, the default data shown in Table 2 can be used. The default percentages provided in

Table 2. Average annual ambient conditions.

Ambient Conditions	Example Percent (%) of Year
Cold Conditions (i.e., less than 45 deg. F)	25
Neutral Conditions (VALE 45-50 deg. F)	50
Hot Conditions (i.e., more than 50 deg. F)	25

Table 2 are based on one cold condition (Winter), two neutral conditions (Spring and Fall) and one hot condition (Summer). For simplicity, each condition/season is assumed to last 3 months.

Weather data is available from various sources including the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) website at a nominal cost of approximately $20 for 1 year of records. This information can be used to identify the percentage time an aircraft requires heating or cooling on an average annual basis. Ambient temperature data from the NOAA NCDC were processed for airport weather stations located in the nine FAA regions. These data, which provide region-specific annual average temperature information, are incorporated in the TEECAAS software and are presented in Appendix A.

3.1.2 Handbook Supplied Data

The Handbook supplies a number of data sets for use by the user:

- APU default TIM data;
- APU power settings; and
- Fuel flow and emission factors.

APU Default TIM data: The emissions and cost calculations described in this Handbook are performed based on the use of the International Civil Aviation Organization (ICAO) set of APU modes of operation which correspond to an aircraft LTO cycle (ICAO 2007). The four APU operating modes defined by the ICAO are the following:

- Start-up (APU Start);
- Normal running for passenger loading (Gate Out);
- High Load (Main Engine Start); and
- Normal running for passenger disembarkation (Gate In).

Table 3 lists the default APU TIM data for the five aircraft categories used in this Handbook.

In most cases, airports planning for alternative ground power/PCA systems may not be able to obtain TIM information for each of these APU modes; total APU use times may be available rather than times for the individual modes. Information provided in this Handbook is compatible with the ICAO manual to enable the Handbook methodology to use that information.

The actual amount of time that aircraft spend at the gate varies widely by aircraft, airport, and airline. User supplied TIM data will need to be reconciled with the APU TIM categories above, as the APU emission factors are directly related to these TIM categories. Based on how VALE

Table 3. APU activity information—default times in mode (TIM).

Aircraft Category	APU Start (min/LTO)	Gate Out (min/LTO)	Main Engine Start (min/LTO)	Gate In (min/LTO)	Total APU Use (min/LTO)	Total Ground-Based Infrastructure Use (min/LTO)
Narrow Body	3	3.60	0.58	15	22.18	18.6
Wide Body	3	3.60	0.58	15	22.18	18.6
Jumbo-Wide Body	3	5.30	2.33	15	25.63	18.6
Regional Jet	3	3.60	0.58	15	22.18	18.6
Turbo Prop	3	3.60	0.58	15	22.18	18.6

APU TIM data source: ICAO, 2007. Note that consistent with the FAA's VALE Technical Report, the alternative systems would only be used during the Gate Out TIM and the Gate In TIM.

Table 4. APU power settings based on the combination of APU modes and ambient conditions.

Mode	Cold Conditions (e.g., less than 45 deg. F)	Neutral Conditions (VALE 45-50 deg. F)	Hot Conditions (e.g., more than 50 deg. F)
APU Start	NL	NL	NL
Gate Out	ECS	NL	ECS
Main Engine Start	MES	MES	MES
Gate In	ECS	NL	ECS

Notes: NL=No-Load, ECS=Environmental Control Systems, MES = Main Engine Start
SOURCE: Swedish Defense Research Agency, 2009.

applications have been prepared for a number of airports, gate block time can be collected and then adjusted down by seven minutes to account for the time the APU will be in operation during the "Gate In" and "Gate Out" modes. The adjusted gate block time reflects the total time that the aircraft is located at the gate and incorporates the four TIM categories presented in Table 3. In general, gate block time should be separated proportionally into the "Gate Out" and "Gate In" modes once the user has subtracted the 3 minutes spent in "APU Start" and the time spent in "Main Engine Start" mode. When aircraft are parked at the gate longer than the total APU times shown in Table 3, the user should proportionally increase the times spent in the "Gate In" and "Gate Out" modes. Users should only alter the "APU Start" or "Main Engine Start" mode times presented above if they have obtained specific information about these modes from the airlines operating at the airport.

APU Power Settings: Emission factors that have been developed for APUs are based on the power or load that is being applied. Table 4 identifies the APU power settings for the four APU operating modes and three ambient conditions (i.e., cold, neutral, and hot). As shown in Table 4, there are three distinct power settings for APUs: No-Load, Environmental Control System, and Main Engine Start. The three APU power settings are described below:

- No-Load (NL): Lowest power setting used during the "APU Start" mode
- Environmental Control System (ECS): Normal running condition used to support the "Gate In" and "Gate Out" modes
- Main Engine Start (MES): Highest power setting used to support the start of the main engines

APU Emission Factors and Fuel Flow: APU fuel flow and emission indices data are presented in Tables 5, 6, and 7 for the three APU power settings. An emissions index (EI) value is an emis-

Table 5. APU fuel and emissions indices for the no-load (NL) condition.

Aircraft Category	FF (kg/s)	EI CO_2 (g/kg fuel)	EI CO (g/kg fuel)	EI THC (g/kg fuel)	EI NO_x (g/kg fuel)
Narrow Body	0.021	3,155	31.75	6.53	5.45
Wide Body	0.035	3,155	10.26	0.87	7.55
Jumbo-Wide Body	0.033	3,155	9.38	0.88	7.41
Regional Jet	0.012	3,155	6.26	1.69	6.14
Turbo Prop	0.012	3,155	6.26	1.69	6.14

FF=Fuel Flow, EI= Emissions Index, CO_2= Carbon dioxide, CO=Carbon monoxide, THC=Total hydrocarbon, NO_x= Nitrogen oxides
Raw data source used to derive these weighted averages: Swedish FOI, 2009. EI CO_2 from FAA's EDMS, 2010.

Table 6. APU fuel and emissions indices for the environmental control systems (ECS) condition.

Aircraft Category	FF (kg/s)	EI CO_2 (g/kg fuel)	EI CO (g/kg fuel)	EI THC (g/kg fuel)	EI NO_x (g/kg fuel)
Narrow Body	0.033	3,155	5.72	0.43	6.85
Wide Body	0.052	3,155	1.14	0.19	10.99
Jumbo-Wide Body	0.061	3,155	0.53	0.12	10.30
Regional Jet	0.019	3,155	6.47	0.49	4.93
Turbo Prop	0.019	3,155	6.47	0.49	4.93

FF=Fuel Flow, EI= Emissions Index, CO_2= Carbon dioxide, CO=Carbon monoxide, THC=Total hydrocarbon, NO_x=Nitrogen oxides
Raw data source used to derive these weighted averages: Swedish FOI, 2009. EI CO_2 from FAA's EDMS, 2010.

Table 7. APU fuel and emissions indices for the main engine start (MES) condition.

Aircraft Category	FF (kg/s)	EI CO_2 (g/kg fuel)	EI CO (g/kg fuel)	EI THC (g/kg fuel)	EI NO_x (g/kg fuel)
Narrow Body	0.038	3,155	4.94	0.29	7.64
Wide Body	0.064	3,155	0.98	0.13	11.53
Jumbo-Wide Body	0.058	3,155	0.53	0.12	11.20
Regional Jet	0.020	3,155	6.48	0.42	4.91
Turbo Prop	0.020	3,155	6.48	0.42	4.91

FF=Fuel Flow, EI= Emissions Index, CO_2= Carbon dioxide, CO=Carbon monoxide, THC=Total hydrocarbon, NO_x=Nitrogen oxides
Raw data source used to derive these weighted averages: Swedish FOI, 2009. EI CO_2 from FAA's EDMS, 2010.

sion factor with the quantity of fuel (e.g., kilogram of fuel) representing the activity data. EIs are provided for the following:

- Carbon dioxide (CO_2);
- Carbon monoxide (CO);
- Total hydrocarbons (THC); and
- Nitrogen oxides (NO_x).

APU-specific EIs and fuel flow (FF) values were obtained with permission from the Swedish Defense Research Agency's APU emissions database (Swedish FOI 2009) and were used to generate weighted averages by aircraft category. These weighted averages were developed by using information regarding the number of aircraft operations performed in the United States by specific aircraft types within the five defined aircraft categories.

POU System Electricity Requirements: Table 8 lists the electricity requirements for a POU system. As presented in Table 8, the electricity requirements associated with providing ground power, cooling, or heating to an aircraft are different and vary by aircraft category. The ground

Table 8. POU system electricity requirements.

Aircraft Category	Ground Power (KW)	Cooling (KW)	Heating (KW)
Narrow Body	23.88	68.64	46.71
Wide Body	37.12	174.04	96.71
Jumbo-Wide Body	53.21	189.95	113.73
Regional Jet	13.30	39.33	16.68
Turbo Prop	26.60	31.16	12.72

SOURCE: ASE, 2011.

Table 9. Central system electricity requirements.

Aircraft Category	Ground Power (KW)	Cooling (KW)	Heating (KW)
Narrow Body	23.88	48.84	46.71
Wide Body	37.12	130.49	96.71
Jumbo-Wide Body	53.21	152.64	113.73
Regional Jet	13.30	27.15	16.68
Turbo Prop	26.60	21.20	12.72

SOURCE: ASE, 2011.

power electricity requirements for POU systems are identical to those for central systems and central systems with airport boilers as discussed below.

The ground power requirements presented in Table 8 reflect the use of a 40% diversity factor. That is, the aircraft electric consumption levels are typically assumed to be 40% of the estimated full loads. This is primarily due to the fact that gate-located power equipment is typically sized larger than the typical aircraft loads presented, so when an aircraft is conducting pre-flight start-up tests and operating many aircraft systems that are not normally operating (e.g., fuel transfer pumps, hydraulic pump motors, etc.), the gate equipment has sufficient capacity to supply the short duration peak loads presented.

Central System Electricity Requirements: Table 9 lists the electricity requirements for a central system. As previously discussed, the ground power requirements presented in Table 9 reflect the use of a 40% diversity factor. That is, the electric consumption levels are 40% of the estimated full loads.

Central System with Airport Boilers Electricity Requirements: Table 10 presents the power requirements for a central system with airport boilers.

Alternative System Ground Power and PCA Power Settings: As presented in Table 11, alternative systems provide different ground power and heating/cooling service based on ambient conditions and mode. It is assumed that aircraft APUs will be operated during the “APU Start” and “Main Engine Start” modes even if alternatives systems (i.e., ground power and PCA) are available.

Emission Factors for Electricity Consumption and Natural Gas Boilers: Emission factors associated with electricity consumption and the use of natural gas boilers by alternative systems are presented in Table 12.

Table 10. Central system with airport boilers electricity requirements.

Aircraft Category	Ground Power (KW)	Cooling (KW)	Heating (KW)	Heating (1,000 BTU/hr)
Narrow Body	23.88	48.84	6.68	128.31
Wide Body	37.12	130.49	16.41	258.33
Jumbo-Wide Body	53.21	152.64	17.96	309.00
Regional Jet	13.30	27.15	3.74	42.90
Turbo Prop	26.60	21.20	3.74	30.00

SOURCE: ASE, 2011.

Table 11. Alternative system ground power and PCA power setting based on the combination of APU modes and ambient conditions.

Mode	Cold Conditions (e.g., less than 45 deg. F)	Neutral Conditions (VALE 45-50 deg. F)	Hot Conditions (e.g., more than 50 deg. F)
APU Start	NL	NL	NL
Gate Out	Power & Heat	Power	Power & Cool
Main Engine Start	MES	MES	MES
Gate In	Power & Heat	Power	Power & Cool

SOURCES: Swedish FOI, 2009 and ICAO, 2007

Table 12. Emission factors for electricity consumption and natural gas boilers.

Source	Pollutant	Emission Factor	Units	Reference
Airport Boilers (Heat from Natural Gas)	CO_2	0.053	g/BTU	AP 42 (USEPA 1998a)
	CO	0.0000374	g/BTU	
	VOC	0.0000024	g/BTU	
	NO_x	0.0000142	g/BTU	
Airport Electricity Consumption (National Power Plants)	CO_2	618	g/KWh	Average US Electricity Emissions - eGrid (USEPA 2010)
	CO	0.066	g/KWh	Bituminous and Subbituminous Coal - AP 42 (USEPA 1998b)
	VOC	0.0012	g/KWh	Summed VOC EFs for Bituminous and Subbituminous Coal - AP 42 (USEPA 1998b)
	NO_x	0.954	g/KWh	Average US Electricity Emissions - eGrid (USEPA 2010)

BTU = British Thermal Unit, KWh = Kilowatt-hour, CO_2= Carbon dioxide, CO=Carbon monoxide, VOC=Volatile organic compound, NO_x=Nitrogen oxides

SOURCES: See references in the table.

3.2 Quantifying Fuel Consumption and Emissions

The common basis for the quantification of fuel consumption and emissions for APUs and alternative systems is the identification of aircraft types that the equipment will service. To simplify the assessments and to ensure that calculations support a planning-level of analysis, all assessments described in this chapter use the aircraft categories described in Table 1 and presented below:

- Narrow Body,
- Wide Body,
- Jumbo—Wide Body,
- Regional Jet, and
- Turbo Prop.

The resolution of data (e.g., emission factors) and calculations performed correspond to the aircraft category level rather than to specific aircraft types. As a resource for planning considerations, it should be understood that the calculations presented in this Handbook reflect a first-order approximation based on the use of national average data in most instances. Although the calculations can potentially be improved through the use of more specific data (e.g., region-specific data), the methods presented herein are to be used strictly for planning purposes and should not be used in support of regulatory compliance. The guidance presented in this Handbook should not be used in lieu of (or in addition to) FAA- and USEPA-required methods and tools.

The following is a basic formula for calculating emissions from APUs and alternative systems:

$$\text{Emissions} = (\text{Emission Factor}) \times (\text{Activity Data})$$

An emission factor represents the rate at which a pollutant is emitted, typically expressed as some amount such as mass (e.g., kg) or volume (e.g., cubic ft) divided by time or various other forms of activity (e.g., mass of fuel burned, electricity consumed, heat used, etc.). Although the units for the emission factors and activity data can take on many different forms, leading to various "intermediate" terms, the emission calculations are still governed by this simple equation.

Keeping in mind the simple equation presented above, emissions for APUs and alternative systems can be calculated in six steps. These six steps are illustrated in Figure 6 and discussed in the following paragraphs.

Step 1: Calculate fuel consumption/energy consumption for the four APU modes and three ambient conditions. Formula 1A presented on the next page is used to calculate APU fuel burn. Formula 1B is used to calculate alternative system electricity consumption. Formula 1C is used to calculate alternative system heat energy consumption and is only applicable to central systems with airport boilers. Users without airport specific data will use data provided in Tables 2, 3, 4, 5, 6,

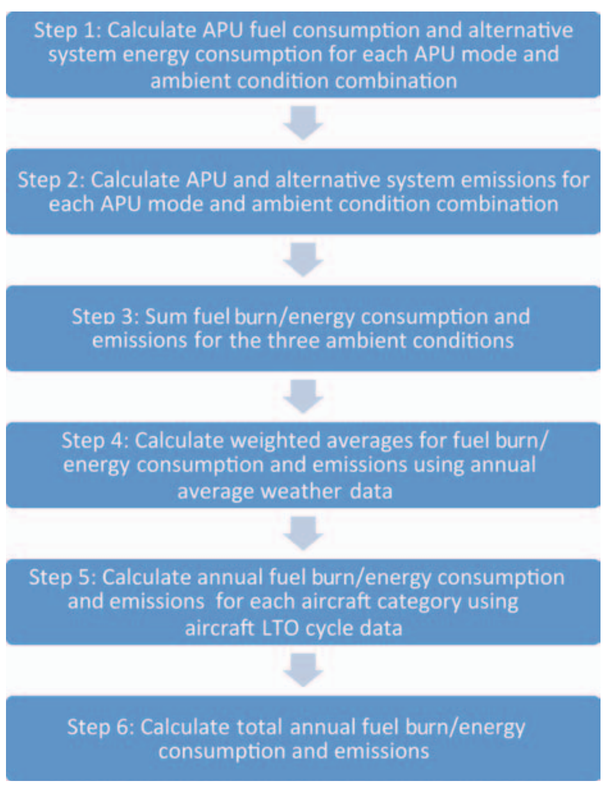

Figure 6. Calculation of fuel burn/energy consumption and emissions.

and 7 to compute APU fuel burn. Users without airport specific data will use data provided in Tables 2, 8, 9, 10, and 11 to compute alternative system electricity and heat energy consumption. Separate calculations are performed for the five aircraft categories presented in Table 1, as applicable.

Step 2: Calculate emissions for the four APU modes and three ambient conditions. Formula 2A is used to calculate APU emissions. Formula 2B is used to calculate emissions from alternative systems. Formula 2C is used to convert APU THC emissions to volatile organic compound (VOC) emissions for comparison to alternative system VOC emissions. Users without airport specific data will use data provided in Tables 5, 6, and 7 to calculate APU-related emissions. Users without airport-specific data will use data provided in Table 12 to compute emissions associated with alternative systems. Separate calculations are performed for the five aircraft categories presented in Table 1, as applicable.

