A Parametric Battery Model for the Conceptual Design of Electric Aircraft

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Electric aircraft conceptual designs usually have an assumed specific power and specific energy for the aircraft's energy storage system that dictates the total capacity and the peak power available. The specific energy and power are inherently linked to the state-of-charge and discharge rate from which they were derived; therefore, they will not directly correspond to the diverse circumstances encountered in various aircraft missions and flight segments. These parameters turn the battery system into a black box, disregard potential electrical restrictions, and disallow the aircraft and battery to be optimized as a system. Peering into this box, this study highlights the importance of incorporating a parametric battery model into the conceptual design workflow by splitting high-level terms such as power into voltage and current and investigating their variability during the discharge process. Through the modeling of these more detailed parameters, this methodology shows the feasibility of using low states-of-charge for contingency operations, including the end of the reserve mission, expanding the amount of usable capacity for electric aircraft. Stark differences in aircraft capabilities can arise between varying fidelity battery models due to late-mission, high-power flight operations. This parametric battery model effectively captures these differences by evaluating the limitations that arise within the individual battery cells and the aircraft powertrain. This paper shows that the unusable charge of a battery is set by the balked landing power requirement and can realistically range from 5% to 44% based on assumptions. This sets the analog to unusable fuel capacity in aircraft with liquid fuel systems. Needing only aircraft- and mission-level inputs and only seconds of run time, this model is a prime fit for the fast, accurate exploration of the electric aircraft conceptual design space.

I. Nomenclature

I	=	current
L/D	=	lift to drag ratio
m	=	mass
n	=	quantity
$n_{parallel}$	=	number of cells in parallel
n_{series}	=	number of cells in series
P_{aux}	=	auxiliary power
P	=	power
Q	=	charge
T	=	thrust
Δt	=	change in time
V	=	voltage
v	=	velocity
η	=	efficiency
$(\cdot)_{batt}$	=	value for the battery
$(\cdot)_{flow}$	=	value for the flow
$(\cdot)_{pack}$	=	value for the pack
$(\cdot)_{powertrain}$	=	value for the powertrain
$(\cdot)_{propeller}$	=	value for the propeller
$(\cdot)_{shaft}$	=	value for the shaft
$(\cdot)_{terminal}$	=	value for the terminal

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II. Introduction

There is a transformation occurring in aviation towards alternative energy sources. In large part, this transformation is being driven by environmental concerns as the Federal Aviation Administration (FAA) works to make the aviation industry "net-zero sustainable" by 2050 [1]. Thus, aerospace companies and organizations worldwide are seeking to reduce aviation's carbon footprint by exploring alternative energy storage methods, such as natural gas, sustainable aviation fuel (SAF), liquid hydrogen, ammonia, and chemical batteries. This study captures more detailed conceptual-level modeling of chemical batteries, as batteries are approaching a specific energy (SE) that would render electric Regional Air Mobility (RAM) operations feasible for small, short-range aircraft with a battery mass fraction (BMF) ranging from 10% to 30% [2] .

1. Electrified Regional Air Mobility

For this study, RAM operations are defined as 9 to 19 passenger (or equivalent weight and volume in cargo) aircraft traveling relatively short distances up to 300 nmi (further details on RAM operations can be found in Ref. [3]). With potentially lower operating costs, electric RAM could open up new or previously abandoned commuter routes [4, 5], and RAM aircraft are an excellent platform for this study for many reasons. First, RAM aircraft are generally under 19,000 lb, and the peak power and energy required of an aircraft increases exponentially with gross weight [6]. Also, since fuel-burning RAM aircraft would lose a lower percentage of their gross weight for regional flights, the additional energy incurred by the constant weight of an electric energy storage system (ESS) is less penalizing.

Electric motors are more efficient at turning stored energy into shaft power, as 80% to 90% of electrical energy is converted into power, whereas combustion engines convert only 20% to 55% of the fuel energy [6]. The efficiency of aircraft combustion engines scales with size, thus the use of an electric motor for smaller powerplants will save more energy per unit power than if implemented in a larger aircraft. Therefore, electrifying RAM operations can result in a large reduction in cost-per-seat-mile from reducing energy use. To find the role SE has in enabling RAM, results of this study include sweeps of SE with constant weight. The effect of using a Parametric Battery Model (PBM) versus Simple Battery Model (SBM) on RAM aircraft cruise range is also determined.

2. Battery Modeling

Maximizing the percentage of onboard battery energy that can be used is key to unlocking the potential of fully electric RAM operations. Identifying key drivers of the state-of-charge (SOC) limits is paramount. Conceptual aircraft designers have traditionally avoided modeling detailed battery chemistry and have used an SE and an allotted weight of the ESS as a quick method to determine the energy available for an all-electric mission. With this technique, battery characteristics are typically assumed to remain constant, with only a few high-level coefficients constraining the total energy capacity. It is also common when modeling batteries to implement a lower SOC limit to avoid electrochemical damage, e.g., a maximum depth of discharge of 90% (or a lower SOC limit of 10%) [7]. The terms charge and capacity are used throughout this paper, and the SOC refers to the battery's capacity at a given time as a proportion of its maximum capacity.

In 2022, McDonald published a series of articles highlighting the need for a more accurate battery model for aircraft design, and this study is a parametric application of his methodologies to a RAM aircraft. He asserted that although batteries are often assumed to have traits similar to fuel, the reality is there are many unique characteristics that set them apart. It is crucial to recognize the distinctions between batteries and fuel and incorporate the unique attributes of batteries into the aircraft design exploration. McDonald's numerous key distinctions between the behavior of batteries and fuel are summarized below [8].

