Powering Electric Aircraft

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Abstract

Electrification of aviation could constitute an effective strategy to propel decarbonization in the aviation sector. The transition away from jet fuel is a massive challenge as battery-powered electrified aircraft will impose charging requirements on airports. In this paper, we study the impact of electrification on electricity demands at several airports across the United States (US). We consider the scenario where domestic US carriers partially deploy 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 demands (both in annual aggregate demands and peak power needs) at airports due to charging events. The data analysis reveals substantial increase in said demands that necessitate commensurate grid upgrades to support deployment of HEA at scale. To mitigate upgrade requirements, we propose a coordinated charging strategy that seeks to flatten the daily charging profile at an airport. In addition, we comment on the role of flexibility in flight schedules in further reducing said peak.

Introduction

The International Civil Aviation Organization (ICAO) had predicted (using a 2018 baseline) a compound average annual growth of 4.2% in demand for air travel over twenty years till 2038 [3]. This rising demand will result in a corresponding increase in greenhouse gas emissions if aviation keeps operating on jet air fuel. The carbon footprint of aviation is quite large. According to Air Transport Action Group (ATAG), commercial aircraft alone belched out 915 million tonnes of CO$_2$ worldwide in 2019, responsible for 2% of all human-induced CO$_2$ emissions from energy consumption [2]. The ongoing COVID-19 pandemic in 2020 has, at least momentarily, limited this projected growth. Should air travel demand bounce back after the pandemic, however, emissions from jet air fuel will pose a serious threat to the vision of a low carbon or even carbon neutral future, as pledged by the European Union and China. Electrification has been identified as a mechanism to significantly reduce the carbon footprint of aviation (see [12]), provided that the increased electricity demand from this change is accompanied by low-carbon energy production. Indeed, the ongoing trend of rapid wind and solar integration in the power grid favors electrification as a viable means of decarbonization.
Electric aircraft are no longer just a futuristic concept, but are very much an emergent technology. Very recently, in August 2020, the United States Department of Energy announced funding opportunities to the tune of $33 million to realize the vision of carbon-neutral hybrid electric single-aisle commercial aircraft. In this paper, we ask if the grid infrastructure at airports are equipped to handle the electricity demands that will go hand-in-hand with this aviation electrification. We expect our results to inform policy regarding the modernization of airports as they undergo this impending transition.

How advanced is the current electric aircraft technology? Various configurations such as turbo-electric, hybrid-electric, and all-electric aircraft have been proposed. For example, authors of [4] analyze flight performance of parallel turbofan systems, and that of [5] and [6] demonstrate benefits of a parallel hybrid propulsion system, utilized to boost power during takeoff and climb. Small electric airplanes with <4 passengers for general aviation are already available. Flight demonstrations are currently being conducted for the commuter class, in planes carrying <20 passengers. The next step is to electrify regional jets, carrying 30 - 100 passengers. A recent National Academies study in [12] found that over 90% of all aviation emissions come from ‘single aisle’ and larger aircraft. Additional technology development and maturation is required before practical electric propulsion systems are available for this aircraft class. Ongoing efforts from the industry and government agencies, notably under NASA’s AATT program in the United States and the Clean Sky program in the European Union, can possibly bring this to fruition in the near future. Even if such technology becomes viable soon–e.g., demonstrated in a relevant environment at a technology readiness level of six (TRL-6)–entry into regular commercial service by various airlines can take several years, often north of a decade. Development of new aircraft lines, their validation and certification processes, followed by establishment of commercial production facilities will likely take time. Meanwhile, electrification will probably proceed more gradually. Possibly, it will adopt the “more electric” approach where auxiliary systems are electrified first, similar to the current designs of Boeing 787 and Airbus A380. Next steps may include electric taxi, hybrid-electric boost during take-off, climb etc. More substantial use of electric propulsion depends on advances in battery technology.

Battery energy density severely limits the range of an electrified aircraft. While jet fuel has a specific energy density of ∼13000 Wh/kg, current batteries offer a mere 200-250 Wh/kg. With such low densities, an electric aircraft needs to haul the weight of a large battery in order to support the energy needs of the flight. Moreover, batteries do not shed their weight en route, as a conventional aircraft does while burning its fuel. That being said, the aviation industry is optimistic and anticipates a rapid rise in battery specific energy density (BSED), as evidenced by [10, 11] [7] [12] [13] [14] [12]. See Table 2 for details. While it remains difficult to predict an exact timeline, there is growing consensus in the industry that short-range, parallel, hybrid aircraft technology will become viable in the near future. Retrofitted conventional regional jets and single-aisle (narrow-body) airplanes have the potential to serve as incipient hybrid electric passenger jets, as [7] envisions. Switching long-range airplanes to an electric configuration will likely take
much longer.

