Analysis of Electrical Grid Capacity by Interconnection for Urban Air Mobility

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A wide range of challenges must be overcome to conduct Urban Air Mobility (UAM) operations at scale with electric vertical take-off and landing aircraft as envisioned. This paper documents an analysis of one potential infrastructure challenge for UAM: available electrical grid power capacity. The success of UAM depends on the availability of electricity, which will be increasingly impacted by the proliferation of ground electric vehicles (EVs) over time. Under the best-case assumption that electricity can be transmitted and distributed as needed within each interconnection (i.e., electrical grid), it is estimated that the maximum number of UAM aircraft that can charge simultaneously in the continental United States will decrease by 20% from about 595 thousand in the year 2021 to about 475 thousand in the year 2050 due to the projected increase in ground EVs.

I. Introduction

MULTIPLE significant challenges need to be overcome to conduct Urban Air Mobility (UAM) operations profitably at scale while also meeting demand. These include technology, infrastructure, regulatory, and acceptance challenges. Over the past several years, progress towards overcoming these challenges has been slower than initially expected. In a December 2018 report, Morgan Stanley Research projected the UAM Total Addressable Market (TAM) worldwide through 2040 at $1.5 trillion [1]. However, in a follow-up report released in May 2021, this projection was revised down to $1.0 trillion [2]. The latter report cites hurdles related to regulation and certification as reasons for the lower projection. These hurdles are expected to be overcome such that the UAM TAM worldwide will increase by an additional $8.0 trillion between 2040 and 2050. However, this projected growth in the UAM TAM could be delayed again if progress towards overcoming these challenges is slower than expected as was the case during the period between the two reports.

In these reports, Morgan Stanley Research examined several scenarios that included regulatory inputs such as state/local/regional government intervention, FAA/EASA oversight, infrastructure development barriers, and public acceptance. This paper analyzes the capacity of the electrical grid, which is just one of the infrastructure challenges that must be overcome for UAM operations to be conducted at scale as envisioned. Other organizations have also analyzed the electrical grid for UAM and/or identified how it could potentially constrain the maximum number of UAM operations. For instance, Black & Veatch analyzed the infrastructure upgrades that would be required to charge UAM electric vertical take-off and landing (eVTOL) aircraft at vertiports [3]. In addition, the Vertical Flight Society qualitatively identified electrical grid infrastructure as an eVTOL supply chain challenge [4].

The primary purpose of this study is to quantitatively assess the power capacity of the electrical grid to conduct UAM operations at scale with eVTOL aircraft as envisioned by estimating and analyzing the number of UAM eVTOL aircraft that can charge simultaneously on the three interconnections (i.e., electrical grids) of which the continental United States (CONUS) is part: 1) Eastern Interconnection, 2) Western Interconnection, and 3) Texas Interconnection [5]. The analysis in this study includes the impact of ground electric vehicles (EVs), which are expected to proliferate and utilize more of the electrical grid over the next several decades. As a result, this is expected to leave less available electrical grid power capacity for UAM and constrain the maximum number of UAM operations.

Bloomberg New Energy Finance [6] and the U.S. Drive Grid Integration Technical Team and Integrated Systems Analysis Technical Team [7]—composed of automotive manufacturers, energy producers, research organizations, and utility companies—projected that the EV percentage of the ground fleet will grow from 0.5% in 2021 to about 50% in 2050. In addition, information services company IHS Markit estimated that EVs will be 40% of the ground fleet in 2050 [8]. Furthermore, additional ground EV models may be capable of charging at faster rates in the future, including direct-current fast charging at greater than 300 kilowatts (kW) [9]. The combination of more ground EVs and higher

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ground EV charging rates will reduce available electrical grid power capacity for UAM and constrain the maximum number of UAM operations.

The remainder of this paper is organized as follows. Section II provides an overview of the electrical grids in North America of which the CONUS is part. Section III details the methodology that was developed to estimate the maximum number of UAM aircraft that can be charging simultaneously and the number of UAM aircraft that can be aloft. Section IV presents the estimates for each region of the CONUS covered by the three electrical grids through the year 2050. Section V explains the need to conduct follow-on research to compute these estimates by metro area. It also discusses the wide range of factors that could change the baseline estimates computed in this study and presents a corresponding sensitivity analysis. Lastly, Section VI summarizes the findings of this study.

II. Background

UAM—defined as passenger- or cargo-carrying air transportation services in and around urban areas—includes both on-demand and scheduled operations [10]. Examples of UAM missions include emergency medical evacuations, rescue operations, humanitarian missions, ground traffic flow assessment, weather monitoring, package delivery, and passenger transport. eVTOL aircraft enable UAM operations to be conducted quietly and efficiently.

The success of UAM depends on the availability of electricity. Without a sufficient supply of it, UAM eVTOL aircraft cannot be flown, and a business case for UAM cannot be made. This study analyzes the best-case scenario for available electrical grid power capacity in which electricity can be transmitted and distributed as needed within each interconnection (i.e., electrical grid).

A. Interconnections in North America

Figure 1 is an illustration of four of the interconnections in North America, of which the CONUS is part of three (all except the Quebec Interconnection).