Step 3: Sum the fuel burn/energy consumption values and emissions values within each ambient condition. Separate calculations are performed for the five aircraft categories presented in Table 1, as applicable. The purpose of this step is to assemble data for each of the three ambient conditions (cold, neutral, and hot) to allow the computation of weighted average fuel burn, energy consumption, and emissions values during Step 4.

Step 4: Calculate weighted average fuel burn/energy consumption and emissions using annual average weather conditions data. See Formula 3. Users without airport-specific weather data will use data provided in Table 2. Separate calculations are performed for the five aircraft categories presented in Table 1, as applicable.

Step 5: Calculate total annual fuel burn and emissions by aircraft category using the results of Step 4 and user-defined or default aircraft LTO cycle data. See Formula 4.

Step 6: Sum fuel burn and emissions across all five aircraft categories to arrive at airport-wide totals.

Calculate APU fuel burn (FB) using the following equation:

$$FB = FF \times TIM \qquad \text{(Formula 1A)}$$

Where: FB = Fuel Burn per mode (kg)
FF = Fuel Flow (kg/s)
TIM = Time in Mode (s)

Calculate electricity (electric energy) consumption required for ground power, heating, and cooling using the following equation:

$$EE = EP \times TIM \qquad \text{(Formula 1B)}$$

Where: EE = Electric Energy consumption per mode (KWh)
EP = Electric Power (KW)
TIM = Time in Mode (hr)

Calculate natural gas consumption required for heating using the following equation:

$$HE = HR \times TIM \qquad \text{(Formula 1C)}$$

Where: HE = Heat Energy consumption per mode (BTU)
HR = Heat Rate (BTU/hr)
TIM = Time in Mode (hr)

Calculate APU emissions for the four modes of APU operation and the three ambient conditions as follows:

$$E = FB \times EI \qquad \text{(Formula 2A)}$$

Where: E = Emissions per mode (g)
FB = Fuel Burn per mode (kg)
EI = Emissions Index (g/kg)

Calculate alternative system emissions for the "Gate Out" and "Gate In" modes and the three ambient conditions as follows:

$$E = EE \times EF \qquad \text{(Formula 2B)}$$

Where: E = Emissions per mode (g)
EE = Electric Energy consumption per mode (KWh)
EF = Emission Factor (g/KWh)

$$E = HE \times EF$$

Where: E = Emissions per mode (g)
HE = Heat Energy consumption per mode (BTU)
EF = Emission Factor (g/BTU)

APU THC emissions can be converted to VOC emissions through the use of the following formula (USEPA 2009; FAA 2010):

$$E_{VOC} = E_{THC} \times CF \qquad \text{(Formula 2C)}$$

Where: E_{VOC} = VOC Emissions per mode (g)
E_{THC} = THC Emissions per mode (g)
CF = Conversion Factor = 1.15

APU and alternative system FB/energy consumption and emissions are weighted using annual average ambient temperature data as follows:

$$\begin{aligned}\text{Weighted average FB or E} = & (\text{Cold condition FB or E} \times \%\text{ cold}) \qquad \text{(Formula 3)}\\ & + (\text{Neutral condition FB or E} \times \%\text{ neutral})\\ & + (\text{Hot condition FB or E} \times \%\text{ hot})\end{aligned}$$

Where: E = Emissions per mode (g)
FB = Fuel Burn per mode (kg)

Weighted average FB and emissions values are multiplied by the total number of LTO cycles per year to obtain "totals per year" by aircraft category as indicated below:

$$\text{Total FB/yr} = \left(\frac{\text{FB}}{\text{LTO}}\right) \times \text{LTO cycles/yr} \qquad \text{(Formula 4)}$$

$$\text{Emissions/yr} = \left(\frac{\text{Emissions}}{\text{LTO}}\right) \times (\text{LTO cycles/yr})$$

Sample FB and emissions calculations for APUs, POU systems, central systems, and central systems with airport boilers are presented in the following sections. These sample calculations make use of the formulas presented in this section and default data presented in Section 3.1.2.

3.2.1 APU Fuel Burn and Emissions

The following sets of data by aircraft category are necessary to calculate APU emissions:

- Number of LTO cycles,
- APU TIM values,
- APU FF and pollutant EIs, and
- Average yearly temperature distribution.

Since fuel consumption and emissions are quantified and typically compared on a yearly basis, the starting point for APU emissions calculations is the specification of aircraft LTO cycles per year for each aircraft category at the airport of interest. This is exemplified in Table 13.

For the purposes of this example, the default data for APU TIM is used from Table 3. Similarly this example makes use of the default ambient conditions data provided in Table 2 to properly use the FF and EI values in Tables 5 through 7. The APU power settings must be correlated to the different APU modes and ambient conditions (e.g., temperature conditions) to determine if heating or cooling is required.

To calculate emissions, the first step is to calculate FB using Formula 1A for each time in mode and ambient condition.

$$FB = FF \times TIM$$

Where: FB = Fuel Burn per mode (kg)
FF = Fuel Flow (kg/s)
TIM = Times in Mode(s) (See Table 3)

Emissions calculations are performed with Formula 2A. Separate calculations are performed for each pollutant and for each aircraft category.

$$E = FB \times EI$$

Where: E = Emissions per mode (g)
FB = Fuel Burn per mode (kg)
EI = Emissions Index for a particular pollutant (g/kg) (See Tables 5 through 7)

Table 13. Example aircraft activity information.

Aircraft Category	LTO cycles/yr
Narrow Body	40,000
Wide Body	2,000
Jumbo-Wide Body	3,000
Regional Jet	60,000
Turbo Prop	7,000
Total	**112,000**

Assuming the number of LTO cycles/yr for each aircraft category is specified, fuel burn and emissions are calculated for each of the four APU modes and three ambient temperature condition combinations. Example fuel burn, CO_2 emissions, and THC emissions calculations for the "APU Start" mode and the "Narrow Body" aircraft category are presented in the following paragraphs. **Please Note: Hand-calculated values presented in this section may not exactly match values presented in the summary figures due to rounding errors.**

TIM for "Narrow Body" aircraft and "APU Start" mode is 3 minutes (See Table 3)

$$\text{TIM} = 3\text{ min} \times 60\text{ s/min} = 180\text{s}$$

$$\text{FB} = \text{FF} \times \text{TIM}$$

FF for "Narrow Body" and "APU Start" is 0.021 kg/s (See Table 5)

$$\text{FB} = (0.021\text{ kg/s}) \times (180\text{s}) = 3.78\text{ kg}$$

$$CO_2\text{ Emissions} = (3.78\text{ kg}) \times \left(3{,}155\frac{\text{g}}{\text{kg}}\right) = 11{,}925.9\text{ g}$$

$$\text{THC Emissions} = (3.78\text{ kg}) \times \left(6.53\frac{\text{g}}{\text{kg}}\right) = 24.683\text{ g}$$

These calculations are repeated for each pollutant and for each aircraft category. The THC emissions can be converted to VOC emissions as indicated below:

$$\text{VOC Emissions} = (24.683\text{ g}) \times (1.15) = 28.385\text{ g}$$

A set of fuel burn and emissions data for the 12 APU mode and ambient condition combinations must be generated. Once the 12 tables are developed, they are summed within each ambient condition as indicated in Figure 7. The summed FB value for the "Narrow Body" aircraft category under cold conditions is:

$$\text{Summed FB} = \text{FB "APU Start"} + \text{FB "Gate Out"} + \text{FB "Main Engine Start"} + \text{FB "Gate In"}$$

$$\text{Summed FB} = 3.780\text{ kg} + 7.128\text{ kg} + 1.330\text{ kg} + 29.700\text{ kg}$$

$$\text{Summed FB} = 41.938\text{ kg}$$

Each of the fuel burn and emissions values in the three tables at the bottom of Figure 7 are multiplied by the corresponding ambient temperature condition percentages in Table 2 and then summed to produce one weighted table. This process is illustrated in Figure 8. For example, the weighted average fuel burn for the "Narrow Body" aircraft category is conducted as follows using Formula 3:

$$\begin{aligned}\text{Weighted average APU FB} = {} & (\text{Cold conditions FB} \times 0.25) \\ & + (\text{Neutral conditions FB} \times 0.50) \\ & + (\text{Hot conditions FB} \times 0.25) \\ = {} & (41.938\text{ kg} \times 0.25) + (28.546\text{ kg} \times 0.50) + (41.938\text{ kg} \times 0.25) \\ = {} & 35.242\text{ kg}\end{aligned}$$

As each of the fuel burn and emissions values represent averages per LTO cycle, each value must be multiplied by the specified number of LTO cycles presented in Table 13. For example,

"APU Start" Mode and Cold Conditions

Aircraft Category	FB (kg)	CO2 (g)	CO (g)	THC (g)	NOx (g)
Narrow Body	3.780	11,925.900	120.015	24.683	20.601
Wide Body	6.300	19,876.500	64.638	5.481	47.565
Jumbo-Wide Body	5.940	18,740.700	55.717	5.227	44.015
Regional Jet	2.160	6,814.800	13.522	3.650	13.262
Turbo Prop	2.160	6,814.800	13.522	3.650	13.262

"Gate Out" Mode and Cold Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	7.128	22,488.840	40.772	3.065	48.827
Wide Body	11.232	35,436.960	12.804	2.134	123.440
Jumbo-Wide Body	19.398	61,200.690	10.281	2.328	199.799
Regional Jet	4.104	12,948.120	26.553	2.011	20.233
Turbo Prop	4.104	12,948.120	26.553	2.011	20.233

"Main Engine Start" Mode and Cold Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	1.330	4,196.150	6.570	0.386	10.161
Wide Body	2.240	7,067.200	2.195	0.291	25.827
Jumbo-Wide Body	8.120	25,618.600	4.304	0.974	90.944
Regional Jet	0.700	2,208.500	4.536	0.294	3.437
Turbo Prop	0.700	2,208.500	4.536	0.294	3.437

"Gate In" Mode and Cold Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	29.700	93,703.500	169.884	12.771	203.445
Wide Body	46.800	147,654.000	53.352	8.892	514.332
Jumbo-Wide Body	54.900	173,209.500	29.097	6.588	565.470
Regional Jet	17.100	53,950.500	110.637	8.379	84.303
Turbo Prop	17.100	53,950.500	110.637	8.379	84.303

Total Cold Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	41.938	132,314.390	337.241	40.905	283.034
Wide Body	66.572	210,034.660	132.990	16.798	711.164
Jumbo-Wide Body	88.358	278,769.490	99.399	15.117	900.229
Regional Jet	24.064	75,921.920	155.247	14.334	121.235
Turbo Prop	24.064	75,921.920	155.247	14.334	121.235

"APU Start" Mode and Neutral Conditions

Aircraft Category	FB (kg)	CO2 (g)	CO (g)	THC (g)	NOx (g)
Narrow Body	3.780	11,925.900	120.015	24.683	20.601
Wide Body	6.300	19,876.500	64.638	5.481	47.565
Jumbo-Wide Body	5.940	18,740.700	55.717	5.227	44.015
Regional Jet	2.160	6,814.800	13.522	3.650	13.262
Turbo Prop	2.160	6,814.800	13.522	3.650	13.262

"Gate Out" Mode and Neutral Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	4.536	14,311.080	144.018	29.620	24.721
Wide Body	7.560	23,851.800	77.566	6.577	57.078
Jumbo-Wide Body	10.494	33,108.570	98.434	9.235	77.761
Regional Jet	2.592	8,177.760	16.226	4.380	15.915
Turbo Prop	2.592	8,177.760	16.226	4.380	15.915

"Main Engine Start" Mode and Neutral Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	1.330	4,196.150	6.570	0.386	10.161
Wide Body	2.240	7,067.200	2.195	0.291	25.827
Jumbo-Wide Body	8.120	25,618.600	4.304	0.974	90.944
Regional Jet	0.700	2,208.500	4.536	0.294	3.437
Turbo Prop	0.700	2,208.500	4.536	0.294	3.437

"Gate In" Mode and Neutral Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	18.900	59,629.500	600.075	123.417	103.005
Wide Body	31.500	99,382.500	323.190	27.405	237.825
Jumbo-Wide Body	29.700	93,703.500	278.586	26.136	220.077
Regional Jet	10.800	34,074.000	67.608	18.252	66.312
Turbo Prop	10.800	34,074.000	67.608	18.252	66.312

Total Neutral Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	28.546	90,062.630	870.678	178.106	158.488
Wide Body	47.600	150,178.000	467.589	39.754	368.295
Jumbo-Wide Body	54.254	171,171.370	437.041	41.572	432.797
Regional Jet	16.252	51,275.060	101.892	26.577	98.926
Turbo Prop	16.252	51,275.060	101.892	26.577	98.926

"APU Start" Mode and Hot Conditions

Aircraft Category	FB (kg)	CO2 (g)	CO (g)	THC (g)	NOx (g)
Narrow Body	3.780	11,925.900	120.015	24.683	20.601
Wide Body	6.300	19,876.500	64.638	5.481	47.565
Jumbo-Wide Body	5.940	18,740.700	55.717	5.227	44.015
Regional Jet	2.160	6,814.800	13.522	3.650	13.262
Turbo Prop	2.160	6,814.800	13.522	3.650	13.262

"Gate Out" Mode and Hot Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	7.128	22,488.840	40.772	3.065	48.827
Wide Body	11.232	35,436.960	12.804	2.134	123.440
Jumbo-Wide Body	19.398	61,200.690	10.281	2.328	199.799
Regional Jet	4.104	12,948.120	26.553	2.011	20.233
Turbo Prop	4.104	12,948.120	26.553	2.011	20.233

"Main Engine Start" Mode and Hot Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	1.330	4,196.150	6.570	0.386	10.161
Wide Body	2.240	7,067.200	2.195	0.291	25.827
Jumbo-Wide Body	8.120	25,618.600	4.304	0.974	90.944
Regional Jet	0.700	2,208.500	4.536	0.294	3.437
Turbo Prop	0.700	2,208.500	4.536	0.294	3.437

"Gate In" Mode and Hot Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	29.700	93,703.500	169.884	12.771	203.445
Wide Body	46.800	147,654.000	53.352	8.892	514.332
Jumbo-Wide Body	54.900	173,209.500	29.097	6.588	565.470
Regional Jet	17.100	53,950.500	110.637	8.379	84.303
Turbo Prop	17.100	53,950.500	110.637	8.379	84.303

Total Hot Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	41.938	132,314.390	337.241	40.905	283.034
Wide Body	66.572	210,034.660	132.990	16.798	711.164
Jumbo-Wide Body	88.358	278,769.490	99.399	15.117	900.229
Regional Jet	24.064	75,921.920	155.247	14.334	121.235
Turbo Prop	24.064	75,921.920	155.247	14.334	121.235

Figure 7. Sample calculations—APU fuel consumption and emissions.

Total Cold Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	41.938	132,314.390	337.241	40.905	283.034
Wide Body	66.572	210,034.660	132.990	16.798	711.164
Jumbo-Wide Body	88.358	278,769.490	99.399	15.117	900.229
Regional Jet	24.064	75,921.920	155.247	14.334	121.235
Turbo Prop	24.064	75,921.920	155.247	14.334	121.235

Total Neutral Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	28.546	90,062.630	870.678	178.106	158.488
Wide Body	47.600	150,178.000	467.589	39.754	368.295
Jumbo-Wide Body	54.254	171,171.370	437.041	41.572	432.797
Regional Jet	16.252	51,275.060	101.892	26.577	98.926
Turbo Prop	16.252	51,275.060	101.892	26.577	98.926

Total Hot Conditions

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	41.938	132,314.390	337.241	40.905	283.034
Wide Body	66.572	210,034.660	132.990	16.798	711.164
Jumbo-Wide Body	88.358	278,769.490	99.399	15.117	900.229
Regional Jet	24.064	75,921.920	155.247	14.334	121.235
Turbo Prop	24.064	75,921.920	155.247	14.334	121.235

Total Weighted

Aircraft Category	FB (kg)	CO_2 (g)	CO (g)	THC (g)	NO_x (g)
Narrow Body	35.242	111,188.510	603.960	109.506	220.761
Wide Body	57.086	180,106.330	300.289	28.276	539.730
Jumbo-Wide Body	71.306	224,970.430	268.220	28.345	666.513
Regional Jet	20.158	63,598.490	128.570	20.456	110.081
Turbo Prop	20.158	63,598.490	128.570	20.456	110.081

Figure 8. Sample calculations—APU weighted fuel consumption and emissions.