For energy storage:

- The energy contained in a battery at the beginning and end of a battery discharge is not the same, unlike the energy in jet fuel.
- The rate at which a battery is charged or discharged can affect the battery cycle life and total amount of energy delivered.
- The capacity of a battery cell degrades over its lifetime; the capacity of a fuel tank does not.
- A fuel tank is sized by energy. For a battery system, both mission energy and power can play a role in sizing.
- Refueling can happen at any rate, whereas fast charging can shorten the lifetime of a battery.

As a power source:

- A battery cell's power changes with its SOC as well as over its lifetime, power available in fuel does not.
- Fuel has no limit to the rate it can be consumed, a battery cell can only discharge at certain rates.
- Only the fuel-burning engines are sized by the power required in a mission. For a battery-electric aircraft, power sizes the motor, powertrain, and sometimes the battery pack itself.
- Overall, battery powered aircraft have a number of factors that make their end-of-mission performance worse, whereas fuel burning aircraft perform better due to the reduction in weight.

In addition to the hindrance of lower power and energy availability at low SOC, fuel consumption has another advantage over battery energy storage: fuel consumption results in a 5% to 40% aircraft weight reduction as the mission progresses [6]. Batteries lack this beneficial feature, and every additional pound of battery weight carried causes the aircraft to consume more energy across its entire mission, further limiting an already challenged energy source. The parameters that will underscore the viability of batteries in aviation are buried deeper than the SE that typical "energy-based," or simple models take into account, and a fast, parametric battery model is essential to compute the ever-changing characteristics of the battery system during the mission, which can critically limit mission capabilities.

The effects of the low-charge or end-of-mission (EOM) power limitations of batteries differ between RAM and other emerging electrified aircraft operations, such as electric vertical takeoff and landing (eVTOL) aircraft. The EOM power requirement for an eVTOL aircraft will be close to its maximum power in order to hover in a vertical flight mode [9], whereas the power required for the balked landing climb of a RAM-sized aircraft may be much lower than the maximum power required. A RAM aircraft may be able to use the capacity below its lower SOC limit set for battery life to meet this power requirement; therefore, the modeling of the exact constraining parameters such as voltage and current is paramount. The capacity below the lower SOC limit set for battery life can also be used for the last portion of the Visual Flight Rules (VFR) reserve mission segment, further extending the amount of charge available for contingency operations. Using a deeper examination of batteries, this study determines how much of this lower SOC can be used for rarely performed emergency segments such as the balked landing and VFR reserve mission.

III. Methods

A. Aircraft Inputs

This study used a twin-engine regional aircraft (TERA) baseline derived from a Cessna 402C. To simplify this analysis, the sum of the electric motor, powertrain, and battery weight of the TERA was set equal to the total weight of the combustion engines and fuel on a standard 402C, keeping the maximum takeoff weight (MTOW) the same. The total weight of the ESS and powertrain is held constant to enable the one-to-one comparison with fuel-burning equivalent aircraft and to avoid changing any aircraft-level parameters or requirements. BMF is a key factor in cruise range [5]; therefore, to enable a realistic mission duration at lower battery SEs, a modified 9-passenger aircraft derived from a Beechcraft B100 [10], with extra battery weight equivalent to the weight of four 170 lb passengers, is used as an extended-range twin-engine regional aircraft (EXTERA). This extra usable weight, or exchange weight, grants the EXTERA a higher BMF and more usable weight for its power bus, motors, and ESS.

B. Mission

Figure 1 portrays the mission profile for this study and features a standard climb, cruise, and descent mission. The reserve section in Fig.1 shows the requirements issued from Title 14 of the Code of Federal Regulations Part 23 and Part 135 (also referred to as §23 or §135). Airworthiness Standards §23.2120 requires the aircraft to meet a balked landing minimum climb gradient while in landing configuration [11]. This gradient does not require maximum power, allowing electric aircraft to leverage their lower power availability late in the mission. Additional energy to complete a 30 minute VFR reserve mission is stipulated by Operating Requirements §135.209 [12]. Assuming a constant propeller efficiency and given a constant aircraft weight, the thrust, velocity, and power required of the aircraft is held constant for each mission segment.

1. Standard Mission

For the initial climb segment, a minimum gradient of 4% is required [11] and the speed cannot fall below 1.2 times the stall speed [13]. For the climb flight segments, the climb angle is increased above the minimum gradient along with the speed until the power level is equal to that of the pack maximum set by the balked landing. The missions flown without a balked landing have a battery that is sized to enable the same rate of climb as those with a balked landing. This power-matching keeps the power-related sizing of the battery the same for all missions. The addition of battery power sizing for a PBM would detract from the main focus of this study but should be investigated in subsequent studies. The PBM is capable of modeling the cruise segment with any power setting, but for this study, cruise was flown at maximum L/D, which results in the best range but lower cruise speeds for the aircraft. All descent and approach segments were flown at a nominal power level of 5% to reflect the low-speed, flight-idle thrust conditions. Taxiing and takeoff are not within the scope of this study and were considered as part of the aircraft climb power and energy requirements.