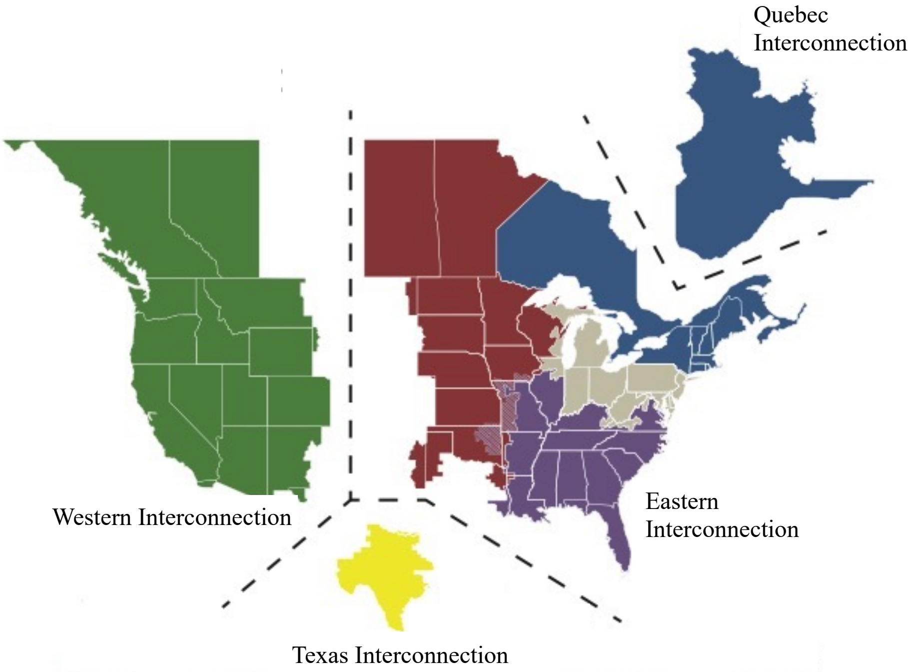

Fig. 1 Interconnections in North America [5].*

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* This information from the North American Electric Reliability Corporation's website is the property of the NERC and available on the website, found here.
(https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/NERC%20Interconnections.pdf)
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B. Electrical Grid Structure

At a high level, each interconnection has a similar structure. As illustrated in Figure 2, electricity is generated at power plants and then transferred using regional transmission lines to local distribution systems and lines to customers. Interconnections can share some generation and transmission capacity regionally, but not distribution capacity, which is local.

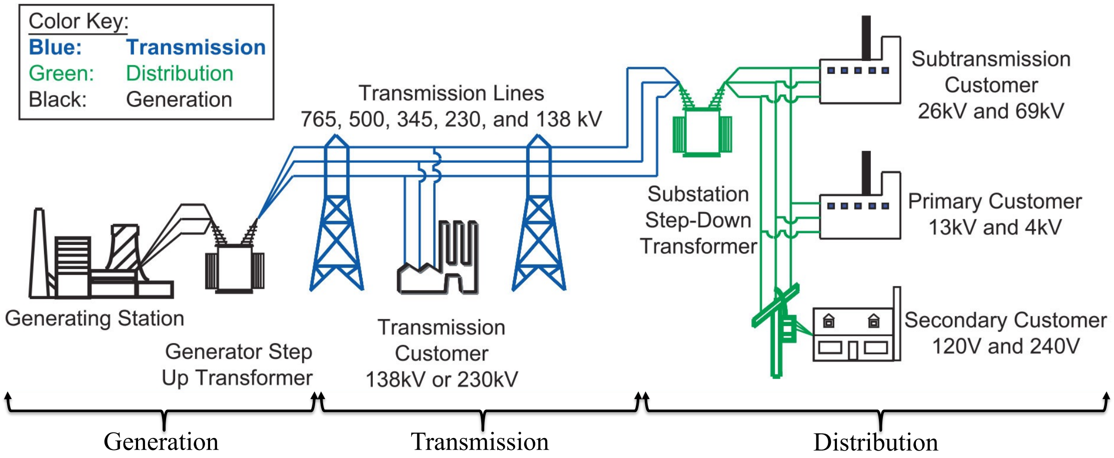

Fig. 2 Electrical grid structure at a high level [11].

1. Generation

Electricity generation is the production of electric power from sources of primary energy such as natural gas, coal, petroleum, nuclear, and renewables (e.g., wind, hydro, solar, biomass, geothermal) [12]. The U.S. Energy Information Administration (EIA) maintains a monthly catalog of the status of utility-scale electric power plants, which are defined as having at least one megawatt of nameplate capacity [13]. This catalog also includes information on each power plant's location. The electricity generation power capacity of each interconnection can be estimated by adding up the nameplate capacities of the electric power plants located in each of them. Step-up transformers increase the voltage of the electricity generated at power plants for subsequent transmission [14].

2. Transmission

Electricity transmission is the regional bulk movement of electricity from electric power plants to local distribution substations using high-voltage transmission lines [15] that "lessen the amount of electricity that is lost to friction in the wires" [16]. Ambient weather conditions—temperature, wind speed and direction, and solar radiation—affect the capacity of transmission lines. In general, transmission lines have greater capacity when temperatures are lower, winds are blowing, and solar radiation is lower (e.g., on cloudy days) [17]. Utilities are investing about \$20 billion per year to maintain existing and build new transmission infrastructure [18].

3. Distribution

Electricity distribution is the local delivery of electricity. First, the high-voltage electricity from regional transmission lines is reduced to lower voltages using step-down transformers at local distribution substations. Then, the lower-voltage electricity is delivered to customers [15]. Utilities are investing about \$50 billion per year to upgrade local distribution systems to be more resilient to extreme weather events, enhance system control during emergencies, and accommodate the expected increase in renewable electricity generation [19].

III. Methodology

This section details the methodology that was developed to estimate the maximum number of UAM aircraft that can be charging simultaneously by estimating the available electrical grid power capacity (Section III.A), estimating the peak electrical power utilized by ground EVs for charging (Section III.B), and dividing the difference by a baseline UAM aircraft charging rate (Section III.C.1). A scaling factor based on what was observed in a NASA simulation study [20] is applied to estimate the number of UAM aircraft that can be aloft (Section III.C.2).

A. Estimation of Available Electrical Grid Power Capacity

Available electrical grid power capacity is estimated by multiplying the estimated electrical grid power capacity (Section III.A.1) and the available electrical grid capacity percentage (Section III.A.2). The estimates are projected through the year 2050 for each of the three interconnections of which the United States is part.

1. *Electrical grid power capacity*

The present-day electrical grid power capacity of each interconnection is calculated by adding up the nameplate capacities of the utility-scale generators [13] in the states that are located mostly or entirely in the interconnection. The District of Columbia is included in the calculations for the Eastern Interconnection.

Figure 3 plots the estimated electrical grid power capacity of each interconnection through 2050 by applying the U.S. EIA's reference projection of national electricity generation capacity compound annual growth rate of 1.54% [21] to each interconnection. If projections of electricity generation capacity growth rates become available at the interconnection, state, and/or county level, these estimates should be re-calculated.