Annual Fuel Burn and Emissions by Aircraft Category

Aircraft Category	FB (Metric Tons)	CO_2 (Metric Tons)	CO (kg)	THC (kg)	NO_x (kg)
Narrow Body	1,409.680	4,447.540	24,158.391	4,380.226	8,830.448
Wide Body	114.172	360.213	600.578	56.553	1,079.459
Jumbo-Wide Body	213.918	674.911	804.659	85.035	1,999.539
Regional Jet	1,209.480	3,815.909	7,714.170	1,227.337	6,604.842
Turbo Prop	141.106	445.189	899.987	143.189	770.565

Total Annual Fuel Burn and Emissions

FB (Metric Tons)	CO_2 (Metric Tons)	CO (kg)	THC (kg)	NO_x (kg)
3,088	9,744	34,178	5,892	19,285

Figure 9. Sample calculations—APU total fuel consumption and emissions.

using the resulting 111,188.510 g/LTO emissions of CO_2 from Figure 8, the total CO_2 emissions for the "Narrow Body" aircraft category would be calculated using Formula 4 as:

$$CO_2\ \text{Emissions} = (111{,}188.510\ \text{g/LTO}) \times (40{,}000\ \text{LTO/yr})$$
$$= 4{,}447{,}540{,}400\text{g/yr}$$
$$= 4{,}447{,}540{,}400\text{g /yr} \times 1\ \text{Metric Ton}/1{,}000{,}000\ \text{g}$$
$$= 4{,}447.540\ \text{Metric Tons/yr}$$

The last step is to sum the fuel burn and emissions across each aircraft category to arrive at airport-wide totals as presented in Figure 9.

3.2.2 POU System Emissions

The following sets of data by aircraft category are necessary to calculate POU system emissions:

- Number of LTO cycles,
- APU TIM values,
- POU system electricity consumption rates for ground power and PCA (heating and cooling),
- Electricity-based emission factors, and
- Average yearly temperature distribution.

Default values are provided in Section 3.1 for all of the data above with the exception of number of LTOs.

To calculate electricity (energy) consumption and emissions for POU systems, the default LTO data and the APU activity data presented in Tables 3 and 13 are used as a starting point. Emissions for POU systems are calculated using information presented in Table 3, the POU system electricity requirement data presented in Table 8, and the emission factors data presented in Table 12.

Please Note: Hand-calculated values presented in this section may not match exactly the values presented in the summary figures due to rounding errors.

In order to calculate emissions from POU systems, the first step is to calculate the electricity (electric energy) consumption required for ground power, heating, and cooling using Formula 1B:

$$EE = EP \times TIM$$

Where: EE = Electric Energy consumption per mode (KWh)
EP = Electric Power (KW) (See Table 8)
TIM = Time in Mode (hr) (See Table 3)

Emissions are then calculated using Formula 2B as follows:

$$E = EE \times EF$$

Where: E = Emissions per mode (g)
EE = Electric Energy consumption per mode (KWh)
EF = Emission Factor (g/KWh) (See Table 12)

Similar to the APU mode and ambient condition combinations, alternative systems also provide different ground power and heating/cooling service based on mode and ambient conditions as presented in Table 11.

When all of the energy and emissions are calculated for each of the six mode and ambient condition combinations (i.e., not including the six conditions associated with "APU Start" and "Main Engine Start" when APU use is required), they need to be weighted based on average yearly ambient conditions. The default percentages in Table 2 are based on one cold condition (winter), two neutral conditions (spring and fall) and one hot condition (summer). Since the weighted values are based on a per LTO cycle basis, they need to be multiplied by the total number of LTO cycles per year to obtain totals per year as indicated below:

$$\text{Total EE/yr} = \left(\frac{\text{EE}}{\text{LTO}}\right) \times (\text{LTO cycles/yr})$$

$$\text{Total Electricity-related CO}_2\text{ Emissions/yr} = \left(\frac{\text{Electricity-related CO}_2\text{ Emissions}}{\text{LTO}}\right) \times (\text{LTO cycles/yr})$$

These calculations are repeated for each of the pollutants of concern, and separate calculations are performed for each aircraft category. Since emission calculations for alternative systems are focused on the "Gate In" and "Gate Out" modes, separate emission calculations must be performed to account for APU-related emissions during the "APU Start" and "Main Engine Start" modes. These APU emissions should be considered separately (i.e., not added numerically to the alternative system emissions) for the following reasons:

1. Since APU emissions occur locally (in terminal areas), they contribute to local air quality issues. In contrast, power plant emissions usually occur outside of the geographic domain of the airport, and hence, generally do not cause localized air quality impacts in the vicinity of the airport.
2. Neither of the emissions is negligible.
3. Although they may be similar, VOC emissions are not equivalent to THC emissions.

Rather than combining these two datasets, they should simply be considered separately as part of the scenario involving the use of an alternative system. If comparing directly with total APU emissions, then these common "APU Start" and "Main Engine Start" mode emissions will cancel out. The example calculations presented herein are based on the use of the example and default data presented in this chapter. Assuming the number of LTO cycles/yr are specified as in Table 13, example calculations for ground power electricity consumption during cold conditions for the "Narrow Body" aircraft category are:

"Gate Out" mode for "Narrow Body" aircraft and cold conditions (See Tables 2, 8, and 11)

$$\text{TIM} = 3.6 \text{ min x } 1 \text{ hr/60 min} = 0.06 \text{ hr}$$

$$\text{EE} = (23.88 \text{ KW}) \times (0.06 \text{ hr}) = 1.433 \text{ KWh}$$

This is repeated for the heating and cooling operations, and then the energy consumption values are summed accordingly to match the combinations specified in Table 11. For example, electric energy consumption from ground power is combined with electric energy consumption for cabin heating:

$$\begin{aligned}\text{Total electric energy consumption} &= \text{ground power electric energy} + \text{cabin heating electric energy}\\ &= 1.433\ \text{KWh} + 2.802\ \text{KWh}\\ &= 4.235\ \text{KWh}\end{aligned}$$

Emissions are calculated as exemplified by this CO_2 emissions calculation:

$$CO_2\ \text{Emissions} = (4.235\ \text{KWh}) \times (618\ \text{g/KWh}) = 2{,}617\ \text{g}$$

Once the six tables (one for each of the six APU mode and ambient combinations) are developed, they are summed within each ambient condition as presented in Figure 10. The three tables at the bottom of Figure 10 represent the sum of the energy and emissions data for the "Gate Out" and "Gate In" modes with each table corresponding to one of the three ambient conditions. The summed electric energy value for the "Narrow Body" aircraft category under the cold ambient condition is:

$$\text{Summed electric energy} = 4.235\ \text{KWh} + 17.648\ \text{KWh} = 21.883\ \text{KWh}$$

The energy and emissions values in the three tables at the bottom of Figure 10 are multiplied by the corresponding percentages in Table 2 and then summed to produce one weighted table as illustrated in Figure 11. For example, the weighting for electric energy consumption for the "Narrow Body" aircraft category is conducted using Formula 3 as follows:

$$\begin{aligned}\text{Weighted average EE} &= (\text{Cold EE} \times 0.25) + (\text{Neutral EE} \times 0.50) + (\text{Hot EE} \times 0.25)\\ &= (21.883\ \text{KWh} \times 0.25) + (7.403\ \text{KWh} \times 0.50) + (28.681\ \text{KWh} \times 0.25)\\ &= 16.342\ \text{KWh}\end{aligned}$$

The energy use and emissions data are summed across each aircraft category to arrive at airport-wide totals as presented in Figure 12.

The final step is to separately consider APU emissions during the "APU Start" and "Main Engine Start" modes of operation as illustrated in Figure 13.

As previously explained, the APU and alternative system emissions data should not be summed for various reasons. They should be considered separately to allow a comprehensive understanding of all emissions and fuel/energy consumption associated with the use of alternative systems.

3.2.3 Central System Emissions

The following sets of data by aircraft category are necessary to calculate central system emissions:

- Number of LTO cycles,
- APU TIM values,
- Central system electricity consumption rates for ground power and PCA (heating and cooling),
- Electricity-based emission factors, and
- Average yearly temperature distribution.

"Gate Out" Mode and Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	4.235	2,617.477	0.280	0.005	4.041
Wide Body	8.030	4,962.416	0.530	0.010	7.660
Jumbo-Wide Body	14.746	9,113.255	0.973	0.018	14.068
Regional Jet	1.799	1,111.658	0.119	0.002	1.716
Turbo Prop	2.359	1,457.986	0.156	0.003	2.251

"Gate In" Mode and Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	17.648	10,906.155	1.165	0.021	16.836
Wide Body	33.458	20,676.735	2.208	0.040	31.918
Jumbo-Wide Body	41.735	25,792.230	2.755	0.050	39.815
Regional Jet	7.495	4,631.910	0.495	0.009	7.150
Turbo Prop	9.830	6,074.940	0.649	0.012	9.378

Total Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	21.883	13,523.632	1.444	0.026	20.876
Wide Body	41.487	25,639.151	2.738	0.050	39.579
Jumbo-Wide Body	56.481	34,905.485	3.728	0.068	53.883
Regional Jet	9.294	5,743.568	0.613	0.011	8.866
Turbo Prop	12.189	7,532.926	0.804	0.015	11.628

"Gate Out" Mode and Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	1.433	885.470	0.095	0.002	1.367
Wide Body	2.227	1,376.410	0.147	0.003	2.125
Jumbo-Wide Body	4.700	2,904.734	0.310	0.006	4.484
Regional Jet	0.798	493.164	0.053	0.001	0.761
Turbo Prop	1.596	986.328	0.105	0.002	1.523

"Gate In" Mode and Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	5.970	3,689.460	0.394	0.007	5.695
Wide Body	9.280	5,735.040	0.612	0.011	8.853
Jumbo-Wide Body	13.303	8,220.945	0.878	0.016	12.691
Regional Jet	3.325	2,054.850	0.219	0.004	3.172
Turbo Prop	6.650	4,109.700	0.439	0.008	6.344

Total Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	7.403	4,574.930	0.489	0.009	7.062
Wide Body	11.507	7,111.450	0.759	0.014	10.978
Jumbo-Wide Body	18.003	11,125.679	1.188	0.022	17.175
Regional Jet	4.123	2,548.014	0.272	0.005	3.933
Turbo Prop	8.246	5,096.028	0.544	0.010	7.867

"Gate Out" Mode and Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	5.551	3,430.642	0.366	0.007	5.296
Wide Body	12.670	7,829.813	0.836	0.015	12.087
Jumbo-Wide Body	21.479	13,274.104	1.418	0.026	20.491
Regional Jet	3.158	1,951.520	0.208	0.004	3.013
Turbo Prop	3.466	2,141.741	0.229	0.004	3.306

"Gate In" Mode and Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	23.130	14,294.340	1.527	0.028	22.066
Wide Body	52.790	32,624.220	3.484	0.063	50.362
Jumbo-Wide Body	60.790	37,568.220	4.012	0.073	57.994
Regional Jet	13.158	8,131.335	0.868	0.016	12.552
Turbo Prop	14.440	8,923.920	0.953	0.017	13.776

Total Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	28.681	17,724.982	1.893	0.034	27.362
Wide Body	65.460	40,454.033	4.320	0.079	62.448
Jumbo-Wide Body	82.269	50,842.324	5.430	0.099	78.485
Regional Jet	16.315	10,082.855	1.077	0.020	15.565
Turbo Prop	17.906	11,065.661	1.182	0.021	17.082

Figure 10. Sample calculations—POU system energy consumption and emissions.

Total Cold Condition

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	21.883	13,523.632	1.444	0.026	20.876
Wide Body	41.487	25,639.151	2.738	0.050	39.579
Jumbo-Wide Body	56.481	34,905.485	3.728	0.068	53.883
Regional Jet	9.294	5,743.568	0.613	0.011	8.866
Turbo Prop	12.189	7,532.926	0.804	0.015	11.628

Total Neutral Condition

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	7.403	4,574.930	0.489	0.009	7.062
Wide Body	11.507	7,111.450	0.759	0.014	10.978
Jumbo-Wide Body	18.003	11,125.679	1.188	0.022	17.175
Regional Jet	4.123	2,548.014	0.272	0.005	3.933
Turbo Prop	8.246	5,096.028	0.544	0.010	7.867

Total Hot Condition

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	28.681	17724.982	1.893	0.034	27.362
Wide Body	65.460	40454.033	4.320	0.079	62.448
Jumbo-Wide Body	82.269	50842.324	5.430	0.099	78.485
Regional Jet	16.315	10082.855	1.077	0.020	15.565
Turbo Prop	17.906	11065.661	1.182	0.021	17.082

Total Weighted

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	16.342	10,099.619	1.079	0.020	15.591
Wide Body	32.490	20,079.021	2.144	0.039	30.996
Jumbo-Wide Body	43.689	26,999.792	2.883	0.052	41.679
Regional Jet	8.464	5,230.613	0.559	0.010	8.074
Turbo Prop	11.647	7,197.661	0.769	0.014	11.111

Figure 11. Sample calculations—POU system weighted energy consumption and emissions.

Annual Energy Consumption and Emissions by Aircraft Category

Aircraft Category	Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
Narrow Body	653.697	403.985	43.144	0.784	623.627
Wide Body	64.981	40.158	4.289	0.078	61.992
Jumbo-Wide Body	131.067	80.999	8.650	0.157	125.038
Regional Jet	507.827	313.837	33.517	0.609	484.466
Turbo Prop	81.527	50.384	5.381	0.098	77.777

Total Annual Energy Consumption and Emissions

Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
1,439	889	95	1.73	1,373

Figure 12. Sample calculations—POU system total energy consumption and emissions.

Similar to the evaluation process for POU systems, users can supply all of the above data or can use default data for all except the locally specific LTO cycles.

To calculate electricity (energy) consumption and emissions for central systems, the aircraft activity data and the APU activity data presented in Tables 3 and 13 are used as a starting point. Note that the electricity requirements for central systems are similar to the electricity requirements for POU systems except for cooling operations. To calculate emissions for central systems, the central system electricity requirements data presented in Table 9 are used in combination with the LTO data presented in Table 13 and the TIM data presented in Table 3. The emission factors are the same as used for the POU system calculations, and are presented in Table 12.

Please Note: Hand-calculated values presented in this section may not exactly match values presented in the summary figures due to rounding errors.

To calculate emissions from central systems, the first step is to calculate the electricity (electric energy) consumption required for ground power, heating, and cooling and then to calculate the emissions using Formula 1B and Formula 2B:

$$\text{EE} = \text{EP} \times \text{TIM}$$

Where: EE = Electric Energy consumption per mode (KWh)
EP = Electric Power (KW) (See Table 9)
TIM = Time in Mode (hr) (See Table 3)

Total Annual Energy Consumption and Emissions

Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
1,439	889	95	1.73	1,373

&

Annual APU Fuel Burn and Emissions - "APU Start" and "Main Engine Start" Modes

FB (Metric Tons)	CO_2 (Metric Tons)	CO (kg)	THC (kg)	NO_x (kg)
455	1,436	6,587	1,297	2,901

Figure 13. Sample calculations—POU system and APU ("APU start" and "main engine start" mode) energy/fuel consumption and emissions.

$$E = EE \times EF$$

Where: E = Emissions per mode (g)
EE = Electric Energy consumption per mode (KWh)
EF = Emission Factor (g/KWh) (See Table 12)

Similar to the APU mode and ambient condition combinations, alternative systems also provide different ground power and heating/cooling service based on the combination of mode and ambient conditions. The mode/ambient condition combinations for alternative systems are listed in Table 11.