Deployment of hybrid electric aircraft (HEA) will require charging the batteries on board, increasing electricity demand at airports. Large-scale electrification will require a well-rounded set of charging services such as grid upgrade to cover peak power demand, charging infrastructures at airports, communication facilities for coordinated charging, etc. In this work, we quantify these needs across several forward-looking HEA adoption scenarios. Specifically, we switch a portion of the fleet of current commercial flights to HEAs under a variety of energy densities and motor factors, and then compute their charging requirements across several major United States airports. By motor factor of an HEA, we mean the the ratio of the peak power delivered by its electric propulsion to that by its jet fuel. Our results indicate a significant increase in airport electricity demands—both in aggregate annual demands as well as in daily peak power requirements. We propose a simple mechanism to reduce peak demands. By setting the charging pattern in alignment with passenger travel needs, air traffic conditions and the availability of charging spots, we estimate that coordinated smart charging can reduce daily peak demands by more than 50% from the case where HEAs charge their batteries at a uniform rate over their dwell time at an airport. Furthermore, minor variations in flight schedules can flatten the power demand profile even more. Finally, we analyze the energy demands from limited growth in battery capabilities as predicted in [6] for the immediate future. Based on our analysis, we believe that enabling charging of HEAs at airports will likely require significant infrastructural upgrades at the airports and the grid that power these airports. Such upgrades need forward planning. One must prepare for them with sufficient lead time.

Results

Increase in Annual Energy Demand

If domestic commercial airline carriers adopt electric aircraft within their fleets, charging events at airports would increase the airports’ electricity demands. We characterize exactly how much this increase will be under different values of battery specific energy densities (BSED) and motor factors (MF). For each combination of BSED and MF, we consider the scenario where all commercial regional flights switch to a hybrid electric model as long as the flight distance is achievable given such BSED and MF values. For this analysis, we assume that each flight arrives with a fully depleted battery that is charged at a uniform rate until it leaves the airport again up to the battery energy capacity needed for its next trip. Implicitly, we assume that enough charging points are available to accommodate all airplanes at any moment in time. We have used the flight schedule data of domestic commercial passenger flights carried out by reporting domestic airlines from the US Department of Transportation’s Bureau of Transportation Statistics (BTS) Airline On-Time Performance Data for each airport of year 2018. Figure 1 plots the projected increase in aggregate annual electricity demands at six large airports in the
United States–Hartsfield-Jackson Atlanta International Airport (ATL), Chicago O’Hare International Airport (ORD), Dallas/Fort Worth International Airport (DFW), Dulles International Airport near Washington D.C. (IAD) and San Francisco International Airport (SFO). The plots reveal that even moderate BSED and MF values for HEAs will lead to a substantial annual battery energy consumption. To appreciate the scale of that increase, notice that aggregate power demand of SFO in 2018 was 311 GWh, according to the DataSanFrancisco program. Figure 1d confirms that en masse electrification of commercial regional flights at SFO with any of the BSED and MF values will considerably amplify said energy demand of 311 GWh. The story is similar for other airports. For example, ORD had an annual total power demand of 441 GWh in 2002 according to the O’Hare Modernization Final Environmental Impact Statement. The projected increase in ORD will more than double that requirement even at BSED = 700 Wh/kg and MF = 25%.

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 trend in Figure 1. To explain this apparent paradox, notice that lighter batteries with improved BSED allow HEAs to operate more flights over longer distances. The increase in the range and the number of flights converted to a hybrid electric model leads to the increase in aggregate charging requirements.

Figure 1: Extra annual electricity demand per annum needed to charge commercial passenger domestic HEAs at airports across US under various battery MF and BSED settings. Airports in the first row serve larger number of enplanements than the airports in the second row.
Figure 2: Histogram of daily peak demands with different BESD and MFs at SFO. Here, (---) plots the histogram for BSED = 500 Wh/kg, MF = 12.5%; (--) plots BSED = 700 Wh/kg, MF = 12.5%; and (- -) plots BSED = 1000 Wh/kg, MF = 12.5%; (---) plots BSED = 500 Wh/kg, MF = 25%; (--) plots BSED = 700 Wh/kg, MF = 25%.