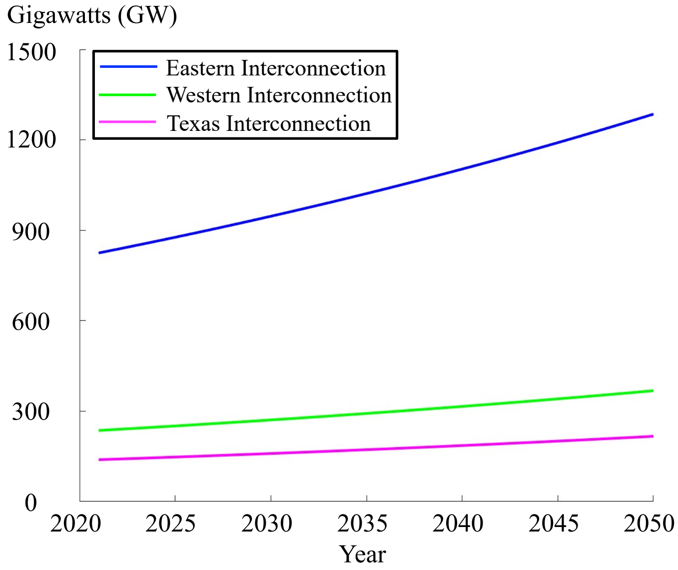

Fig. 3 Estimates of electrical grid power capacity by interconnection.

2. *Available electrical grid capacity percentage*

The electricity generated is utilized for a wide range of purposes, including but not limited to space heating and cooling, water heating, refrigeration, lighting, ventilation, and computing. The Federal Reserve Bank of St. Louis estimated that electrical grid utilization across the United States in 2019 was around 75% [22]. As such, on average during 2019, about 25% of the electrical grid was not utilized. In this study, it is assumed that utilization continues to be at this level through 2050 and that 5% is held in reserve for maintenance, contingencies, and other purposes. The remaining 20% of electrical grid capacity is the focus of this study.

B. Estimation of Peak Electrical Power Utilized by Ground EVs for Charging

Peak electrical power utilized by ground EVs for charging is estimated by multiplying the projected number of ground vehicles (Section III.B.1), the projected EV percentage of the ground fleet (Section III.B.2), the estimated peak percentage of ground EVs that are charging (Section III.B.3), and a ground EV charging rate that is common for Level 2 charging now (Section III.B.4). As in the prior section, these estimates are projected through the year 2050 for each of the three interconnections of which the United States is part.

1. *Number of ground vehicles*

The present-day number of ground vehicles in each interconnection is calculated by adding up the number of motor vehicle registrations in the states that are located mostly or entirely in the interconnection [23]. As in the prior section, the District of Columbia is included in the calculations for the Eastern Interconnection. Then, the number of ground vehicles for each year through 2050 is projected by applying the U.S. Census Bureau's base scenario projection of national population compound annual growth rate of 0.52% [24]. As illustrated in Figure 4, the number of ground vehicles in the CONUS is projected to increase from about 335 million in 2021 to about 389 million in 2050.

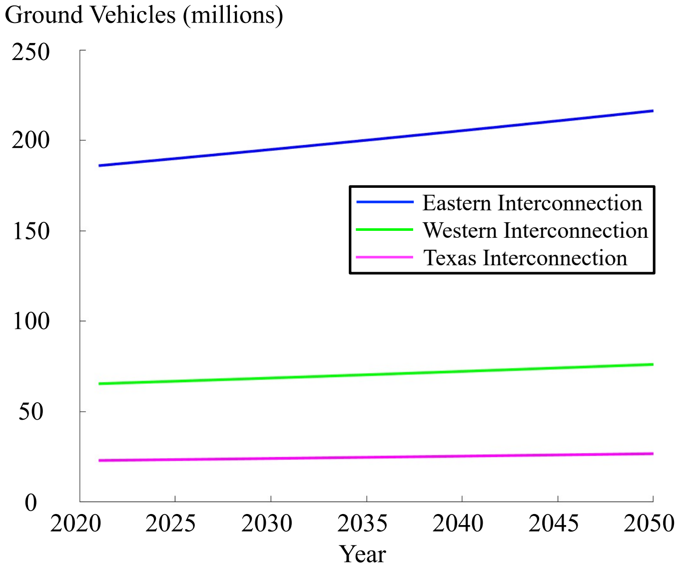

Fig. 4 Estimates of ground vehicles by interconnection.

2. Ground EV percentage

Bloomberg New Energy Finance [6] and the U.S. Drive Grid Integration Technical Team and Integrated Systems Analysis Technical Team [7] projected that the EV percentage of the ground fleet will grow from 0.5% in 2021 to about 50% in 2050. IHS Markit estimated that EVs will be 40% of the ground fleet in 2050 [8]. In this study, it is assumed that the EV percentage of the ground fleet increases linearly between 2021 and 2050. Figure 5 plots the estimated number of ground EVs for each interconnection through 2050 by applying the IHS Markit estimate as a lower bound on the impact of ground EVs on available electrical grid power capacity for UAM.

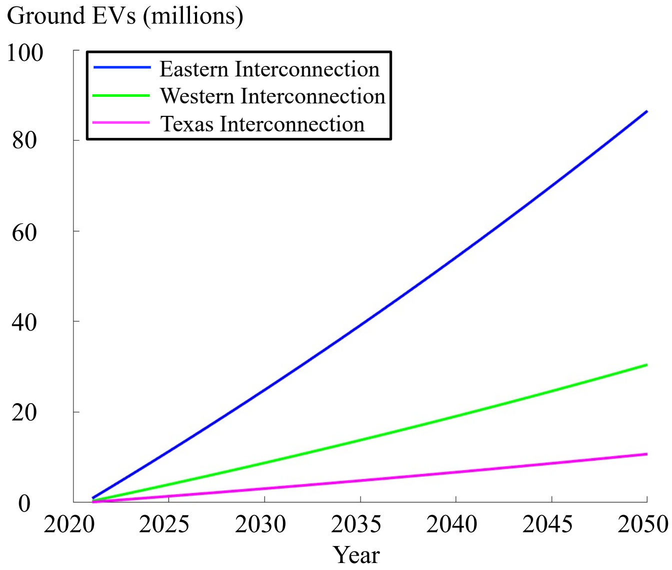

Fig. 5 Estimates of ground EVs by interconnection.

3. Peak percentage of ground EVs charging

The U.S. Drive Grid Integration Technical Team and Integrated Systems Analysis Technical Team developed several ground EV charging demand profiles [7]. The highest peak occurs in the "uncontrolled" charging demand profile "where EVs charge immediately at full power once connected and continue until completely charged." This peak occurs around the weekday evening commute, with about 20% of ground EVs charging. The demand for UAM trips and charging are also expected to have a peak around this time [20]. This coinciding of demand for electricity may limit the extent to which the demand for UAM trips can be met.