When all of the energy and emissions are calculated for each of the six mode and ambient condition combinations (i.e., not including the six conditions associated with "APU Start" and "Main Engine Start" when APU use is required), they need to be weighted based on average yearly ambient conditions. Since the weighted values are based on a per LTO cycle basis, they need to be multiplied by the total number of LTO cycles per year to obtain totals per year as indicated below:

$$\text{Total EE/yr} = \left(\frac{\text{EE}}{\text{LTO}}\right) \times (\text{LTO cycles/yr})$$

$$\text{Total Electricity-related } CO_2 \text{ Emissions/yr} = \left(\frac{\text{Electricity-related } CO_2 \text{ Emissions}}{\text{LTO}}\right) \times (\text{LTO cycles/yr})$$

The example calculations presented below are based on the use of the LTO cycles/yr data listed in Table 13. Central system electricity consumption and emissions were calculated for each of the six (6) mode and ambient temperature condition combinations. Calculations for ground power electricity consumption for the "Narrow Body" aircraft category for the "Gate Out" mode are presented below:

$$\text{TIM} = 3.6 \text{ min} \times 1 \text{ hr}/60 \text{ min} = 0.06 \text{ hr}$$

$$\text{EE} = (23.88 \text{ KW}) \times (0.06 \text{ hr})$$
$$= 1.433 \text{ KWh}$$

These calculations are repeated for the heating and cooling operations, and then the energy consumption values are summed. For example, for cold conditions, electric energy consumption from ground power is combined with electric energy consumption for cabin heating:

$$\text{Total electric energy consumption} = \text{ground power electric energy} + \text{cabin heating electric energy}$$
$$= 1.433 \text{ KWh} + 2.802 \text{ KWh}$$
$$= 4.235 \text{ KWh}$$

Emissions of CO_2 are calculated as follows for the "Narrow Body" aircraft category for the "Gate Out" mode and cold conditions:

$$CO_2 \text{ Emissions} = (4.235 \text{ KWh}) \times (618 \text{ g/KWh})$$
$$= 2{,}617 \text{ g}$$

Once the six tables are developed, they are summed within each ambient condition as indicated in Figure 14. For example, the energy values in each of the two tables on the left side of

"Gate Out" Mode and Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	4.235	2,617.477	0.280	0.005	4.041
Wide Body	8.030	4,962.416	0.530	0.010	7.660
Jumbo-Wide Body	14.746	9,113.255	0.973	0.018	14.068
Regional Jet	1.799	1,111.658	0.119	0.002	1.716
Turbo Prop	2.359	1,457.986	0.156	0.003	2.251

"Gate In" Mode and Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	17.648	10,906.155	1.165	0.021	16.836
Wide Body	33.458	20,676.735	2.208	0.040	31.918
Jumbo-Wide Body	41.735	25,792.230	2.755	0.050	39.815
Regional Jet	7.495	4,631.910	0.495	0.009	7.150
Turbo Prop	9.830	6,074.940	0.649	0.012	9.378

Total Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	21.883	13,523.632	1.444	0.026	20.876
Wide Body	41.487	25,639.151	2.738	0.050	39.579
Jumbo-Wide Body	56.481	34,905.485	3.728	0.068	53.883
Regional Jet	9.294	5,743.568	0.613	0.011	8.866
Turbo Prop	12.189	7,532.926	0.804	0.015	11.628

"Gate Out" Mode and Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	1.433	885.470	0.095	0.002	1.367
Wide Body	2.227	1,376.410	0.147	0.003	2.125
Jumbo-Wide Body	4.700	2,904.734	0.310	0.006	4.484
Regional Jet	0.798	493.164	0.053	0.001	0.761
Turbo Prop	1.596	986.328	0.105	0.002	1.523

"Gate In" Mode and Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	5.970	3,689.460	0.394	0.007	5.695
Wide Body	9.280	5,735.040	0.612	0.011	8.853
Jumbo-Wide Body	13.303	8,220.945	0.878	0.016	12.691
Regional Jet	3.325	2,054.850	0.219	0.004	3.172
Turbo Prop	6.650	4,109.700	0.439	0.008	6.344

Total Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	7.403	4,574.930	0.489	0.009	7.062
Wide Body	11.507	7,111.450	0.759	0.014	10.978
Jumbo-Wide Body	18.003	11,125.679	1.188	0.022	17.175
Regional Jet	4.123	2,548.014	0.272	0.005	3.933
Turbo Prop	8.246	5,096.028	0.544	0.010	7.867

"Gate Out" Mode and Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	4.363	2,696.458	0.288	0.005	4.162
Wide Body	10.057	6,214.979	0.664	0.012	9.594
Jumbo-Wide Body	18.183	11,237.352	1.200	0.022	17.347
Regional Jet	2.427	1,499.886	0.160	0.003	2.315
Turbo Prop	2.868	1,772.424	0.189	0.003	2.736

"Gate In" Mode and Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	18.180	11,235.240	1.200	0.022	17.344
Wide Body	41.903	25,895.745	2.766	0.050	39.975
Jumbo-Wide Body	51.463	31,803.825	3.397	0.062	49.095
Regional Jet	10.113	6,249.525	0.667	0.012	9.647
Turbo Prop	11.950	7,385.100	0.789	0.014	11.400

Total Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	22.543	13,931.698	1.488	0.027	21.506
Wide Body	51.959	32,110.724	3.429	0.062	49.569
Jumbo-Wide Body	69.646	43,041.177	4.597	0.084	66.442
Regional Jet	12.540	7,749.411	0.828	0.015	11.963
Turbo Prop	14.818	9,157.524	0.978	0.018	14.136

Figure 14. Sample calculations—central system energy consumption and emissions.

Figure 14 are summed to generate the total energy value in the one table at the bottom left corner. The resulting three tables at the bottom of Figure 14 represent the sum of the energy and emissions data for the "Gate Out" and "Gate In" modes with each table corresponding to one of the three ambient conditions. The summed electric energy value for the "Narrow Body" aircraft category under cold conditions is:

$$\text{Summed electric energy} = 4.235 \text{ KWh} + 17.648 \text{ KWh}$$
$$= 21.883 \text{ KWh}$$

Each of the energy and emissions values in the three tables at the bottom of Figure 14 are multiplied by the corresponding ambient conditions percentages data presented in Table 2 and then summed to produce one weighted table as illustrated in Figure 15.

For example, the weighting for electric energy consumption for the "Narrow Body" aircraft category is conducted as follows:

$$\text{Weighted average EE} = (\text{Cold EE} \times 0.25) + (\text{Neutral EE} \times 0.50) + (\text{Hot EE} \times 0.25)$$
$$= (21.883 \text{ KWh} \times 0.25) + (7.403 \text{ KWh} \times 0.50) + (22.543 \text{ KWh} \times 0.25)$$
$$= 14.808 \text{ KWh}$$

As each of the energy and emissions values in the table represent averages per LTO cycle, each value must be multiplied by the specified number of LTO cycles for each aircraft category (presented in Table 13). For example, using the resulting 9,151.298 g/LTO CO_2 emissions in Figure 15, the total CO_2 emissions for the narrow body aircraft category would be calculated as:

$$\text{Total Electricity-based } CO_2 \text{ Emissions} = (9{,}151.298 \text{ g/LTO}) \times (40{,}000 \text{ LTO/yr})$$
$$= 366{,}051{,}920 \text{ g/yr}$$
$$= 366 \text{ Metric Tons/yr}$$

Then the energy and emissions are summed across each aircraft category to arrive at system level totals as presented in Figure 16. The final step is to separately consider APU emissions during the "APU Start" and "Main Engine Start" modes as presented in Figure 17. As previously explained, these two sets of data should not be summed for various reasons.

3.2.4 Central System with Airport Boiler Emissions

To calculate electricity (energy) consumption and emissions for central systems using airport boilers for heating, the default LTO data and the APU activity data presented in Tables 3 and 13 are used as a starting point. The APU TIM values serve as the underlying activity data for alternative systems to allow for an appropriate basis for comparison. To calculate emissions, data presented in Table 3 need to be combined with the central system electricity and heat energy requirements data presented in Table 10, and emission factors data presented in Table 12.

Please Note: Hand-calculated values presented in this section may not match the values presented in the summary figures exactly due to rounding errors.

Total Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	21.883	13,523.632	1.444	0.026	20.876
Wide Body	41.487	25,639.151	2.738	0.050	39.579
Jumbo-Wide Body	56.481	34,905.485	3.728	0.068	53.883
Regional Jet	9.294	5,743.568	0.613	0.011	8.866
Turbo Prop	12.189	7,532.926	0.804	0.015	11.628

Total Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	7.403	4,574.930	0.489	0.009	7.062
Wide Body	11.507	7,111.450	0.759	0.014	10.978
Jumbo-Wide Body	18.003	11,125.679	1.188	0.022	17.175
Regional Jet	4.123	2,548.014	0.272	0.005	3.933
Turbo Prop	8.246	5,096.028	0.544	0.010	7.867

Total Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	22.543	13,931.698	1.488	0.027	21.506
Wide Body	51.959	32,110.724	3.429	0.062	49.569
Jumbo-Wide Body	69.646	43,041.177	4.597	0.084	66.442
Regional Jet	12.540	7,749.411	0.828	0.015	11.963
Turbo Prop	14.818	9,157.524	0.978	0.018	14.136

Total Weighted

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	14.808	9,151.298	0.977	0.018	14.127
Wide Body	29.115	17,993.194	1.922	0.035	27.776
Jumbo-Wide Body	40.533	25,049.505	2.675	0.049	38.669
Regional Jet	7.520	4,647.252	0.496	0.009	7.174
Turbo Prop	10.875	6,720.626	0.718	0.013	10.375

Figure 15. Sample calculations—central system total weighted energy consumption and emissions.

Annual Energy Consumption and Emissions by Aircraft Category

Aircraft Category	Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
Narrow Body	592.317	366.052	39.093	0.711	565.070
Wide Body	58.230	35.986	3.843	0.070	55.552
Jumbo-Wide Body	121.600	75.149	8.026	0.146	116.006
Regional Jet	451.190	278.835	29.779	0.541	430.435
Turbo Prop	76.124	47.044	5.024	0.091	72.622

Total Annual Energy Consumption and Emissions

Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
1,299	803	86	1.56	1,240

Figure 16. Sample calculations—central system total energy consumption and emissions.

In order to calculate emissions from central systems, the first step is to calculate the electricity (electric energy) consumption required for ground power, heating, and cooling using Formula 1B:

$$EE = EP \times TIM$$

Where: EE = Electric Energy consumption per mode (KWh)
EP = Electric Power (KW) (See Table 10)
TIM = Time in Mode (hr) (See Table 3)

Heat energy consumption through the airport boilers can be calculated using Formula 1C:

$$HE = HR \times TIM$$

Where: HE = Heat Energy consumption per mode (BTU)
HR = Heat Rate (BTU/hr) (See Table 10)
TIM = Time in Mode (hr) (See Table 3)

Emissions are then calculated as follows:

$$E = EE \times EF$$

Where: E = Emissions per mode (g)
EE = Electric Energy consumption per mode (KWh)
EF = Emission Factor (g/KWh) (See Table 12)

Total Annual Energy Consumption and Emissions

Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
1,299	803	86	1.56	1,240

&

Annual APU Fuel Burn and Emissions - "APU Start" and "Main Engine Start" Modes

FB (Metric Tons)	CO_2 (Metric Tons)	CO (kg)	THC (kg)	NO_x (kg)
455	1,436	6,587	1,297	2,901

Figure 17. Sample calculations—central system and APU ("APU start" and "main engine start" mode) energy/fuel consumption and emissions.

$$E = HE \times EF$$

Where:
E = Emissions per mode (g)
HE = Heat Energy consumption per mode (BTU)
EF = Emission Factor (g/BTU) (See Table 12)

As described previously, alternative systems provide different ground power and heating/cooling service based on the combination of APU mode and ambient conditions as presented in Table 11.

For cabin heating (i.e., under the cold ambient conditions), the "Power & Heat" designation in Table 11 refers to the use of ground power for electrical components (lighting, pneumatics, etc.), the use of electricity to operate AHUs, and the supply of heat from the airport boilers. The "Heat" term is used to encompass the latter two sources of energy consumption and emissions (AHUs and boilers) in a central system that uses airport boilers.

The boiler heat energy consumption (BTU) is added to the overall central system electric energy consumption (KWh) using the following unit conversion:

$$1\ BTU = 0.00029\ KWh$$

When all of the energy and emissions are calculated for each of the 6 mode and ambient condition combinations (i.e., not including the six conditions associated with "APU Start" and "Main Engine Start" when APU use is required), they need to be weighted based on average yearly ambient conditions. The weighting is only conducted for electric energy consumption and corresponding emissions (i.e., not for airport boiler heat energy consumption and corresponding emissions).

Since the resulting weighted values and the boiler results are based on a per LTO cycle basis, they need to be multiplied by the total number of LTO cycles per year to obtain totals per year as indicated by the following:

$$\text{Total EE/yr} = \left(\frac{EE}{LTO}\right) \times (\text{LTO cycles/yr})$$

$$\text{Total Electricity-related } CO_2 \text{ Emissions/yr} = \left(\frac{\text{Electricity-related } CO_2 \text{ Emissions}}{LTO}\right) \times (\text{LTO cycles/yr})$$

$$\text{Total HE/yr} = \left(\frac{HE}{LTO}\right) \times (\text{LTO cycles/yr})$$

$$\text{Total Boiler-related } CO_2 \text{ Emissions/yr} = \left(\frac{\text{Boiler-related } CO_2 \text{ Emissions}}{LTO}\right) \times (\text{LTO cycles/yr})$$

These calculations are repeated for each pollutant of concern. Because the total electricity-related values only represent the "Gate Out" and "Gate In" modes, the APU FB and emissions for the "APU Start" and "Main Engine Start" modes need to be considered separately as described previously.

The example calculations presented in this section rely on the LTO cycles/yr data specified in Table 13. Electricity consumption and emissions are calculated for each of the six mode and ambient condition combinations. Example calculations for ground power electricity consumption and heat energy consumption for the "Narrow Body" aircraft category follow.

"Gate Out" and cold conditions combination:

$$\text{TIM} = 3.6\,\text{min} \times (1\ \text{hr}/60\ \text{min}) = 0.06\ \text{hr}$$

$$\text{EE} = (23.88\ \text{KW}) \times (0.06\ \text{hr}) = 1.433\ \text{KWh}$$

$$\text{HE} = (128.31 \times 1000\ \ \text{BTU/hr}) \times (0.06\ \text{hr}) = 7{,}698.6\ \text{BTU}$$

These calculations are repeated for the heating and cooling operations, and then the energy consumption values are summed accordingly to match the combinations specified in Table 11. For example, electric energy consumption associated with ground power is combined with electric energy consumption by AHUs in the following calculations provided:

$$\begin{aligned}\text{Total electric energy consumption} &= \text{ground power electric energy} + \text{AHU electric energy}\\ &= 1.433\ \text{KWh} + 0.401\ \text{KWh}\\ &= 1.834\ \text{KWh}\end{aligned}$$

Emissions are calculated as exemplified by these CO_2 emissions calculations:

$$\text{Electricity-related } CO_2 \text{ Emissions} = (1.834\ \text{KWh}) \times (618\ \ \text{g/KWh}) = 1{,}133\ \text{g}$$

$$\text{Boiler-related } CO_2 \text{ Emissions} = (7{,}698.6\ \text{BTU}) \times (0.053\ \ \text{g/BTU}) = 408\ \text{g}$$

This is repeated for each pollutant and for each aircraft category and each ambient temperature category.

Unlike the electricity-based results, only two of these boiler-based tables are necessary since the use of the boiler's heat energy corresponds to just two mode/ambient condition combinations: (1) "Gate Out" and cold conditions and (2) "Gate In" and cold conditions.

Once the six electricity-based tables and two boiler-based tables are developed, they are summed within each ambient condition as presented in Figures 18 and 19, respectively.

For example, the energy values in each of the two electricity-related tables on the left side of Figure 18 are summed to generate the total energy value in the one table at the bottom left corner. The resulting three tables at the bottom of Figure 18 represent the sum of the energy and emissions data for the "Gate Out" and "Gate In" modes with each table corresponding to one of the three ambient conditions. In contrast, the resulting single boiler-based table presented in Figure 19 corresponds to cold conditions.

The following are the summed electric energy and boiler heat energy values for the "Narrow Body" aircraft category under cold conditions:

$$\text{Summed electric energy} = 1.834\ \text{KWh} + 7.640\ \text{KWh} = 9.474\ \text{KWh}$$

$$\text{Summed boiler energy} = 7{,}698.6\ \text{BTU} + 32{,}077.5\ \text{BTU} = 39{,}776.1\ \text{BTU}$$

Each of the energy and emissions values in the three electricity-based tables at the bottom of Figure 18 and at the bottom of Figure 19 are multiplied by the corresponding

"Gate Out" Mode and Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	1.834	1,133.165	0.121	0.002	1.749
Wide Body	3.212	1,984.892	0.212	0.004	3.064
Jumbo-Wide Body	6.287	3,885.170	0.415	0.008	5.997
Regional Jet	1.022	631.843	0.067	0.001	0.975
Turbo Prop	1.820	1,125.007	0.120	0.002	1.737

"Gate In" Mode and Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	7.640	4,721.520	0.504	0.009	7.289
Wide Body	13.383	8,270.385	0.883	0.016	12.767
Jumbo-Wide Body	17.793	10,995.765	1.174	0.021	16.974
Regional Jet	4.260	2,632.680	0.281	0.005	4.064
Turbo Prop	7.585	4,687.530	0.501	0.009	7.236

Total Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	9.474	5,854.685	0.625	0.011	9.038
Wide Body	16.594	10,255.277	1.095	0.020	15.831
Jumbo-Wide Body	24.079	14,880.935	1.589	0.029	22.972
Regional Jet	5.282	3,264.523	0.349	0.006	5.039
Turbo Prop	9.405	5,812.537	0.621	0.011	8.973

"Gate Out" Mode and Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	1.433	885.470	0.095	0.002	1.367
Wide Body	2.227	1,376.410	0.147	0.003	2.125
Jumbo-Wide Body	4.700	2,904.734	0.310	0.006	4.484
Regional Jet	0.798	493.164	0.053	0.001	0.761
Turbo Prop	1.596	986.328	0.105	0.002	1.523

"Gate In" Mode and Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	5.970	3,689.460	0.394	0.007	5.695
Wide Body	9.280	5,735.040	0.612	0.011	8.853
Jumbo-Wide Body	13.303	8,220.945	0.878	0.016	12.691
Regional Jet	3.325	2,054.850	0.219	0.004	3.172
Turbo Prop	6.650	4,109.700	0.439	0.008	6.344

Total Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	7.403	4,574.930	0.489	0.009	7.062
Wide Body	11.507	7,111.450	0.759	0.014	10.978
Jumbo-Wide Body	18.003	11,125.679	1.188	0.022	17.175
Regional Jet	4.123	2,548.014	0.272	0.005	3.933
Turbo Prop	8.246	5,096.028	0.544	0.010	7.867

"Gate Out" Mode and Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	4.363	2,696.458	0.288	0.005	4.162
Wide Body	10.057	6,214.979	0.664	0.012	9.594
Jumbo-Wide Body	18.183	11,237.352	1.200	0.022	17.347
Regional Jet	2.427	1,499.886	0.160	0.003	2.315
Turbo Prop	2.868	1,772.424	0.189	0.003	2.736

"Gate In" Mode and Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	18.180	11,235.240	1.200	0.022	17.344
Wide Body	41.903	25,895.745	2.766	0.050	39.975
Jumbo-Wide Body	51.463	31,803.825	3.397	0.062	49.095
Regional Jet	10.113	6,249.525	0.667	0.012	9.647
Turbo Prop	11.950	7,385.100	0.789	0.014	11.400

Total Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	22.543	13,931.698	1.488	0.027	21.506
Wide Body	51.959	32,110.724	3.429	0.062	49.569
Jumbo-Wide Body	69.646	43,041.177	4.597	0.084	66.442
Regional Jet	12.540	7,749.411	0.828	0.015	11.963
Turbo Prop	14.818	9,157.524	0.978	0.018	14.136

Figure 18. Sample calculations—central system with airport boiler electricity-based energy consumption and emissions.