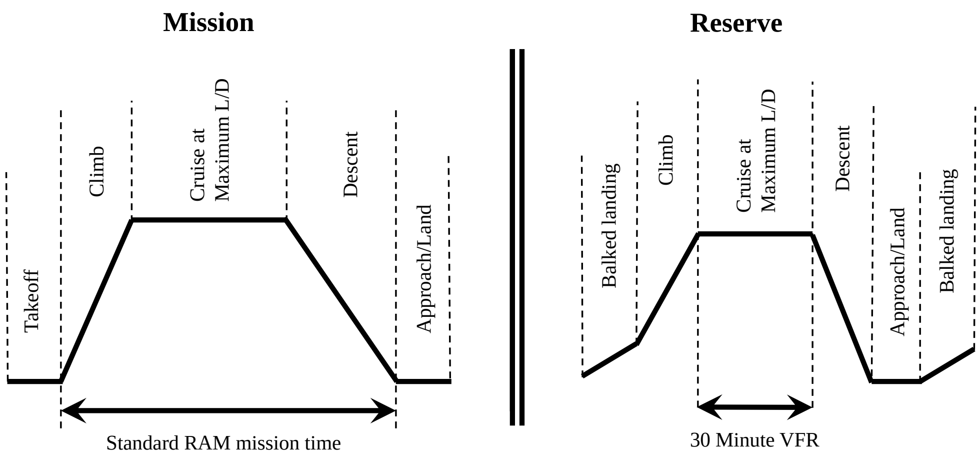

Fig. 1 Example mission profile of a RAM aircraft used within this study.

2. VFR Reserve and Balked Landing

The RAM aircraft considered for this paper would be certified under the Part 23 Airworthiness Standards for Normal Category Airplanes. RAM aircraft will be operating under 14 CFR Part 135, for which the daytime VFR flight reserve requirement is to have sufficient energy (fuel or battery) to perform a powered climb to cruise altitude and loiter at design cruise speed for 30 minutes [12]. For each mission, the reserve flight segment characteristics are identical to those of climb and cruise. The aircraft must be able to perform a balked landing at the end of a mission in the landing configuration, at a climb gradient of 3% at a speed at least 1.3 times greater than the aircraft stall speed in the landing configuration (landing gear extended and full flaps) [11]. The balked landing has a much higher drag coefficient because of deployed landing gear and high-lift devices (HLD) and a lower Oswald's efficiency due to the HLD aerodynamic and lift interference. Given this required gradient, speed, and configuration, a balked landing scenario potentially represents a high power requirement at a depleted SOC, which must be investigated since unlike fuel, a battery may not be able to supply as much power at the end of the mission [8]. Due to the low power required to cruise at maximum L/D, the balked landing or climb segments set the maximum power for the aircraft when modeling the maximum L/D mission.

3. Mission Power and Order-of-Operations

To most accurately simulate the availability of power, the mission is "flown" backwards in time, from the lower to the upper SOC limit. The end of the reserve mission balked landing drives the lower SOC limit, requiring a minimum charge to deliver the power required, and the rest of the reserve mission balked landing is iterated from that point. The rest of the VFR reserve descent, 30 minute cruise, reserve climb, and first balked landing is modeled after this, in that order. The PBM verifies before beginning the iteration of each segment that the charge is high enough to provide the required power. If the charge is not sufficient for any segment's required power, then said segment is now the driver of the new minimum SOC. The segments that require a lower charge are stepped forward in time. For this study, the power requirements of the other segments did not exceed the power required for the reserve mission balked landing climb gradient. Once the energy and power requirements for the reserve mission segments are determined, the standard mission descent and climb missions are calculated. Next, the variable-length cruise segment is flown from the end-of-climb SOC until the battery has hit the SOC at the beginning of the descent segment. The lower SOC limit can be set by an arbitrary value to protect the battery health (i.e., for a mission without any reserve segments), or by the energy and power required for an end-of-mission reserve cruise or balked landing.

The range of the aircraft with a PBM will be compared to that of an SBM. For the SBM, the cruise duration is determined by the energy remaining in the battery after accounting for the mandated mission segments. The SBM will take into account power and segment time when computing the energy used by each segment. Similar to the PBM, the SBM will use the capacity below the 10% lower SOC for reserve segments only, but a typical SBM will not capture the high power requirement as a mission constraint. Therefore, the PBM is critical to confirm that an all-electric mission can be performed.

C. Power and Electric Powertrain

The power and energy required for each mission segment is based on the thrust, velocity, and climb gradients of each segment. The power required to be imparted into the flow, P_{flow}, is the product of the velocity and thrust required for the flight path.

$$P_{flow} = T \cdot v \tag{1}$$

The shaft power is the power that must be delivered to the shaft and is related to the flow power, P_{flow}, and the efficiency of the propeller blade, η_{prop}.

$$P_{shaft} = \frac{P_{flow}}{\eta_{prop}} \tag{2}$$

The last efficiency included in the calculation of the energy and power requirements of the mission is that of the electric powertrain, $\eta_{powertrain}$, which leads to the power required by the battery.

$$P_{batt} = \frac{P_{shaft}}{\eta_{powertrain}} \tag{3}$$

The $\eta_{powertrain}$ term accounts for a number of components between the battery and the motor shaft, each modeled with respective values of efficiency as power travels through the aircraft powertrain. Components include a direct current (DC) to alternating current (AC) inverter, or motor controller, that converts the DC voltage from the battery system to a form necessary to control the motor. To size the powertrain and battery power required, a single converter efficiency is selected, but an efficiency curve for the converter is also integrated within the iterative mission calculations at each time step. Additional components within the power bus include circuit breakers and wires for safety and power distribution. The motors are modeled with constant efficiency for this study. Combining $\eta_{prop} = 0.8$ and $\eta_{powertrain} = 0.89$ results in an overall battery-to-flow efficiency of $\eta_{total} = 0.71$. Once the power out of the battery is calculated, it can be multiplied by the time of each mission segment, Δt, to get the energy delivered by the battery.

$$E_{batt} = P_{batt} \cdot \Delta t \tag{4}$$

All components in the electric powertrain are sized based on the maximum power requirement, from either the balked landing or one engine inoperative (OEI) climb gradient of 2% [11]. The powertrain weight varies with the mission power requirement, resulting in approximately 10.2% of the exchange weight for the TERA and 6.3% of the exchange weight for the EXTERA. The electric powertrain sizing method and power level is the same for both the SBM and PBM models, with the remaining exchange weight of the converted aircraft allocated for the battery, which can be sized by power or energy requirements.