4. Ground EV charging rate

The rate at which ground EVs can be charged is the lesser of the maximum charging acceptance rate of the vehicle and the maximum delivery rate of the charging station. In this study, it is assumed that ground EVs charge at 7.2 kW on average, which is a common delivery rate for Level 2 charging now [25].

Multiplying this value with the projections of the number of ground vehicles by interconnection (Section III.B.1), the projections of the EV percentage of the ground fleet (Section III.B.2), and the estimated peak percentage of ground EVs that are charging (Section III.B.3) results in the estimates of the peak electrical power utilized by ground EVs for charging by interconnection that are illustrated in Figure 6.

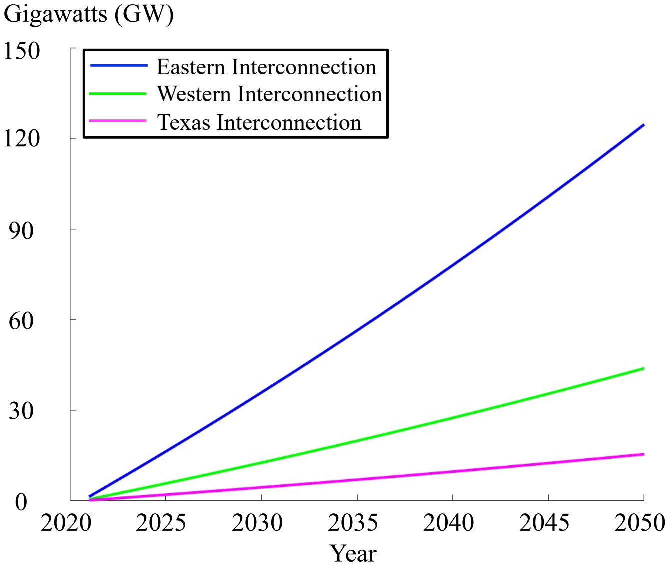

Fig. 6 Estimates of peak electrical power utilized by ground EVs for charging by interconnection.

C. Estimation of Maximum Number of UAM Operations

The maximum number of UAM aircraft that can be charging simultaneously is estimated using the results from Section III.A and Section III.B. First, available electrical grid power capacity for UAM is calculated by taking the difference between available electrical grid power capacity (Section III.A) and peak electrical power utilized by ground EVs for charging (Section III.B). Then, the maximum number of UAM aircraft that can be charging simultaneously is estimated by dividing that difference by a baseline UAM aircraft charging rate (Section III.C.1). After that, the number of UAM aircraft that can be aloft is calculated by applying a scaling factor based on what was observed in a NASA simulation study [20].

1. Baseline UAM aircraft charging rate

In a NASA simulation study, the electrical energy to conduct a baseline 20-nmi flight at 130 kts with cruise power level of 200 kW was estimated to be 156 MJ, which is equal to 43.34 kWh [20]. This approximately corresponds to the electrical energy that would be utilized by the NASA Revolutionary Vertical Lift Technology project's UAM quadrotor eVTOL aircraft reference model [26]-[27]. Assuming 7 minutes of recharging (based on one industry concept of operations [28]), a charging rate of about 371 kW would be required. In this study, a moderately higher baseline UAM aircraft charging rate of 400 kW is utilized to estimate the maximum number of UAM aircraft that can be charging simultaneously because real-world UAM flight operations and charging typically will not occur under ideal conditions.

2. Operational states of UAM aircraft

In the same NASA simulation study, it was observed that 30% of the UAM aircraft in the system were charging at a vertiport, 50% were aloft, and 20% were parked at a vertiport but not charging [20]. Thus, estimates of the number of UAM aircraft that can be aloft are calculated by multiplying the estimates of the number of UAM aircraft that can be charging simultaneously with a scaling factor of 5/3.

D. Summary of Calculations

The methodology in Section III.A through Section III.C is summarized in the mathematical expressions below. For each interconnection, the maximum number of UAM aircraft that can be charging simultaneously is calculated by dividing the available electrical grid power capacity for UAM by the baseline UAM aircraft charging rate of 400 kW. The former is calculated by taking the difference between available electrical grid power capacity (Section III.A)—which is calculated by multiplying the electrical grid power capacity and the national percentage of the electrical grid that is not utilized on average (75%) or assumed to be held in reserve (5%)—and peak electrical power utilized by ground EVs for charging (Section III.B)—which is calculated by multiplying the number of ground vehicles, the percentage of EVs in the ground fleet, the peak percentage of ground EVs charging, and a baseline average ground EV charging rate of 7.2 kW (Section III.C.1).

$$NumUamCharging = \frac{AvailElecGridCapacityUam}{UamChrgRate}$$

$$= \frac{AvailElecGridCapacity - EvPeakChrg}{UamChrgRate}$$

$$= \frac{ElecGridCapacity \cdot (1 - ElecGridUtil - ElecGridRes) - (NumGroundVeh \cdot PctEv \cdot PctEvChrg \cdot EvChrgRate)}{UamChrgRate}$$

$$= \frac{ElecGridCapacity \cdot 0.2 - (NumGroundVeh \cdot PctEv \cdot 0.2 \cdot 7.2\ kW)}{400\ kW}$$

where

$NumUamCharging$ is the maximum number of UAM that can be charging simultaneously
$AvailElecGridCapacityUam$ is the available electrical grid power capacity for UAM (Section III.A-B)
  $AvailElecGridCapacity$ is the available electrical grid power capacity (Section III.A)
    $ElecGridCapacity$ is the electrical grid power capacity (Section III.A.1)
    $ElecGridUtil$ is the percentage of the electrical grid that is utilized (75%; Section III.A.2)
    $ElecGridRes$ is the percentage of the electrical grid assumed to be held in reserve (5%; Section III.A.2)
  $EvPeakChrg$ is the peak electrical power utilized by ground EVs (Section III.B)
    $NumGroundVeh$ is the number of ground vehicles Section III.B.1)
    $PctEv$ is the percentage of EVs in the ground fleet (Section III.B.2)
    $PctEvChrg$ is the peak percentage of ground EVs that are charging (Section III.B.3)
    $EvChrgRate$ is the baseline average ground EV charging rate (7.2 kW; Section III.B.4)
$UamChrgRate$ is the baseline UAM aircraft charging rate (400 kW; Section III.C.1)