Heat (Boiler) Data - "Gate Out" Mode and Cold Conditions

Aircraft Category	Heat Energy (BTU)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	7,698.600	408.026	0.288	0.018	0.109
Wide Body	15,499.800	821.489	0.580	0.037	0.220
Jumbo-Wide Body	27,295.000	1,446.635	1.021	0.066	0.388
Regional Jet	2,574.000	136.422	0.096	0.006	0.037
Turbo Prop	1,800.000	95.400	0.067	0.004	0.026

Heat (Boiler) Data - "Gate In" Mode and Cold Conditions

Aircraft Category	Heat Energy (BTU)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	32,077.500	1,700.108	1.200	0.077	0.456
Wide Body	64,582.500	3,422.873	2.415	0.155	0.917
Jumbo-Wide Body	77,250.000	4,094.250	2.889	0.185	1.097
Regional Jet	10,725.000	568.425	0.401	0.026	0.152
Turbo Prop	7,500.000	397.500	0.281	0.018	0.107

Heat (Boiler) Data - Cold Conditions

Aircraft Category	Heat Energy (BTU)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	39,776.100	2,108.133	1.488	0.095	0.565
Wide Body	80,082.300	4,244.362	2.995	0.192	1.137
Jumbo-Wide Body	104,545.000	5,540.885	3.910	0.251	1.485
Regional Jet	13,299.000	704.847	0.497	0.032	0.189
Turbo Prop	9,300.000	492.900	0.348	0.022	0.132

Figure 19. Sample calculations—central system with airport boiler heat (boiler)-based energy consumption and emissions.

percentages in Table 2 and then summed to produce weighted tables as presented in Figures 20 and 21.

For example, the weighting for electric energy consumption for the "Narrow Body" aircraft category is conducted as follows:

$$
\begin{aligned}
\text{Weighted average EE} &= (\text{Cold EE} \times 0.25) + (\text{Neutral EE} \times 0.50) + (\text{Hot condition EE} \times 0.25) \\
&= (9.474\ \text{KWh} \times 0.25) + (7.403\ \text{KWh} \times 0.50) + (22.543\ \text{KWh} \times 0.25) \\
&= 11.706\ \text{KWh}
\end{aligned}
$$

Similar weighting is necessary for the boiler-based results for one ambient condition (cold conditions) as indicated by the example for the "Narrow Body" aircraft category:

$$
\begin{aligned}
\text{Weighted HE} &= (\text{Cold conditions HE} \times 0.25) \\
&= 39{,}776.1\ \text{BTU} \times 0.25 \\
&= 9{,}944.025\ \text{BTU}
\end{aligned}
$$

The energy and emissions values in the tables in Figures 20 and 21 represent averages per LTO cycle. Each value must be multiplied by the appropriate LTO cycles for the aircraft

Total Cold Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	9.474	5,854.685	0.625	0.011	9.038
Wide Body	16.594	10,255.277	1.095	0.020	15.831
Jumbo-Wide Body	24.079	14,880.935	1.589	0.029	22.972
Regional Jet	5.282	3,264.523	0.349	0.006	5.039
Turbo Prop	9.405	5,812.537	0.621	0.011	8.973

Total Neutral Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	7.403	4,574.930	0.489	0.009	7.062
Wide Body	11.507	7,111.450	0.759	0.014	10.978
Jumbo-Wide Body	18.003	11,125.679	1.188	0.022	17.175
Regional Jet	4.123	2,548.014	0.272	0.005	3.933
Turbo Prop	8.246	5,096.028	0.544	0.010	7.867

Total Hot Conditions

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	22.543	13,931.698	1.488	0.027	21.506
Wide Body	51.959	32,110.724	3.429	0.062	49.569
Jumbo-Wide Body	69.646	43,041.177	4.597	0.084	66.442
Regional Jet	12.540	7,749.411	0.828	0.015	11.963
Turbo Prop	14.818	9,157.524	0.978	0.018	14.136

Total Weighted

Aircraft Category	Energy (KWh)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	11.706	7,234.061	0.773	0.014	11.167
Wide Body	22.892	14,147.225	1.511	0.027	21.839
Jumbo-Wide Body	32.433	20,043.367	2.141	0.039	30.941
Regional Jet	6.517	4,027.491	0.430	0.008	6.217
Turbo Prop	10.179	6,290.529	0.672	0.012	9.711

Figure 20. Sample calculations—central system with airport boiler weighted electricity-based energy consumption and emissions.

Heat (Boiler)-based Energy Use and Emissions - Cold Conditions

Aircraft Category	Heat Energy (BTU)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	39,776.100	2,108.133	1.488	0.095	0.565
Wide Body	80,082.300	4,244.362	2.995	0.192	1.137
Jumbo-Wide Body	104,545.000	5,540.885	3.910	0.251	1.485
Regional Jet	13,299.000	704.847	0.497	0.032	0.189
Turbo Prop	9,300.000	492.900	0.348	0.022	0.132

Heat (Boiler)-based Energy Use and Emissions - Weighted

Aircraft Category	Heat Energy (BTU)	CO_2 (g)	CO (g)	VOC (g)	NO_x (g)
Narrow Body	9,944.025	527.033	0.372	0.024	0.141
Wide Body	20,020.575	1,061.090	0.749	0.048	0.284
Jumbo-Wide Body	26,136.250	1,385.221	0.977	0.063	0.371
Regional Jet	3,324.750	176.212	0.124	0.008	0.047
Turbo Prop	2,325.000	123.225	0.087	0.006	0.033

Figure 21. Sample calculations—central system with airport boiler weighted heat (boiler)-based energy consumption and emissions.

category of interest as presented in Table 13. For example, using CO_2 emissions data from Figures 20 and 21, total CO_2 emissions for the "Narrow Body" aircraft category are calculated using the following equations:

$$\text{Total Electricity-related CO}_2\text{ Emissions/yr} = \left(\frac{7234.061\text{ g}}{\text{LTO}}\right) \times (40{,}000\text{ LTO/yr})$$
$$= 289{,}362{,}440\text{ g/yr}$$
$$= 289.362\text{ Metric Tons/yr}$$

$$\text{Total Boiler-related CO}_2\text{ Emissions/yr} = \left(\frac{527.033\text{ g}}{\text{LTO}}\right) \times (40{,}000\text{ LTO/yr})$$
$$= 21{,}081{,}320\text{ g/yr}$$
$$= 21.081\text{ Metric Tons/yr}$$

Then the energy and emissions data are summed across each aircraft category to arrive at airport-wide totals as presented in Figure 22 below for the electricity-based results.

The boiler-based results are presented in Figure 23.

The final step is to separately consider the APU emissions during the "APU Start" and "Main Engine Start" modes along with the electricity-based and boiler-based results as presented in Figure 24.

As previously explained, these sets of data should not be summed for various reasons. They should be considered separately to allow a comprehensive understanding of all emissions and fuel/energy consumption associated with the use of alternative systems.

Annual Electricity-based Energy Consumption and Emissions by Aircraft Category

Aircraft Category	Electric Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
Narrow Body	468.224	289.362	30.903	0.562	446.686
Wide Body	45.784	28.294	3.022	0.055	43.678
Jumbo-Wide Body	97.298	60.130	6.422	0.117	92.822
Regional Jet	391.019	241.649	25.807	0.469	373.032
Turbo Prop	71.252	44.034	4.703	0.086	67.974

Total Annual Electricity-based Energy Consumption and Emissions

Electric Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
1,074	663	71	1.29	1,024

Figure 22. Sample calculations—central system with airport boiler total electricity-based energy consumption and emissions.

Annual Heat (Boiler)-based Energy Consumption and Emissions by Aircraft Category

Aircraft Category	Heat Energy (mmBtu)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
Narrow Body	397.761	21.081	14.876	0.955	5.648
Wide Body	40.041	2.122	1.498	0.096	0.569
Jumbo-Wide Body	78.409	4.156	2.932	0.188	1.113
Regional Jet	199.485	10.573	7.461	0.479	2.833
Turbo Prop	16.275	0.863	0.609	0.039	0.231

Total Annual Heat (Boiler)-based Energy Consumption and Emissions

Heat Energy (mmBtu)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
732	39	27	1.76	10

Figure 23. Sample calculations—central system with airport boiler total heat (boiler)-based energy consumption and emissions.

Annual Electricity-based Energy Consumption and Emissions

Energy (MWh)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
1,074	663	71	1.29	1,024

&

Annual Heat (Boiler)-based Energy Consumption and Emissions

Heat Energy (mmBtu)	CO_2 (Metric Tons)	CO (kg)	VOC (kg)	NO_x (kg)
732	39	27	1.76	10

&

Annual APU Fuel Burn and Emissions - "APU Start" and "Main Engine Start" modes

FB (Metric Tons)	CO_2 (Metric Tons)	CO (kg)	THC (kg)	NO_x (kg)
455	1,436	6,587	1,297	2,901

Figure 24. Sample calculations—central system with airport boiler.

3.3 Estimating Costs for Alternative Systems

As discussed previously, this Handbook includes cost data for three types of alternative systems: POU systems, central systems, and central systems with airport boilers. Portable diesel-powered systems are not included since reliable cost data could not be obtained. However, future revisions to this Handbook could potentially address portable diesel-powered systems. Cost data presented in the Handbook only allow comparison of the three types of alternative systems. The underlying cost rates represent industry averages on a national level and were supplied by AERO Systems Engineering, Inc. (ASE 2011) based on 2010 dollars.

In the following sections, cost calculation methodologies are described for the following cost components:

- Capital,
- Operating, and
- Maintenance.

Similar to the emissions data presented earlier in this chapter, the cost data presented in this section are summarized by aircraft category except for maintenance costs which are based on total gate usage. Cost scenarios are based on various factors including number of gates per aircraft category, equipment life expectancy, and number of LTOs per year. Since all of the underlying cost rate data used in this Handbook generally represent 2010 values, the calculated costs can be adjusted accordingly using a suitable inflation rate to make the costs representative of current values. However, it should be noted that the development of projections based on inflation can be complicated due to the timing of cost payments and other factors. For example, operating and maintenance costs should be adjusted according to when (e.g., which year) the payments will be made. Even capital costs may not be paid in a lump sum (i.e., financing may be involved). The following sections provide directions on calculating each of the aforementioned cost components and total cost for each alternative system using 2010 cost rates. The user can then either use the 2010-based results for comparison purposes or adjust the results for inflation using a suitable approach.

3.3.1 POU System Costs

3.3.1.1 Input Data

The following sets of data by aircraft category are necessary to calculate POU system costs:

- Number of gates,
- POU system capital costs per gate,
- Cost of electricity,
- POU system maintenance costs per gate, and
- POU system electric energy consumption data (See Section 3.2.2).

Although these datasets are necessary, the user is generally only expected to supply the number of gates by aircraft category. The default data presented in this section are used for all other variables.

3.3.1.2 Results

The following set of life-cycle costs by aircraft category and airport-wide totals are calculated:

- Capital costs,
- Operating costs, and
- Maintenance costs (only airport-wide totals).

Table 14. Example number of gates specified along with other APU activity data.

Aircraft Category	APU Start (min/LTO)	Gate Out (min/LTO)	Main Engine Start (min/LTO)	Gate In (min/LTO)	Example LTO/yr	Example Number of Gates
Narrow Body	3	3.60	0.58	15	40,000	12
Wide Body	3	3.60	0.58	15	2,000	1
Jumbo-Wide Body	3	5.30	2.33	15	3,000	4
Regional Jet	3	3.60	0.58	15	60,000	18
Turbo Prop	3	3.60	0.58	15	7,000	3

SOURCE: Environmental Science Associates, 2011.

3.3.1.3 Methodology

Along with the specification of APU TIM values and the total number of LTO cycles per year for emissions calculation purposes, the number of gates also needs to be specified to calculate alternative system costs as presented in Table 14.

The number of gates and the number of LTOs/yr for each aircraft category are interrelated and, therefore, must be carefully estimated to ensure proper (realistic) scenarios are modeled. The basic data used to calculate POU system costs are presented in Tables 15 through 17.

Capital costs are calculated based on multiplying the number of gates by the prorated costs indicated in Table 15. The Level 1 and Level 2 option costs were approximated as being roughly the same as indicated in Table 15. The following equations are used to calculate the capital costs to install POU system ground power and PCA units:

$$\text{POU system capital cost} = (\text{POU system power capital cost}) + (\text{POU system PCA capital cost})$$

$$\text{POU system power capital cost} = (\text{Equipment and basic install cost} + \text{Level 1 cost} + \text{Level 2 cost}) \times (\text{number of gates})$$

$$\text{POU system PCA capital cost} = (\text{Equipment and basic install cost} + \text{Level 1 cost} + \text{Level 2 cost}) \times (\text{number of gates})$$

Table 15. POU system capital costs.

Aircraft Category	POU Power ($/gate)			POU PCA ($/gate)		
	Equipment and Basic Install	Level 1 Electric	Level 2 Electric	Equipment and Basic Install	Level 1 Electric	Level 2 Electric
Narrow Body	$49,000	$15,000	$15,000	$87,000	$15,000	$15,000
Wide Body	$74,000	$30,000	$30,000	$108,833	$43,333	$43,333
Jumbo - Wide Body	$134,000	$60,000	$60,000	$293,900	$103,500	$103,500
Regional Jet	$42,000	$15,000	$15,000	$70,500	$15,000	$15,000
Turbo Prop	$42,000	$15,000	$15,000	$70,500	$15,000	$15,000

Level 1 Electric: Assumes some electrical feeder work needs to be installed and that there is infrastructure to terminate into within the building.
Level 2 Electric: Assumes infrastructure needs to be installed such as adding breakers to existing distribution gear, or adding bus taps existing gear and setting new distribution panels, or adding switchgear sections.
SOURCE: ASE, 2011.

Table 16. Nominal electricity and natural gas costs.

Cost Factors	Example Cost Rates
Average Cost of Electricity ($/KWh)	0.07
Average Cost of Natural Gas ($/mmBtu)	4

SOURCE: ASE, 2011.

These calculations are performed for each of the five aircraft categories, as applicable. Then, the individual costs are summed to obtain the total capital cost.

Operating costs for POU systems are calculated using an average cost rate for electricity ($/KWh) as presented in Table 16, total electricity consumption per year (KWh/yr) data, and information regarding the anticipated useful life of the POU system equipment.

$$\text{POU system operating cost} = (\text{Total electric energy consumption, KWh/yr}) \times (\text{cost of electricity, \$/KWh}) \times (\text{number of years equipment used})$$

Similar to capital costs, these calculations can be performed for each of the aircraft categories if cost per category is necessary. Otherwise, the total electric energy consumption for all aircraft categories can be used.

To calculate maintenance costs, the total number of gates across all aircraft types is used as follows:

$$\text{POU system maintenance cost} = (\text{Total number of gates}) \times (\text{POU system maintenance cost, \$/gate-yr}) \times (\text{number of years equipment used})$$

Table 17. POU system maintenance costs per gate.

Number of Gates	POU System Maintenance Cost ($/gate-yr)
<8	$5,698
8	$5,698
16	$5,698
24	$5,698
30	$5,698
40	$5,698
50	$5,698
60	$5,698
70	$5,698
80	$5,698
90	$5,698
100	$5,698
>100	$5,698

SOURCE: ASE, 2011.

As indicated in Table 17, the POU system maintenance cost rate is constant (not adjusted based on the number of gates to be served by the POU system). This is due to the fact that each gate requires the same effort to maintain, and therefore, the costs are additive. Although this table could be simplified, its format is maintained for consistency with the corresponding rates used for central systems.

POU systems are considered to have a life span of approximately 15 years while central systems are considered to have life spans of about 20 years (the FAA's VALE program technical manual specifies that PCA units have life spans of about 13 years and ground power equipment are expected to have life spans of about 20 years). Therefore, cost assessments should generally be conducted within the limits of the life spans. However, if a cost assessment needs to surpass the POU's life span (i.e., if conducting a 20-year comparison assessment against a central system), then the maintenance costs for POUs need to be increased by 3% of the initial capital cost per gate per year.

The total cost of a POU system is simply the addition of the three cost components:

$$\begin{aligned}\text{Total POU system cost} &= (\text{POU system capital cost})\\ &+ (\text{POU system operating cost})\\ &+ (\text{POU system maintenance cost})\end{aligned}$$

As previously explained, these costs can be modified as necessary to reflect present day values using a suitable inflation rate such as 2%.

