Impacts of Regional Air Mobility and Electrified Aircraft on Airport Electricity Infrastructure and Demand

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National Renewable Energy Laboratory

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List of Acronyms

ABE	Lehigh Valley International Airport
BESS	battery energy storage systems
COS	Colorado Springs Airport
DER	distributed energy resource
EV	electric vehicle
EVI-EnSite	Electric Vehicle Infrastructure – Energy Estimation and Site Optimization tool
EVSE	electric vehicle supply equipment
Georgia Tech	Georgia Institute of Technology
MACRS	modified accelerated cost recovery system
NASA	National Aeronautics and Space Administration
NPV	net present value
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
PHF	Newport News-Williamsburg Airport
PV	photovoltaics
RE	renewable electricity
SOC	state of charge

Executive Summary

The U.S. aviation system is an important part of the nation's economy, transporting hundreds of millions of passengers and billions of pounds of freight annually (FAA 2022). In the coming decades, air transportation of people and cargo is set to expand; however, several challenges currently face the aviation sector, including achieving greenhouse gas emissions reduction goals, serving larger populations through regional and local airports, managing aircraft noise, and reducing the cost of operations, to name a few.

As battery chemistries have advanced, many entities—such as the Federal Aviation Administration, the National Aeronautics and Space Administration (NASA), and private industries—have expressed interest in understanding electric aircraft and the opportunities they present. Electric aircraft, similar to electric vehicles (EVs), come in two major types: hybrid electric and battery-electric aircraft. Battery-electric aircraft require the use of charging infrastructure on the ground between flights, whereas hybrid electric aircraft may recharge during flight, which also increases overall flight efficiency, though some also charge on the ground (Schwab et al. 2021).

Both types of electric aircraft have several major advantages and drawbacks compared to conventional aircraft. Advantages include having significantly lower fuel and operating costs, quieter operation, and usually the ability to generate additional torque, allowing them to take off from shorter runways (Antcliff et al. 2021). Drawbacks include range concerns, lower passenger or cargo capacity, and charging times that would disrupt current commercial airline travel schedules (Antcliff et al. 2021).

Due to their advantages and drawbacks, electric aircraft are likely not as useful in a business-as-usual scenario, where they would be placed at large airport hubs to serve long flights. If electric aircraft were used in a more localized scenario, they have the potential to transform the U.S. transportation sector. Rather than flying in a traditional hub-and-spoke scenario with large concentrations of aircraft at large hubs, electric aircraft could connect smaller regional or local airports directly. At these smaller airports, electric aircraft could efficiently utilize shorter runways, and due to their quiet operation, electric aircraft could serve rural communities with fewer local noise impacts. Electric aircraft have the potential to help:

1. Increase mobility opportunities for rural or small communities.
2. Transform decentralized airports into renewable energy hubs, where local solar and wind installations could power the electric aircraft and send excess energy back to the community.
3. Decrease regional (short-distance) airplane travel costs.
4. Reduce ground transportation congestion and emissions.

This report summarizes an analysis of the electrical infrastructure that might be necessary to serve electric aircraft at a subset of airports where potential electric aircraft flight demand has been provided. Additionally, an estimate for the amount of on-site distributed energy resources (DERs)—i.e., solar photovoltaics (PV) and battery energy storage systems (BESS)—that could be used to serve electric aircraft in cost-effective scenarios is provided.

A team of researchers from the Georgia Institute of Technology (Georgia Tech) estimated the market potential for regional flights (Justin, Payan, and Mavris 2021, 2022; Justin et al. 2022; Morejón Ramírez et al. 2021). These flight demand data were used to estimate the on-ground charging electricity demand needed to service regional electric aircraft. Several airports in this study volunteered their interval and monthly baseline electricity demand data to build a prototypical airport baseline electricity demand profile that could be scaled. Electricity cost rates were selected from the mid-Atlantic region or generated from mid-Atlantic regional averages. These electricity demand profiles and electricity cost rates were evaluated utilizing two tools from the National Renewable Energy Laboratory (NREL)—the REopt® and Engage™ models—for a total of 162 modeled airports in the mid-Atlantic region and one airport in Colorado (chosen based on data availability). The capacity expansion and dispatch models estimated DERs that would be needed to support the hypothetical electric aircraft flight demand. Potential available land area at each airport was analyzed by NASA and provided to NREL as an upper limit for potential PV deployment. Figure ES-1. shows these steps visually in this work.

Figure ES-1. Analysis methodology

The analysis resulted in a few key findings. First, in all cases, the electric aircraft charging electricity demand was larger than the airport baseline electricity demand for even a modest number of flights (approximately five per day). This meant that existing airport infrastructure was usually not sufficient to service electric aircraft. Second, although Engage and REopt predicted different levels of DER deployment based on differences in model inputs, in almost all cases, some level of on-site electric infrastructure or DERs was recommended to economically serve electric aircraft. The buildouts of electric infrastructure or DERs were a reasonable amount (less than 1% of airport land used for DERs) for the airport size. This suggests that with proper planning and investment, electric aircraft could be supported at all airports studied. The economic benefit of DER buildout was likely due to the short window and high peaks of airplane charging that are particularly favorable when modeling BESS technologies. Third, in those cases studied, airport land area was never a constraining factor in the buildout of PV. Often, the PV buildout was less than 1% of available land at airports, meaning that land area used by PV was not a significant burden on the airport, even in cases with high PV deployment.

This report presents a first-of-a-kind study to couple airport electric infrastructure impacts with electric aircraft. There remains significant future work to be done. Immediately, the NREL team plans to work with the Georgia Tech team to analyze electricity costs and electric aircraft flight demand with additional scenarios being evaluated. Additionally, more airport data are needed to better understand airport baseline electricity demand and to better represent diverse sites. Finally, the NREL team plans to work more closely with utilities in future work to better understand utilities' concerns with electric aircraft and to incorporate potential electricity rate structures into the analysis, with the potential to influence the design of electric aircraft charging electricity rates.

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1 Introduction

Each day, millions of pounds of cargo and millions of passengers are safely and successfully transported through the U.S. aviation system. In 2021, U.S. airlines carried approximately 674 million passengers and 44.5 billion pounds of freight. Air travel is estimated to contribute more than 10 million jobs to the U.S. economy and 5.2% to the U.S. gross domestic product (FAA 2022); however, air transportation also has several challenges that need to be overcome. First, air transportation produces approximately 3% of U.S. total greenhouse gas emissions (IPCC 2014; EPA 2022). Second, the majority of air travel is concentrated at only a fraction of airport hubs, with 0.6% of airports servicing 70% of domestic air travel (Antcliff et al. 2021). This is a result of economies of scale, where large aircraft are more economical to fly than smaller aircraft but require concentrated infrastructure in large communities. Medium- and long-haul aircraft are the primary users of aviation fuel and require large runways to cover the desired distance. For aircraft with more than nine seats, security checks are required, which increase passenger onboarding time (Code of Federal Regulations 2002). Two primary concerns surrounding the current airport system are noise and emissions impacting local communities. For large aircraft, there is currently no drop-in replacement for emissions-free air travel. There have been proposed replacements of conventional fuel with biomass fuel, hydrogen, or emissions-free synthetic carbon (Oakleaf et al. 2022), but these efforts have mostly targeted business-as-usual air travel, which maintain the challenges related to large aircraft air travel (FAA 2015; Blakey, Rye, and Wilson 2011).

One potential solution for some of these issues is electric aircraft, available in either battery or hybrid versions. Electric aircraft have become an important topic for research by the Federal Aviation Administration and National Aeronautics and Space Administration (NASA) because they have the potential to solve several of these stated challenges. Electric aircraft reduce local aircraft emissions, require shorter runway lengths for takeoff and landing, operate with less noise, and have reduced operating costs (Schwab et al. 2021; Antcliff et al. 2021). Electric aircraft could also increase rural transportation access by using small regional airports at a reasonable cost. By leveraging underutilized airports, electric aircraft could serve short-haul flights between regional airports and large airport hubs, instead of requiring passengers to commute to and from large airport hubs.

Before electric aircraft can be introduced into the U.S. air transportation system, additional research must be performed. Much of this research involves the aircraft themselves and is outside the scope of the analysis presented in this report. The goal of this report is to estimate the impact on airport infrastructure needed to support electric aircraft charging based upon provided passenger demand scenarios. In pursuit of this goal, several steps were taken, including constructing representative charging and demand profiles, estimating new infrastructure needed, and estimating the distributed energy resources (DERs) needed to use renewable energy technologies to charge electric aircraft. These steps are described in greater detail below.

First, the National Renewable Energy Laboratory (NREL) Electric Vehicle Infrastructure – Energy Estimation and Site Optimization tool (EVI-EnSite) was used to construct representative electric aircraft charging profiles for input into the analysis. Using the constraints of the electric aircraft and transportation demand modeling, the Georgia Institute of Technology (Georgia

Tech) built a series of estimated demand profile for electric flights (Justin, Payan, and Mavris 2021, 2022; Justin et al. 2022; Morejón Ramírez et al. 2021). This analysis produced an estimated repeating daily schedule that included flight arrival and departure time for thousands of flights that could replace car travel on the regional level. The baseline 2040 demand case was selected from the Georgia Tech models, centered at 162 airports in the mid-Atlantic region. Using the landing and departure times specified by the Georgia Tech schedule, EVI-EnSite was used to generate three electricity charging profiles. These profiles resulted in three charging cases. First, the airplanes were allowed to plug in and remain charging for the duration of their time on the ground (hereafter referred to as "residence" time). Second, the airplanes were allowed to plug in and charge up to 3 MW. Third, the airplanes were allowed to charge up to 3 MW and complete their charging within 15 minutes or less, representing the most realistic turnaround time for such aircraft. These three cases produced an electricity charging profile for each airport and for the mid-Atlantic region. This region was chosen by Georgia Tech as described in Section 2.1.1.

Second, the NREL Engage tool was used to estimate the need for new infrastructure to the airport versus building on-site renewable energy generation and energy storage (in the form of lithium-ion batteries). Engage is a capacity expansion and dispatch model that meets electricity demand annually and hourly using the least-cost available energy. Using the electricity demand profiles generated in the first step, Engage assumed infrastructure upgrade, solar, energy storage, and charging station costs to estimate the least-cost way of meeting the electricity demand created by the airplane charging profiles. Engage assumed a utility tariff based on the mid-Atlantic region that included both commodity ($/kWh) and demand ($/kW) prices. Using these inputs, Engage estimated the airport upgrades needed and the potential for on-site renewable energy at all 162 airports used in the analysis.

Third, NREL's REopt[1] platform was used to conduct detailed analysis of solar-plus-storage opportunities at two airports. REopt is a techno-economic modeling and optimization tool used to identify the life cycle cost-optimal DERs to meet a site's energy goals, including cost savings, decarbonization, and resilience, where the life cycle cost of energy represents the present value of all capital costs, incentives, operation and maintenance (O&M) costs, and electricity costs throughout the analysis period (Cutler et al. 2017). REopt analysis is improved when hourly or 15-minute interval data are available. Thus, the two airports selected were airports that provided interval data to this study, Colorado Springs (COS) and Newport News-Williamsburg (PHF). PHF was part of the original mid-Atlantic region airports provided by Georgia Tech, and flight data for PHF were used. COS was not part of the original 162 airports but was analyzed due to the availability of interval data. Flight data for COS were approximated using Lehigh Valley International Airport (ABE), which had a similar order of magnitude for annual enplanements.

The following sections introduce electric aircraft, the methodology used to conduct this study, the results, and the conclusions from this work.

1.1 Electrified Aircraft

Designs for electric aircraft have existed since the 1970s, including many unmanned vehicles for both military and commercial purposes (Jansen et al. 2022, 2020; Hepperle 2012). Electric

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[1] See https://reopt.nrel.gov/.

aircraft include a range of versions, some of which contain onboard power generation systems (i.e., solar panels or fuel cells) and others that contain no onboard generation but store energy using batteries. Some electric aircraft are driven only by electric propulsion, whereas others are similar to hybrid cars, where electric and fossil-fuel propulsion work together to power the aircraft. In all cases, the unifying definition of electric aircraft is that some fraction of the propulsion system is driven by an electric motor or turbine.

One of the earliest designs for electric aircraft was project Helios, a long-range electric aircraft equipped with solar panels that could stay aloft for more than 24 hours, designed to be an atmospheric satellite (Figure 1).

Figure 1. Project Helios solar-powered electric aircraft.

Photo from NASA under the public domain

More recently, electric aircraft have been reexamined as a potential carrier of passengers and cargo in a commercial setting, especially as battery chemistries and charging infrastructure have advanced (Hepperle 2012). Figure 2 shows NASA’s latest electric aircraft, the X-57, which was designed to demonstrate electric propulsion with distributed propellers along the span of the wing. Electric aircraft have several advantages over traditional fossil-fueled aircraft. First, because the power-to-weight ratio and efficiency of the motors are not largely dependent on peak power level (as opposed to fossil-fueled engines or turbines, which typically get more efficient and/or a higher power-to-weight ratio at higher peak power levels), electric aircraft can use distributed propulsion, where the propulsion system (in this case, electric motors and propellers) is distributed across the lift surface. This allows for increased efficiency and quieter operation. Additionally, because the motors are electric, this allows for additional torque at lower motor speeds. This excess torque can be used by the aircraft to operate propellers at lower speeds, reducing noise in cases where propeller noise may otherwise be the dominant noise source.

Because of their increased energy efficiency, electric aircraft have the opportunity to reduce the cost of air transportation while also reducing emissions from aircraft operations. It is estimated that this could result in additional flights and particularly increase accessibility to smaller regional airports, which currently serve only a small fraction of air transportation. For smaller airports to support such transport, it will be important for any necessary charging infrastructure to be analyzed and deployed simultaneously with electric aircraft, which is one part of the analysis included in this report.

Figure 2. NASA X-57 electric aircraft.

Photo from NASA under the public domain

1.2 Airport Electrical Distribution System

Airports fall into various size categories of electrical service, making it difficult to generalize airport infrastructure by utility customer class. The airport electrical facilities receive their electrical energy through facilities that interconnect with those of the serving utility. As is the case with other utility customers, the scale of the facilities and operations of an airport largely determine the electrical consumption and demand of the airport and, in turn, the topology and capacities of the components of the airport electrical system.

The voltage of the utility distribution system (4.6–25 kV), which carries electrical energy from distribution substations over distribution power lines, is referred to as “primary distribution voltage” or “primary voltage.” For most customers, commercial and residential, the utility typically owns the infrastructure, including the distribution transformer and some downstream components to the “service entrance,” where the electrical service is routed through the electric meter and into the business or residence.

Larger utility customers can sometimes benefit from owning and operating their own distribution transformer(s) and consuming electricity directly from the distribution system at primary voltage. This is referred to as “primary service” and “primary billing.” Because these customers purchase and maintain equipment otherwise provided by the utility, the cost of their delivered power is reduced. Even larger industrial and commercial customers can sometimes further reduce their cost of utility electricity by owning and maintaining portions of the distribution system and portions or all of the distribution substation or transmission substation, though the choice of ownership demarcation is multifaceted and situation-specific. When the customer consumes power at transmission voltage, the arrangement is referred to as “transmission service” and the tariff or billing arrangement as “transmission billing.”

Small airports, such as local or regional airports, with few operations and facilities might receive service from a single utility meter and service from a single-phase overhead distribution line and a single distribution transformer, both owned and operated by the electric utility. In such cases, the airport typically owns only the equipment downstream from the electric service entrance to the office building or hangar facilities.

At the other end of the scale, large airports might have large terminal buildings, hangars, and emergency operations facilities. Some larger airports have electrical consumption and demand sufficient to warrant transmission-level utility service and airport ownership of dedicated distribution substation(s) with multiple distribution substation transformers and an airport-owned electric distribution system. It is common for airports with multiple facilities to have multiple utility service interconnection points with the utility distribution system and corresponding utility revenue meters. Other airports may have a single or one main utility account and meter, either one or more primary, or even transmission-level meter(s) and own and operate the downstream, on-site substation and/or distribution system infrastructure.

1.3 Electric Aircraft Charging Infrastructure

Similar to electric vehicles (EVs) today, there will be a range of charging speeds to meet electric flight demand in the future. A range of charging speeds could include slow charging that will charge the airplane within 1–8 hours and fast charging that will charge the airplane within as little as 15 minutes, to accommodate shorter residence times. This range of charging times corresponds to a range of electric aircraft applications. Some cargo planes will fly to a location in the morning and stay all day only to return in the evening, whereas some passenger planes will land and take off as quickly as they can exchange passengers, maximizing operational efficiency of the aircraft.

Electric vehicle supply equipment (EVSE) varies based on the onboard electronics of the EV. Traditionally, EVs have an onboard component to convert AC to DC for charging the batteries. In an electric aircraft, however, onboard charging electronics would be minimal to reduce weight. Instead, it is likely that electric aircraft will charge with DC.

Different DC fast-charging components include an inverter, inverter controller, and potentially a DC bus (if there are multiple charging points behind the AC-to-DC inverter). In electrical infrastructure, a bus refers to a node consisting of a high-capacity conductor, often in the form of a highly conductive metal bar, that distributes electricity among lines connecting it to system components such as incoming or outgoing lines and loads, generators, and transformers. The physical hardware, plug shape, and cyber interconnection protocol that connect the electric aircraft and the associated power the charger can send will depend on the developed charging standards, which is currently an area of active research. Several proposed charging standards are included for 600 kW, 1.2 MW, and 3 MW (Walker, Moore, and Birky 2020; Kane 2021). Designing or selecting future EVSE charging standards is outside the scope of the present work; however, all the electric aircraft based on the Georgia Tech-provided flight schedule can be charged during their residence time at less than 3 MW of power. This was therefore assumed to be the upper limit of the potential EVSE installed at airports for electric aircraft.

For battery-electric aircraft to become viable in the market, the electric charging infrastructure must be developed in parallel with the aircraft while also addressing the challenges associated with integrating electric charging into existing airports. The first charger on the market was developed by Pipistrel, an aircraft manufacturer that built the first electric aviation charging station in the United States in 2019 at the Compton/Woodley Airport (Pipistrel 2022). This charging station consists of Pipistrel's SkyCharge system, which can charge two aircraft at 20 kW or one at 40 kW. It takes an hour to fully charge an Alpha Electro aircraft, a small two-seat electric airplane, which demonstrates a great start for small-scale charging infrastructure for personal-use planes. However, this charging rate is too slow to meet commercial flight schedules. On a slightly larger scale, Clay Lacy Aviation, a fixed-base operator service company, has announced an agreement with electric aircraft manufacturer Eviation to provide charging for a nine-passenger aircraft, Eviation's Alice. This charging system requires 30 minutes or less to charge per flight hour, with a maximum range of up to 815 kilometers. Eviation's Alice eCargo planes are set to be deployed in 2024, kicking off the commercialization of electric aircraft within the short-haul aviation sector.

With these plans to deploy electric aircraft in the next decade, there are challenges relating to the increased electricity demand associated with electric aircraft, as well as the charging systems to accommodate increased electric aircraft penetration levels at airports. Two main charging strategies are being studied to increase the efficiency of large-scale charging: plug-in charge and battery swap. Plug-in charge is the traditional way in which aircraft are plugged directly into a charging station on the ground. This method requires high-power chargers, which are currently unavailable on the market, to meet flight schedules. The battery swap method involves switching out a depleted aircraft battery with a fully charged one at the gate. This method can reduce peak charging power and electricity costs by allowing flexibility in the time intervals in which the battery can be charged; however, this method requires spare batteries, which increases battery costs, including at the O&M levels. There are additional factors and constraints that discourage the use of swappable batteries, though these considerations are better summarized in other publications (Justin et al. 2020; Guo et al. 2021), and an in-depth discussion is avoided here for brevity. Considering these factors, plug-in charging systems seem the most effective for future aircraft charging and are therefore the focus of this study, especially with companies like Pipistrel and ChargePoint developing and deploying chargers in the near future. In theory, an airport could employ both plug-in charging and battery swapping.

In the case of plug-in charging, however, charging times will remain a huge hurdle to overcome. To provide a better understanding of why charging times will remain a hurdle, Table 1 summarizes energy transfer rates for traditional liquid jet fuel (refueling trucks and hydrant systems) and proposed or deployed plug-in chargers (Pipistrel and ChargePoint). As can be seen, the energy that can be transferred per unit time is orders of magnitude larger for liquid fuels.

Table 1. Comparison of Fueling and Charging Methods by Power[2]

Fuel/Charge Method	*kBtu/min*	*Gal/min*	*MW*
Refueling trucks	27,000–81,000	200–600	475–1,424
Hydrant system	81,000–135,000	600–1,000	1,424–2,374
Pipistrel's SkyCharge 20-kW charger	1.13	0.0084	0.02
ChargePoint 2-MW charger	113	0.84	2

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[2] Unit conversion values were calculated from the U.S. Department of Transportation's Bureau of Transportation Statistics: https://www.bts.gov/content/energy-consumption-mode-transportation.

2 Methodology

This section describes the methodology employed in this analysis. First, electric aircraft load profiles were simulated across 162 airports, described in Section 2.1, using EVI-EnSite based on the flight schedule predicted by the Georgia Tech team. NREL’s REopt model was used to evaluate the techno-economic potential for solar plus storage for two airport case studies designed to reduced on-site energy costs, described in Section 2.2. NREL’s Engage model was simultaneously used to simulate electric aircraft charging infrastructure needs coupled to potential on-site DER buildout for all 162 airports in a cost-optimal configuration, as detailed in Section 2.3. Methodologies employed in the Engage and REopt analyses were closely aligned, but given differences in the model structures and analysis scopes, there are some differences between the two methodologies. Figure 3 shows the major steps used in this analysis.

Figure 3. Analysis methodology for this work

2.1 Electrified Aircraft Charging Demand

There are several established methods for estimating customer demand for a novel technology based on the technology’s capability, economics, and customer behavior. For this work, the electric flight demand data were provided by Georgia Tech using their published methodology (Justin, Payan, and Mavris 2021, 2022; Justin et al. 2022; Morejón Ramírez et al. 2021). This section briefly describes the method, along with alternative methods that could be used and some potential drawbacks and opportunities for future work.

2.1.1 Georgia Tech Methodology: Travel Replacement

The original goal of the Georgia Tech research was to estimate the change in air travel that would come from offering electric regional flight, using the mid-Atlantic region to do so. The high population and airport density there make it amenable as a first pass for electric flight opportunities. The Georgia Tech model used a national travel survey from the Federal Highway Administration to identify origin/destination pairs and associated demand on these routes, as well as the time to travel between these origin/destination pairs via ground transportation, air transportation, or some combination thereof. The model considered a regression of airfares and estimates of travel time/cost preferences to determine if the choice to fly was rational, and this information was used to first estimate the demand for regional air travel, and then to develop a flight schedule that would return an operator (e.g., airline) a profit. Some demand was not served because it could not be served profitably, but in the baseline scenario, Georgia Tech found that 162 airports in the region could offer profitable regional airline service with almost 2,300 daily flights with a fleet of nearly 700 aircraft that included all-electric and hybrid electric models.

The major advantages of the Georgia Tech model are twofold. First, because the majority of flights are round-trip, electric flight demand likely cannot exceed what the local population would support. Using the vehicle miles traveled as an input to the flight demand can be useful for estimating the upper limit of available customers. Second, the Georgia Tech approach allows for estimating electric flight demand at local and regional airports. As stated, approximately 70% of U.S. air travel goes through 0.6% of airports (Antcliff et al. 2021). Electrified flight would likely enable a rebalancing by providing environmentally friendly and economically competitive services from local and regional airports. The Georgia Tech approach applied a mode-choice model to estimates of long-distance travel in 2040 to assess the fraction of passengers that would still travel by ground transportation in 2040 and the fraction of passengers that would use these new services using electric aircraft from more convenient regional airports. Table 2 provides an example of the output data from Georgia Tech: airport codes, arrival and departure times, and the electricity used for the previous flight (in kilowatt-hours) that needs to be restored through charging in the residence time (departure minus arrival times).

Table 2. Example Output Data of Georgia Tech Electrified Flight Study

Airport Code	Arrival Time	Traveling To	Departure Time	Electricity Used (kWh)
BDR	12/31/19 19:05	BOS	1/1/20 7:15	183.9
BDL	1/1/20 7:24	PWM	1/1/20 7:45	223.1
4B8	12/31/19 18:56	BOS	1/1/20 7:15	145.2
HFD	12/31/19 18:29	JFK	1/1/20 6:45	132.3
HVN	12/31/19 18:06	ABE	1/1/20 6:45	187.2

2.1.2 Electrified Aircraft Charging Profiles

From a power systems perspective, electric aircraft interface with the power system only during charging, meaning that electric aircraft can be reduced to their charging profile when studying regional energy impacts. Infrastructure must be capable of both supplying the total energy needed (measured in kilowatt-hours or megawatt-hours) and delivering that energy to the aircraft at rates (electricity demand, measured in kilowatts or megawatts) that reasonably support economic airport and aircraft operations.

Charging personal EVs is difficult to predict. For example, customers do not always choose the cheapest method for charging. Often, especially with personal EVs, customers choose charging options that minimize range anxiety, rather than only considering convenience or price

(Morrissey, Weldon, and O'Mahony 2016; Franke and Krems 2013). Although fleet operators would likely have different decision points, there will still be an adoption curve with electric aircraft. For example, there might be an opportunity for airplanes to depart with less than full state of charge (SOC)[3] based on the scheduled flight distance and travel conditions, but airlines might choose not to do this to maintain maximum battery reserves. Operators might also choose to use lower SOCs if electricity is cheaper at their destination. However, unlike liquid fuel, the battery does not change weight with the SOC, so there may be no other advantage from the airline's perspective to depart not fully charged.

Presented here is only a small discussion of how preferences and operational behavior might affect airplane charging. Some assumptions were needed around airplane charging behaviors without conducting a full sensitivity analysis on the results. To reduce the scope to a tractable level, three charging cases were implemented, and their associated 15-minute interval electricity demand profiles were calculated. The first case charged airplanes among an unlimited number of airplane chargers with a preference for charging slowly, essentially as long as their residence time. The second case constrained chargers to a maximum power and charge rate while attempting to minimize the number of fast chargers because charger infrastructure would likely be expensive, and airports would seek to reduce the number of chargers needed. The third case hypothesized that electric aircraft charging might fall under a novel rate schedule set by utilities where the utility delivered enough power to guarantee that the airplane would charge within 15 minutes or less (in line with current airport operations around fossil fuels). The EV infrastructure tool EVI-EnSite was used in conjunction with these constraints to produce an electricity demand based on the electric aircraft flight schedules (Zhu et al. 2021). All three cases are discussed in greater detail in the following sections.

The three cases produced very different electric aircraft charging electricity demands. A computer program was written to enact the rules of the three cases on the flight demand schedule at each airport to produce an electricity demand using EVI-EnSite. Future analysis should seek to work more closely with utilities, airports, airlines, electric aircraft manufactures, and EVSE manufacturers to reduce uncertainty and develop more realistic charging scenarios. For all cases and individual airports, charging demand was repeated every 24 hours to create an annual electricity demand profile for the airport from electric aircraft charging.

2.1.2.1 Case 1: Unlimited Chargers

The first case of unlimited chargers is meant to represent charging the batteries at the slowest rate the flight schedule would allow and assumed that an unlimited number of chargers would be available at a single airport.

First, a 15-minute buffer was assumed upon landing or takeoff for the planes to taxi to any charging location. Then, the planes were charged at the slowest rate possible while reaching 100% SOC during their residence time. If multiple planes landed at the same time, it was assumed that there were always enough chargers to connect to every plane and site load was unconstrained. Figure 4 shows the histogram[4] distribution of the charging duration, which is the

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[3] SOC is a measure of the energy available in a battery given as a percentage of total battery capacity.

[4] Histograms show the frequency of a variable, with the y-axis being the frequency and the x-axis being the variable. These histograms help show the distribution of charging times and power needed by the provided flight demand.

time airplanes spent plugged into EVSE infrastructure. Figure 5 shows the airplane charging electricity demand distribution for each flight (not cumulative for an airport). These two figures show that most flights do not use what might be considered fast charging (>50 kW). Although future economic work might replace this, under the provided airplane schedule, it is not necessary in the case of unlimited chargers for airplanes to have access to dedicated 350-kW or greater EVSE.

Using these schedules and the assumptions of unlimited chargers, EVI-EnSite was able to estimate the charging profiles, including timing related to chargers slowing down as they approached full SOC. Full charging profiles of the airplanes are given in Section 3: Results. Note that charging speeds are likely incompatible with the rapid turnaround of airplanes and should be thought of as a lower bound for electric aircraft charging electricity demand.

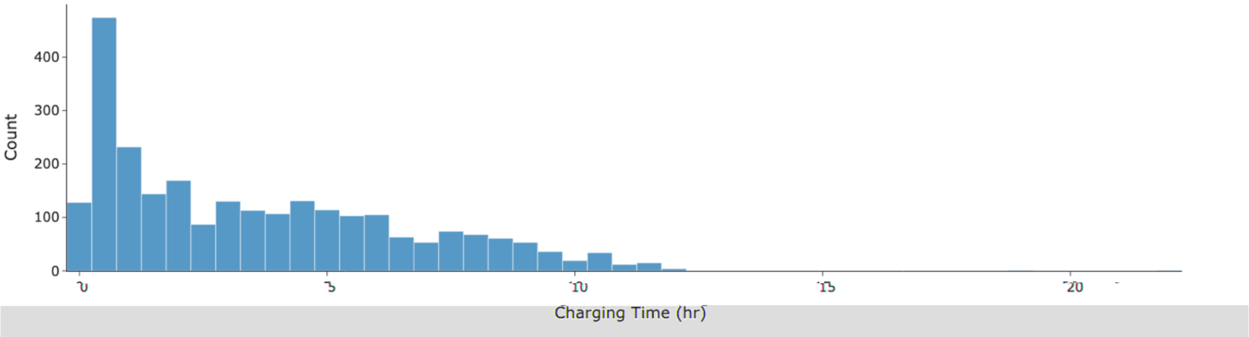

Figure 4. Histogram of airplane residence time in hours

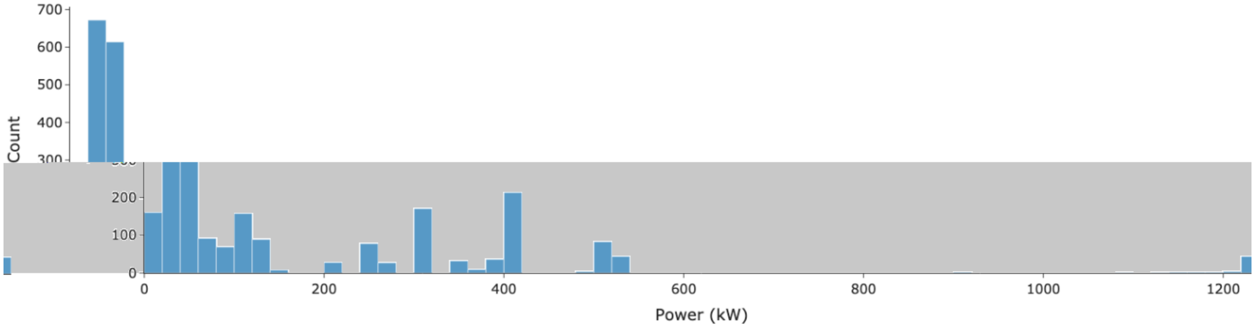

Figure 5. Histogram of airplane charging power demand

2.1.2.2 Case 2: Chargers With a Maximum Power Draw

From the unlimited charger case, it was desirable to project what is arguably more likely. Given that EVSE for this level of power is expensive, there would likely be some optimization at the airports to increase the charging rate of airplanes from the unlimited charging scenario while simultaneously decreasing the number of EVSE chargers needed to support electric flight. Several levels of EVSE chargers were examined, and the fastest charging power of 3 MW was chosen, which is currently predicted to be the highest EVSE available.

For this case, similar to the unlimited case, a 15-minute buffer was assumed upon landing or takeoff for the planes to taxi to any charging location. Then, each airport was assigned a number of chargers, starting with one. If a charger was available when the airplane landed, it was placed on a charger and charged up to 3 MW while not exceeding a 4C charging rate[5] for the battery (from 0% to 100% fully charged within 15 minutes). Although the plane was on the charger, the number of available airport chargers was reduced by one, since the plane was using that charger. The planes were charged to 100% SOC, and then their charge completion time was given. If any plane's charge time exceeded its residence time, the code restarted and increased the number of available chargers at an airport by one. In this way, the minimum number of chargers needed at an airport was found while allowing for a power draw of up to 3 MW per airplane. The start and stop time of each airplane was then provided to EVI-EnSite, which produced a 15-minute aircraft electricity charging demand profile.

2.1.2.3 Case 3: Chargers With a Guaranteed Charge Time

The final case selected for this work is similar to chargers with a maximum power draw but builds on knowledge of the potential for a hypothetical EV charging rate. As utilities expand their EV support, some have adopted custom tariff structures for EV chargers. Based on existing airport schedules, it might be feasible for the utility to manage the electric aircraft charging while guaranteeing complete charge within 15 minutes. This guaranteed charge time never exceeds the 4C charge rate while supplying electric aircraft electricity demand.

For this case, similar to the unlimited and maximum power draw cases, a 15-minute buffer was assumed upon landing or takeoff for the planes to taxi to any charging location. Then, each airport was assigned a number of chargers, starting with one, similar to the maximum power draw case described previously. If a charger was available when the airplane landed, it was placed on a charger and charged to 100% SOC within 15 minutes while not exceeding either 3 MW or the 4C charging rate for the battery. While the plane was on the charger, the number of available airport chargers was reduced by one. The planes were charged to 100% SOC, and then their charge completion time was given. If any plane's charge time exceeded its residence time, the code restarted and increased the number of available chargers at an airport by one. In this way, the minimum number of chargers needed at an airport was found while ensuring all planes were serviced by the electric aircraft charger for no more than 15 minutes. The start and stop time of each airplane was then provided to EVI-EnSite, which produced a 15-minute aircraft electricity charging demand profile.

2.1.3 Baseline Airport Electricity Demand

Each airport is different in its baseline electricity demand profile, which currently doesn't include electric aircraft charging; however, a prototypical airport was needed to attempt to transfer the impacts of electric aircraft charging between airports. Two airports, Colorado Springs (COS) and Newport News-Williamsburg (PHF), volunteered their site electricity demand profiles, which could then be scaled based on monthly or annual consumption to form a baseline airport electricity demand profile.

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[5] Charging rates are often estimated as *X*C, where *X* is the fraction of an hour (4C equates to one-quarter of an hour) needed to charge the battery from 0% to 100% SOC.

Baseline airport electricity demand profiles were simulated for COS and PHF using the following airport-provided data:

- Interval data[6]: Six weeks (1/1/2021 through 2/12/2021) of 5-minute interval data were provided by COS for the airport's largest meter.
- Monthly consumption data: A full year of monthly consumption data were provided by both COS and PHF.

To develop a full year of a representative 15-minute load profile for each airport, the 6 weeks of COS interval data were assumed to be representative of the load shape at each airport, day to day and week to week. This pattern was appended to cover a full year, and it was scaled to the monthly consumption values provided. The simulated airport loads used in this analysis are summarized in Table 3 and shown Figure 6.

Note that COS has distributed metering at the main terminal; the meter with the largest load provides approximately 25.5% of the main terminal annual load (or approximately 22% of the overall airport campus annual load). At PHF, the main terminal is served by a single meter, which comprises approximately 78.7% of the overall airport campus annual load. For COS, although the main terminal is billed at multiple meters, the analysis considers the total main terminal load.

Table 3. Airport Baseline Load Summary

	Peak Demand (kW)	Annual Load (MWh)
COS	1,752	7,413
PHF	743	3,640

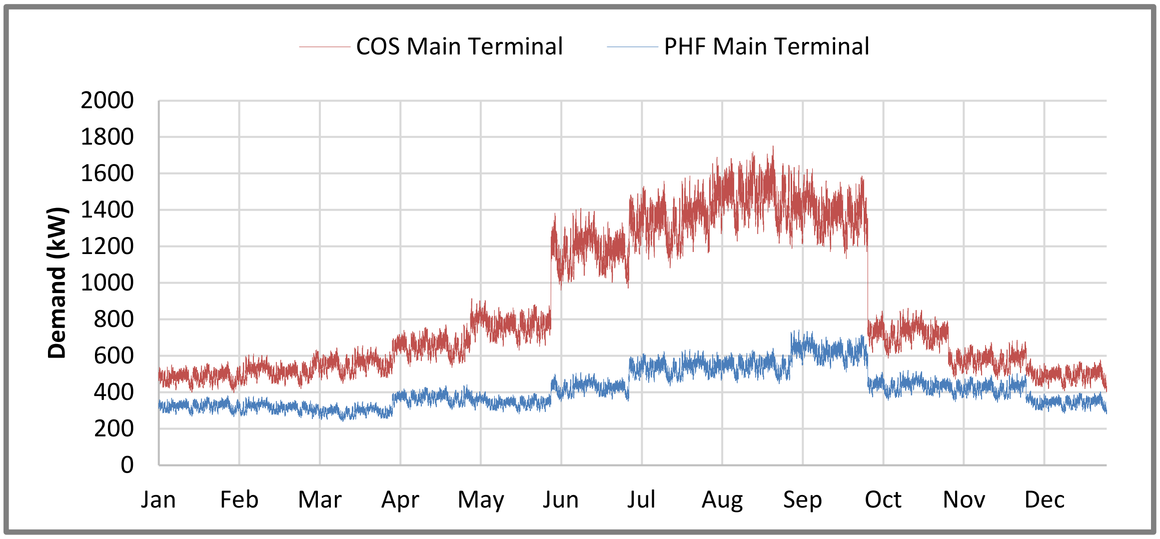

Figure 6. Simulated airport baseline load profile

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[6] Interval data refers to the instantaneous power demand (in kilowatts) recorded at some fixed time interval (usually 15 minutes).

2.2 Evaluating Distributed Energy Resource Opportunities With REopt

NREL's REopt platform was used to conduct detailed analysis of solar-plus-storage opportunities at two airports: PHF in Virginia and COS in Colorado. These two airports provided interval electricity data that enabled their REopt analysis. PHF was part of the original 162 airports with provided flight data by Georgia Tech. COS was not part of this group, and therefore flight data from ABE were used as proxy for COS electrified aircraft flight demand.

REopt is a techno-economic modeling and optimization tool used to identify the life cycle cost-optimal DERs to meet a site's energy goals, including cost savings, decarbonization, and resilience, where the life cycle cost of energy represents the present value of all capital costs, incentives, O&M costs, and electricity costs throughout the analysis period. For this analysis, the electricity tariff for several airports was provided to NREL along with a year's worth of monthly electricity consumption data and some limited interval electricity demand data that were used to estimate a full year of a representative load profile.

REopt was then used to identify the cost-optimal solar-plus-storage system sizing for the baseline airport load along with the three electric aircraft charging load scenarios noted in Section 2.1. Additionally, REopt was used to identify the cost-optimal solar-plus-storage system sizing to achieve 25%, 50%, 75%, or 100% of annual electricity consumption for these load scenarios. This section summarizes the site data, techno-economic modeling assumptions, and scenarios evaluated for the REopt analysis at COS and PHF.

2.2.1 Electric Load Modeling

Based on the methodology described in Section 2.1, three aircraft charging load scenarios were developed for each airport. Although the results of that work are described in more depth in Section 3, the resulting load scenarios used in the REopt analysis at COS and PHF are summarized in Table 4, Figure 7, and Figure 8. Note that COS was not included in the data from Georgia Tech, so data for ABE were used as a proxy for the COS aircraft charging electricity demand simulation based on number of enplanements.

These profiles show how significantly the addition of electric aircraft could increase annual consumption and peak demand. At COS, annual consumption increases approximately four times, and peak demand increases >10 times. At PHF, annual consumption increases approximately 1.3 times, and peak demand increases approximately two times. These significant load increases might require infrastructure upgrades and/or necessitate a utility rate change.

Table 4. Charging Cases Summary

Load Scenario	Charging Time Limit	COS		PHF	
		Peak kW	Annual MWh	Peak kW	Annual MWh
Baseline airport	N/A	1,752	7,413	743	3,640
Baseline + Charging Case 1	None	25,265	26,981	938	4,919
Baseline + Charging Case 2	30 minutes	19,161	28,176	1,549	4,995
Baseline + Charging Case 3	15 minutes	21,580	28,425	1,574	4,995

Note that the colored lines in Figure 7 and Figure 8 correlate to the text colors and charging cases shown in Table 4.

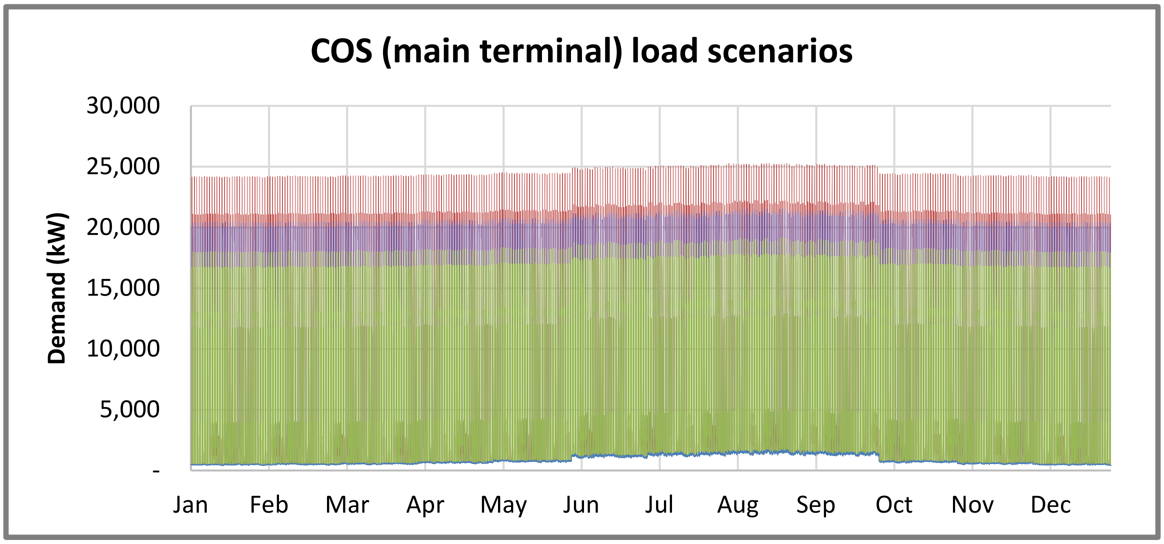

Figure 7. Baseline plus aircraft charging load profiles—COS

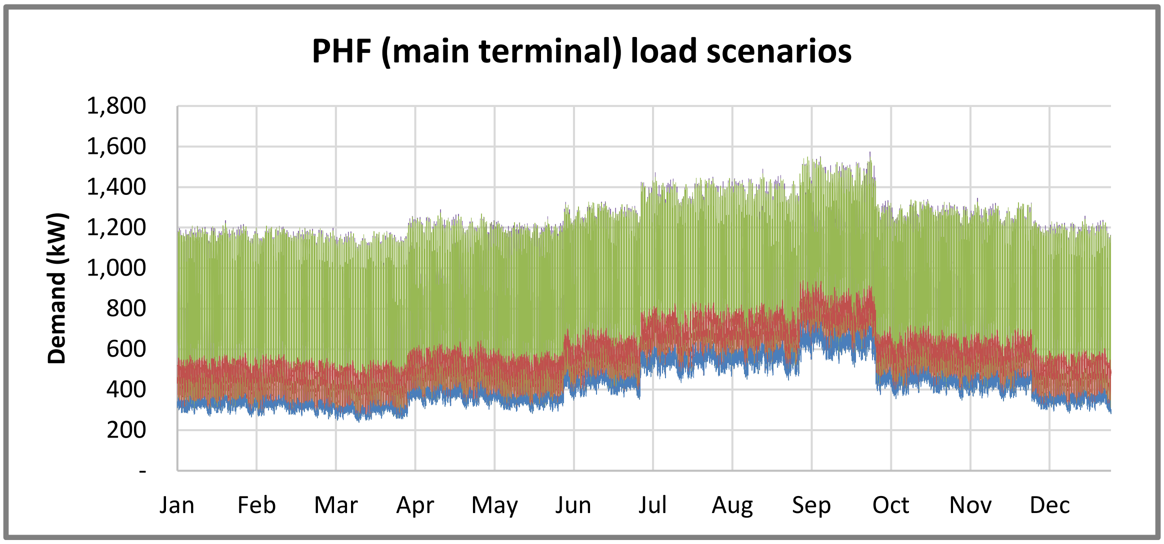

Figure 8. Baseline plus aircraft charging load profiles—PHF

2.2.2 Electric Utility Rates

Utility rates—structure and magnitude for the prices paid on electricity consumed—have a significant impact on the cost of grid electricity and thus impact EV charging, solar photovoltaics (PV), and battery energy storage project economics. COS receives electric utility service from Colorado Springs Utilities on Schedule E8T: Industrial Time-of-Day Service 500-kW Minimum, with Green Power Service. PHF receives electric utility service from Dominion Energy on Schedule 130: Municipal and County—Large Miscellaneous Light and Power Service, Secondary. These rates are summarized in Table 5 and Table 6.

Table 5. Utility Rate Summary—COS

Type			Charge	Units	Notes
Fixed charges			$21.0248	per day	Not included in modeling because this cost is unchanged by the presence of DERs
Energy charges ($/kWh)			$0.0343	per kWh	
Demand charges, daily ($/kW)	On-peak	Winter (Oct.–Mar.): M–F, 4 p.m.–10 p.m. Summer (Apr.–Sep.): M–F 11 a.m.–6 p.m.	$0.7257	per kW-day [a]	Basis: The greatest 15-minute load during on-peak hours in the billing period, adjusted for power factor. Power factor adjustment not included in modeling.
	Off-peak	All other hours	$0.4354		Basis: The greatest peak 15-minute load during off-peak hours in the billing period, adjusted for power factor. Power factor adjustment not included in modeling. 68% of the maximum demand (overall, no time-of-use component) during the last 12 billing periods minus the on-peak billing demand. This lookback was not included in modeling.

[a] REopt does not currently offer a daily demand rate structure option, so daily demand charges were converted to representative monthly demand charges.

Table 6. Utility Rate Summary—PHF

Type	Basis	Charge	Units	Notes
Fixed charges		$91.69	per month	Not included in modeling because this cost is unchanged by presence of DERs
Energy charges ($/kWh)	First 24,000 kWh	$0.06837	per kWh	Total kWh billed in month. Note: If kW-supply >1,000, add 210 kWh for each kW-supply >1,000; this additional charge was not included in modeling.
	Next 186,000 kWh	$0.06081		
	Additional kWh	$0.05741		
Demand charges, monthly ($/kW)	First 700 kW-dist.	$2.06340	per kW-dist.	Billed as highest of: • Highest average kW measured in any 30-minute interval (modeled as 15-minute kW) during current billing month or preceding 11 billing months. • 50 kW.
	Next 4,300 kW-dist.	$1.65112		
	Additional kW-dist.	$1.41940		
	All reactive kVA (rkVa)	$0.16551	per rkVA	Billed as highest average kVA in any 30-minute interval during current billing month. Modeled as part of kW-dist., assuming power factor of 85%.
	All kW-supply	$16.65469	per kW-supply	Billed as highest of: • Highest average kW measured in any 30-minute interval during current billing month. • 90% of highest average kW measured in any 30-minute interval during the billing months of June through September of the preceding 11 billing months. • 50 kW. If kW-supply calculated as described above >1,000, recalculate as highest of: • Highest kW measured in any on-peak 30-minute interval: Summer (June–September) on-peak: Monday–Friday, 10 a.m.–10 p.m.; Winter (October–May) on-peak: Monday–Friday, 7 a.m.–10 p.m.). • 90% of highest average kW measured in any 30-minute interval during the billing months of June through September of the preceding 11 billing months. • 1,000 kW.

2.2.3 Techno-Economic Assumptions

The techno-economic assumptions for economic, PV, and battery modeling used in the REopt analysis are summarized in Table 7, Table 8, and Table 9, respectively. The model evaluated the techno-economic solar PV and lithium-ion battery energy storage over a 25-year analysis period based on assumptions about technology capital, O&M, and replacement costs; technology performance based on geographical renewable energy availability; and discount rates, inflation, and electricity cost escalation rates. Two ownership models—direct purchase and third-party financing—were evaluated; see Section 2.2.4 for more information about these and other scenarios.

Table 7. Economic Assumptions

Economic Inputs	Assumptions
Technology	Solar PV + lithium-ion battery energy storage
Analysis period	25 years
Ownership model	Direct purchase, third-party financing
Discount rate (nominal)	Airport: 5% Developer: 5.64% (for third-party financing scenario only)
Inflation rate	2.5% per NREL's Annual Technology Baseline 2021 (NREL 2021a)
Electricity cost escalation rate (nominal)	Average 1.9%/year per U.S. Energy Information Administration for U.S. commercial electricity, 25 years (U.S. Energy Information Administration 2019)

Table 8. Solar PV Assumptions

Solar PV Inputs	Assumptions
System type	Ground-mounted PV
Technology resource	Typical meteorological year weather file from the National Solar Radiation Database (NSRDB) via PVWatts®: COS capacity factor = 18.6%, PHF capacity factor = 16.2% (NREL 2021b)
DC-to-AC ratio	1.2
System loss	14%
Tilt	Tilt = latitude for each site
Azimuth	180° (south-facing)
Capital costs	$1,592/kW DC per NREL's Annual Technology Baseline 2021 (NREL 2021a)
O&M costs	$17/kW/year per NREL's Annual Technology Baseline 2021 (NREL 2021a)
Incentives	**Direct purchase:** None, assuming airports are not taxpaying entities and thus cannot take advantage of tax incentives **Third-party financing:** 26% investment tax credit, 5-year MACRS[a] depreciation and 100% bonus MACRS
Net metering limit	**COS:** 25-kW AC net metering limit, though larger may be considered, and generation cannot exceed 120% of annual site load for nonresidential customers, per Colorado Springs Utilities' net metering policy.[b] Given the distributed metering at COS and the uncertainty about the net metering limit, the analysis does not enforce a net metering limit for COS. **PHF:** 3-MW net metering limit, and generation cannot exceed 150% of annual site load for nonresidential customers, per Dominion Energy's net metering policy.[c]

[a] Modified accelerated cost recovery system

[b] See https://www.csu.org/Documents/ElectricTariff.pdf?csf=1&e=VqAeSg.

[c] See https://cdn-dominionenergy-prd-001.azureedge.net/-/media/pdfs/virginia/terms-and-conditions/vatc25ra.pdf?la=en&rev=23280dd2f29e4b5c91ca2f163976a50e.

Table 9. Battery Energy Storage Assumptions

Battery Energy Storage Inputs	Assumptions
Battery type	Lithium-ion
AC-AC round-trip efficiency	89.9% (includes inverter and rectifier efficiencies of 96%)
Minimum SOC	20%
Capital costs	$388/kWh plus $775/kW, based on Wood Mackenzie's *U.S. Energy Storage Monitor* (Wood Mackenzie 2022)
Replacement costs (year 10)	$220/kWh plus $440/kW, based on Wood Mackenzie's *U.S. Energy Storage Monitor* (Wood Mackenzie 2022)
Incentives	**Direct purchase:** None, assuming airports are not taxpaying entities and thus cannot take advantage of tax incentives; thus, no limitation on battery charging from grid, as would be the case if trying to maximize tax incentives. **Third-party financing:** 26% investment tax credit, 5-year MACRS depreciation, and 100% bonus MACRS; thus, battery is limited to PV-only charging (no charging from grid) to maximize tax incentives.

2.2.4 Scenarios Evaluated

Different scenarios were evaluated utilizing REopt for COS and PHF, including electric load profile scenarios with different charging cases, ownership model scenarios for direct purchase or third-party financing, and energy goal scenarios. Solar plus storage was evaluated for several scenarios at each airport:

1. **Electric load profile scenarios:**
    A. **Current electricity demand:** the airport's current (baseline) electricity demand profile.
    B. **Future electricity demand projections:** the airport's current electricity demand profile plus three projected aircraft charging load scenarios:
        i. **Charging Case 1:** no aircraft charging time limit.
        ii. **Charging Case 2:** 30-minute aircraft charging time limit.
        iii. **Charging Case 3:** 15-minute aircraft charging time limit.
2. **Ownership model scenarios:**
    A. **Direct purchase:** The airport purchases (owns and operates) the system directly and thus cannot take advantage of federal tax incentives (assuming the airport is not a taxpaying entity).
    B. **Third-party financing:** A developer owns and operates the system, allowing the project to benefit from federal tax incentives but incurring additional financing costs to pay the developer.
3. **Energy goal scenarios:**

A. **Overall cost-optimal:** How can the site minimize the life cycle cost of electricity?
B. **25%, 50%, 75%, 100% annual renewable energy:** How can the site achieve *X*% annual renewable energy with on-site solar plus storage at least cost? Note that for this analysis, renewable generation accounting is on a net annual basis, meaning that each kilowatt-hour of exported renewable generation does "count" as renewable generation.

2.3 Estimating Airport Infrastructure and DER With Engage

For this study, the aspects of utility electrical infrastructure of interest are the demand capacity of the airport-utility interconnection and the cost to increase the capacity of the airport-utility to the level necessary to meet charging demand. The aspects of the airport electrical distribution system of interest are the power-carrying capacity of the airport distribution system from the airport-utility interconnection to the charging infrastructure, the capital costs of the components in these circuits, and the operating costs of the components. The operating costs of concern are the costs of the energy purchased from the utility, which typically consist of the commodity cost of the energy consumed and the demand cost of the peak power delivered by the utility to the customer during the billing period. The aspects of airport generation and storage of interest are the power production capacity of PV, the power production or dispatch capacity of the battery energy storage systems (BESS), the energy storage capacity of the BESS, and the capital and operating costs of the PV and BESS and supporting hardware.

The primary distinction made in this study between the utility distribution system and the airport distribution system with respect to costs is that airport on-site distribution system upgrades include underground lines in conduits and concrete pad-mounted distribution transformers, based on the assumption that airports will generally want to limit on-site overhead electrical distribution facilities near airplane operations. For electric distribution utilities, this assumption is not made; instead, it is assumed the utility (when constructing new distribution system lines off the airport land) elects to construct overhead distribution lines with risers connecting these facilities to the airport's underground electrical facilities.

2.3.1 Electrical System Capacity Expansion

When the utility distribution system must accommodate a new or increasing load, the distribution system design engineers must estimate the new load to be served compared to the capacities of and existing loads on any existing distribution substations, feeders, and distribution transformers. When a utility customer—such as an airport, a college campus, or a military base—has a need to accommodate new electrical load, it might engage in similar design considerations and processes. In addition to the new electricity service, commodity, and demand charges the customer might face for a new service and utility account, consumption, and demand, it will incur the costs of construction for new on-site lines, transformers, and facilities, such as EV charging facilities. It is also often the case that if new utility distribution infrastructure or interconnect infrastructure is needed, the utility will make the customer responsible for the costs of those facilities. This design is historically conducted by rules of thumb by distribution system engineers, allowing for capacity safety factors in the distribution lines and transformers that consider projected annual coincident peak loads among aggregated loads served downstream of each device.

Design decisions for utility system capacity expansion are highly system- and location-specific. Design decisions for adding capacity to already power-dense, crowded areas—where existing capacity is stretched thin, and land is unavailable—are particularly challenging, and electrical capacity expansion problems involving the utility distribution system are rarely subject to simple algorithmic, formulaic answers. There are, however, some reasonable assumptions that can be made for exploring what might be technically necessary and cost-effective for serving new electric aircraft charging demand at airports. The following section details the assumptions and model structure for the capacity expansion study conducted using NREL's Engage model.

2.3.2 Assumptions and Model Structure

To explore capacity expansion at numerous airports across the mid-Atlantic region of the United States, NREL adopted a standard infrastructure model of a utility and airport distribution system framed by some simplifying assumptions. The researchers represented this system in a computational capacity expansion model and explored modeled cost-optimal capacity expansion solutions. The capacity expansion models were designed as follows.

The infrastructure represented in the standard model can be broken down into three categories: charging infrastructure, utility and on-site electrical distribution, and on-site renewable generation and storage. Table 10 shows the corresponding infrastructure components.

Table 10. Summary of Infrastructure Modeling Assumptions

Category	Item Type	Item	Description
Charging infrastructure	Charging stations (including EVSE cost, installation, wiring, concrete, etc.) Number of chargers and capacities as needed per charging case	50-kW Level 3	Equipment, materials, and installation: $52,250
			Yearly O&M: $3,200
		150-kW Level 3	Equipment, materials, and installation: $191,250
			Yearly O&M: $3,200
		350-kW Level 3	Equipment, materials, and installation: $684,850
			Yearly O&M: $3,200
		3-MW Level 3	Equipment, materials, and installation: $900,000
			Yearly O&M: $3,200
	Dedicated distribution transformers (concrete pad-mounted, least-cost combination as needed per charging case)	1.5 MVA	$37,200
		1.0 MVA	$28,900
		500 kVA	$20,000
Utility and on-site electrical distribution (see Table 11, Table 12, and Table 13 for component descriptions and costs)	Utility grid supply	3 MW	Overhead-to-underground riser, new primary meter
		6 MW	New overhead feeder back to utility distribution substation, overhead-to-underground riser, new primary meter
		10 MW	New substation and all needed downstream infrastructure
	On-site distribution	Underground feeder	
On-site renewable generation and storage (see Table 14 and Table 15 for assumptions)	Generation	PV	
	Storage	BESS	

In each case, the infrastructure in the charging infrastructure category was completely determined by the charging case. The charging schedules—which determine, for example, the number of aircraft simultaneously charging and at what power level over time—also determine the amount of distribution transformer capacity that will be needed to supply the chargers. Thus, the model is not optimizing among different configurations of charging infrastructure. Charging infrastructure is completely determined by the charging cases, which are predetermined.

The airport infrastructure and on-site underground distribution line, as well as the utility electrical supply that it provides under a utility tariff or rate structure, the PV, and the BESS, each with corresponding costs, are competed in the model as it optimizes for a cost-minimal combination of capacities and dispatch schedules to meet the charging load. This cost-minimal mix of infrastructure capacities and dispatch schedules is the focus of this study, along with the resulting costs and cost breakdowns.

The standard model design was based on the conservative assumption (at risk of overrepresenting costs) that spare capacity does not exist in the airport on-site distribution system in the area where fast charging of aircraft would be done. Though there could be spare capacity in the on-site distribution system, it would likely not be available in the locations where aircraft would need to charge and would likely not be sufficient to serve fast chargers in those locations, so in every case a new on-site distribution feeder or feeders and new on-site distribution transformers would be needed. It was also assumed that a new utility meter would be installed with a corresponding new utility account to serve the new load. For this reason, existing airport load and corresponding utility costs were not modeled because the new and separate utility account and associated tariff warrant cost analysis independent of existing site electric consumption and demand. These assumptions might not be valid for large airports that own and manage their own substation and electric primary distribution systems and use transmission metering and billing. At such airports, even large additive electrical loads could possibly accrue to the existing account with the serving utility, which would recommend an accounting of baseline airport electrical load in analysis. As a simplifying assumption in the absence of airport infrastructure data, estimation and accounting of baseline airport electrical load was not undertaken.

When modeling capacity expansion from the financial perspective of the utility customer, it can be important to model the existing load to account for the economic impacts of a reduction in the existing load (for example, from new solar PV and storage behind an existing meter). If a new grid interconnection, new metering, and a new utility account with its own tariff are assumed, however, and new PV and storage behind the new meter, the cost of airport utilities associated with existing meters and utility accounts will not change as a result of the added load and any PV and storage, and the additional load and infrastructure can be independently evaluated.

The analysis assumed that the cost of PV and BESS included the cost of the balance of the system, including interconnection to the charging infrastructure. In every case, the model selected an on-site underground feeder of sufficient capacity to supply the charging infrastructure from the grid supply of the capacity that the model elected to build. The needed grid supply and on-site underground feeder capacities could be reduced, however, to the extent that the model elected to build sufficient on-site PV and BESS.

As for the cost of the resulting electricity demand and consumption from the utility, the modeled utility meter counted costs on the basis of both energy commodity and monthly demand.

On the utility side of the meter, existing spare capacity assumptions were as follows:

- If the additional load the utility was required to serve was less than 3 MW, it was assumed that there was enough substation and local feeder capacity to accommodate such load, and the utility would not need to make substation or feeder upgrades. The only utility cost would be for an underground riser to the assumed overhead utility feeder and a new primary meter. The new airport underground feeder would connect on the load side of the new meter.

- If the additional load the utility was required to serve was more than 3 MW and less than 6 MW, it was assumed that the utility would need to build a new overhead feeder back to a distribution substation one mile away and would incur that cost as well as the underground riser, but that the distribution substation has at least 6-MW spare capacity.
- If the additional load the utility was required to serve was more than 6 MW, the utility (or airport) would be required to build a new distribution substation of 10 MW or more capacity.

Note that if the model builds and dispatches on-site PV and storage, *additional load the utility was required to serve* is affected by but different from the new charging load, because the load the utility is required to serve is based on the combination of the charging load, electricity production of the PV, charging and discharging of the storage and the line, transformer, and inverter losses in the on-site infrastructure.

The costs of new utility and on-site airport distribution system components are summarized in Table 11, Table 12, and Table 13.

Table 11. Cost Breakdown of New 3-MW Supply

Component	Cost
Overhead-to-underground riser	$45,000
New primary meter	$15,000
New on-site underground 0.5-mile, 900-A, 6,840-kVA feeder	$2,006,047
Total	$2,066,047

Table 12. Cost Breakdown of New 6 MW of Supply

Component	Cost
Overhead-to-underground riser	$45,000
New primary meter	$15,000
New overhead feeder back to utility distribution substation	$1,395,000
New on-site underground 0.5-mile, 900-A, 6,840-kVA feeder	$2,877,507
5 × 1.5-kVA and 1 × 500-kVA transformers	$206,600
Total	$4,125,907

Table 13. Cost Breakdown of New 10 MW of Supply

Component	Cost
10-MW distribution substation	$5,000,000
New on-site underground 0.5-mile, 10-MVA feeder	$3,000,000
6 × 1.5-MVA and 1 × 1-MVA transformers	$252,100
Total	$7,747,900

For both the on-site and airport asset upgrades, the model assumed 15-year loan financing at a 5% interest rate. Tables 14 and 15 summarize the assumptions for PV and BESS.

Table 14. Land Use, Cost, and Financing Assumptions for PV

Parameter	Configuration
Land area per kilowatt nameplate PV capacity	6 acres/MW
Capital cost	$1,600/kW
Annual O&M cost	$17/kW
Annual interest rate	5%
Financing period	25 years

Table 15. Capital Cost, Utilization, Efficiency, and Financing Assumptions for BESS

Parameter	Configuration
Capital cost of nameplate power capacity	$840/kW
Capital cost of nameplate energy storage capacity	$420/kWh
Minimum SOC	20%
AC round-trip efficiency	89.9%
Annual interest rate	5%
Financing period	25 years

Two utility tariff cases were modeled across all airports and charging cases, one (Rate 1) with a high commodity rate and low demand rate, and the other (Rate 2) with a relatively high demand rate and low commodity rate. Table 16 summarizes the characteristics of the rate cases.

Table 16. Utility Tariff Cases

Rate	Commodity Rate ($/kWh)	Demand Rate ($/kW)
1	0.085	8
2	0.02	20

The Engage model simulations were based on 15-minute intervals during a 1-year (8,760-hour) analysis period for 35,040 total time intervals per scenario. The PV production profiles were based on hourly interval data, and the charging profiles were resampled from the 1-minute charging intervals modeled by EVI-EnSite to 15-minute intervals used by Engage. The 15-minute interval choice for the Engage models was selected as the most common interval period used by utilities for demand billing purposes; thus, it is the most appropriate for the techno-economic analysis of the capacity expansion of grid service versus on-site generation and storage.

3 Results

This section provides results for both the REopt and Engage analysis, as well as summaries of systemwide findings.

3.1 Electrified Aircraft Charging Electricity Demand

The first set of results is related to the electric aircraft charging electricity demand. From the three cases in the introduction, charging electricity demand was estimated using EVI-EnSite. Figure 9 shows the systemwide electric aircraft charging electricity demand.

In Case 1, electric aircraft were allowed to charge for nearly their full residence time, and it can be thought of as the potential lower bound for charging electricity demand for the given flight demand. The "lower bound," however, does not imply that it is always lowest on the chart shown in Figure 9 because electric aircraft will need to charge longer to reach 100% SOC. The faster charging cases—two and three—have higher peaks, but at times they go to zero for individual airports once the electric aircraft have finished charging, whereas Case 1 will have a charging electricity demand nearly the entire time the airplane is on the ground (barring the 15-minute buffer provided for taxiing). Case 2 has a constrained number of chargers that charge the airplanes no faster than 4C but are allowed to draw up to 3 MW. Case 3 guarantees that all airplanes are charged within 15 minutes on the chargers. Case 3 has the highest peak due to the number of coincident charging vehicles that were changed every 15 minutes, whereas Case 2 has fewer coincident charging vehicles, resulting in a peak similar to Case 1 but lower than Case 3.

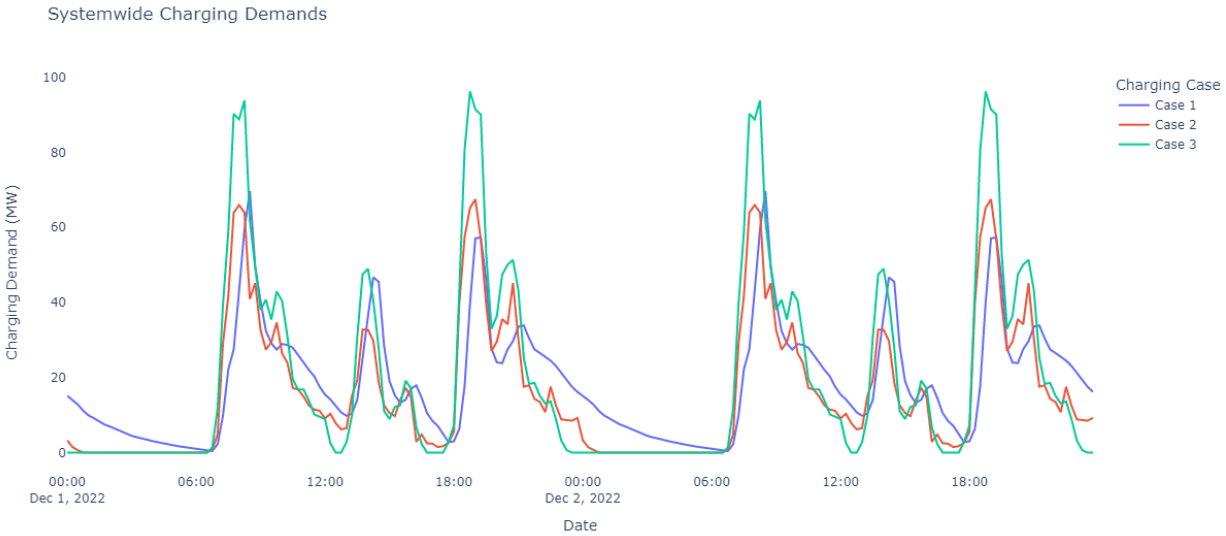

Figure 9. Systemwide aircraft charging demand

3.2 DER Opportunities at Two Case Study Airports—REopt Results

Solar PV and BESS were evaluated at COS and PHF airports for four electricity demand profiles (current baseline airport load and three charging load projections), two ownership models (direct purchase and third-party financing), and five energy goal scenarios (cost-optimal and 25%, 50%, 75%, and 100% annual renewable energy). Summary results—system sizing, annual renewable energy penetration, and net present value (NPV)—are presented and discussed in Section 3.2.1.

3.2.1 Cost-Optimal Solar Plus Storage

Table 17 summarizes the system sizing and NPV for the cost-optimal systems for all four load scenarios at both airports and both ownership models. These results indicate the following key takeaways:

- With current baseline airport loads, a small PV and battery system serving 3%–5% of the annual site load with renewable energy is cost-optimal at each airport via direct purchase. With third-party financing, the cost-optimal system at COS would serve approximately 20% of the annual site load, whereas the cost-optimal system at PHF would meet 100% of the annual site load. This difference between the two airports is driven by differences in utility rates at the two airports; PHF has higher energy charges ($0.0574–$0.0684/kWh) than COS ($0.0343/kWh).
- For both airports and all load scenarios, the cost-optimal systems identified with third-party financing have larger PV systems and similarly sized batteries to the direct purchase scenarios. These results suggest that the incentives facilitated by third-party financing provide more cost savings than developer costs.
- With the addition of aircraft charging loads:
    - Larger battery energy storage becomes cost-optimal due to the increased peak-shaving potential with these very “peaky” loads. This is particularly true at COS, where the peak demands with aircraft charging are 10.9 to 14.4 times greater than that of the baseline airport load, even though the annual consumption increases only 3.6 to 3.8 times with the addition of the aircraft charging loads. In comparison, at PHF, the peak demands with aircraft charging are 1.3 to 2.1 times greater than that of the baseline airport load, with an increase in annual consumption of 1.4 times with the addition of the aircraft charging loads.
    - Cost-optimal PV system sizing also increases with the addition of the aircraft charging loads due to the increase in annual load and because the large batteries being sized for peak shaving can help increase PV utilization by storing excess generation for later use.
    - NPVs substantially increase due to these larger system sizes, driven particularly by demand charge savings.

Table 17. Summary Results: Cost-Optimal System Sizing and NPV

Airport	**COS**				**PHF**			
Load Scenario	**Current Load**	**Current Load + Charging Case 1**	**Current Load + Charging Case 2**	**Current Load + Charging Case 3**	**Current Load**	**Current Load + Charging Case 1**	**Current Load + Charging Case 2**	**Current Load + Charging Case 3**
Energy goal	**Cost-optimal**							
Direct purchase								
PV capacity (kW-DC)	100	2,590	3,760	4,160	110	140	250	350
Battery inverter capacity (kW)	150	20,650	16,590	19,220	50	70	700	740
Battery energy capacity (kWh)	290	31,300	27,970	29,650	80	110	1,380	1,450
Annual % renewable energy	3%	18%	25%	28%	5%	5%	8%	12%
NPV ($ million)	**$0.40**	**$87.56**	**$67.26**	**$75.56**	**$0.09**	**$0.11**	**$0.91**	**$0.96**
Third-party financing								
PV capacity (kW-DC)	740	9,230	11,000	10,960	2,120	2,860	2,920	2,920
Battery inverter capacity (kW)	370	21,200	17,150	19,750	30	80	570	580
Battery energy capacity (kWh)	1,690	34,320	30,310	31,910	70	270	1,350	1,400
Annual % renewable energy	20%	66%	76%	75%	100%	100%	100%	100%
NPV ($ million)	**$0.59**	**$87.04**	**$67.33**	**$75.61**	**$0.47**	**$0.64**	**$1.40**	**$1.41**

3.2.2 Solar Plus Storage To Achieve Annual Renewable Energy Goals

This section shows the results of the set-and-seek to achieve decarbonization goals such as annual renewable electricity (RE) targets at 25%, 50%, 75%, and 100%. These results are summarized in Figure 10, and Figure 11.

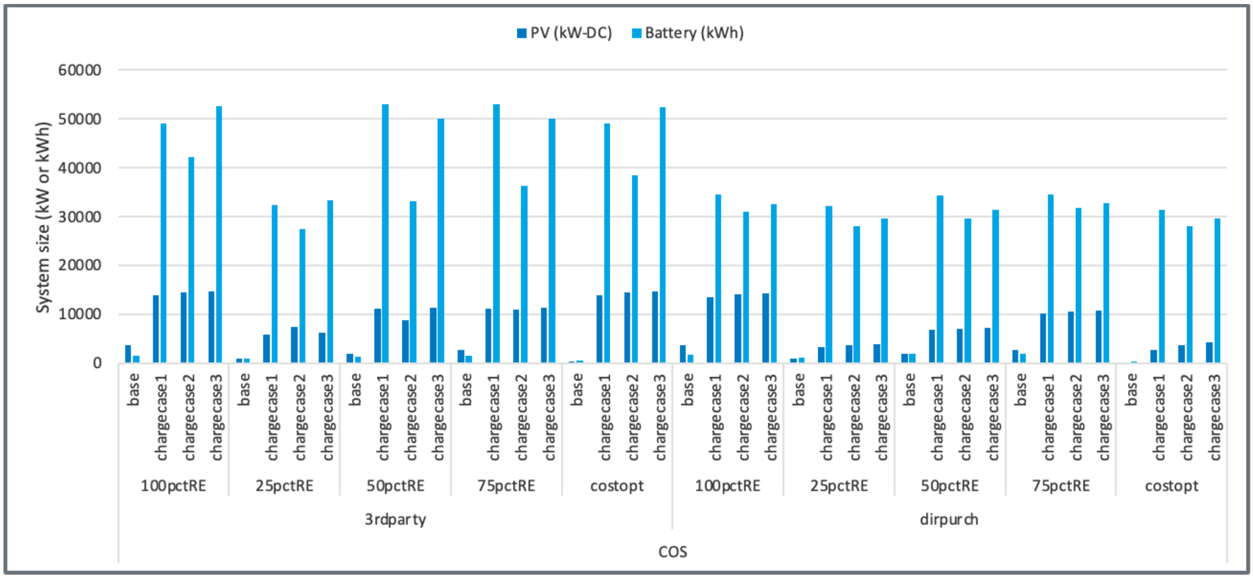

Figure 10. COS technology capacity buildout for each charging and renewable energy deployment case

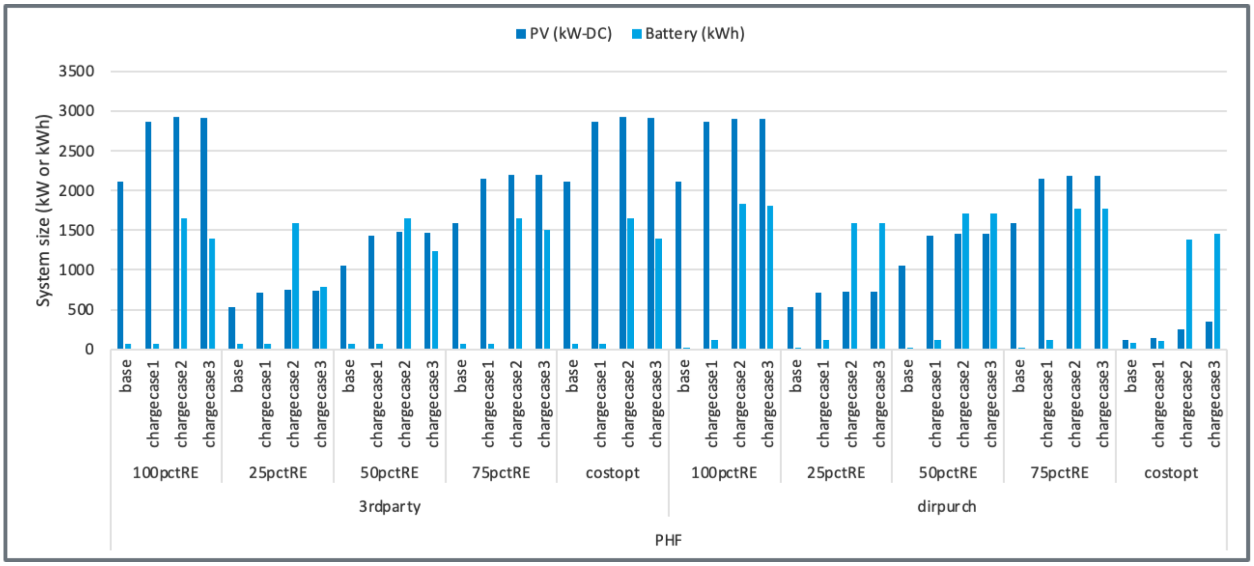

Figure 11. PHF technology capacity buildout for each charging and renewable energy deployment case

Table 18. PHF Technology Capacity Buildout and Economic Results for Each Charging Case and Renewable Energy Deployment Case

Airport	**PHF**									
Load scenario	Current load					Current load + charging case 2				
Energy goal	Cost-optimal	25% RE	50% RE	75% RE	100% RE	Cost-optimal	25% RE	50% RE	75% RE	100% RE
Direct purchase										
PV capacity (kW DC)	110	530	1,060	1,590	2,120	250	730	1,450	2,180	2,910
Battery inverter capacity (kW)	50	30	30	30	30	700	750	780	800	820
Battery energy capacity (kWh)	80	20	20	20	20	1,380	1,580	1,710	1,770	1,830
Annual % RE	5%	25%	50%	75%	100%	8%	25%	50%	75%	100%
NPV ($ million)	$0.09	$0.04	−$0.07	−$0.17	−$0.28	$0.91	$0.85	$0.72	$0.58	$0.44
Third-party financing										
PV capacity (kW DC)	2,120	530	1,060	1,590	2,120	2,920	730	1,460	2,190	2,920
Battery inverter capacity (kW)	30	30	30	30	30	570	370	480	570	570
Battery energy capacity (kWh)	20	20	20	20	20	1,350	850	1,130	1,470	1,350
Annual % RE	100%	25%	50%	75%	100%	100%	25%	50%	75%	100%
NPV ($ million)	$0.48	$0.22	$0.31	$0.39	$0.48	$1.40	$0.74	$1.03	$1.23	$1.40

3.3 Airport Electric Infrastructure and DER Cost Optimization—Engage Results

There are five combinations of on-site PV, on-site stationary BESS, and grid supply capital improvements that—depending on the magnitude and shape of the charging load, the quality of the solar resource, and the utility tariff—result in the least-cost capability to meet the given charging load:

- Combination 1: PV plus BESS plus grid supply
- Combination 2: PV plus BESS
- Combination 3: BESS plus grid supply
- Combination 4: PV only
- Combination 5: Grid only.

Combinations 1–3 were the ones the model recommended as the least-cost solutions in different scenarios. In no case did the model recommend grid only or PV only.

To help understand these results, note that the following are invariant among the modeled scenarios:

1. Across all rates and charging cases (see Table 16 for rate assumptions and the list of charging case descriptions under "Future electricity demand projections" in Section 2.2.4), the unit costs, cost per kilowatt nameplate capacity or carrying capacity, and cost per kilowatt-hour of energy storage capacity of all infrastructure components do not change.
2. For a given charging case, the charging infrastructure (number of chargers and AC-to-DC converter), the distribution transformer for the charging infrastructure, and the on-site distribution line that feeds the charging infrastructure are determined prior to/independent of the least-cost infrastructure optimization.

The drivers (key factors that varied among scenarios) of the differences in the results are:

1. Number and types (aircraft type and energy consumed in flight just completed) of flights per day, which is one determinant of electricity demand. This varies across airports.
2. Location and resulting solar resource of the airports.
3. Variation in charging profiles (represented by the charging profile cases) resulting in lower and higher peak electricity demand (though the total charging energy per day at each individual airport does not change). Charging profiles vary across charging cases and across airports.
4. Differences in applied utility tariffs (represented by application of the two tariffs).

Figure 12 shows the overall nameplate power capacity buildouts by charging case and utility tariff.

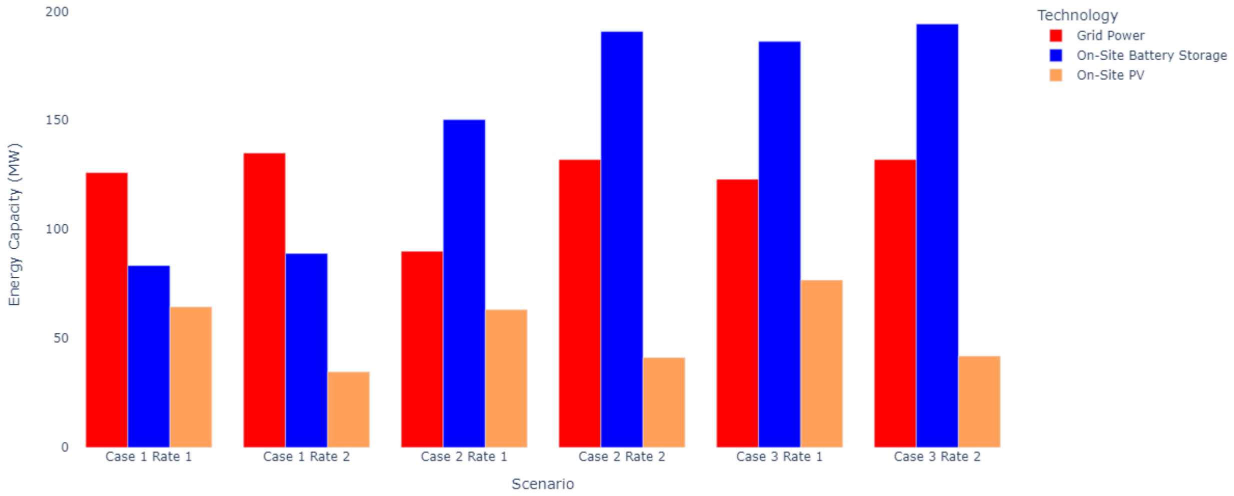

Figure 12. Component nameplate power capacity buildouts by charging case and utility tariff

Table 19 summarizes, by charging case and utility tariff, the number of airports that had each category of solution. Note that in each row across categories, 162 airports are represented.

Table 19. Number of Airports by Charging Case and Utility Tariff in Each Infrastructure Category

Case	Rate	PV + BESS + Grid Supply (1)	PV + BESS (2)	BESS + Grid Supply (3)
1	1	49	113	0
1	2	16	117	29
2	1	50	112	0
2	2	6	118	38
3	1	41	121	0
3	2	4	119	39

3.3.1 Combination 1: PV Plus Storage Plus Grid Supply

This buildout reflects two different economic use cases where the model finds it optimal to build some level of grid interconnection, on-site PV, and on-site storage. This can take one of two forms based on the levelized cost of energy of the PV and the utility tariff. If the price and performance of the PV make it competitive with the tariff, the charging load is mostly met with PV and a large battery, with grid power helping to fill in during peak loads or nighttime charging. These results are shown in Table 20 and Figure 13.

Table 20. Example Combination 1: Component Capacities for PV Plus Storage Plus Grid Supply

Component	Capacity
Grid supply	3 MW
Distributed PV	3.2 MW
Distributed BESS	7.2 MW/6.7 MWh

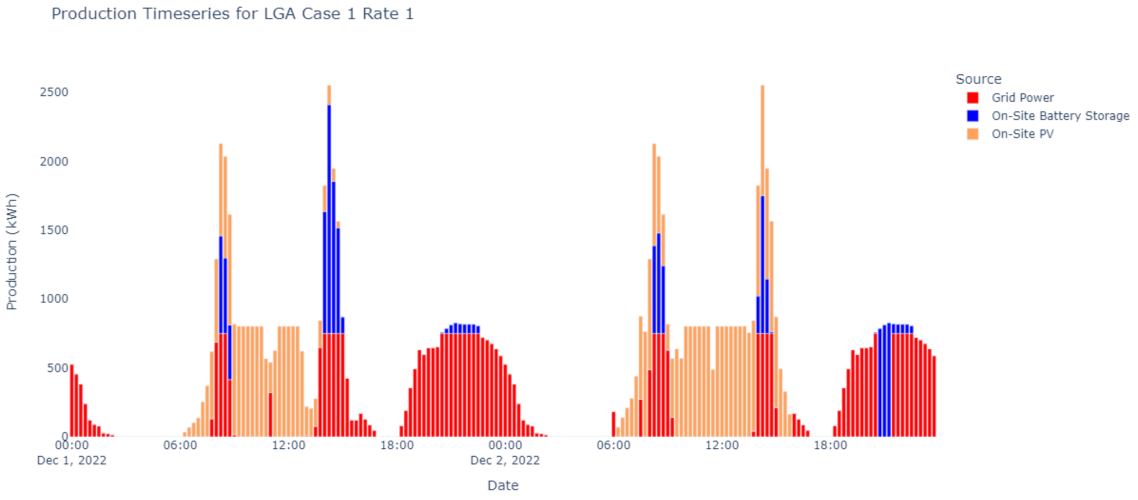

Figure 13. Production time series for LaGuardia Airport (LGA) Case 1, Rate 1

If the PV is more expensive than the utility rate, especially if the commodity rate is low, the model primarily runs off the grid with PV, helping to reduce peak loads. This can help the airport stay under 3 MW of peak load and avoid having to pay for the more expensive infrastructure upgrades. These results are shown in Table 21 and Figure 14.

Table 21. Example Combination Two: Component Capacities for PV Plus Storage Plus Grid Supply

Component	Capacity
Grid supply	3 MW
Distributed PV	1.3 MW
Distributed BESS	7.6 MW/7.5 MWh

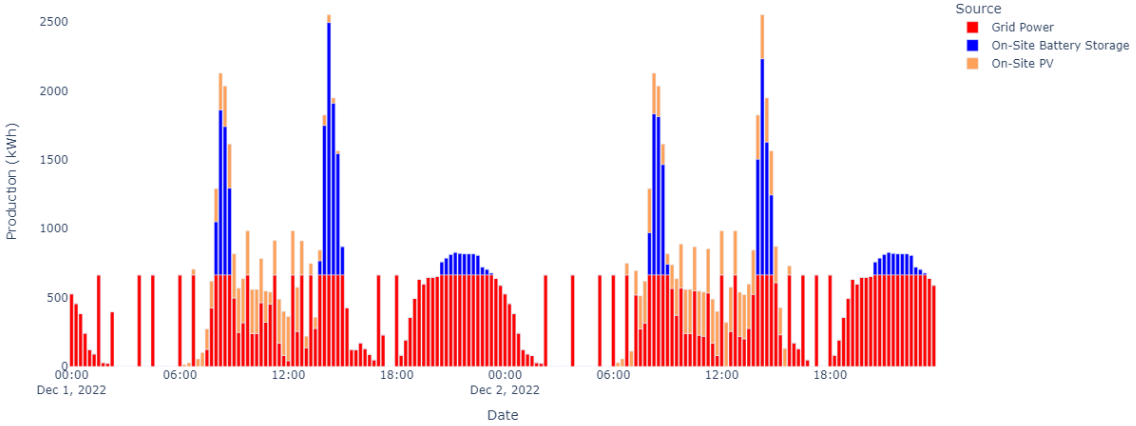

Figure 14. Production time series for LaGuardia Airport Case 1, Rate 2

3.3.2 Combination 2: PV Plus Storage

In this category of buildout, the charging demand is met solely by PV plus BESS. Most airports with this ideal buildout are smaller airports, such as airports with a single daily flight in the schedule. The demand for smaller loads and single flights can be easily met with on-site PV and storage without having to install any of the more expensive airport infrastructure. These results are shown in Table 22 and Figure 15.

Table 22. Example Combination 2: Component Capacities for PV Plus BESS

Component	Capacity
Grid supply	0 MW
Distributed PV	472 kW
Distributed BESS	343 kW/6.5 MWh

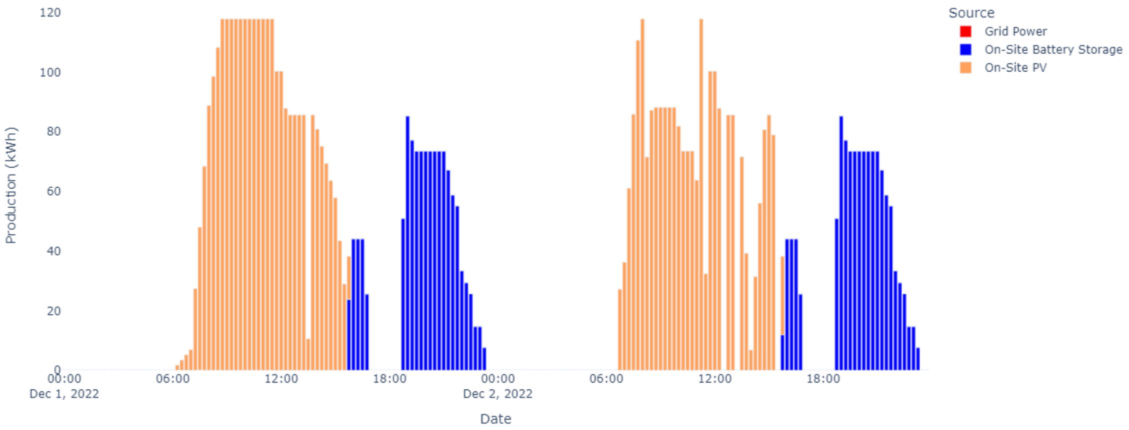

Figure 15. Production time series for Northeast Philadelphia Airport (PNE) Case 1, Rate 1

The results imply that for airports with scenario results in the combination 2 category, the new charging load can be met with only PV plus BESS, implying that the new load could be "grid independent." This may be the case, and for airports with only small existing loads that build PV and BESS for charging, it might be economical to use the new equipment to serve existing load as well, disconnecting from the grid. It is important to bear in mind, however, that this analysis was based on globally applied assumptions around a standard topology of electrical service, airport geographic scale, and utility tariffs that may not apply to smaller airports. This is an area appropriate for future study, including refinement of assumptions for airports of different sizes.

3.3.3 Combination 3: Storage Plus Grid Supply

This buildout is more common with larger airports and loads in cases where the tariff is cheaper than PV on a per-kilowatt-hour basis. When it is not economic to build PV, but an airport still needs to shave peaks to avoid more expensive grid infrastructure upgrades, storage can be built that charges from the grid between peaks, reducing the peaks. These results are shown in Table 23 and Figure 16.

Table 23. Example Combination 2: Component Capacities for BESS Plus Grid Supply

Component	Capacity
Grid supply	3 MW
Distributed PV	0 MW
Distributed BESS	782 kW/1.7 MWh

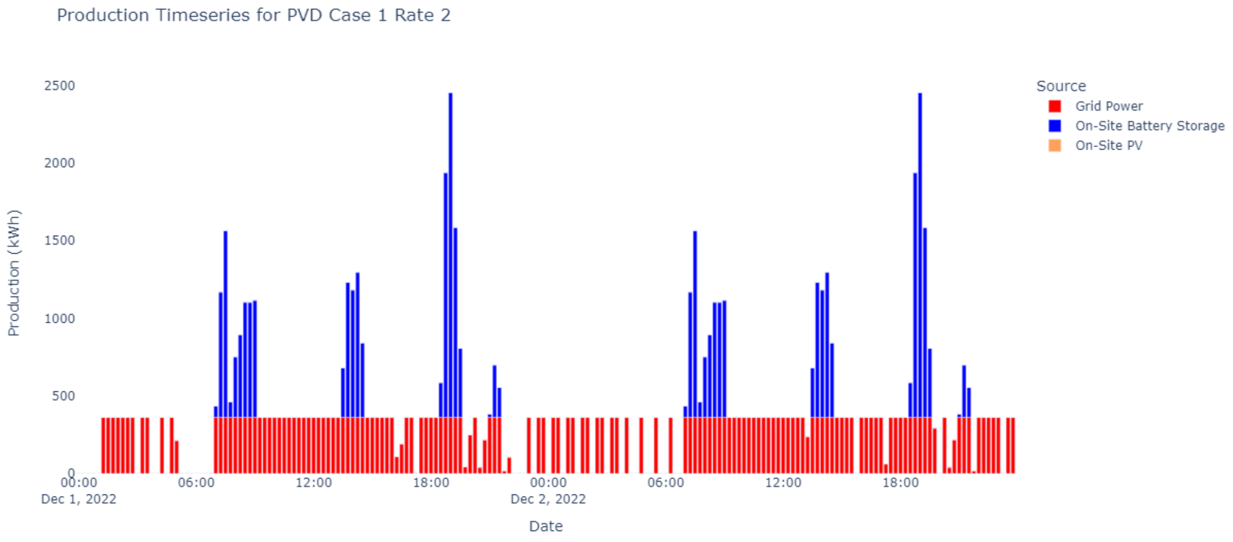

Figure 16. Production profile for Rhode Island T. F. Green International Airport (PVD) Case 1, Rate 2

3.3.4 Impacts of Aircraft Charging on Overall Electricity Consumption and Demand

The overall impact of the charging demand on the regional bulk power grid ranges from approximately 25 MW to 35 MW of peak aggregate load across the mid-Atlantic region. This is a small percentage of the gigawatt-level loads present on the bulk power grids of the independent system operators that service the study area. In all the charging and rate cases, the PV and storage significantly reduce the load peaks to help maintain a more consistent grid draw.

Figures 17, 18, and 19 each show, with Rate 1 applied, a representative day of the aggregate grid, PV, and BESS dispatch (stacked bars above the horizontal axes) to meet the aggregate charging demand (black bars below the horizontal axes) and the aggregate BESS charging demand (blue bars below the horizontal axes) for charging cases 1, 2, and 3, respectively. December 1 and 2 were chosen to show days of relatively lower production. Solar production in December can be expected to be relatively lower because December days have relatively fewer hours of daylight than average in the mid-Atlantic, there tend to be more cloudy days, and (though the solar production model doesn't currently account for it) snow cover on PV panels limits or shuts off their production. December 1 and 2 were not chosen for especial low solar production in December due to weather, but only on the basis of fewer solar hours per day in December.

In each charging case with Rate 1 applied, though the demand rate is relatively low, the charts show that the combination of PV plus storage is doing a lot to reduce the aggregate peak load from aircraft charging across the region, but in general, the grid load retains considerable variability (the aggregate net load factor is considerably less than unity).

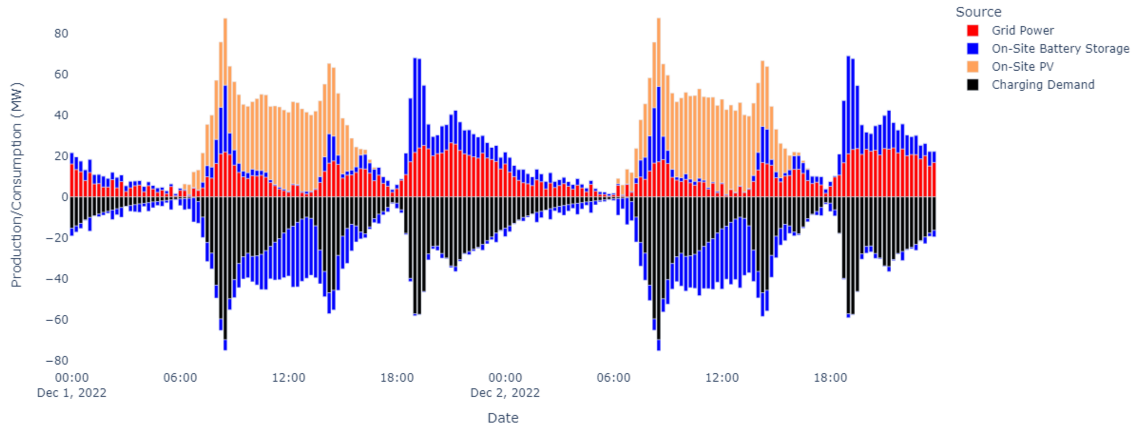

Figure 17. Systemwide production, demand, and charging profiles for Charging Case 1, Rate 1

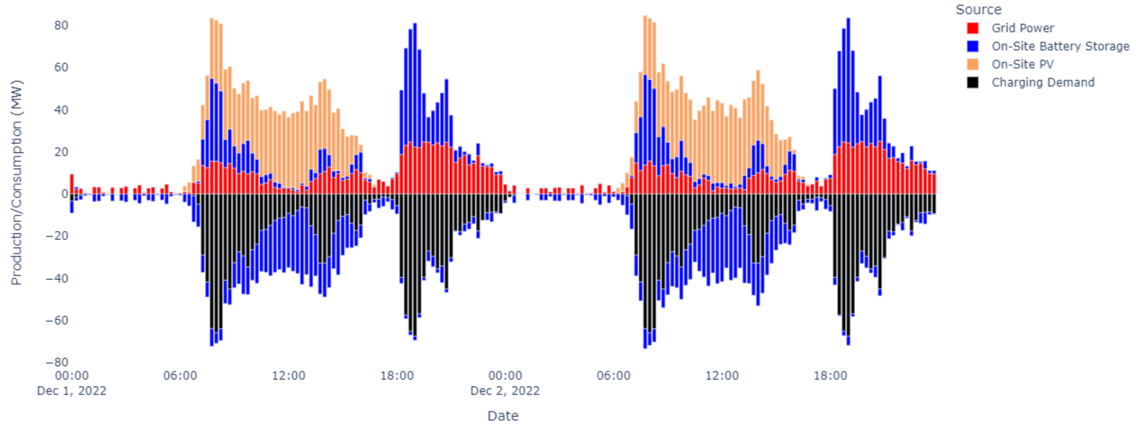

Figure 18. Systemwide production, demand, and charging profiles for Charging Case 2, Rate 1

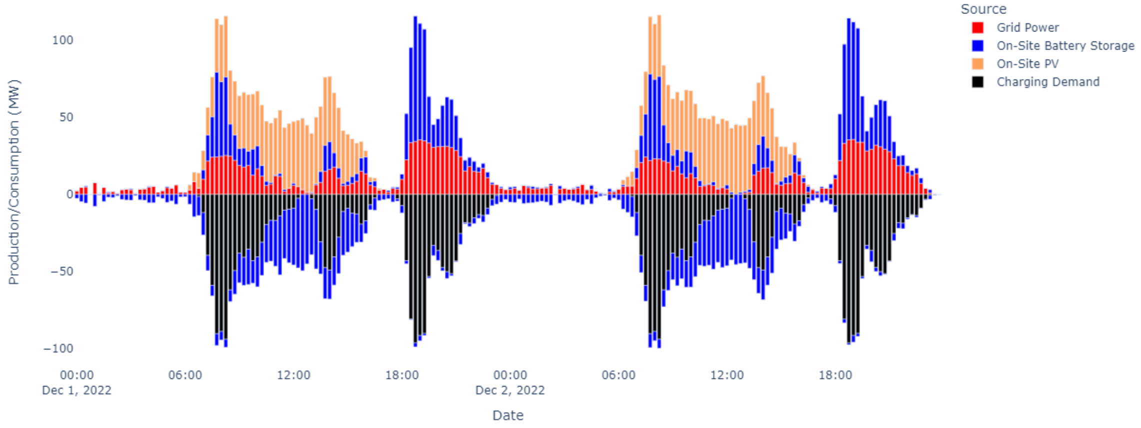

Figure 19. Systemwide production, demand, and charging profiles for Charging Case 3, Rate 1

Figures 20, 21, and 22 each show, with Rate 2 applied, a representative day of the aggregate grid, PV, and BESS dispatch (stacked bars above the horizontal axes) to meet the aggregate charging demand (black bars below the horizontal axes) and the aggregate BESS charging demand (blue bars below the horizontal axes) for charging cases 1, 2, and 3, respectively. Similarly, a day in December when solar production can be expected to be relatively lower was chosen.

In each charging case with Rate 2 applied, when the demand rate is relatively high and the commodity rate is low, the charts show that the combination of PV and BESS is doing a lot more than in the Rate 1 scenarios to reduce the aggregate peak load from aircraft charging across the region, but in general, the grid load retains considerable variability (the aggregate net load factor is considerably less than unity). Comparing, for example, Figure 19 (Charging Case 2, Rate 1) with Figure 22 (Charging Case 3, Rate 2) shows that with the low commodity rate and high demand rate in the latter scenario, the consumption of commodity energy from the grid is much greater across the day than in the former scenario, but the PV and storage are being heavily used in the latter scenario to limit demand, resulting in lower peak grid consumption and smoother grid consumption. Note that much more dispatch from BESS is required in the latter scenario to reduce demand to a greater extent and across more hours of the day, resulting in a greater necessary investment in on-site BESS.

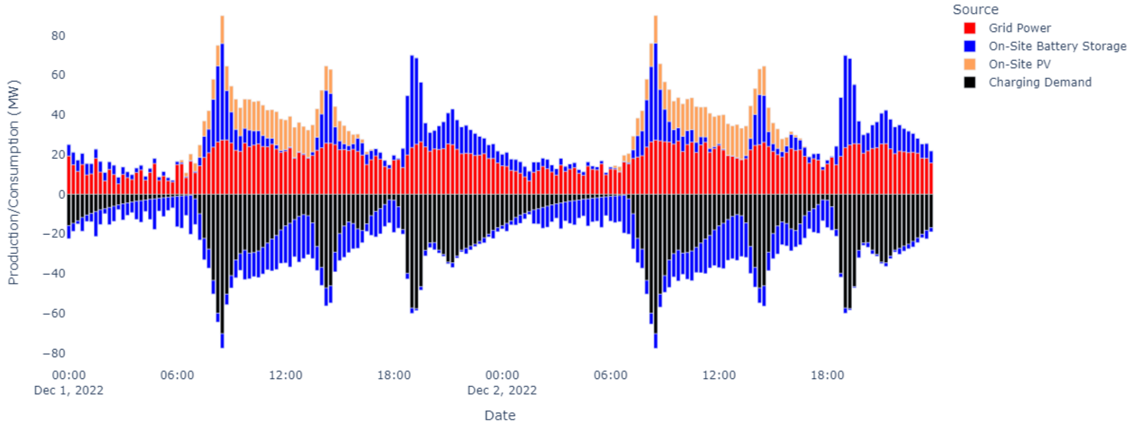

Figure 20. Systemwide production, demand, and charging profiles for Charging Case 1, Rate 2

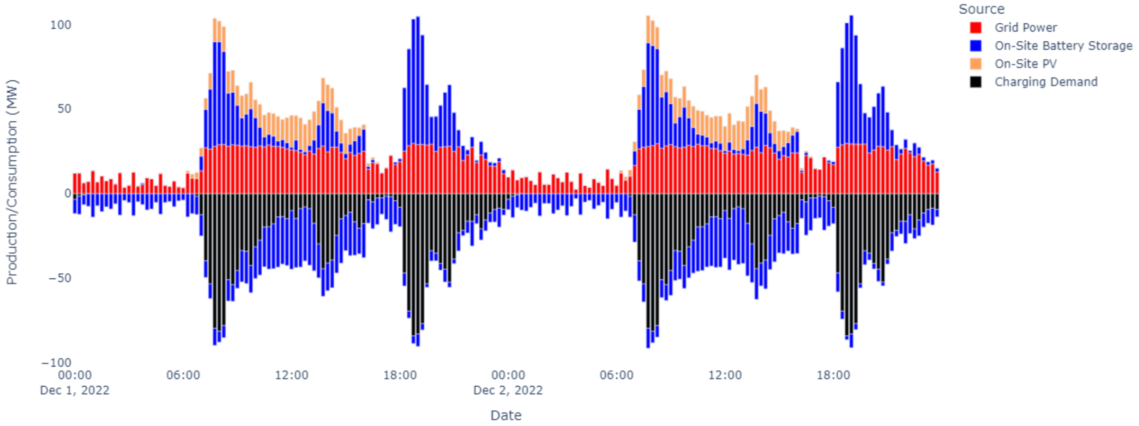

Figure 21. Systemwide production, demand, and charging profiles for Charging Case 2, Rate 2

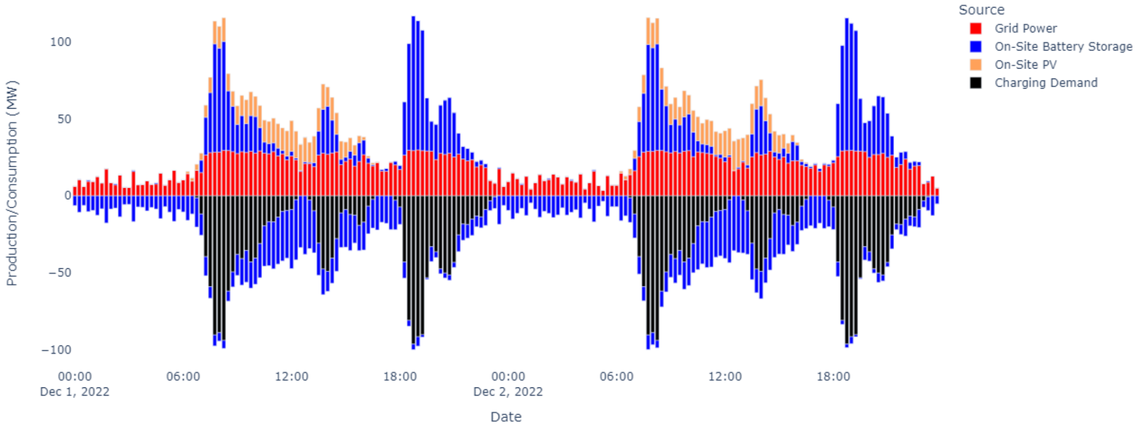

Figure 22. Systemwide production, demand, and charging profiles for Charging Case 3 Rate 2

4 Discussion and Conclusion

For this analysis, the electricity tariffs for several airports were provided to NREL, along with a year's worth of monthly electricity consumption data and some limited interval electricity demand data, which were used to estimate a full year of a representative load profile. REopt was then used to identify the cost-optimal solar-plus-storage system sizing for the baseline airport load along with three electric aircraft charging load scenarios. Additionally, REopt was used to identify the cost-optimal solar-plus-storage system sizing to achieve 25%, 50%, 75%, or 100% of annual electricity consumption for these four load scenarios. Engage was used to estimate the potential buildout of the local infrastructure coupled with the potential buildout of on-site DERs. The focus of this work was on the outputs of Engage and REopt. The respective sections of this report describe the inputs and results of these models; however, looking across all the outputs, several high-level takeaways can be concluded.

First, in all cases examined, adding even a few airplanes resulted in the electric aircraft charging electricity demand quickly becoming the dominant electricity demand on the airport site. As described in the section on REopt, the electric aircraft charging electricity demand resulted in a peak approximately an order of magnitude larger than the airport baseline electricity demand. Electric aircraft charging electricity demand often had a peak of several megawatts, and the total for the region was approximately 100 MW (depending on the charging cases). This was an order of magnitude larger than any estimated airport baseline electricity demand. This is important to consider both for small regional airports and larger airports. Larger airports, while having a larger airport baseline electricity demand, would also likely service a larger number of electric aircraft. Because each flight requires megawatt-level charging for most flight schedules, even larger airports could quickly see their airport baseline electricity demand overshadowed by even a modest deployment of electric aircraft.

Second, in nearly all completed models for all airports and all charging cases, there was some buildout of DERs including BESS. The airplane charging electricity demand was very sharp, causing sudden peaks in airport electricity demand. To either avoid demand charges or reduce energy infrastructure buildout, both REopt and Engage estimated that a nontrivial amount of DERs would be cost-effective. For the Engage analysis, PV deployment ranged from 100 kW to more than 4 MW, and battery inverter capacity ranged from 50 kW to more 19 MW. In the Engage analysis, some airports did not build out any DERs, but the highest of all airports built up to 24 MW of BESS capacity and up to approximately 6 MW of PV capacity.

An important finding is the profile of energy output to the aircraft charging electricity demand. If an airport built DERs, they were not fully used only to serve aircraft charging electricity demand but mostly to reduce the peak aircraft charging electricity demand. This meant that the on-site DERs could be used to export energy back to the electric grid when not being used for aircraft charging. This has the potential to transform regional airports into energy hubs. When comparing the needs of various U.S.-based decarbonization plans to available nationwide airport capacity, regional airports have the potential to serve a nontrivial role in the total buildout of PV infrastructure. Future work should be conducted to estimate the total potential for PV deployment on regional airports to establish this upper limit. The BESS were also deemed to be cost-competitive in many cases; however, there is an important caveat. REopt and Engage both assumed a fixed lifetime for the batteries based on an average once-daily discharge cycle. But, in the airport cases studied, the BESS would often serve airplane charging electricity demand multiple times per day. This type of high-performance charging and discharging profile might impact battery duration and overall economics. Additional research should be done to estimate battery life when serving aircraft charging electricity demand.

Third, the DER buildout at all these airports was not constrained by land. These small airports have a significant land area such that all of them were able to accommodate the solar power needed to supply cumulative energy demand in a given year. This means that for rural airports in particular, space is not a constraining factor on solar energy buildout. The land area at each airport was estimated by NASA, and in all cases, the buildout of DERs used less than 1% of the land area that was potentially available for DERs.

The advent of electric aircraft could bring about significant emissions reductions in U.S. air travel, a revitalization of rural economies by adding significant passenger demand to local and regional airports, and significant improvements to the experience of air travel by providing a faster onboarding and quieter flight experience. Estimating the infrastructure needed to support this transition is essential to ensure that the electricity sector is prepared for this technology as much as the aviation sector is and that local and regional airports make decisions now to support this electric flight future.

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