D. Simple Battery Model

1. Overview

The SBM represents a basic battery model for an aircraft, relying solely on SE to determine its mission capabilities, a method that has been used in various studies [5, 7, 14–16]. The specific energy is used along with the allotted battery weight to determine the amount of energy available for the mission segments. For example, a 100 kg battery with a 150 Wh/kg pack SE has 15,000 Wh of energy. To model the most constraining case for the battery, an end-of-life (EOL) limit of 90% of the maximum capacity is used. Also, a discharge range of 95% starting SOC to 10% ending SOC is applied in addition to the EOL limit to enable faster charging and to avoid potential electrochemical damage reducing the battery life-cycle [8]. The primary issue with utilizing the SE parameter to model the amount of energy within the battery system is that the SE value is completely dependent on the rate at which the battery was discharged to obtain the SE value. The SE term will change with rate of discharge [8], and the factory-rated discharge rate will not always be the same as when the battery is discharged during the mission, meaning that this term is an inaccurate description of the usable energy within the battery per unit mass.

2. Specific Power

In addition to the previously mentioned studies that use energy-based modeling, others studies, troubled by the low SE of state-of-the-art (SOA) batteries, invoke the need of single-use, or "primary," Al-air batteries for electrified aircraft operations [6, 15]. These primary batteries have potential for use as high-energy backup systems with ultra-high SE values of 800 Wh/kg [6] or 1500 Wh/kg [15], but proportionally these ESSs have a very low specific power (SP) of 0.13 kW/kg [17]. Both studies incorporating this type of single-use battery do not mention the available power of the Al-air battery per unit weight and have required only a certain discharge rate, or C-rate, from the battery, unrelated to the chemistry or SP. This resulted in one study using ultra-high SE Al-air primary batteries for high-power operations on the order of MW [15], which would require tens of thousands of kilograms of the Al-air battery, highlighting the potential consequences of assuming batteries as merely a "box of energy" with consistently high power readily available.

The incorporation of an SP parameter into a low fidelity model such as this may increase the accuracy without invoking the need of a PBM; this was done to size the battery in NASA's Mild Hybrid Design Exploration [18]. The study incorporated an SP in the battery sizing method, and this drove the size of the battery system rather than SE. In the Mild Hybrid study, the power that the ESS is capable of providing is based on the SP and the weight of the battery pack. For example, a 100 kg pack with a 120 W/kg SP has 12,000 W of power. This use of SP implies the common assumption that battery power characteristics are similar to jet fuel, where the peak power value is available at any point during the discharge of the battery [16, 18]. The issue with this usage of the SP to model a battery system is that the SP of a battery is highly nuanced to how the battery is being used. When correctly using the SP term, one must specify a corresponding SOC at which this SP was measured, because the SP of a battery is closely linked to the SOC of the battery [8]. Since the SOC is constantly changing throughout a mission, and the SOC at which high power segments will occur will change across various mission types, this leads to the conclusion that the SP is an imprecise definition of available battery power for modeling various RAM missions.

E. Parametric Battery Model

1. Process

As stated in the preceding section, SE and SP are not enough to accurately model the available power and energy for any RAM aircraft and mission. The PBM is utilized to delve deeper into the battery system with a detailed mission plot showing the temporal behavior of the parameters within the battery cells and pack. Figure 2 portrays the flow of data from the aircraft parameters and mission concept of operations (ConOps) to the PBM and SBMs as they iterate to simulate the mission.