3.3.1.4 Example Calculations

The example calculations presented below are based on the use of the example and default data presented in this chapter and assuming a 15-year usage period. Using the LTO cycles/yr and gates data specified in Table 14, the POU system capital cost for the narrow body aircraft category is:

$$\begin{aligned}\text{POU system power capital cost} &= \$49{,}000/\text{gate} + \$15{,}000/\text{gate} + \$15{,}000/\text{gate}\\ &= \$79{,}000/\text{gate}\end{aligned}$$

$$\begin{aligned}\text{POU system PCA capital cost} &= \$87{,}000/\text{gate} + \$15{,}000/\text{gate} + \$15{,}000/\text{gate}\\ &= \$117{,}000/\text{gate}\end{aligned}$$

$$\begin{aligned}\text{POU system capital cost} &= \$79{,}000/\text{gate} + \$117{,}000/\text{gate} \times (12\ \text{gates})\\ &= \$2{,}352{,}000\end{aligned}$$

These calculations are repeated for each of the other aircraft categories using the LTO cycle data presented in Table 14, resulting in the final values shown in Table 18.

Operating costs are calculated using the total electric energy consumption data presented in Figure 25.

The operating cost for the narrow body aircraft category is:

$$\begin{aligned}\text{Narrow body aircraft category electric energy consumption} &= 653.697\ \text{MWh/yr}\\ &= 653{,}697\ \text{KWh/yr}\\ &\quad (\text{Note: } 1\ \text{MWh} = 1{,}000\ \text{KWh})\end{aligned}$$

Table 18. POU system capital costs—example calculations.

Aircraft Category	Capital Cost ($)
Narrow Body	$2,352,000
Wide Body	$329,500
Jumbo-Wide Body	$3,019,600
Regional Jet	$3,105,000
Turbo Prop	$517,500
TOTAL =	$9,323,600

POU System Energy Consumption and Emissions by Aircraft Category

Aircraft Category	Energy (MWh/yr)	CO_2 (Metric Tons/yr)	CO (kg/yr)	VOC (kg/yr)	NO_x (kg/yr)
Narrow Body	653.697	403.985	43.144	0.784	623.627
Wide Body	64.981	40.158	4.289	0.078	61.992
Jumbo-Wide Body	131.067	80.999	8.650	0.157	125.038
Regional Jet	507.827	313.837	33.517	0.609	484.466
Turbo Prop	81.527	50.384	5.381	0.098	77.777

Figure 25. Sample electric energy consumption data—POU system.

$$\text{POU system operating cost} = (653{,}697\ \text{KWh/yr}) \times (\$0.07/\text{KWh}) \times (15\ \text{years})$$
$$= \$686{,}382$$

These calculations are conducted for each aircraft category and then summed as shown below in Table 19.

As with the emissions calculations, these costs represent average weighted values because the electric energy consumption values account for the distribution of ambient conditions (i.e., 25% cold, 50% neutral, and 25% hot).

For maintenance costs, the total number of gates (38) shown in Table 14 is used as follows:

$$\text{POU system maintenance cost} = (38\ \text{gates}) \times (\$5{,}698/\text{gate-yr}) \times (15\ \text{years})$$
$$= \$3{,}247{,}860$$

Table 19. POU system operating costs—example calculations.

Aircraft Category	Operating Cost ($)
Narrow Body	$686,382
Wide Body	$68,230
Jumbo-Wide Body	$137,620
Regional Jet	$533,218
Turbo Prop	$85,603
TOTAL =	$1,511,053

The total cost is calculated as:

$$\text{Total POU system cost} = \$9,323,600 + \$1,511,053 + \$3,247,860$$
$$= \$14,082,513$$

3.3.2 Central System Costs

Input Data

The following sets of data by aircraft category are necessary to calculate central system costs:

- Number of gates,
- Central system capital costs per gate,
- Cost of electricity,
- Central system maintenance costs per gate, and
- Central system electric energy consumption data (See Section 3.2.3).

Although these datasets are necessary, the user is generally only expected to supply the number of gates by aircraft category. The default data presented in this section are used for all other variables.

Results

The following set of life-cycle costs by aircraft category and airport-wide totals are calculated:

- Capital costs,
- Operating costs, and
- Maintenance costs (only airport-wide totals).

Methodology

Along with the specification of APU TIM values and the total number of LTO cycles per year for emissions calculation purposes, the number of gates also needs to be specified to calculate alternative system costs as presented in Table 14.

The number of gates and the number of LTOs/yr for each aircraft category are interrelated and, therefore, must be carefully estimated to ensure proper (realistic) scenarios are modeled. The basic data used to calculate central system costs are presented in Tables 20 and 21. Information presented previously in Table 16 is also used to calculate central system costs.

Capital costs are calculated based on multiplying the number of gates by the prorated costs indicated in Table 20.

$$\text{Central system capital cost} = (\text{Central system power capital cost} + \text{Central system PCA capital cost}) \times (\text{total number of gates})$$

Table 20. Central system capital costs.

	Central Power ($/gate)	Central PCA ($/gate)
Aircraft Category	**Equipment and Basic Install**	**Equipment and Basic Install**
Narrow Body	$52,741	$228,283
Wide Body	$82,493	$313,779
Jumbo — Wide Body	$164,986	$644,166
Regional Jet	$37,974	$197,154
Turbo Prop	$37,974	$197,154

SOURCE: ASE, 2011.

Table 21. Central system maintenance costs.

Number of Gates	Central System Maintenance Cost ($/gate-yr)
8	$3,404
16	$2,870
24	$2,700
30	$2,636
40	$2,615
50	$2,557
60	$2,533
70	$2,524
80	$2,510
90	$2,490
100	$2,485
>100	$2,480

SOURCE: ASE, 2011.

These calculations are performed for each of the five aircraft categories, as applicable. Then, the individual costs are summed to obtain the total capital cost.

Operating costs for central systems are calculated using an average cost rate for electricity ($/KWh) as presented in Table 16; total electricity consumption per year (KWh/yr) data; and information regarding the anticipated useful life of the central system equipment.

$$\text{Central system operating cost} = (\text{Total electric energy consumption, KWh/yr}) \times (\text{cost of electricity, \$/KWh}) \times (\text{number of years equipment used})$$

Similar to capital costs, these calculations can be performed for each of the aircraft categories if cost-per-category is necessary. Otherwise, the total electric energy consumption for all aircraft categories can be used.

To calculate maintenance costs, the total number of gates across all aircraft types is used as follows:

$$\text{Central system maintenance cost} = (\text{Total number of gates}) \times (\text{Central system maintenance cost, \$/gate-yr}) \times (\text{number of years equipment used})$$

As presented in Table 21, the lowest number of gates shown is eight. This is to indicate that central systems should not be used to support fewer than eight gates, as POU systems would be more cost effective.

Finally, the total cost is simply the addition of the three cost components:

$$\text{Total Central system cost} = (\text{Central system capital cost}) + (\text{Central system operating cost}) + (\text{Central system maintenance cost})$$

Table 22. Central system capital costs—example calculations.

Aircraft Category	Capital Cost ($)
Narrow Body	$3,372,297
Wide Body	$396,272
Jumbo-Wide Body	$3,236,608
Regional Jet	$4,232,297
Turbo Prop	$705,383
TOTAL =	$11,942,857

As previously explained, these costs can be modified as necessary to reflect present day values using a suitable inflation rate such as 2%.

Example Calculations

The example calculations presented herein are based on the use of the example and default data presented in this chapter and assuming a 15-year usage period. Assuming the number of LTO cycles/yr and gates are specified as in Table 14, the central system capital cost for the narrow body aircraft category is:

$$\text{Central system capital cost} = (\$52{,}741/\text{gate} + \$228{,}283/\text{gate}) \times (12 \text{ gates})$$
$$= \$3{,}372{,}297$$

These calculations are repeated for each of the other aircraft categories resulting in the final values shown in Table 22.

Operating costs are calculated using the total electric energy consumption data developed from the emissions calculations as presented in Figure 26.

The operating cost for the narrow body aircraft category is:

$$\text{Narrow body aircraft category electric energy consumption} = 592.317 \text{ MWh/yr}$$
$$= 592{,}317 \text{ KWh/yr}$$
$$(\text{Note: } 1 \text{ MWh} = 1{,}000 \text{ KWh})$$

$$\text{Central system operating cost} = (592{,}317 \text{ KWh/yr}) \times (\$0.07/\text{KWh}) \times (15 \text{ years})$$
$$= \$621{,}933$$

These calculations are conducted for each aircraft category and then summed as shown in Table 23.

Central System Energy Consumption and Emissions by Aircraft Category

Aircraft Category	Energy (MWh/yr)	CO_2 (Metric Tons/yr)	CO (kg/yr)	VOC (kg/yr)	NO_x (kg/yr)
Narrow Body	592.317	366.052	39.093	0.711	565.070
Wide Body	58.230	35.986	3.843	0.070	55.552
Jumbo-Wide Body	121.600	75.149	8.026	0.146	116.006
Regional Jet	451.190	278.835	29.779	0.541	430.435
Turbo Prop	76.124	47.044	5.024	0.091	72.622

Figure 26. Sample electric energy consumption data—central system.

Table 23. Central system operating costs—example calculations.

Aircraft Category	Operating Cost ($)
Narrow Body	$621,933
Wide Body	$61,142
Jumbo-Wide Body	$127,680
Regional Jet	$473,749
Turbo Prop	$79,930
TOTAL =	$1,364,433

As with the emissions calculations, these costs represent average weighted values because the electric energy consumption values account for the distribution of ambient conditions (i.e., 25% cold, 50% neutral, and 25% hot).

For maintenance costs, the total number of gates (38) shown in Table 14 is used to interpolate for the maintenance cost rate in Table 21:

30	2,636
38	?
40	2,615

$$\text{Central system maintenance cost rate for 38 gates} = \left\{\left(\frac{(38-30)}{(40-30)}\right)\times(2{,}615-2{,}636)\right\}+2{,}636$$

$$= \$2{,}619.2/\text{gate-yr}$$

Then the maintenance cost is calculated as:

$$\text{Central system maintenance cost} = (38\text{ gates})\times(\$2{,}619.2/\text{gate-yr})\times(15\text{ years})$$

$$= \$1{,}492{,}944$$

The total cost is calculated as:

$$\text{Total Central system cost} = \$11{,}942{,}857+\$1{,}364{,}433+\$1{,}492{,}944$$

$$= \$14{,}800{,}234$$

3.3.3 Central System with Airport Boiler Costs

3.3.3.1 Input Data

The following sets of data by aircraft category are necessary to calculate central system with airport boiler costs:

- Number of gates,
- Central system capital costs per gate,
- Cost of electricity,
- Cost of natural gas,
- Central system maintenance costs per gate, and
- Central system electric energy consumption data and heat energy consumption data (See Section 3.2.4).

Although these datasets are necessary, the user is generally only expected to supply the number of gates by aircraft category. The default data presented in this section are used for all other variables.

3.3.3.2 Results

The following set of life-cycle costs by aircraft category and airport-wide totals are calculated:

- Capital costs,
- Operating costs, and
- Maintenance costs (only airport-wide totals).

3.3.3.3 Methodology

Along with the specification of APU TIM values and the total number of LTO cycles per year for emissions calculation purposes, the number of gates also needs to be specified to calculate alternative system costs as presented in Table 14.

The number of gates and the number of LTOs/yr for each aircraft category are interrelated, and therefore, must be carefully estimated to ensure proper (realistic) scenarios are modeled. The basic data used to calculate central system costs were previously presented in Tables 16, 20, and 21.

Capital costs are calculated based on multiplying the number of gates by the prorated costs indicated in Table 20:

$$\begin{aligned}\text{Central system capital cost} = &(\text{Central system power capital cost})\\ &+(\text{Central system PCA capital cost})\end{aligned}$$

These calculations are performed for each of the five aircraft categories, as applicable. Then, the individual costs are summed to obtain the total capital cost. Capital costs associated with the use of the airport boilers' heat energy are relatively small and are not evaluated in this Handbook.

Operating costs for central systems with airport boilers are calculated using an average cost rate for electricity ($/KWh) and natural gas ($/mmBtu) as presented in Table 16; total electricity consumption per year (KWh/yr) data; total heat energy consumption per year (mmBtu/yr) data; and information regarding the anticipated useful life of the equipment.

$$\begin{aligned}\text{Central system electricity-related operating cost} = &(\text{Total electric energy consumption, KWh/yr})\\ &\times(\text{cost of electricity, \$/KWh})\\ &\times(\text{number of years equipment used})\end{aligned}$$

For operating costs associated with the airport boiler(s), the following equation is used to calculate operating costs:

$$\begin{aligned}\text{Central system boiler-related operating cost} = &(\text{Total heat energy consumption, mmBTU/yr})\\ &\times(\text{cost of natural gas, \$/mmBTU})\\ &\times(\text{number of years equipment used})\end{aligned}$$

Then the total operating cost is simply the sum of these two costs:

$$\begin{aligned}\text{Central system operating cost} = &\text{Central system electricity-related operating cost (\$)}\\ &+\text{Central system boiler-related operating cost (\$)}\end{aligned}$$

Similar to capital costs, these calculations can be performed for each of the aircraft categories if cost per category is necessary. Otherwise, the total electric energy and total heat energy consumptions for all aircraft categories can be used.

To calculate maintenance costs, the total number of gates across all aircraft types is used as follows:

$$\text{Central system maintenance cost} = (\text{Total number of gates}) \times (\text{Central system maintenance cost, \$/gate-yr}) \times (\text{number of years equipment used})$$

As indicated in Table 21, the lowest number of gates shown is eight. This is to indicate that central systems should not be used to support fewer than eight gates, as POU systems would be more cost effective.

Finally, the total cost is simply the addition of the cost components:

$$\text{Total central system cost} = (\text{Central system capital cost}) + (\text{Central system electricity-related operating cost}) + (\text{Central system boiler-related operating cost}) + (\text{Central system maintenance cost})$$

As previously explained, these costs can be modified as necessary to reflect present day values using a suitable inflation rate such as two percent.

3.3.3.4 Example Calculations

The example calculations are based on the use of the example and default data presented in this chapter and assuming a 15-year usage period. Assuming the number of LTO cycles/yr and gates are specified as in Table 14, the central system capital cost for the narrow body aircraft category is:

$$\text{Central system capital cost} = (\$52{,}741/\text{gate} + \$228{,}283/\text{gate}) \times (12\ \text{gates}) = \$3{,}372{,}297$$

These calculations are repeated for each of the other aircraft categories resulting in the final values presented in Table 24.

Operating costs are calculated using the total electric energy and heat energy consumption data developed from the emissions calculations as presented in Figures 27 and 28.

Table 24. Central system with airport boiler capital costs—example calculations.

Aircraft Category	Capital Cost ($)
Narrow Body	$3,372,297
Wide Body	$396,272
Jumbo-Wide Body	$3,236,608
Regional Jet	$4,232,297
Turbo Prop	$705,383
TOTAL =	$11,942,857

Electricity-based Energy Consumption and Emissions by Aircraft Category

Aircraft Category	Electric Energy (MWh/yr)	CO_2 (Metric Tons/yr)	CO (kg/yr)	VOC (kg/yr)	NO_x (kg/yr)
Narrow Body	468.224	289.362	30.903	0.562	446.686
Wide Body	45.784	28.294	3.022	0.055	43.678
Jumbo-Wide Body	97.298	60.130	6.422	0.117	92.822
Regional Jet	391.019	241.649	25.807	0.469	373.032
Turbo Prop	71.252	44.034	4.703	0.086	67.974

Figure 27. Sample electric energy consumption data—central system with airport boiler.

Heat (Boiler)-based Energy Consumption and Emissions by Aircraft Category

Aircraft Category	Heat Energy (mmBtu/yr)	CO_2 (Metric Tons/yr)	CO (kg/yr)	VOC (kg/yr)	NO_x (kg/yr)
Narrow Body	397.761	21.081	14.876	0.955	5.648
Wide Body	40.041	2.122	1.498	0.096	0.569
Jumbo-Wide Body	78.409	4.156	2.932	0.188	1.113
Regional Jet	199.485	10.573	7.461	0.479	2.833
Turbo Prop	16.275	0.863	0.609	0.039	0.231

Figure 28. Sample heat energy consumption data—central system with airport boiler.

The operating cost for the narrow body aircraft category is:

$$\text{Narrow body aircraft category electric energy consumption} = 468.224 \text{ MWh/yr}$$
$$= 468{,}224 \text{ KWh/yr}$$
$$(\text{Note: } 1 \text{ MWh} = 1{,}000 \text{ KWh})$$

$$\text{Central system electricity-related operating cost} = (468{,}224 \text{ KWh/yr}) \times (\$0.07/\text{KWh}) \times (15 \text{ years}) = \$491{,}635$$

$$\text{Narrow body aircraft category heat energy consumption} = 397.761 \text{ mmBTU/yr}$$

$$\text{Central system boiler-related operating cost} = (397.761 \text{ mmBTU/yr}) \times (\$4/\text{mmBTU}) \times (15 \text{ years}) = \$23{,}866$$

These calculations are conducted for each aircraft category and then summed as shown in Tables 25 and 26.

As with the emissions calculations, these costs represent average weighted values because the electric and heat energy consumption values account for the distribution of ambient conditions (i.e., 25% cold, 50% neutral, and 25% hot).