The two equations below estimate the number of UAM aircraft that can be aloft and the number of UAM aircraft that may be parked at a vertiport but not charging by applying a scaling factor of 5/3 and 2/3, respectively, based on what was observed in a NASA simulation study [20].

$$NumUamAloft = NumUamCharging \cdot \left(\frac{5}{3}\right)$$

$$NumUamNotCharging = NumUamCharging \cdot \left(\frac{2}{3}\right)$$

IV. Results

Estimates of the maximum number of UAM aircraft that can be charging simultaneously and the number of UAM aircraft that can be aloft were calculated through the year 2050 utilizing the methodology described in Section III. Figure 7 plots these estimates for each of the three interconnections of which the United States is part. The curves in Figure 7 correspond to both vertical axes based on the 3:5 ratio of UAM aircraft charging to UAM aircraft aloft that was observed in a NASA simulation study [20]. For the CONUS, it is estimated that there is available electrical grid power capacity in 2021 for about 595 thousand UAM aircraft to be charging simultaneously and 991 thousand UAM aircraft to be aloft.

The EV percentage of the ground fleet is projected to increase from 0.5% in 2021 [6]-[7] to 40% in 2050 [8]. As ground EVs utilize more of the electrical grid, there will be less available electrical grid power capacity for UAM. In 2050, it is estimated that the maximum number of UAM operations in the CONUS will be about 20% lower compared to now. The Eastern Interconnection has the largest decrease in the maximum number of UAM aircraft charging (about 78 thousand) and UAM aircraft aloft (about 130 thousand). The Western Interconnection has the largest decrease by percentage (36.4%). The Texas Interconnection holds steady in terms of both the maximum number of UAM aircraft charging (about 69 thousand) and UAM aircraft aloft (about 115 thousand). This is due to having a high electrical grid capacity relative to the number of ground vehicles in the region such that the projected 1.54% compound annual growth rate of the former offsets the projected 0.52% compound annual growth rate and increase in the EV percentage of the latter.

Although the overall decrease for the CONUS of 20% may appear to be moderate, this analysis is for a best-case scenario in which electricity can be transmitted and distributed as needed within each interconnection. This is not the situation now, though. Trillions of dollars in investments to enhance both distribution [29] and transmission [30] infrastructure may be needed to achieve this.

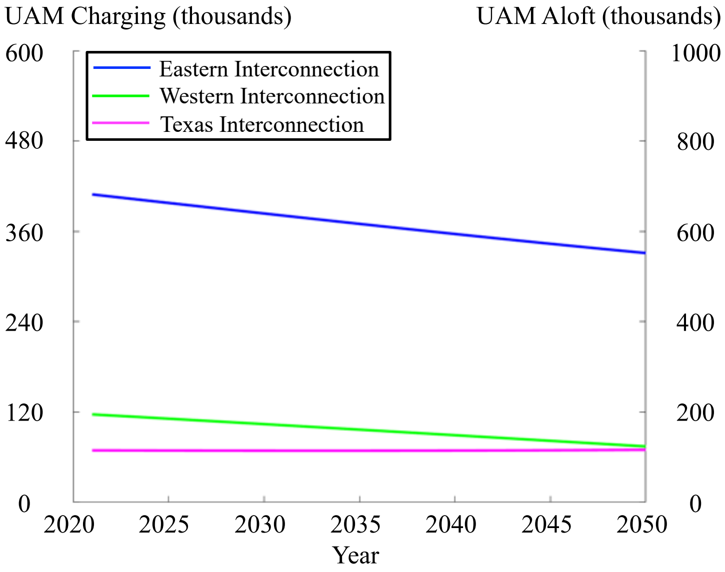

Fig. 7 Projections of maximum number of UAM operations by interconnection.

V. Discussion and Sensitivity Analysis

This study estimates the maximum number of UAM aircraft that can be charging simultaneously and the number of UAM aircraft that can be aloft in each interconnection using baseline input values and projections. However, it may be valuable to conduct a follow-on study to also compute these estimates by individual metro areas (Section V.A) because the amount of electrical power that can be shared within each interconnection is limited by the capacity of transmission lines. Furthermore, as shown in the sensitivity analysis in this section, the number of UAM operations possible will vary depending on a wide range of factors that affect available electrical grid power capacity (Section V.B), UAM aircraft charging rate (Section V.C), peak percentage of ground EVs charging (Section V.D), ground EV charging rate (Section V.E), ground EV percentage (Section V.F), electricity generation capacity growth rate (Section V.G), and population growth rate (Section V.H). These sections are ordered from most sensitive to least sensitive.

A. Analysis by Metro Area

This study estimates the maximum number of UAM operations under the assumption that electricity can be shared as needed amongst the metro areas within an interconnection. However, as explained in the Results section, this is a best-case scenario that is not the situation now and would require major investments to achieve in the future. As such, it may be valuable to conduct a follow-on study to estimate the maximum number of UAM operations in a worst-case scenario in which metro areas can only utilize the electricity that can be generated by the facilities within their borders.

These estimates would be calculated using a methodology similar to what was described in Section III with two differences. First, electrical power capacity would be calculated separately for each metro area by only adding up the nameplate capacities of the utility-scale generators located in the counties that compose each metro area. Second, it would be assumed that the per capita ground motor vehicle ownership for each metro area is the same as the current per capita ground motor vehicle ownership for the state in which it is mostly or entirely located. This assumption is necessary because motor vehicle registration data by metro area is not available. In the follow-on study, a sensitivity analysis should be performed on this assumption.

Regarding the scope of the follow-on study, it may be reasonable to focus on the metro areas that would be more likely to have sustainable markets for UAM operations. More specifically, the follow-on study could focus on metro areas that have population sizes like those that UAM operators have already announced as target markets. For example, Joby Aviation announced plans to “focus initially on Los Angeles, Miami, and the New York and San Francisco Bay Area metropolitan areas” [31]. In addition, Lilium announced plans to develop a network in Florida that is centered in Orlando, with service to the Miami, Tampa, and Jacksonville metro areas [32].