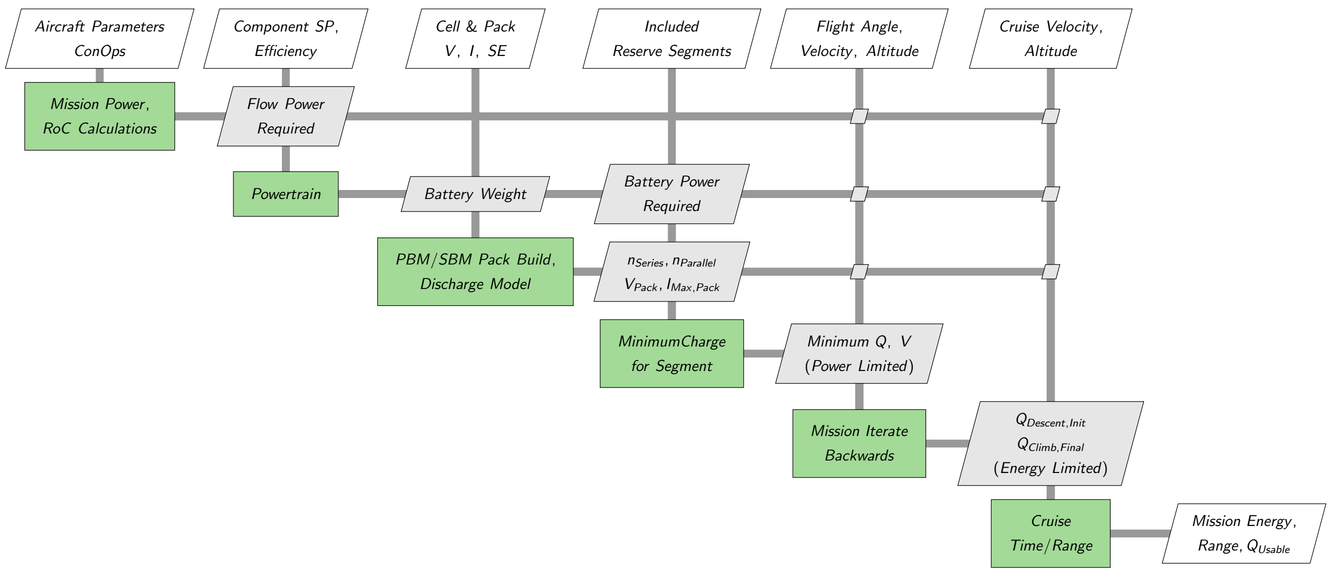

Fig. 2 eXtended Design Structure Matrix (XDSM) with the PBM and SBM.

2. Cell and Pack Inputs

The PBM sizes the system at the cell level. Parameters for a conservative SOA case are shown in Table 1, taken from the cells used in the NASA X-57 Maxwell [19]. The pack-to-cell knockdown factor used in this model is approximately 25% overhead, or extra weight. This factor is an improvement from the X-57's more than 35% but tracks with SOA battery packs [20]. For redundancy, the battery pack is a simplified version of the X-57 battery configuration [19], divided into two systems with multiple submodules. The exact number of cells in each submodule is not modeled in this study to enhance model flexibility, but it is required that at least two cells be in parallel and that all submodules have the same number of cells in parallel. A sweep of the SE values is used to compare to the SBM, implemented by changing the capacity, or total amount of charge (in amp-hours) that each battery cell can hold. Table 1 shows the cell and pack properties of the X-57 [21] compared to a TERA and EXTERA aircraft. The SE and SP values shown in Table 1 for the X-57 were acquired from Ref. [19] at a current of 10 A, and the TERA and EXTERA were calculated at 10 A at maximum SOC.

Table 1 Cell and Pack Properties

Property	X-57	TERA	EXTERA	Units
Cell mass	48	48	48	g
Max mission current	9	20	20	A
Nominal voltage	3.6	4.2	4.2	V
Nominal capacity	3	3	3	Ah
Total pack weight	350 (772)	495 (1092)	1550 (3418)	kg (lb)
Pack SE	150	137	137	Wh/kg
Pack SP	343	751	751	W/kg
Max pack voltage	525	900	900	V
Max pack current	200	800	1200	A
Max power draw	160	580	1027	kW

3. Maximum Pack Current

Also shown in Table 1 are the maximum pack voltage and current used for one of the runs discussed later. These assumed pack limits are inputs to the battery model at the pack level and are the absolute maximum limits on the system, regardless of how much current the cells are capable of providing. Other factors may limit the pack current further below the pack maximum, such as the maximum cell current given by the cell manufacturer. If this value multiplied by the number of cells in parallel is less than the pack current, this is the new maximum current the aircraft is able to use. This cell-limited current occurs in the TERA modeled in this study, but as the MTOW and BMF were increased, the pack level current became the active constraint. The lowest current used in this study, 800 A, is more than double that of NASA's X-57's 363 A [19]. If the battery packs were distributed per motor, like in the X-57, the overall current level would be lower. In this study it is assumed the current limits in place are for a single battery. Neither pack current has yet been demonstrated on a RAM-sized aircraft, but missions performed with current values of the X-57 resulted in completely infeasible missions for these aircraft as they are much heavier and require more power than the X-57. Some companies in the eVTOL industry are beginning flight tests of higher current systems, such as those with a pack voltage of 800 V and maximum power of 1.3 MW [22].

4. *Maximum Pack Voltage*

A cell-driven limit to pack size does not occur for voltage, as the product of the cell peak voltage and the number of cells in series is set equal to the prescribed pack maximum voltage. This maximum pack voltage was set by investigating existing powertrains in electrified aircraft and other vehicles. An ultra-high voltage system in the thousands of volts would reap many benefits of a lower current system–less heat, smaller cable diameter and weight, and higher efficiencies–but a major reason why most electric vehicle systems are not ultra-high voltage is Corona discharge [23]. Also known as voltage breakdown, Corona discharge is the arcing of voltage between conductors in an electrical system, and it is a function of the operating atmospheric pressure: the lower the pressure, the further the partial discharges can travel [23]. Presently, aircraft such as the Boeing 787 operate at a bipolar voltage of ±270 volts direct current (VDC) [24], and NASA's X-57 was designed for a maximum of 538 VDC [25]. Some studies suggest that a bipolar voltage of ±540V or even higher can be safely achieved [23]. Operating at altitudes above 30,000 ft at a higher voltage requires much more durable insulation of the conductors in the system [23] and is outside the scope of this study. Due to the relatively low cruise altitude of our RAM operations, a higher nominal voltage of 900 V was chosen. A 900 V system is only slightly above the 800 V battery systems currently used by some electric car manufacturers and by some eVTOL manufacturers, whose vehicles operate at a similar altitude to RAM aircraft [22, 26]. Future work will investigate the effects of modifying the pack voltage in addition to the current values.

5. *Cell Discharge Model*

Figure 3 shows the cell-level model created for this study, which is derived from the X-57 cell data in Table 1. The various dashed lines in the figure represent the original discharge data of this cell at various C-rates, and the voltage values were interpolated linearly onto the charge-current plane for the data points between. Voltage refers to the potential energy or force behind electrons in a circuit or battery, and current is the measure of the flow of these electrons. As the SOC of the cell decreases, the available voltage drops more than 25%, a prominent trend in Fig. 3 regardless of C-rate. As the available voltage decreases with SOC, the battery must provide more current for the same amount of output power. The same applies to a single SOC; if there is a high power load, the voltage of the cell will decrease as it requires a higher current to deliver this power. This issue is made worse at low SOC because the voltage is already lower than it would be at a high SOC. The impact of these interactions between voltage and current becomes more critical as the SOC decreases. If a high power requirement exists at a low SOC, then the mission can be power-limited due to the cell and pack maximum current.

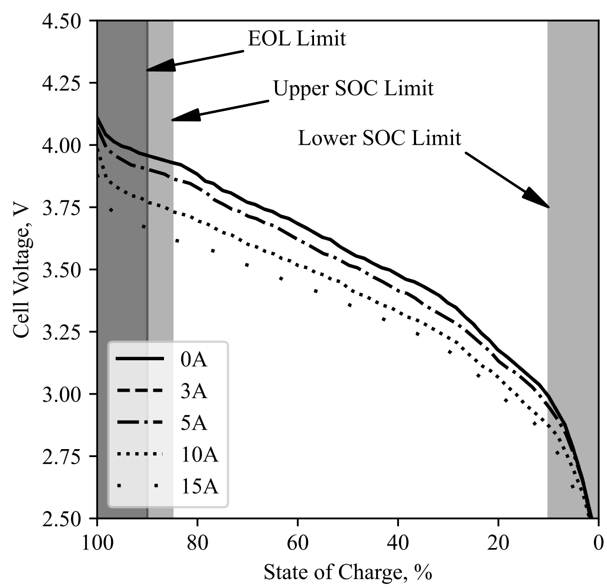

Fig. 3 Discharge characteristics of a single X-57 battery cell.

When determining a cell's usable charge range, this model incorporates flags to toggle different battery scenarios. The EOL region shows the unusable battery energy under the curve, above the maximum usable capacity of the cell. This constraint is set by an EOL flag which limits the maximum SOC to 90% of the original at entry into service (EIS), or a predefined SOC limit if the user prefers the charge to not exceed a specific capacity. Battery internal resistance modeling as a function of EOL is outside the scope of this study. The same SOC SBM limits of 95% and 10% are applied to the PBM in addition to the EOL constraint. The upper constraint leads to lower charging times, due to the constant voltage phase of charging that occurs after the battery is charged to a high SOC. In this constant voltage charge, current is constantly decreasing, taking increasing time to charge the battery to the highest possible SOC [8]. The lower limit of the battery SOC is commonly implemented to extend the battery lifespan, and the capacity below this value is not considered available for mission planning [6]. The capacity below this SOC limit can in fact be used for infrequent flight operations such as balked landing or reserve segments where safety takes precedent over the prolonging of battery life, provided the power required can be met.

It is important to note that an upper limit on the capacity will have a greater effect on the mission for the PBM than for the SBM. This is because the higher the SOC of the battery, the higher the voltage, and the slower it is able to discharge while providing the same power. If the model is simulating a normal flight without additional reserve segments, the end of the descent phase occurs at the lower SOC limit. The lower SOC limits are compared with the minimum charge required to perform a reserve mission, balked landing, and both.

6. Parameterized Model

X-57 cell data relating battery voltage and SOC for different C-rates are utilized to create a parameterized battery cell model, enabling manual adjustment of the cell behavior that controls the resulting pack properties upon formation. The battery cell in this model can be customized to perform like any generic cell as long as parameters such as minimum and maximum charge, voltage, and current of the cell are known. When changing the upper limits of capacity, current, or voltage, the overall discharge curve properties scale with the same slope as the original lithium-ion cell, unless the lower end values are raised as well. Thus, doubling the capacity of a 3 Ah cell to a 6 Ah cell may result in a slightly lower voltage at the lower SOC limit depicted in Fig. 3, but these effects were very small and did not have a substantial impact on the PBM performance. For simplicity, only the higher value of parameters, such as the maximum charge, voltage, or current, are altered. To compare directly to the assorted SE values in the SBM, the overall charge (capacity) of each cell is modified to raise the overall pack specific charge (SC), or SE, for the PBM. SC refers to the electric charge carried per unit mass, instead of the amount of energy.

7. Pack Configuration

With a fixed battery weight for the TERA and EXTERA, each aircraft has a predetermined number of cells. The entire battery is constructed by arranging cells in series until their maximum voltage available during the mission reaches the pre-set maximum voltage (900 V for this study). Equation 5 defines V_{pack} as the product of the cell (terminal) voltage, V_L, and the number of cells in series.

$$V_{pack} = V_L \cdot n_{series} \tag{5}$$

Next, the remaining battery cells not arranged in series are configured in parallel, determining the number of cells in parallel per submodule, as well as the total number of submodules. These submodules are subsequently interconnected in series, with the overall number of cells in series equaling the aggregate of n_{series} in each submodule. In this calculation, fractional numbers of cells are allowed to avoid submodule configurations affecting the final results. Detailed submodule construction is outside the scope of this study and is assumed to take place later in the design process.

$$n_{parallel} = \frac{n_{total}}{n_{series}} \tag{6}$$

The pack current, I_{pack}, is the product of the cell or terminal current, I_L, and the number of cells in parallel within each submodule.

$$I_{pack} = I_L \cdot n_{parallel} \tag{7}$$

Equation 8 constructs the complete battery pack power available at any time during the missions as a function of the package voltage and current, less the auxiliary power requirements for the aircraft.

$$P_{pack} = (I_{pack} \cdot V_{pack}) n_{pack} - P_{aux} \tag{8}$$

There may be other elements in practice that modify the number of cells in parallel, namely, to bring the pack current down or otherwise optimize the system, but these methods are not considered in this paper.

IV. Results

In this section, visual representations and data tables illustrate battery performance given power demands specific to climb, cruise, descent, and reserve segments. Unless specified otherwise, all of the following results are for the maximum range mission flown at maximum L/D and 10,000 ft in the 1976 U.S. Standard Atmosphere, which results in true airspeeds of 130 kts for the TERA and 136 kts for the EXTERA. These speeds are relatively slow for fixed-wing aircraft and result in an optimistic range for the relatively low SE battery in an EXTERA. The aircraft for this study use a powertrain sized by the highest power requirement from either the balked landing segment or a OEI case. The OEI requirement is a 2% climb gradient at 400 ft above the takeoff surface, and depending on the power required from an individual motor, sized the motor and relevant components within the electric powertrain. The converter efficiency within $\eta_{powertrain}$ was integrated into the iterative segment calculations with an efficiency curve to approximate penalties for voltage changes.

A. Standard, Balked landing, and Reserve Mission

Fully electric aircraft were assumed to adhere to the same regulations as their fuel-burning counterparts. For a RAM aircraft operating under the requirements for VFR under Part 135, there must be enough energy and power to fly a missed approach segment, a reserve cruise segment, and perform a balked landing at the end of the reserve mission [11]. In this study, a balked landing was modeled before the reserve mission, rather than a missed approach for simplicity. The balked landing has a higher power requirement than a missed approach due to the aircraft configuration, but this was not found to substantially impact any results in this study since it does not occur at a power constrained SOC.

When the aircraft has no separate ESS for reserve segments, accounting for all of the end-of-mission requirements is the most taxing of the three scenarios investigated in this study. With a pack level SE of 600 Wh/kg, the EXTERA maximum L/D mission without reserve achieves a maximum cruise range of 190 nmi compared to just 77 nmi with reserve segments. Accounting for reserve segments is clearly detrimental to cruise range, but the mission model allows the battery charge to be lower than an arbitrarily prescribed minimum at the end of the reserve mission (such as 10%). The prescribed minimum is not enforced for the end of the reserve mission because the reserve is a contingency operation and an operational energy requirement, not a routine mission requirement that would be exercised daily (and likely not used in its entirety for the life cycle of any individual aircraft). Figure 4 shows the battery charge, power, voltage, and current behavior for two separate missions: the standard mission without any energy stored for reserve (but with the prescribed minimum SOC enforced), and the standard mission with a reserve and two balked landings (one before and one after the reserve mission).

The pack level limits of 900 V, 1200 A, and their resulting peak pack power are shown as dotted and dashed black lines in Fig. 4. When combining the decay in voltage with a maximum current constraint, the peak power drops more than 20% by the end of the mission, as seen by the dashed line in the plots showing power versus time. Due to its high power requirement, the balked landing segment at the end of the mission in Fig. 4b requires a minimum charge of approximately 5%. The balked landing is then iterated backwards in time from an SOC of 5%, meaning that the charge below this is entirely unusable. Note that the balked landing performance requirement sets the absolute minimum SOC that can be used for mission planning. The remaining SOC is analogous to the unusable fuel volume in aircraft with liquid fuel systems–it is energy that cannot be used for primary or reserve mission planning purposes.

The minimum SOC ensures the battery can provide enough voltage to meet the high power requirement for the entire segment duration without exceeding the pack current limit of 1200 A. This maximum pack current limit makes it incredibly challenging to meet a high power requirement when the available voltage declines. The exponential decrease in available cell voltage in the last 10% of the battery capacity only exacerbates this issue. A power-derived SOC limit of 5% means that the battery must be at least at 5% capacity to meet the balked landing climb gradient power. This new power-derived SOC limit enables half of the remaining capacity below the arbitrary 10% SOC limit to be used for infrequent reserve mission operations. If the arbitrary lower limit of 10% were to be increased to 15% or 20%, then the lower capacity enabled for reserve mission segments would increase. The use of this lower SOC capacity for the reserve mission segments leaves more capacity available for the standard mission. This low-power and low-SOC section of the battery is only suitable for use when its power limitations are properly modeled. It is assumed that if the need to perform a reserve mission arises, the health of the battery is no longer a priority. The analysis to quantify the impact on battery longevity from this use case is beyond the scope of this study.