For maintenance costs, the total number of gates (38) shown in Table 14 is used to interpolate for the maintenance cost rate in Table 21:

30	2,636
38	?
40	2,615

Table 25. Electricity-related operating cost—example calculations.

Aircraft Category	Electricity-related Operating Cost ($)
Narrow Body	$491,635
Wide Body	$48,073
Jumbo-Wide Body	$102,163
Regional Jet	$410,569
Turbo Prop	$74,815
TOTAL =	$1,127,255

SOURCE: ASE, 2011.

Table 26. Boiler-related operating cost—example calculations.

Aircraft Category	Boiler-related Operating Cost ($)
Narrow Body	$23,866
Wide Body	$2,402
Jumbo-Wide Body	$4,705
Regional Jet	$11,969
Turbo Prop	$977
TOTAL =	$43,918

SOURCE: ASE, 2011.

$$\text{Central system maintenance cost rate for 38 gates} = \left\{\left(\frac{38-30}{40-30}\right)\times(2{,}615-2{,}636)\right\}+2{,}636$$
$$= \$2{,}619.2/\text{gate-yr}$$

Then the maintenance cost is calculated as:

$$\text{Central system maintenance cost} = (38\text{ gates})\times(\$2{,}619.2/\text{gate-yr})\times(15\text{ years})$$
$$= \$1{,}492{,}944$$

The total cost is calculated as:

$$\text{Total Central system with airport boiler cost} = \$11{,}942{,}857$$
$$+\$1{,}127{,}255$$
$$+\$43{,}918$$
$$+\$1{,}492{,}944$$
$$= \$14{,}606{,}974$$

3.4 Results Comparisons

The calculated fuel/energy consumption, emissions, and costs by themselves can be useful in providing rough estimates that can be used for planning purposes. The usefulness of these results needs to be considered in light of their accuracy level, which can generally be described as

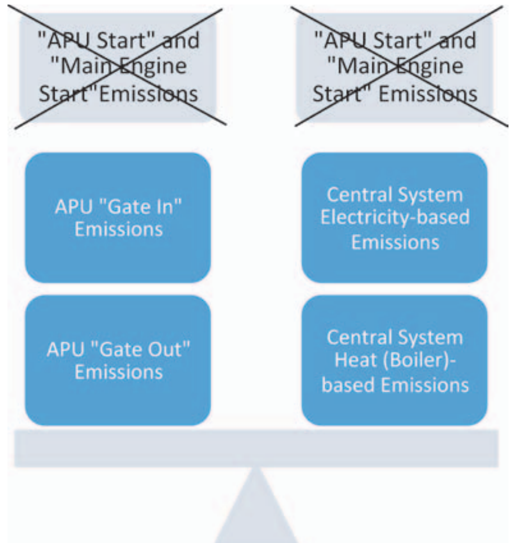

Figure 29. Comparison of emissions—APU vs. central system with airport boiler.

an order-of-magnitude. As such, their usefulness increases when they are compared (i.e., comparison of results from different scenarios). Comparisons must be carefully conducted to make sure only like items are compared under the same timeframes.

In comparing fuel/energy consumption and emissions between APUs and alternative systems (including between different alternative systems), two issues need to be addressed. First, although different timeframes or periods can be used, it is recommended as part of this Handbook to compare results on a yearly basis (e.g., emissions inventory for a year).

Second, since the APU is commonly used during the "APU Start" and "Main Engine Start" modes even when alternative systems are available, the fuel consumption and emissions for those two modes will cancel out as illustrated in Figure 29.

Third, as explained in Chapter 2, it should be understood that direct emissions from APUs occurring "locally" at the airport have different impacts than the indirect emissions occurring from the generation of electricity at power plants that are outside of the airport boundary. In this case, only the APU emissions are assumed to have an impact on local airport air quality while the power plant emissions are assumed to have no direct impact on local air quality in the vicinity of the airport. Criteria pollutant emissions from power plants are generally only accounted for in a detailed life-cycle assessment, and greenhouse gas emissions associated with electricity generation are categorized as indirect emissions within an airport emissions inventory. The user needs to be cognizant of these differences in order to properly consider their importance in planning decisions.

For comparisons involving costs, there are also three issues to consider. First, the timeframes for costs (i.e., operating and maintenance) should generally be conducted on an expected life-cycle basis (e.g., 15 years). Although only one life-cycle number of years can be used in a single set of cost calculations, it is recommended that the user evaluate other equipment life cycles (e.g., 5 years, 10 years, 15 years, etc.) to understand cost differences between the different alternative systems.

Second, although total costs for alternative systems can be compared, it is recommended that capital, operating, and maintenance cost estimates be preserved and compared to allow a greater understanding of the factors that influence total costs. This may also allow the user to identify better strategies in terms of using existing financial resources to implement alternative systems.

Third, the costs can be adjusted for inflation and other economic factors. The 2010 dollar-based costs data provided in the Handbook for each alternative system allow "apples-to-apples" comparisons, but the advanced user may wish to make adjustments to the cost data to evaluate the effects on total costs associated with different acquisition/payment strategies (e.g., lump sum payment vs. long-term financing).

CHAPTER 4

Qualitative Evaluations

Beyond the calculated emissions and costs, there are various qualitative issues that need to be addressed to allow proper assessment of alternative systems. For example, implementation of an alternative system could result in emissions reductions compared to the use of APUs, but if adoption of the alternative system by the airlines is uncertain or if funding is uncertain, the environmental benefits of the alternative systems may be outweighed by other factors. Also, there are finer levels of assessments not appropriate at the planning stage that should still be qualitatively considered since they can help to further define the advantages and disadvantages of each type of alternative system. These types of important issues need to be addressed and/or resolved at the planning stage before finer assessments can or should be conducted.

4.1 Infrastructure Requirements and Comparisons

The issue of infrastructure requirements encompasses many issues such as the availability of an electrical system to support the implementation of alternative systems. For example, Level 1 and Level 2 electric infrastructures refer to the availability of electrical feeders, breakers, bus taps, distribution panels, etc., that are necessary before POU systems can be used. Such infrastructures are also included as part of central system basic installation packages.

Infrastructure issues also include the potential to move loading bridges/aircraft parking positions to new locations and how that will affect the current or planned implementation of alternative systems. Structural and electrical support necessary to install POU systems or AHUs and gate boxes at new locations must be considered during the planning phase for alternative systems. The structural integrity of the PBB will also need to be considered when installing these types of equipment. The overall impacts on reliability and maintenance will need to be carefully considered (at least qualitatively) when changes to these systems are introduced.

When considering the implementation of alternative systems, airport operators also need to consider the locations where aircraft would be provided ground power and/or PCA. For example, electricity could be provided at remain over night (RON) and cargo aircraft parking positions, whereas it would be unusual to provide PCA at these locations, except in colder climates. At general aviation airports or at general aviation facilities that are located at commercial service airports, suitable locations need to be identified to properly mount fixed alternative systems since aircraft are typically not accessed by loading bridges. For remote RON locations, a reasonable choice would be to use portable diesel units to provide electricity and PCA. These types of issues are important to consider when selecting the appropriate alternative system. It should also be understood that if an APU is used at RON locations, it will generally not be used all night. In contrast, if an alternative system is available at RON locations, it will likely be used all night. As such, different usage times (different TIM values) may need to be used when calculating emissions for remote aircraft parking positions.

An often overlooked item that should be considered when evaluating different alternative ground power/PCA systems is the installation location of the PCA and ground power equipment mounted on the PBB. The GSE industry manufacturers have designed equipment to be mounted at various locations on or near the PBB. Experience has shown that ground power system equipment mounted beneath the cab of the PBB will invariably suffer more damage from mobile ramp equipment than will equipment mounted at the rotunda or side of the PBB (ASE 2011).

Typically, a POU unit (PCA or ground power), is mounted at the cab end of an apron drive bridge. Having the refrigerant and the compressors located in this environment significantly increases the risk of refrigerant leaks and endangers the useful life of the compressors. Typically, the compressors used in the POU units are for light commercial applications and are designed to be mounted in a stationary unit with a small horsepower blower motor. Past studies and experience have shown that a compressor subjected to the airport ramp environment will typically have to be replaced within the first 5 to 10 years of operation (ASE 2011). Damage to POU units can be caused by ramp equipment, routine movement of the bridge, and/or increased wear and tear due to the demanding application.

Central system equipment, such as AHUs and gate boxes, can be mounted at the rotunda end of an apron drive bridge with a side mounted telescoping air duct and on the side of the PBB with a dogleg assembly, respectively. This arrangement affords greater protection from damage by mobile equipment on the ramp/apron. The ramp environment is dangerous for any piece of equipment, regardless of type. In a central system, the compressors and the refrigerant system reside in a more controlled environment accessed only by maintenance personnel, thereby eliminating the possibility of damage due to the ramp environment.

POU system equipment typically weighs substantially more than central system gate equipment. The POU air conditioning equipment can weigh approximately 9,000 pounds for wide body gates and approximately 12,000 lbs for jumbo-wide body aircraft gates. The impact to the operation and maintenance of the PBB should be researched before making a decision to implement POU systems, especially when the airport operator is retrofitting older, existing PBBs.

While a POU system may cause some PBB-related weight issues, it does have greater mobility than a central system. Should an owner move his/her gates from one concourse/terminal to another, the POU system equipment are simply relocated as well. On a central system, the gate equipment mobility is governed by whether the new facility has central equipment or not (e.g., central plant, electrical infrastructure, etc.). If it does not, the owner must consider selling the equipment, or possibly transferring it to another of the owner's facilities.

Related to the issue of operation and maintenance is that of equipment/system reliability. An apparent advantage of a POU system is that if one unit fails, it only affects one gate, whereas a central system failure may affect all aircraft gates served by the central system. Although this is primarily true, it is rare for a problem to completely disable an entire central system, and often the central plant continues to operate while repairs are being made. For example, if a chiller fails, today's central systems are generally equipped with thermal storage which will essentially replace the failed chiller during the peak cooling hours, allowing repairs to take place. There are levels of redundancy which can be incorporated to further ensure the systems remain online, but in the past, the redundant systems have typically been considered unnecessary. The components utilized in central systems are all industrial-rated equipment that can reliably operate for longer life cycles and are typically utilized in large factories for comfort cooling and industrial processes. Essentially, they are utilized in processes and situations where downtime is detrimental to delivering products and services, and therefore, reliability is of utmost concern. In contrast, POU equipment is typically manufactured with commercial grade components. These components are generally used in such applications as convenience stores or small office buildings.

Although POU system components may have shorter life spans, they still provide the convenience of modularity when either upgrading or replacing older equipment. Individual units can be modified without affecting the other units. New technologies and hardware can be investigated without making major capital investments as may be necessary with central systems. This type of flexibility may be more desirable to an airport than having lower operating and maintenance costs.

4.2 Operational Considerations and Comparisons

The operational differences between POU and central systems are mainly based on operating strategies that can improve energy efficiencies and/or maintenance strategies. The inherent differences in these systems offer noticeable operational tradeoffs that need to be considered.

In general, central systems are more efficient than a distributed POU system in providing cooled air to aircraft (ASE 2011). This holds true for centralized PCA systems located in office complexes as well. Central systems at airports are mainly water-based. Water is heated or cooled at a central location and then transmitted to the gate location where it is used to heat or cool air that is then transmitted into the aircraft. A centrally located, water-cooled chiller system is more efficient than multiple air-cooled, direct expansion air conditioning units since water is more thermally conductive than air, has a higher specific heat, and has a higher density. These factors indicate that for the same mass flow, water can absorb and remove a greater amount of heat than air. By utilizing the thermally superior heat transfer properties of water, a central system can be designed to be more energy efficient than a POU system.

Another factor to consider is the price of electricity during peak periods. Many electricity providers charge a premium for electricity usage during the provider's daily peak periods. This suggests a possibility to significantly reduce utility charges by utilizing thermal storage during peak periods. This does not imply that the PCA system capacity should be reduced such that thermal storage is necessary to meet the peak cooling loads. It does suggest, however, that although the central system should be sized to provide the necessary peak cooling demands, during the utility provider's peak periods, thermal storage could be used to reduce the system's power consumption. This could also ensure a lower overall system electricity demand for the system's owner. The key is being able to target this peak demand period, which has been attempted in the past with varied levels of success. However, by utilizing modern control systems, targeting the utility's peak demand period can be accomplished with minimal additional programming. This programming could include software routines that monitor the plant's actual demands, and when changes are detected in the loading, peak usage periods can be automatically redefined. Proper usage of thermal storage systems can easily save thousands or hundreds of thousands of dollars a year depending on the size and electricity requirements of the PCA system. This design principle is not possible with the use of a POU system. These types of differences in operating costs and potential for efficiencies tend to be beyond the scope of assessments conducted at a planning level, but need to be considered in the decision-making process since they could noticeably increase the difference in operating costs between POU and central systems.

Central systems that use heat from existing airport boilers benefit from lower operating costs due to the lower cost of natural gas-derived heat energy. The cost calculations presented in Section 3.3 illustrate the difference in operating costs between a central system using electrically-generated heat and boiler (natural gas)-generated heat.

One potential refinement to the operational cost data that is beyond the scope of a planning-level assessment is the concept of discount rates. This refers to the potential use of savings from capital costs that can be invested to help pay for utility costs in future years. That is, if a POU system with noticeably lower capital cost is selected, the difference (the money saved) in capital cost between the POU system and a central system can be grown through some investment options to help offset future growth in utility costs.

To improve the overall energy consumption and, therefore, cost estimates, the distribution of ambient conditions needs to be as accurate as possible. Assuming the default distribution of 25% cold, 50% neutral, and 25% hot conditions for airports in areas that are predominantly in one condition could have a significant impact on the calculated results.

4.3 Local and Corporate Airline Support

With the implementation of alternative systems, airlines must also have trained personnel to properly use the equipment (i.e., know how and when to connect ground power and PCA to the aircraft). In general, all airlines (at least at the corporate level) support the use of these systems as they represent a win-win situation where aircraft fuel consumption, emissions, and APU maintenance costs can be reduced. However, there are situations where airline pilots will use their APUs even though alternative systems are available.

In addition to the issue of personnel training (or availability), there may be other reasons why APUs are used when ground power/PCA systems are available. For example, on quick turnaround flights, the use of APUs may be considered easier and less disruptive than switching to alternative systems. Some airports have rules in place to try to force airlines to use the systems if an aircraft is parked at the gate longer than a designated amount of time. Unless an airline constantly monitors the activities of its pilots and crews, it may be difficult for the airline to enforce the use of the alternative systems. Ultimately, it may depend on the pilot's willingness to shut down the APUs.

It is also possible that there could be some overlap in the use the APUs and alternative systems when one is turned on and the other is slow to turn off. In addition, some gates with non-working alternative systems would require the use of APUs, hence giving the impression that APUs are being used when alternative systems are available.

Although there can be many reasons why alternative systems are not used (or may not appear to be used), it is clear that airlines need to agree to have their personnel (pilots, ground workers, etc.) follow protocols to use these systems. There needs to be good communication between airport operators and airlines to ensure support of alternative systems at the corporate level, and communication between corporate airline staff and flight crews and ground personnel at each airport. Indeed, airport operators should place more emphasis on ensuring local airline personnel agree to the use of alternative systems.

4.4 Ownership of Emissions and Fuel Consumption Reductions

Although currently not a major consideration, there is an evolving concern over the ownership of greenhouse gas emissions reductions. With the development of airport greenhouse gas emissions inventories and airport climate action plans, a question will likely come up: who takes credit for the reduction in aircraft APU emissions? The airlines will likely say that they should receive any ERCs. Airport operators may argue that since they invested in the alternative systems, they should receive the credits. Based on the World Resource Institute's (WRI's) scope definitions, APUs are owned by the airlines and so are APU-related emissions. Hence, any reductions thereof should be claimed by the airlines. However, airport operators have been developing greenhouse gas inventories based on the airport community as a whole (i.e., "airport sources" include sources owned by the airport, tenants, and the public). Although airport operators acknowledge they do not own aircraft APUs, different airports have used varying definitions of control to justify taking credit for APU emissions reductions.

One possibility is to award the reductions on the basis of monetary contribution to the development of the alternative system. That is, the reductions could be split between an airport and an airline using the alternative system if both parties contributed to the development of the system. This is a difficult issue and one that will likely not be resolved in the near future. It will continue to evolve as airports and airlines continue to look for opportunities to reduce their carbon footprints.

Regarding the ownership of the emissions due to airport electricity usage (i.e., electricity used by alternative systems), the evolving approach appears to be based on who receives the "bill" and pays for the electric energy. That is, even if the tenants (airlines) pay an airport through sub-metering, the airport's control over the payment to the utilities is used as the reason for allocating the resulting indirect emissions to the airport.

4.5 Equipment Noise

In general, noise levels generated by aircraft APUs and alternative systems are relatively low such that their impact on local communities is negligible. However, in a few cases, APU noise can actually cause a disturbance if a community is located in close proximity to the airport and if a clean line-of-sight exists between the source of the noise and the receiver (i.e., no structural obstructions to impede the noise). Therefore, while noise from APUs is not a primary concern of most airport noise abatement officers, airport management needs to be cognizant of where communities are in relation to aircraft parking areas and other locations where APUs are operated.