Peak Power Requirements for Charging HEAs

Grid infrastructure to deliver power at airports must be designed to cover daily peak power demands from HEAs and that from the rest of the airport. In Figure 2, we plot histograms of daily peaks due to HEAs at several airports. Notice that the average power demand of SFO in 2018 was 35 MW, according to the DataSanFrancisco program. With MF = 12.5% and BSED of 500, 700 and 1000 Wh/kg, we obtain a median peak power requirement of 25.8, 33.7 and 54.7 MW, respectively, that has a comparable order to the average power demand at SFO. With MF = 25% and BSED of 500 and 700 Wh/kg, the same numbers are 29.7 and 45.5 MW, respectively. Strikingly, highest daily peak demands can be ~82 MW with MF = 12.5% and BSED = 1000 Wh/kg, that is more than double the average power demand of 35 MW at SFO.

Equipment upgrade for power delivery will typically account for possible demand growth scenarios over a 20-30 year time-horizon. Given the upward trend in air-travel as the ICAO predicts, our projected increases in power demands due to HEAs will likely provide a lower bound on the necessary upgrades. Thus, significant penetration of electric aircraft will pose an enormous challenge to the grid infrastructure at and surrounding
Peak Shaving via Smart Charging

Recall that our results in Figures 1 and 2 are obtained with a charging schedule that maintains a uniform charging rate throughout the time an aircraft spends at an airport. A smart charging schedule can naturally shave the resulting peak power demands. Next, we investigate the potential of coordinated charging that can partially alleviate the burdens of said peaks in power demands.

We cast the question of deciding charging schedules for HEAs as an optimization problem. We assume that flight schedules remain the same, meaning that the arrival and the departure times for each flight are given by the data in BTS airline on-time performance database. Table 1 records the results of our analysis from eight airports for the days in which we obtained the highest daily peak power demand from HEAs in our prior analysis. For these experiments, we consider a MF of 25% and BSED of 700 Wh/kg.

<table>
<thead>
<tr>
<th>Airport</th>
<th>Number of flights being replaced</th>
<th>Highest peak (MW) under naive charging</th>
<th>Shaved peak (MW) under smart charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATL</td>
<td>212,205</td>
<td>194.5</td>
<td>98.5</td>
</tr>
<tr>
<td>ORD</td>
<td>158,991</td>
<td>138.7</td>
<td>63.5</td>
</tr>
<tr>
<td>DFW</td>
<td>103,177</td>
<td>94.3</td>
<td>38.9</td>
</tr>
<tr>
<td>SFO</td>
<td>66,737</td>
<td>60.3</td>
<td>25.2</td>
</tr>
<tr>
<td>IAD</td>
<td>35,085</td>
<td>55.1</td>
<td>27.1</td>
</tr>
<tr>
<td>SAN</td>
<td>20,876</td>
<td>30.3</td>
<td>14.6</td>
</tr>
<tr>
<td>CLE</td>
<td>25,516</td>
<td>30.4</td>
<td>15.9</td>
</tr>
<tr>
<td>BMI</td>
<td>1,179</td>
<td>8.5</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Table 1: Highest daily peak power demand in several airports with naive and smart charging.

The optimization problem favors flat aggregate charging profiles of HEAs across flights over a day. Figure 3 compares charging profiles that result from naive uniform charging rate and the smart coordinated charging scheme. The results in Table 1 and Figure 3 are encouraging in that they illustrate that burdens of infrastructure upgrades for powering HEAs can substantially reduce (to the tune of 50% in some cases) through smart charging.

The higher the number of flights, the larger the potential gains from smart scheduling appear to be. For example, daily peak demand at ORD could hit 138.7 MW on September 4, 2018 if it operated HEAs under uniform charging. The same peak gets shaved to 63.5 MW through our optimization design, per Table 1. ORD had north of 39,873K enplanements in year 2018 and is one of the busiest airports in the United States. In comparison, BMI in Bloomington (Illinois) had only 213K enplanements. This relatively smaller airport improves its highest peak from 8.5 MW to 7.8 MW through smart charging, a rather modest decrease compared to that obtained at ORD.
Figure 3: Demand requirements that result from uniform charging rate (---) and from smart scheduling (—) under the setting of BESD = 700 Wh/kg and MF = 25%.

Peak Power Reduction from Marginal Change in Flight Schedules

Can alteration of flight schedules alleviate upgrade requirements, in addition to the design of smart charging schedules? We remark that planning of flight schedules is inherently complex (see [15]) and remains beyond the scope of this paper. We, however, explore the sensitivity of power demand to minor changes in flight schedules to illustrate the impact that flight rescheduling with HEAs can have on peak power requirements.

Consider the charging requirements from HEAs at IAD based on the flight schedules on BTS Airline ontime performance data. Figure 4 shows a daily peak demand of 55.1 MW under naive charging. Peak demand drops to 27.1 MW with smart charging. Figure 4 confirms that the charging profile even under smart charging is not flat and exhibits two ‘humps’. These humps hint at the possibility of further flattening the power demand curve if one could alter the flight schedules. To illustrate said potential, we selectively alter flight departures by 30 minutes. This minor shift achieves a peak shaving of 5 MW. This 18.5% peak reduction obtained through a minor variation in flight schedule illustrates that joint optimization of flight operations and charging requirements can reduce grid upgrade requirements.

Estimates of Charging Requirements in the Near Future

Despite ambitious targets for battery technology from the aviation industry in Table 2, battery experts project a more conservative growth in battery capabilities at least in the next decade. Authors of a recent study in [8] anticipate that the 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. Den-
Figure 4: Charging profiles with naive uniform charging rate ( ), smart charging ( ), and smart charging with marginally altered flight schedules ( ) at IAD on 12/6/2018.

Sities beyond 700 Wh/kg are possibly more than a decade away. In light of this study, we compare our earlier results to those with a much smaller BSED of 355 Wh/kg. With such a battery configuration, the authors of [6] advocate battery use as the energy source only during takeoff and climb. Following [6], we restrict the range of such flights to 287 mi and take $\gamma = 30.589$ Wh per passenger-mile. Figure 5 provides a collection of histograms of daily peak electricity demands for charging HEAs across major airports in the US with such limited battery use. Figure 5 unsurprisingly shows that the distributions of peaks in the busier airports (top row) are more right-skewed than those that are less busy (bottom row). The increase in daily peak demands are not negligible, but not nearly as high as that with the BSED and MF configurations we investigated before. Such increases in electricity demands are much more manageable with moderate upgrades to the grid infrastructure required to support HEAs in the near future. For example, the median charging requirement in ORD and SFO are 6.88 MW and 2.01 MW, respectively, an order of magnitude smaller than with higher BSED values. In addition, the annual electricity demand of HEAs in SFO is estimated to be 3.67 GWh. Given that the SFO electricity consumption over 2018 is 311 GWh, such increases can likely be accommodated through selective updates to the distribution grid or through on-site generation at SFO, e.g., from an envisioned solar farm. Nevertheless, grid upgrades will become far more important from 2030 onward, when battery technology is expected to break the 500 Wh/kg barrier. Only then can HEAs meaningfully exploit the on-board batteries for taxi, takeoff, cruise, approach, and landing, requiring a sizeable increase in charging infrastructure at the airports.
Figure 5: Histogram of daily peak demand with HEAs capable of flying up to 287 mi on BSED = 355 Wh/kg

**Discussion**

If electrified aircraft adoption accelerates, powering them will substantially increase electric power demands at airports across the US. Realizing that the technology evolution for electric aircraft is uncertain, we focus on HEA concepts that are actively being pursued in academic and industry research. See Table 2 for a summary of prior works on regional and single-aisle HEA concepts that are relevant to commercial operation of short-range flights in the foreseeable future. These studies capture the aviation industry’s anticipation of a steep climb in BSED capabilities, thus favoring the need for our study.

<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>[10, 11]</td>
</tr>
<tr>
<td>Bauhaus</td>
<td>Parallel hybrid</td>
<td>1,000 - 1,500</td>
<td>[7]</td>
</tr>
<tr>
<td>UTRC</td>
<td>Parallel hybrid</td>
<td>Not specified</td>
<td>[12]</td>
</tr>
<tr>
<td>Airbus</td>
<td>Series hybrid</td>
<td>800</td>
<td>[13]</td>
</tr>
<tr>
<td>Cambridge</td>
<td>Parallel hybrid</td>
<td>750</td>
<td>[14]</td>
</tr>
<tr>
<td>Georgia Tech</td>
<td>Parallel hybrid</td>
<td>750</td>
<td>[12]</td>
</tr>
</tbody>
</table>

Table 2: Summary of regional and single-aisle hybrid electric aircraft concepts and research
Our analysis quantifies a surge in annual aggregate energy demands and daily peak power demands from possible switching of domestic commercial passenger flights to HEAs. Industrial expectations of BSED values in the range of 500 and 750 between year 2030 to 2050 can roughly double the annual energy demands at leading airports in the US. We assume that all flight paths that become achievable with a BSED-MF combination is operated with the HEA option. This scenario assumes the most aggressive uptake of HEAs based on current flight schedules. With gradual roll-out of HEAs, said increase should therefore be lesser than our projections. However, this decrease can very well be offset by a concomitant rise in the number of flights and the number of passengers, given the recent trends in air-travel that shows fast-paced growth right up until the onset of the pandemic.

In this paper, we only consider electrification of domestic commercial passenger airplane, but neglect long-haul wide-body international flights, freight and military flights. Given the serious range limitations that battery weight poses, it will likely remain challenging to switch long-haul flights to the hybrid option in the near future. While we do not consider freight and other sectors, we remark that our analytic framework can easily be extended to them. These sectors can only increase electricity demands at airports, bolstering our key message for the need to proactively prepare for aviation electrification.

Our analysis tells a more dire story about the required grid infrastructure upgrades. Busy airports such as ATL, ORD and DFW may need to invest heavily in grid equipment in order to support peak charging activities of HEAs. These peaks can be quite high, e.g., 194.5 MW surge at ATL with flight schedules on 4/12/2018 as per the BTS Airline On-time Performance data. There is a silver lining, however. Coordinated charging of HEAs can shave peak power requirements, often to the tune of 50\% at large airports. This reduction will directly translate into reduced requirements on grid infrastructure upgrades. The ability to coordinate charging of HEAs across the fleets of multiple airline companies will likely rely on customized power purchase contracts between the airport authorities and the airlines, the design of which remains an interesting direction for future research. More broadly, we expect the rules of engagement among three parties—the airline companies, the airport authorities and the electricity distribution utility—to evolve over time with the electrification of aviation.

Smart scheduling works better when the charging requirements are “flexible”. Higher air traffic flow often presents more opportunities to modify the charging schedule across multiple airplanes. Thus, potential peak power reduction from coordinated demand management is higher at larger hubs such as ATL, ORD and DFW than at smaller airports such as BMI. In addition, marginally altering flight schedules can further reduce said peak. If electrification efforts pick up, airlines will need to accommodate charging capabilities at various airports within their flight scheduling process.

Our electricity demand projections are more long-term in that the BSED-MF combinations we consider for Figures 1 are expected to materialize beyond 2030. The near-term expectations from battery technology are much more modest. Our analysis indicates that with such batteries, used only during takeoff and climb, electricity demand growth is
much smaller and manageable for the various airports.

The upgrade requirements in the very near future must not, however, guide the upgrade decisions. More stringent greenhouse gas emission regulation can change the timeline and boost earlier deployment of electric aircraft. Infrastructure upgrades are typically expensive and time-consuming, meaning that the power grid and the airports must prepare early for transition to HEAs.

Electrification of aviation will likely result in reduction in demand for jet air fuel. We hope that this decrease is not offset by the continuing rise in air travel, given the solid trends before March 2020. Powering short-to-medium haul commercial flights will need substantial increment in electricity generation. Such an increase will only lead to reduced greenhouse gas emissions if electricity generation relies on cleaner technology than jet air fuel. The good news is that wind and solar power generation is expanding at record rates. With renewable electricity production, electrification of aviation, and more broadly transportation, can unlock opportunities to accelerate a carbon-free future.

### Methods

We first describe our data analytic framework to compute electricity demands with naive uniform charging rates. We then describe an optimization problem that seeks to flatten the demand profile over a day.

For our analysis, we utilize flight schedules of domestic commercial passenger flights carried out by reporting domestic airlines from the US Department of Transportation’s Bureau of Transportation Statistics (BTS) Airline On-Time Performance Data to compute charging requirements. The dataset describes all non-stop domestic flights released by reporting US carriers. Relevant details for each flight includes its tail number, scheduled and actual departure/arrival times, origin and destination airports, and non-stop distance.

### Electricity Requirements with Uniform Charging Rate

The electricity demands of HEAs depend on the size of the domestic fleet that gets electrified, the type of flights being electrified, distances traveled and their charging schedules. In our analysis, we consider the most aggressive HEA uptake scenario where a commercial regional flight becomes an HEA if the flight distance is within its range. We 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. For each airport, we list all short-range domestic flights that had a dwell time longer than 15 minutes at that airport in 2018 from the BTS dataset. These airplanes are of two types—regional jets and narrow body aircraft. We then utilize the range capabilities of retrofit hybrid electric regional jets and narrow body aircraft from [9], included in Supplementary Table 2. Thus, with a BSED-MF combination, we consider all flights with travel distances less than the range from Supplementary Table 2 as HEAs.
Assume that each HEA arrives at airport with zero charge in its battery. It then charges at a constant rate that is chosen so that the battery is charged up to the energy needs of the next flight leg by its departure time. Power required to serve such a flight leg is $P = \frac{E}{T}$, where $E$ is the battery energy requirement and $T$ is the dwell time at airport (in minutes). Furthermore, the battery energy is given by

$$E = p \times d \times \gamma \quad \text{(1)}$$

required to travel $d$ miles with $p$ passengers. Here, $\gamma$ denotes 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, yields the total number of seats on the plane. Throughout this analysis, we assume uniformly that 85% of all seats are filled in each flight to estimate $p$. This load factor matches the yearly average estimates of the same by BTS (see [1]).

The values of parameter $\gamma$ for HEAs are adopted from [9], assuming a battery-pack voltage of 128V. Their analysis accounts for battery energy consumed during taxi, take-off, 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 from Supplementary material Table 1. Battery sizes required for BSED below 700 Wh/kg and MF above 50% are deemed impractical to use for any flight distance.

To illustrate the power demand requirements through an example, consider a single hybrid electric retrofit of Embraer ERJ 170-200 aircraft with tail number N178SY operating a 599 miles flight from SFO to SLC (Salt Lake City, UT) on 05/29/2018. N178SY arrives at SFO at 17:02 PM and leaves for SLC at 17:53 PM. For different MF and BSED configurations, we compute $E$ from (1) and report in Table 3. Dividing $E$ by 60 minutes yields the power requirements of N178SY from 17:02 to 17:53 PM on 05/29/2018. Also note that this example illustrate the case where a hybrid electric aircraft does not have the range ability to cover a flight mission of distance 599 miles under the setting of BSED being 500 Wh/kg and MF being 25%.

<table>
<thead>
<tr>
<th>MF (%)</th>
<th>BSED (Wh/kg)</th>
<th>Power Requirement (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>500</td>
<td>1.23</td>
</tr>
<tr>
<td>25</td>
<td>700</td>
<td>2.52</td>
</tr>
</tbody>
</table>

Table 3: Power requirements of N178SY for flight from SFO to SLC.

Divide each day into 1440 one-minute intervals. Adding the charging requirements following the above procedure for all flights in a given 1-min interval yields the charging requirements for that interval. We plot a sample charging profile for ORD on 7/9/2018 with MF=12.5%, but BSED of 500, 700 and 1000 Wh/kg in Figure 6. Such profiles across
all days in 2018 for each airport yield our results for annual energy and peak power requirements to power HEAs.

![Graphs showing daily power consumption profiles](image1)

(a) MF=12.5%, BSED=500Wh/kg  (b) MF=12.5%, BSED=700Wh/kg  (c) MF=12.5%, BSED=1000Wh/kg

Figure 6: Daily power consumption profiles (on day 7/9/2018) at ORD for HEAs with various BSED and MF values. Here, ( ) plots power requirements of single-aisle aircraft, ( ) denotes the same for regional jets, ( ) is the sum of the above two profiles

![Histograms and CDFs of flight distances](image2)

(a) Regional Jets  (b) Single Aisle Aircraft

Figure 7: Histograms and cumulative distribution functions (CDFs) of flight distances in ORD over 2018

We comment on an interesting observation from Figure 6. Notice that as BSED increases, single-aisle aircraft begin to account for the lion’s share of charging requirements. To explain this, we plot the frequency of different flight distances with the 300K+ regional jets and single aisle aircraft at ORD in 2018 in Figure 7. The distance distribution of single-aisle aircraft is more right-skewed than that of regional jets. Indeed, the median distance of flights for single-aisle aircraft is 867 mi and for regional jets is 409 mi. As larger travel distances are made possible with higher BSED, more single-aisle aircraft switch to become HEAs. These airplanes travel longer distances that typically require more energy than regional jets traveling short distances. Thus, they constitute the bulk of the energy needs at higher BSED as shown in Figure 6.

In the case of near future scenario, we restrict the maximum distance of flights to 287 mi and the battery energy (Wh) per passenger per mi is computed as $\gamma = 301 \times 1.05 \times$
Several remarks on our analytic framework are in order. First, a battery pack aboard an HEA cannot be charged at an arbitrary rate and must abide by the ratings of the battery and the charging equipment. We ignore such rate limitations in our calculations. Second, arriving HEAs at an airport may have residual charge in their batteries that will impact charging requirements at the airport. We ignore such possibilities in our analysis. Third, we ignore the possibility that an HEA may need to charge enough to complete a round-trip journey from and to that airport if the destination location lacks necessary HEA charging infrastructure. Fourth, batteries often have efficiency losses that we ignore. Accounting for such losses will further increase the energy demands of HEAs. Relaxing one or more of these assumptions are relegated to future work.

The Optimization Problem for Smart Charging

Assume HEA operate under current flight schedule. We aim to flatten the aggregate charging profile over a pre-specified time horizon by managing charging demand of electrified aircraft that are hooked up to the grid. An any one moment during the time horizon, we coordinate the charging power delivered to each airplane that participates in charging events so that their cumulative charging requirement is minimal. We also ensure each aircraft has the capacity to commit its next flight.

Recall that a day is divided into $T = 1440$ one-minute intervals. Suppose, we consider the charging of $N$ HEAs, numbered $1, \ldots, N$. For aircraft $n = 1, \ldots, N$, let $t_n^A$ and $t_n^D$, respectively, denote its arrival and departure times at the airport gate. Define $E_n$ as its total energy needs for the next flight leg, calculated exactly as we did for naive charging. With $c_n(t)$ denoting the energy draw by HEA $n$ in period $t$, we formulate the smart charging problem as

$$
\begin{align*}
\text{minimize} \quad & \sum_{t=1}^{T} \left( \sum_{n=1}^{N} c_n(t) \right)^2, \\
\text{such that} \quad & \sum_{t=1}^{T} c_n(t) = E_n, \quad c_n(t) = 0 \text{ for } t \notin [t_n^A, t_n^D], \quad n = 1, \ldots, N
\end{align*}
$$

over $c_n(t)$ for $n = 1, \ldots, N$ and $t = 1, \ldots, T$. The constraints encode the requirement that HEA $n$ must fulfill its charging obligations over the time it is parked at the airport gate. The quadratic objective function is such that it seeks to flatten the charging profile within the constraints described. The quadratic program is solved using python with a Gurobi solver to generate the results in Table 1 and Figures 3 and 4.
Supplementary Information

<table>
<thead>
<tr>
<th>Type</th>
<th>MF (%)</th>
<th>BSED (Wh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>700</td>
</tr>
<tr>
<td>ERJ-175</td>
<td>12.5</td>
<td>31.1</td>
</tr>
<tr>
<td></td>
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<td>57.3</td>
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</table>

Supplementary Table 1: Battery energy usage $\gamma$ in Wh per passenger-mile of ERJ-175 and Boeing 737-700.

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<th>Type</th>
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<th>BSED (Wh/kg)</th>
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</table>

Supplementary Table 2: Maximum range of HEAs in miles

Data availability

Flight schedules of domestic commercial passenger flights carried out by reporting domestic airlines are retrieved from the US Department of Transportation’s Bureau of Transportation Statistics (BTS) Airline On-Time Performance Data at [https://www.transtats.bts.gov/Tables.asp?DB_ID=120](https://www.transtats.bts.gov/Tables.asp?DB_ID=120)

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Author contributions

B.H carried out data analysis and wrote the manuscript. S.B contributed to revising and reviewing of the manuscript. K.H reviewed and edited the manuscript.
References