B. Available Electrical Grid Power Capacity

This study used a baseline available electrical grid power capacity of 20% based on the present-day utilization of the electrical grid [22]. However, the actual available electrical grid power capacity for UAM varies by season, time of day, metro area, and interconnection. In addition, electrification in other areas—heating, cooling, lighting, and computing, for example—could also affect the amount of available electrical grid power capacity for UAM.

Figure 8 illustrates the estimates of the maximum number of UAM operations in the CONUS through the year 2050 for different values of available electrical grid power capacity. The low value of 5% is based on what occurred in the late 1960s, early 1970s, and late 1990s [22] and the high value of 35% is a symmetrical representation of what could occur with continued investments and technological advancements in electricity generation [21], transmission [29], and distribution [30]. In the case of the low value, eventually there may not be available electrical grid power capacity for any UAM operations. However, this case is highly unlikely to occur because available electrical grid capacity has generally increased since 2000 due to increased investments in the electrical grid. By comparison, in the case of the high value, additional investments that increase available electrical grid power capacity could enable an increase in the maximum number of UAM operations instead of the decrease seen in the baseline case.

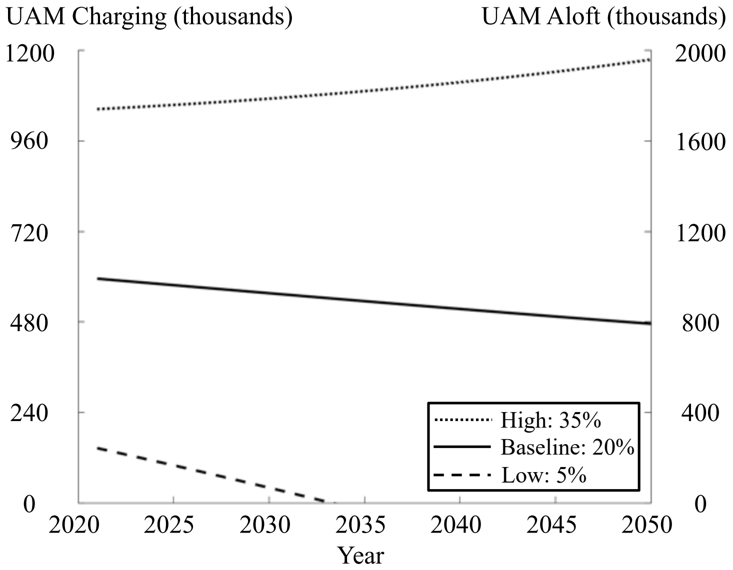

Fig. 8 Sensitivity analysis of available electrical grid power capacity.

C. UAM Aircraft Charging Rate

This study utilized a baseline UAM eVTOL aircraft charging rate of 400 kW, which approximately corresponds to 7-minute recharging [28] of the NASA Revolutionary Vertical Lift Technology project's UAM quadrotor eVTOL aircraft reference model after a 20-nmi flight at 130 kts with cruise power level of 200 kW [26]-[27]. However, actual UAM aircraft charging rates may vary for different UAM aircraft (fully electric or hybrid) conducting different missions under different operating and environmental conditions.

Figure 9 illustrates the estimates of the maximum number of UAM operations in the CONUS through the year 2050 for different UAM aircraft charging rates. The high value of 600 kW is what Black & Veatch determined would "futureproof the design of the infrastructure required" [3]. The low value of 200 kW is a symmetrical representation of what could occur with technological advancements in UAM aircraft such as reducing structural mass and increasing battery energy density. The high value is 150% (or 3/2) of the baseline value and could result in two-thirds of the maximum number of UAM operations in the baseline case. The low value is 50% (or 1/2) of the baseline value and could result in double the maximum number of UAM operations in the baseline case. This is expected because UAM aircraft charging rate is the only variable in the denominator of the mathematical expression utilized to compute these estimates.

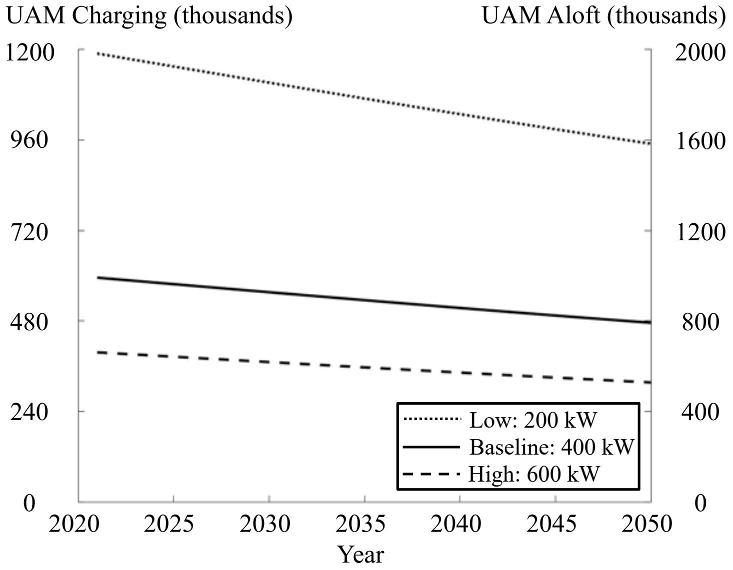

Fig. 9 Sensitivity analysis of UAM aircraft charging rate.

D. Peak Percentage of Ground EVs Charging

In this study, peak ground EV charging occurred around the weekday evening commute, with 20% of ground EVs charging during this time. However, the actual value may vary depending on prevailing electricity rate plans (e.g., time-of-use plans) and operating and environmental conditions (e.g., during summer or winter). Furthermore, this value may decrease over time as more distributed solar photovoltaic and battery storage systems are deployed and ground EV charging infrastructure is built, which collectively would enable more off-grid and off-peak charging of ground EVs.

Figure 10 illustrates the estimates of the maximum number of UAM operations in the CONUS through the year 2050 for different values of peak percentage of ground EVs charging around the weekday evening commute. In addition to the upper-bound uncontrolled charging demand profile that had a peak of 20% of ground EVs charging, the U.S. Drive Grid Integration Technical Team and Integrated Systems Analysis Technical Team developed a lower-bound managed charging demand profile that had a peak of 5% of ground EVs charging during this time using "mechanisms including price signals, direct control, incentives, etc" [7]. These measures could enable an increase in the maximum number of UAM operations instead of the decrease seen in the baseline case. Also, as illustrated by the dashed curve that was calculated using an intermediate value of 10%, a shift of half of ground EVs charging during this time to other times of day could result in a similar reversal, though to a lesser extent.