As there is very little information on APU and alternative system noise (Tam 2005; Kwan 2010), a noise measurement program was conducted at San Francisco International Airport (SFO) in December 2010 to determine the relative differences between APU and alternative system noise levels. The APU noise measurements were conducted at a distance of 50 ft from the APU exhaust (i.e., at aircraft tail points) for various aircraft types. Because of background noise levels on the ramp (e.g., nearby aircraft operating on main engines), it was difficult to obtain reliable noise measurement data for alternative system equipment. Therefore, manufacturer noise specifications data for alternative systems were used as the basis for propagating noise levels to the same location used for APU noise measurements.

With the exception of AHUs, noise levels generated by alternative system components are generally lower or negligible compared to either the noise generated by APUs or background noise levels at busy commercial service airports like SFO. Central plant chillers and boilers are generally enclosed in a building and accessible only to maintenance staff and hence are not a major contributor to noise levels on the ramp.

Therefore, the conclusion from the limited noise investigation conducted for this research project is that alternative systems are generally quieter than APUs. The only exception is with the AHUs associated with centralized systems which generate noise levels that are comparable to the lower end of the APU noise levels. However, since the AHU noise levels were derived from manufacturer specifications for maximum levels, the actual AHU noise levels could be lower. This assessment was conducted at a hypothetical distance of 50 ft from the tail end of parked aircraft. Higher fidelity noise measurement studies could potentially be conducted to include the impact of airport structures and other features (e.g., roadways and vegetation) in order to better determine potential impacts to local communities.

References

AERO Systems Engineering, Inc. (ASE). *Internal Cost Data*. 2011.

Aerospaceweb.org. *400 Hz Electrical Systems*. http://www.aerospaceweb.org/question/electronics/q0219.shtml. 2010.

Boeing Commercial Airplanes (Boeing). *Airport Noise and Emissions Regulations*. http://www.boeing.com/commercial/noise/list.html. Copyright 1995–2011.

Federal Aviation Administration (FAA). *Emissions and Dispersion Modeling System (EDMS) Version 5.1.3 User's Manual*. FAA Office of Environment and Energy (AEE). FAA-AEE-07-01. Revision 8. November 15, 2010a.

Federal Aviation Administration (FAA). *Voluntary Airport Low Emission Program, Technical Report, Version 7*. FAA Office of Airports, Airport Planning and Programming. DOT/FAA/AR-04/37. Revised. December 2, 2010b.

Federal Aviation Administration (FAA). Aviation Environmental Design Tool (AEDT). http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/aedt/. Updated February 2, 2011a.

Federal Aviation Administration (FAA). *VALE Program Grant Summary, FY 2005–FY 2011 (Part A)*. http://www.faa.gov/airports/environmental/vale/media/VALE_grant_summary.pdf. Updated March, 29 2011b.

International Civil Aviation Organization (ICAO). *Airport Air Quality Guidance Manual*. ICAO Doc 9889. 2007.

Kwan, Jimmy and Eric S. J. Yang. "Auxiliary Power Unit Noise of Boeing B737 and B747 Aircraft." ISSN 0105-175X, p. 899–902. http://adsabs.harvard.edu/abs/1992STIA. . .9588468K. 2010.

Swedish Defense Research Agency (Swedish FOI). *APU Emissions Database, Version 1.1*. April 15, 2009.

Tam, Christopher K. W., et al. "Combustion Noise of Auxiliary Power Units." A Paper Presented at the 11th AIAA/CEAS Aeroacoustics Conference (26th AIAA Aeroacoustics Conference). AIAA 2005-2829. Monterey, CA. May 23–25, 2005.

United States Environmental Protection Agency (USEPA). *AP 42, Fifth Edition, Volume I, Chapter 1: External Combustion Sources, Section 1.4: Natural Gas Combustion*. EPA Technology Transfer Network. http://www.epa.gov/ttn/chief/ap42/ch01/index.html. July 1998a.

United States Environmental Protection Agency (USEPA). *AP 42, Fifth Edition, Volume I, Chapter 1: External Combustion Sources, Section 1.1: Bituminous and Subbituminous Coal Combustion*. EPA Technology Transfer Network. http://www.epa.gov/ttn/chief/ap42/ch01/index.html. September 1998b.

United States Environmental Protection Agency (USEPA). *Recommended Best Practice for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet, and Turboprop Engines, Version 1.0*. USEPA Assessment and Standards Division, Office of Transportation and Air Quality, USEPA, and AEE-300—Emissions Division, Office of Environment and Energy, FAA. EPA-420-R-09-901. May 2009.

United States Environmental Protection Agency (USEPA). *eGrid 2007, Version 1.1*. http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html. 2010.

APPENDIX A

Annual Average Ambient Temperature Data

Table A-1 presents annual average temperature data for airports located in the nine FAA regions. This information was obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) website.

Table A-1. Annual average ambient temperature conditions by FAA region.

		Percent (%) of the Year		
FAA Region	**Weather Station Location**	**Cold Conditions {<45 degrees F}**	**Neutral Conditions {45-50 degrees F}**	**Hot Conditions {>50 degrees F}**
New England	Boston Logan International Airport	37	9	54
Eastern	Washington Reagan National Airport	28	7	65
Southern	Atlanta Municipal Airport	22	8	70
Southwest	Dallas Fort Worth International Airport	17	6	77
Central	Kansas City International Airport	36	5	59
Great Lakes	Chicago O'Hare International Airport	42	7	51
Western-Pacific	Los Angeles International Airport	0.3	2.7	97
Northwest Mountain	Renton Municipal Airport	21	22	57
Alaskan	Anchorage International Airport	63	9	28
	National Average =	**30**	**8**	**62**

SOURCE: National Oceanographic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) website (http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter).

APPENDIX B

List of Acronyms

AC	Alternating Current
ACRP	Airport Cooperative Research Program
AEDT	Aviation Environmental Design Tool
AERC	Airport Emission Reduction Credits
AHU	Air Handling Unit
AIP	Airport Improvement Program
APU	Auxiliary Power Unit
BTU	British Thermal Unit
CAA	Clean Air Act
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DC	Direct current
EA	Environmental Assessment
ECS	Environmental Control System
EDMS	Emissions and Dispersion Modeling System
EE	Electric Energy Consumption
EI	Emissions Index
EIS	Environmental Impact Statement
ERC	Emission Reduction Credit
FAA	Federal Aviation Administration
FB	Fuel Burn
FF	Fuel Flow
FOI	Swedish Defense Research Agency
FONSI	Finding of No Significant Impact
ft	Feet
g	Grams
GARB	General Airport Revenue Bond
GPU	Ground Power Unit
GSE	Ground Support Equipment
hr	Hour
HE	Heat Energy Consumption
HR	Heat Rate (BTU/hr)
HVAC	Heating, Ventilation, and Air Conditioning
Hz	Hertz
ICAO	International Civil Aviation Organization
kg	Kilograms
kVA	Kilovolt-Ampere

KW	Kilowatt
KWh	Kilowatt-Hour
LTO	Landing and Takeoff
mmBTU	Million BTU
MWh	Megawatt-Hour
NAA	Nonattainment Area
NAAQS	National Ambient Air Quality Standards
NCDC	National Climatic Data Center
NEPA	National Environmental Policy Act
NO_2	Nitrogen Dioxide
NOAA	National Oceanic and Atmospheric Administration
NO_x	Nitrogen Oxides
Pb	Lead
PBB	Passenger Boarding Bridge
PCA	Pre-conditioned Air
PFC	Passenger Facility Charge
PM	Particulate Matter
POU	Point of Use
O_3	Ozone
s	Second
SIP	State Implementation Plan
SO_2	Sulfur Dioxide
TEECAAS	Tool for Evaluating Emissions and Costs of APUs and Alternative Systems
THC	Total Hydrocarbons
TIM	Time in Mode
TRB	Transportation Research Board
US	United States
USEPA	United States Environmental Protection Agency
VALE	Voluntary Airport Low Emissions
VDC	Volts Direct Current
VOC	Volatile Organic Compound
yr	Year

APPENDIX C

List of Helpful Websites

FAA VALE Program
http://www.faa.gov/airports/environmental/vale/

FAA EDMS
http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/edms_model/

FAA AEDT
http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/aedt/

NOAA Weather data site
http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter

EPA Technology Transfer Network (TTN)—AP42 Emission Factors
http://www.epa.gov/ttn/chief/ap42/index.html

EPA eGrid Emission Factors
http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html

APPENDIX D

Frequently Asked Questions

1. **Question: Why should an airport implement an alternative system?**

   Answer: An alternative system can help reduce airport emissions, resulting in improvements to local air quality. Airport Emission Reductions Credits (AERCs) can be issued for clean infrastructure projects under the FAA's Voluntary Airport Low Emissions program. AERCs can potentially be used to offset emissions associated with planned capital improvement projects in the context of National Environmental Policy Act (NEPA) assessments and General Conformity evaluations. When alternative systems are available, airlines can reduce APU usage, thereby reducing fuel consumption and overall APU maintenance.

2. **Question: Can an airport operator and one or more airlines pool resources to implement an alternative system?**

   Answer: Yes, airlines and the airport operator can jointly fund the construction of alternative systems. An important consideration in such cases is how the systems will be managed if an airline decides to leave the airport.

3. **Question: What are the pollutants of concern emitted by APUs and alternative systems?**

   Answer: APUs and alternative systems emit both criteria pollutants (e.g., CO, NO_x, SO_x, etc.) as well as greenhouse gases (e.g., CO_2). Criteria pollutants emitted by APUs at the airport contribute to the degradation of local air quality near the airport. The use of alternative systems effectively transfers the emissions of criteria pollutants to off-site power plants which are not considered in local airport air quality assessments. In contrast, greenhouse gases emitted by both APUs and power plants need to be accounted for when greenhouse gas emissions assessments are conducted in support of climate action plans and related studies.

4. **Question: What are the impediments to implementing an alternative system?**

   Answer: There are several potential factors that may impede the implementation of an alternative system, but the most significant is usually cost. The airport operator and/or airlines will need to carefully consider their needs with the pros and cons of POU and central systems.

5. **Question: How is the implementation of an alternative system usually funded?**

   Answer: Funding has been obtained from a mixture of PFC programs, AIP grants, GARBs or other bonds, and more recently, through the FAA's VALE program as well as privately funded programs (e.g., airline-driven).

6. **Question: What type of alternative system is best for smaller airports?**

   Answer: In general, there is no solution that is always best for smaller airports. As with larger airports, there are many factors that need to be taken into account including available funding level, number of gates involved, aircraft types serviced, etc. With that in mind, smaller airports usually correspond to lower levels of funding, lower number of gates, smaller aircraft types, etc. In such cases, depending on how small the facility is, POU and portable diesel-powered systems may be better than central systems.

7. **Question: What are the cost differences between different alternative systems?**

   Answer: POU systems generally have much lower up-front capital costs while central systems are generally more efficient and have longer-lasting components which results in lower operating and maintenance costs. The overall cost differences can be determined using a life-cycle cost assessment but will depend on various factors including the number of gates affected, aircraft types serviced, the expected service lives of the systems, etc.

8. **Question: What are the differences between the APU emissions calculation methodology presented in this handbook versus the method used in the FAA's Emissions and Dispersion Modeling System (EDMS) and/or Aviation Environmental Design Tool (AEDT)?**

   Answer: The methods are similar in that they both involve the multiplication of activity data with emission factors to calculate emissions. However, the source, form, and resolution of the datasets are significantly different. The FAA's EDMS/AEDT uses single, average emission factors (kg/hr) for each APU that were obtained from various sources including the USEPA. In contrast, the Handbook uses data from the Swedish Defense Research Agency (FOI) which represent the latest set of measured data for different power settings as a function of fuel flow (g/kg fuel). Although the Swedish FOI data suffices for the five aircraft categories used in the Handbook, the EDMS/AEDT has a more comprehensive dataset (covers more APU types).

9. **Question: What type of alternative system is best for large busy airports with many passenger boarding gates?**

   Answer: In general, there is no solution that is always best for larger airports. As with smaller airports, there are many factors that need to be taken into account including available funding level, number of gates involved, aircraft types serviced, etc. With that in mind, larger airports usually correspond to higher funding levels, higher number of gates, larger aircraft types, etc. In such cases, unless the flexibility of a POU system is desirable, the efficiencies and longer-lasting components may make central systems a better choice for long term cost savings. The more gates that are involved, the more savings are realized.

10. **Question: Who is responsible for APU emissions?**

    Answer: For greenhouse gases, airlines are responsible if using a strict ownership definition. As such, the emissions would be listed under the Scope 1 category within the World Resource Institute's (WRI's) protocols. This would mean that the airlines also could receive credit for any reductions in these emissions. However, from a control standpoint, an airport operator could argue that the influence (control) it can exert over the tenants (airlines) in reducing their APU emissions through the use of alternative systems would entitle the airport operator to receive the reduction credits, especially if the airport operator also funded the implementation of the alternative systems. This is an evolving issue. For criteria pollutants, the responsibility is project-based and usually that of the airport operator. The airport operator is responsible for accounting for APU emissions in its emission inventories as well as being able to claim credits for APU emissions reductions.

11. **Question: Can an airport operator require an airline to use an alternative system?**

    Answer: Yes, as a tenant, an airline is subject to the rules and requirements set forth by the airport operator. However, this does not ensure compliance as an objecting airline has the right to leave the airport. Also, in practice, airlines and their employees may not always obey such a requirement especially if the airport operator is lax in enforcing it.

12. **Question: Which alternative system is better—POU or central system?**

    Answer: Each of these systems has advantages and disadvantages. POU systems offer flexibility since each system is self-contained and can be added, modified, or removed without impact to other systems. POU systems have relatively low capital costs. In contrast, central systems have higher capital costs and less flexibility, but offer greater efficiencies and more durable components that result in lower operating and maintenance costs as well as longer life spans.

13. **Question: Will the use of alternative systems (as opposed to using APUs) reduce emissions and noise?**

    Answer: In general, the use of alternative systems will reduce both noise and emissions. While criteria pollutant emissions would still occur at electric power plants, they are estimated to be significantly lower than what the APUs would have produced. Greenhouse gas emissions at the power plants are also predicted to be significantly lower. Noise levels generated by the electrical components of alternative systems are much lower than APU noise levels, while air handling units (AHUs) can generate similar noise levels to APUs.

14. **Question: Can the emissions calculations in this Handbook be used to satisfy VALE and NEPA requirements or greenhouse gas emissions evaluations?**

    Answer: No. The Handbook and its components are only to be used for planning purposes.

15. **Question: How do you assess emissions for aircraft that remain overnight (RON) at a gate location?**

    Answer: To conduct this assessment, the total usage times for either the APUs or alternative systems will need to be estimated. It should be noted that if APUs are used, they will likely be shut off during the night while alternative systems may be used throughout the night. The total usage time should be split between the "Gate In" and "Gate Out" modes based on the distribution of the default TIM values for these modes. It is recommended that unless actual data is available, the default TIM values for the "APU Start" and the "Main Engine Start" modes be used.

APPENDIX E

Assumptions

In developing this Handbook, many assumptions were made related to the emission characteristics and operating parameters for APUs and alternative systems. These assumptions are discussed in detail in Chapters 1–4. Key assumptions are repeated here for clarity:

- APU TIM values were obtained from ICAO and are used as a starting point for the quantitative assessments described in Chapter 3.
- In Chapter 3, TIM values for APUs are assumed to be identical to usage times for alternative systems. That is, airlines will operate the alternative systems for the same amount of time they would have operated APUs if an alternative system were not available. However, it is anticipated that APU and alternative system usage times at remote RON locations are not the same. At remote RON parking positions, APUs are usually shut down at night whereas alternative systems are often used all night. Therefore, different usage times (different TIM values) may be needed to accurately compare emissions associated with the use of APUs and/or alternative systems at remote aircraft parking positions.
- Data from the FAA's VALE technical manual were used to define the three ambient temperature conditions described in Chapter 3 (e.g., hot, neutral, and cold). The three ambient temperature conditions in turn define if aircraft cooling is required (hot), aircraft heating is required (cold), or no aircraft cooling or heating is required (neutral).
- The research team assumed that the "APU Start" and the "Main Engine Start" modes are common for the use of APUs and alternative systems. In other words the research team assumed that aircraft APUs are operated during the "APU Start" and "Main Engine Start" modes regardless of whether an alternative ground power and PCA system is available. For simplicity, the research team assumed that no other ground support equipment is required to support aircraft during these modes (e.g., an air start unit).
- Since total hydrocarbons (THC) emission factors for electricity consumption were not available, an approximate volatile organic compounds (VOC) emission factor was derived from existing VOC species data maintained by the USEPA.
- A 40% diversity factor was used to account for the average percent of the full power loads consumed by aircraft.
- All cost data and results are presented in 2010 dollars. No specifications are provided to reconcile the impacts of inflation and other economic factors.
- As indicated in the various cost tables, the source of all capital and maintenance costs is AERO Systems Engineering, Inc. The capital costs for alternative system power and PCA are conservatively based on the highest capacity for each power (kVA) and PCA (tonnage) ranges that are applicable to each aircraft category.
- The average cost of electricity ($/KWh) and natural gas ($/mmBTU) are nominal average values derived from various internet searches.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation