Abstract—Electrification of aviation can potentially mitigate carbon emissions of air travel. Battery-electric and hybrid electric aircraft will impose charging requirements on airports. In this paper, we study the impacts of electrification on electricity demands at O’Hare International (ORD) airport. We consider the scenario where domestic US carriers partially adopt hybrid electric aircraft (HEA), but operate their airplanes based on current flight schedules. Under various battery technology evolution scenarios, we then compute the increase in electricity demand (both daily average and peak) to operate flights at ORD. The data analysis reveals substantial increase in airport energy demands that demands grid upgrades at airports.

I. INTRODUCTION

In 2018, jet fuel for aviation produced 251 million metric tons of CO₂ in the US, accounting for 4.8% of all CO₂ emissions from energy consumption, as per US Energy Information Administration. Aircraft-generated emissions are predicted to triple in volume by 2050, says the International Civil Aviation Organization. Electric aircraft can reduce the dependency of air travel on jet fuel and utilize electricity instead. If the trend of renewable integration in the power grid continues, transition to electric aircraft will reduce the carbon footprint and the climate impact of this industry.

Various configurations such as turbo-electric, hybrid-electric, and all-electric aircraft have been proposed. For example, authors of [1] analyze flight performance of parallel turbofan systems, and that of [2] and [3] demonstrate benefits of parallel hybrid propulsion system utilized to boost power during takeoff and climb. The future of commercial airline operation with electric aircraft crucially depends on projected advances in battery technology that enables electric propulsion. While jet fuel has a specific energy density of ~13000 Wh/kg, current batteries offer a mere 200-250 Wh/kg. To derive the same amount of energy, batteries therefore weigh considerably more than its aviation fuel counterpart. Moreover, fuel depletes over the course of the flight. Thus, an aircraft loses weight during travel. The higher the weight of an aircraft, the greater is the energy required to propel it. Battery weight poses a fundamental challenge to operation of electric aircraft. Weight considerations limit the range of distances such aircraft can travel.

The aviation industry anticipates a rapid rise in battery specific energy density (BSED), as evidenced by Table I. There is a growing consensus in the industry that commercial operation of short-range parallel hybrid aircraft will become viable in the near future. Energy requirements of hybrid electric aircraft (HEA) also depend on the motor factor (MF) that equals the ratio of the peak power delivered by electric propulsion to that by jet fuel. Retrofitted conventional regional jets and single-aisle (narrow-body) airplanes has the potential to serve as an incipient hybrid electric passenger jets, as [4] envisions. Switching long-range airplanes to an electric configuration will likely take much longer.

<table>
<thead>
<tr>
<th>Research group</th>
<th>Architecture</th>
<th>BSED (Wh/kg)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing-GE SUGAR Volt</td>
<td>Parallel hybrid</td>
<td>750</td>
<td>[5], [6]</td>
</tr>
<tr>
<td>Banhaus</td>
<td>Parallel hybrid</td>
<td>1,000 - 1,500</td>
<td>[4]</td>
</tr>
<tr>
<td>UTRC</td>
<td>Parallel hybrid</td>
<td>Not specified</td>
<td>[7]</td>
</tr>
<tr>
<td>Airbus</td>
<td>Series hybrid</td>
<td>800</td>
<td>[8]</td>
</tr>
<tr>
<td>Cambridge</td>
<td>Parallel hybrid</td>
<td>750</td>
<td>[9]</td>
</tr>
<tr>
<td>Georgia Tech</td>
<td>Parallel hybrid</td>
<td>750</td>
<td>[7]</td>
</tr>
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</table>

TABLE I: Summary of regional and single-aisle hybrid electric aircraft concepts and research

If commercial airline carriers adopt electric aircraft within their fleets, charging events at airports would increase the airports’ electricity demands. In this paper, we seek to quantify that increase. Such an analysis will aid grid infrastructure investments required to support electrification of aviation. In Section II, we consider flights that landed in or departed from O’Hare International Airport (ORD) in 2018. By systematically switching a portion of the flights to HEAs under a variety of BSED and MF values, we compute their charging requirements in Section III. The analysis suggests significant increase in electricity demands—both in annual aggregate energy and daily peak power requirements. We also analyze the energy demands from limited growth in battery capabilities as predicted in [3] for the near future. The results indicate that BSED greater than 500 Wh/kg will require significant upgrades to the grid to fully leverage HEAs within commercial airline operations.

ORD is one of the largest airports in the US, operating north of 900K flights annually. Charging requirements will be naturally higher at larger airports. A switch to HEAs will rely on capital-intensive and time-consuming upgrades of the grid infrastructure at such airports. Our framework to calculate electricity demands, however, applies more generally. We present preliminary results with data from Los Angeles International Airport (LAX) in Section IV. The paper concludes with remarks and future directions in Section V.

II. METHODOLOGY TO COMPUTE CHARGING REQUIREMENTS FOR REGIONAL FLIGHTS

Electricity demands of HEAs will depend on how many flights switch over to HEAs as well as on their flight and charging schedules. Number of HEA-operated flight legs will depend on the battery technology that determines the maximum range of such aircraft. We make several assumptions to
determine ranges. Then, we utilize flight schedules of domestic commercial flights from the US Department of Transportation’s Bureau of Transportation Statistics (BTS) to compute charging requirements. We assume that flight schedules do not change, even though airlines adopt HEAs to replace conventional aircraft in their fleet. Modification of flight schedules to accommodate both charging requirements and passenger demands remains an interesting direction for future work.

We use the BTS Airline On-Time Performance data for flights in 2018 to compute energy demands. The dataset describes all non-stop domestic flights reported by certified US carriers. Relevant details for each flight includes its tail number, scheduled and actual departure and arrival times, origin and destination airport, and non-stop distance. We process the data to construct a dataframe shown in Table II as follows: (i) filter flights with arrival or departure to be ORD, (ii) group the data by date, (iii) group by tail number on a given day, and sort by departure time for a given tail number. This newly constructed data-frame allows us to conclude how long each airplane stays at ORD that proves useful to compute its charging requirement at ORD.

In computing the charging profiles, we only consider domestic commercial flights. Thus, our analysis does not reflect charging requirements of long haul, wide body international flights, freight and military aviation. Given serious range limitations of HEAs, international flights will likely utilize conventional aircraft in the near future. Our analysis can be repeated to cover freight and other sectors to more accurately estimate the energy needs of airports.

We only consider HEAs obtained from retrofitting conventional aircraft with electric propulsion systems. Novel HEA designs optimized for electric propulsion, e.g., in [10], will no doubt alter the conclusions drawn from this study, and are left for future efforts.

A. Energy Requirement of a Single Flight

Battery energy needed to travel $d$ miles with $p$ passengers on an HEA is given by

$$ E = p \times d \times \gamma, $$

where $\gamma$ is the battery energy usage per passenger-mile. For each flight in the BTS database, we use the tail-number to identify the aircraft type from airplane manufacturer’s websites, that in turn, gives us the total number of seats on the plane. We assume a uniform load factor of 85% to estimate $p$ for each flight, consistent with yearly average load factor estimates by BTS.

The values of $\gamma$ for HEAs are adopted from [11], assuming a battery-pack voltage of 128V. Their analysis accounts for battery energy consumed during taxi, takeoff, cruise, approach, and landing. To estimate $\gamma$ for a flight in the BTS dataset, we first identify whether it is a regional jet or a single-aisle (narrow-body) aircraft. For regional jets, we utilize $\gamma$ for ERJ-175 and for that of Boeing 737-700 for single-aisle aircraft. Values are given in Table III. Notice that battery sizes required for BSED below 700 Wh/kg and MF above 50% are deemed impractical for any useful flight range.

B. Flight Legs that Operate HEAs

In the BTS dataset, regional jets and narrow body aircraft each accounted for nearly half of the 300K+ short-range domestic flights that had a dwell time at ORD in 2018. We assume that all domestic commercial flights operate an HEA to serve a trip if it becomes feasible to do so, given the flight range of the aircraft with an MF and BSED combination. Adoption of HEAs by airline companies in practice will likely deviate from such operation. A similar study with possible HEA adoption paths is relegated to future work.

Range capabilities of retrofit hybrid electric regional jets and narrow body aircraft are adopted from [11] in Table IV. Figure 1 provides the distribution of flight distances with regional jets and single aisle aircraft from the BTS dataset. Flight range together with the distance distribution determine the number of flights operated with HEAs.
C. Power Demand for Each Flight Leg

Assume that each HEA arrives at ORD with a depleted battery. It immediately starts charging at a constant rate that allows it to charge the battery up to the energy needs of the next flight leg, by the time it leaves the gate for its next destination. Thus, power required to serve an outgoing flight is given by

\[ P = \frac{E}{T}, \]

where \( E \) is given by (1) and \( T \) is the dwell time at ORD. Divide each day into 1440 one-minute intervals. Adding the charging requirements of all flights in a given 1-min interval yields the charging requirements for that interval. We omit flights with connection times shorter than 15 minutes at ORD.

Our approach to compute charging requirements ignores several practical considerations. First, maximum charging rates typically depends on the ratings of the battery and its charging equipment. We ignore such upper bounds on this rate. Second, HEAs with stops at ORD may vary in their charging requirements. Residual charge in the battery can cover portion of the energy requirements of the next flight. It may be necessary to charge an HEA for a round-trip journey from ORD and back to compensate for possible lack of charging infrastructure at the destination airport. Third, batteries often have roundtrip efficiency losses, that we ignore.

To illustrate the power demand requirements through an example, consider a single hybrid electric retrofit of Boeing 737-800 aircraft with tail number N33289 operating a 1012-miles flight to TPA (Tampa, FL) on 03/20/2018. N33289 arrives at ORD at 10:41 AM and leaves for TPA at 11:41 AM.

For different MF and BSED configurations, we compute \( E \) from (1) and report in Table V. Dividing \( E \) by 60 minutes yields the power requirements of N33289 from 10:41 to 11:41AM on 03/20/2018.

<table>
<thead>
<tr>
<th>MF (%)</th>
<th>BSED (Wh/kg)</th>
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<tbody>
<tr>
<td></td>
<td>500</td>
</tr>
<tr>
<td>12.5</td>
<td>4.36 MW</td>
</tr>
<tr>
<td>25</td>
<td>9.28 MW</td>
</tr>
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</table>

TABLE V: Power requirements of N33289 for flight to TPA.

III. ANALYSIS OF CHARGING REQUIREMENTS AT ORD

Having described our data and method to compute charging requirements of HEAs, we now present the results from our analysis. In the sequel, compare the demand increase from HEAs to the average power consumption of 50.3MW at ORD in 2002, computed from the aggregate annual electricity demand of 440.7 GWh, according to the O’Hare Modernization Final Environmental Impact Statement, published in 2005.

Fig. 2 illustrates that moderate MF and BSED values lead to annual battery energy consumption comparable to aggregate demand of ORD in 2002. This plot confirms that electrification of commercial airlines can considerably amplify electricity demand requirements at airports.

For a given MF, one might expect total energy consumption from batteries on HEAs to decrease with BSED, as one requires lighter batteries to deliver the same amount of power. However, that is not always the case as Figure 2 reveals. To explain this apparent paradox, notice that lighter batteries with improved BSED allows HEAs to operate more flights over longer distances, increasing aggregate charging requirements.

Grid infrastructure to deliver power at airports must be able to cover daily peak power demands from HEAs. The histograms in Figure 3 suggest a substantial increase in peak power demands. For MF = 12.5%, BSED of 500,700 and 1000 Wh/kg yield median peak power requirements of 70.6, 101.2 and 169.4 MW, respectively. Highest daily peak demands can be \( \sim 250 \text{MW} \), indicating the need for significant grid upgrades.
Fig. 3: Histogram of daily peak demands with different MFs. Here, (●) plots the histogram for BSED = 500 Wh/kg, (□) plots with BSED = 700 Wh/kg, and (■) plots with BSED = 1000 Wh/kg.

Fig. 4: Average daily power consumption profiles for HEAs with various MF and BSED configurations. Here, (●) plots power requirements of single-aisle aircraft, (□) denotes the same for regional jets, (■) denotes the sum-total of the above two, and (■) denotes the average consumption over the day.

Compare these numbers to 50.3 MW, the average power demand on ORD in 2002.

Fig. 5: Profile of charging requirements on 08/10/2018 with MF = 12.5%, BSED = 1000 Wh/kg.

A representative charging profile of ORD airport for HEAs in Figure 5 has a peak demand of 187 MW, while the average demand is 74 MW, that is lesser than half the peak. This analysis suggests that peak demands can be considerably reduced by optimizing the flight and its charging schedule instead of operating HEAs with current schedules. The design of efficient flight and charging schedules accounting for airlines operating HEAs within their fleet defines an interesting research question.

Daily charging profiles averaged across 2018 in Figure 4 indicate that energy requirements of regional jets are significantly smaller than that of single-aisle aircraft. Figure 1 suggests that single-aisle aircraft serve more long-distance flights than regional jets. For regional jets, the median distance of flights is 409 mi. The same number for single-aisle aircraft is 867 mi. Longer distances translate to higher energy requirements. The gap between the two different aircraft classes increases as larger ranges are made possible with higher BSED at a constant MF.

A. Estimates of Charging Requirements in the Near Future

Despite ambitious targets for battery technology from aviation industry in Table I, battery experts project more conservative growth in battery capabilities in the next decade. Recent study in [12] anticipates that current BSED of 200-250 Wh/kg will grow to 300 Wh/kg at pack level by 2025 and 400-500 Wh/kg by 2030. Densities beyond 700 Wh/kg are more than a decade away. In light of this study, we compare our earlier results to one with a restricted battery performance with BSED = 355 Wh/kg. With such a battery configuration, the authors of [3] advocate to use batteries as the energy source only during takeoff and climb. Following [3], we restrict the range of such flights to 287 mi and take $\gamma = 3.0589$ Wh per passenger-mile. Figure 6 provides the histogram of daily peak electricity demands for charging HEAs under this restricted...
setting. The median charging requirement is 6.88MW, an order of magnitude smaller than with higher BSED values. And, the annual energy demand of HEAs is 18.4 GWh. Such increases can likely be accommodated through selective updates to the distribution grid or through on-site generation at ORD, e.g., from the envisioned solar farm. As battery technology breaks the 500 Wh/kg barrier, HEAs can exploit the onboard batteries for taxi, takeoff, cruise, approach, and landing, requiring a commensurate increase in charging infrastructure at the airports.

Fig. 6: Histogram of daily peak demand with HEAs capable of flying up to 287 mi on BSED = 355 Wh/kg.

IV. PRELIMINARY RESULTS FROM CASE STUDY FOR LAX

Our framework can be applied to analyze the charging requirements of HEAs at any major airport in the US. Figure 7 depicts the annual demands from HEAs with BTS data for LAX. Median daily peak power demands become 31.0 MW, 55.9 MW, 90.6 MW, respectively with BSED = 500, 700, 1000 Wh/kg and MF = 12.5%. Compare these numbers to the total electricity use of 184 GWh in 2015 according to [13], that amounts to 21.0 MW of average power.

Fig. 7: Aggregate annual electricity demand of HEAs at LAX under various battery MF and BSED settings.

V. CONCLUDING REMARKS

In this paper, we estimate the demand requirements from HEAs that replace a portion of short-range domestic flights that pass through ORD. This work defines the first step towards answering the larger question: is the grid infrastructure at the airports, and the power system more broadly, ready for aviation electrification? We make several assumptions about range capabilities and calculate charging requirements of HEAs using existing flight schedules out of ORD under various BSED and MF projections. Our results indicate that while near-term capabilities of HEAs will only marginally affect airport electricity demands, the increase will be substantially higher with the anticipated growth in battery technology. Supporting grid infrastructure will play a key role in successfully electrifying the aviation industry. We aim to utilize our framework for a comprehensive study of power requirements from HEAs at all major airports in the US. We also aim to study how airlines with partially electrified fleets would design their flight schedules and charging plans to account for energy requirements of electric aircraft.

REFERENCES