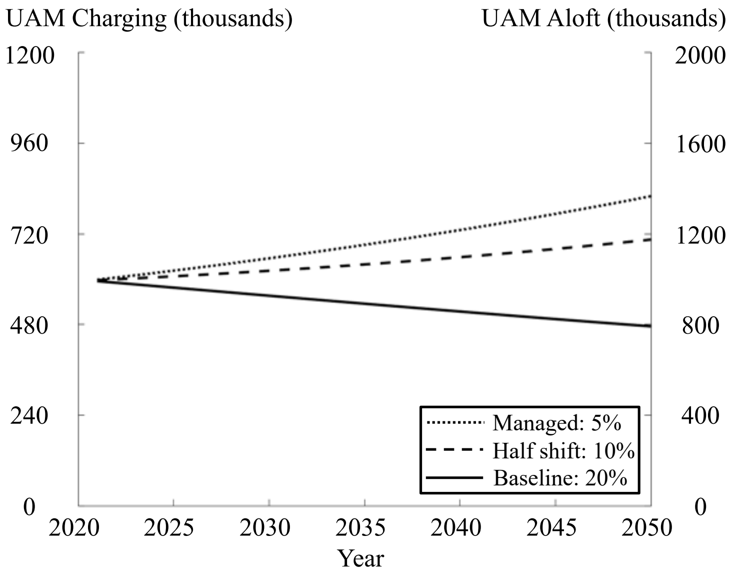

Fig. 10 Sensitivity analysis of peak percentage of ground EVs charging.

E. Ground EV Charging Rate

The rate at which ground EVs can be charged is the lesser of the maximum charging acceptance rate of the vehicle and the maximum delivery rate of the charging station. In this study, it was assumed that ground EVs charge at 7.2 kW on average, which is a common delivery rate for Level 2 charging now [25]. However, ground EVs may have higher charging acceptance rates and more faster-charging infrastructure is expected to be installed in the future.

Figure 11 illustrates the estimates of the maximum number of UAM operations in the CONUS through the year 2050 for different ground EV charging rates. The low value of 4.8 kW and the high value of 9.6 kW are other Level 2 charging options [33]. The latter would reduce available electrical grid power capacity for UAM and the maximum number of UAM operations to a greater extent than in the baseline case. The former would enable an increase in the maximum number of UAM operations instead of the decrease seen in the baseline case. However, this may require advancements in ground EV efficiency and battery technology, without which this case may be unlikely because a lower charging rate could increase ground EV charging times by hours.

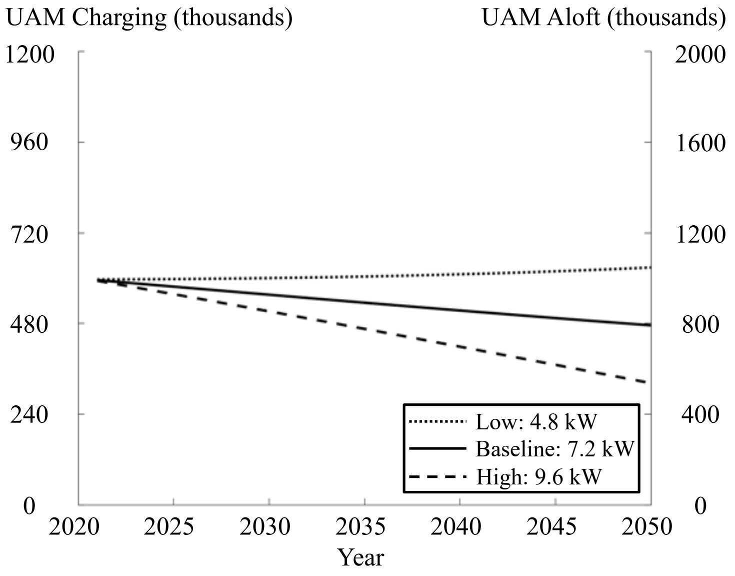

Fig. 11 Sensitivity analysis of ground EV charging rate.

F. Ground EV Percentage

In the baseline estimates in this study, the EV percentage of the ground fleet was projected to grow from 0.5% in 2021 [6]-[7] to 40% in 2050 [8]. Several factors could change these projections, including the relative price of ground EVs compared to internal combustion engine ground vehicles, the extent to which ground EV charging infrastructure is built, and government policies and incentives to spur ground EV ownership.

Figure 12 illustrates the estimates of the maximum number of UAM operations in the CONUS through the year 2050 for different ground EV percentages. The high value of 50% in 2050 is based on the projections by Bloomberg New Energy Finance [6] and the U.S. Drive Grid Integration Technical Team and Integrated Systems Analysis Technical Team [7]. In this case, ground EVs would utilize more of the electrical grid, which would reduce available electrical grid power capacity for UAM and the maximum number of UAM operations to a greater extent than in the baseline case. The low value of 30% is a symmetrical representation of what could occur if ground EV ownership is less than expected. In this case, the maximum number of UAM operations could hold steady through 2050.

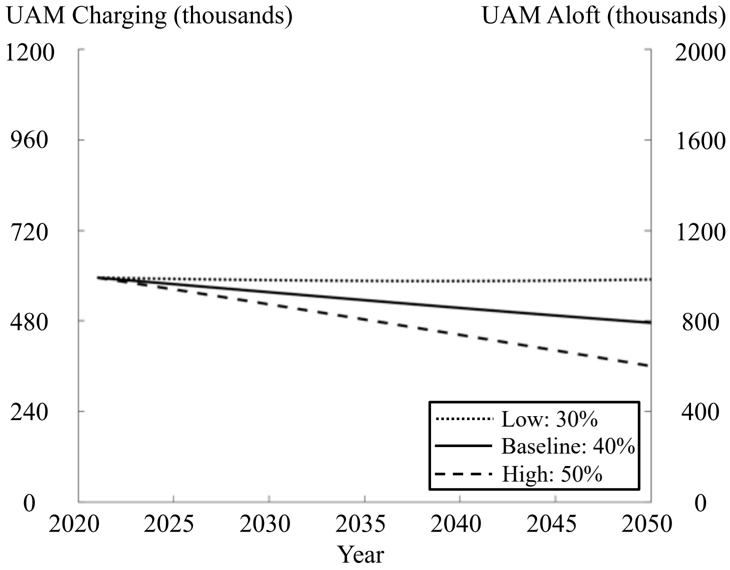

Fig. 12 Sensitivity analysis of ground EV percentage.

G. Electricity Generation Capacity Growth Rate

The baseline estimates in this study utilized the U.S. EIA’s baseline series projection of national electricity generation capacity compound annual growth rate of 1.54% through the year 2050. However, the actual growth rate depends on many factors, including the supply of primary energy sources (e.g., natural gas, coal, petroleum, nuclear, wind, hydro, solar), cost of renewable electricity generation technologies, and economic growth.

Figure 13 illustrates the estimates of the maximum number of UAM operations in the CONUS through the year 2050 for different U.S. EIA projections of national electricity generation capacity compound annual growth rates. The estimates for the scenarios with the highest compound annual growth rate (low cost of renewables) and the lowest compound annual growth rate (high cost of renewables) are shown. The former could enable the maximum number of UAM operations to hold steady. By comparison, the latter would reduce the maximum number of UAM operations to a greater extent than in the baseline case.

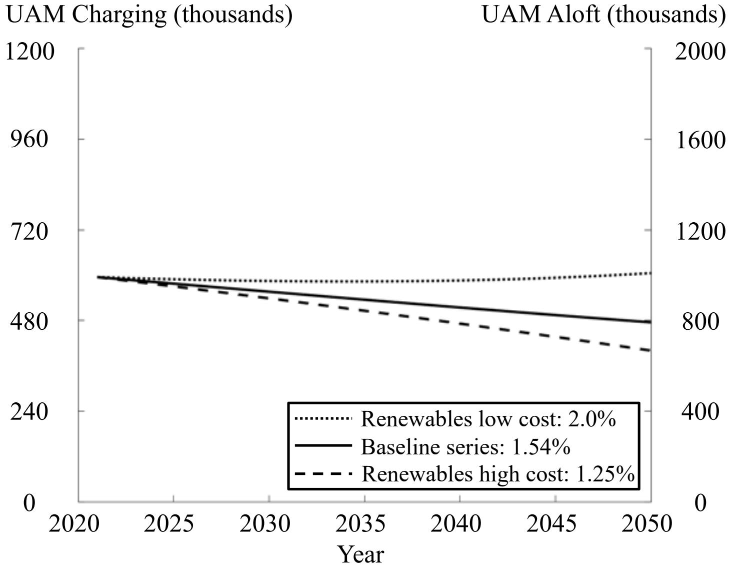

Fig. 13 Sensitivity analysis of electricity generation capacity growth rate.

H. Population Growth Rate

The baseline estimates in this study utilized the U.S. Census Bureau's baseline series projection of national population compound annual growth rate of 0.52% through the year 2050. However, the actual growth rate and, thus, the number of ground EVs and resulting impact on available electrical grid power capacity for UAM depends on many factors, including fertility, mortality, and migration rates.

Figure 14 illustrates the estimates of the maximum number of UAM operations in the CONUS through the year 2050 for different U.S. Census Bureau projections of national population compound annual growth rates. The estimates for the scenarios with the lowest compound annual growth rate (low immigration) and the highest compound annual growth rate (high immigration) are shown. In both cases, the maximum number of UAM operations is estimated to decrease over time at similar rates as the baseline case.

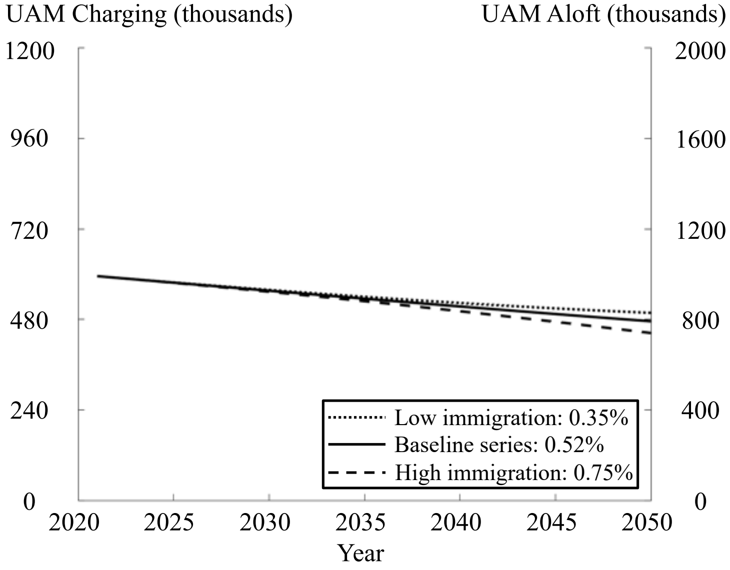

Fig. 14 Sensitivity analysis of population growth rate.

VI. Conclusions

The success of UAM depends on the availability of electricity. Without a sufficient supply of it, UAM eVTOL aircraft cannot be flown and a business case for UAM cannot be made. This paper documents a methodology that was developed and utilized to estimate the maximum number of UAM aircraft that can be charging simultaneously and the number of UAM aircraft that can be aloft as a function of available electrical grid power capacity, ground EV ownership, peak percentage of ground EVs charging, ground EV charging rate, and UAM aircraft charging rate.

Under the best-case assumption that electricity can be transmitted and distributed as needed within each interconnection, it is estimated that there is available electrical grid power capacity in the CONUS in the year 2021 for about 595 thousand UAM aircraft to be charging simultaneously and about 991 thousand UAM aircraft to be aloft. However, due to the proliferation of ground EVs, these estimates may decrease by 20% by the year 2050. These estimates may be even lower if electrical grid utilization, ground EV ownership, ground EV charging rates, or UAM aircraft charging rates are higher than in the baseline case. As such, in addition to technology, regulatory, acceptance, and other infrastructure challenges, available electrical grid power capacity may become a formidable constraint to be overcome to conduct UAM operations at scale as envisioned, especially since electricity cannot be transmitted and distributed as needed within each interconnection now and trillions of dollars of investments to enhance transmission and distribution infrastructure may be needed.

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