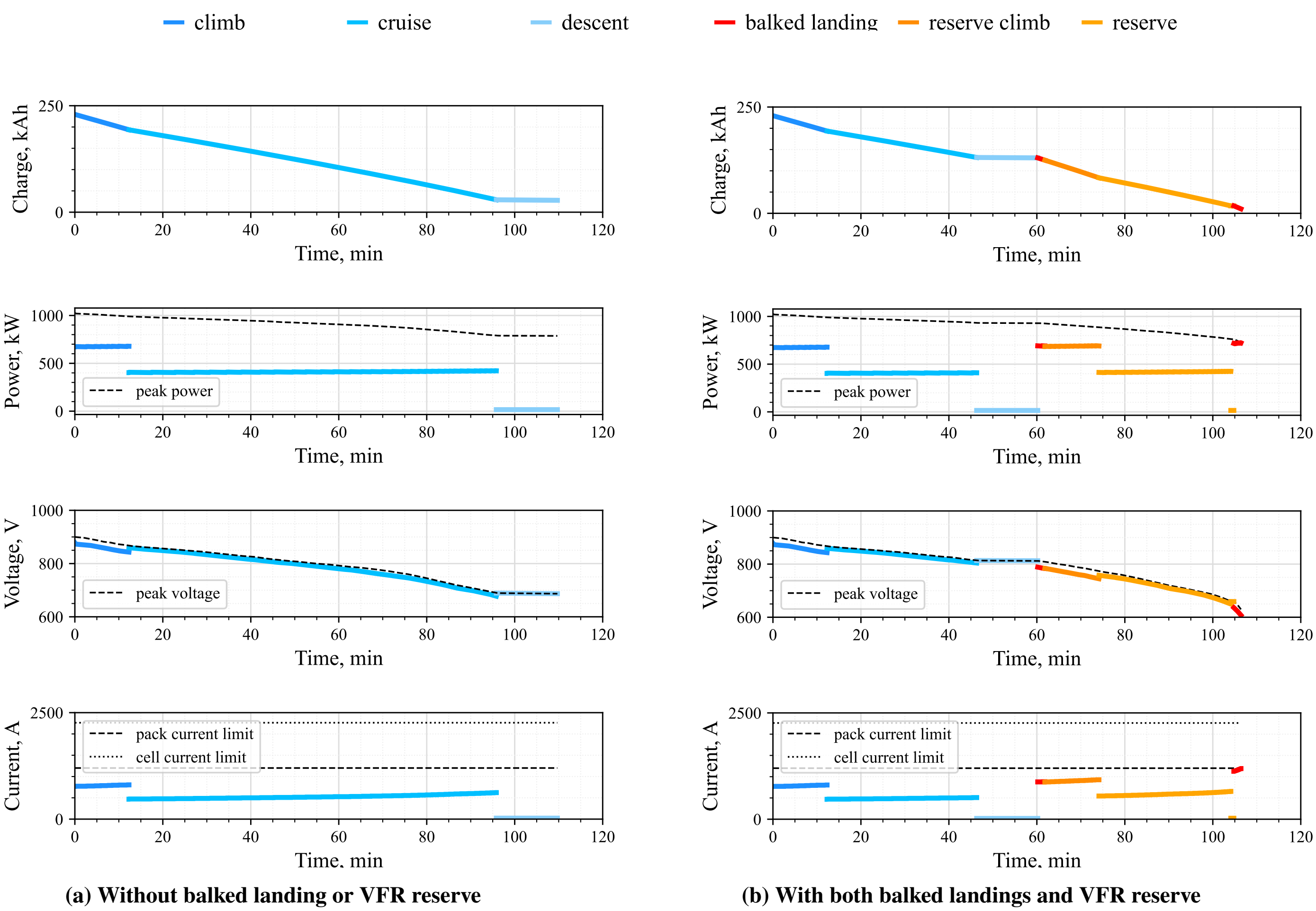

Fig. 4 EXTERA 600 Wh/kg pack discharge behavior for the max range mission showing impacts of including balked landings and VFR reserve.

B. Aircraft Comparison

Previous analysis showed that the TERA vehicle required an SE of 675 Wh/kg to achieve the RAM goal of at least 100 nmi [3] without including any reserve segments, thus the EXTERA with extra battery weight was also investigated. When performing sweeps of SE values, the TERA required at least 250 Wh/kg of pack-level battery SE to complete climb at any power setting that meets requirements, reach cruise for a few minutes, and attain the minimum SOC limit at the end of descent, all with zero margin for reserve.

Thus, the 16% BMF of the TERA is insufficient at the SE values used in this study even prior to adding the requirement of storing extra energy for reserve mission(s). Figure 5 shows the cruise range of a TERA and EXTERA with a 800 Wh/kg battery pack, which is the minimum required SE for the TERA to reach cruise with energy for a full reserve mission. The cruise ranges for the TERA and EXTERA in the missions shown are approximately 11 nmi and 162 nmi. A pack SE of 800 Wh/kg is extremely optimistic, but the aircraft used in this study are far from optimal for electrification in terms of BMF and other aircraft parameters, such as maximum L/D and speed at which this maximum is attained.

The added energy capacity in terms of additional BMF in the EXTERA facilitates better observation of parameter behavior for missions flown with a lower battery SE. The immense performance disparity between the two aircraft highlights the benefit of a higher BMF for RAM aircraft. The 16% BMF for the TERA is relatively low due the battery and powertrain weight being set equal to the sum of the aircraft fuel and engine weight, whereas the EXTERA has additional weight allocated for the ESS. The EXTERA BMF of 29% is almost double that of the TERA, meaning that there is more energy-storing mass for every pound of MTOW. This study was deliberately simplified to show the impact of changing BMF and SE on the battery performance for a retrofit electric aircraft concept (TERA and EXTERA). Further studies are planned to take a more in-depth look at the RAM aircraft design space.

The difference in power between the two aircraft is expected due to the 11,800 lb MTOW of the EXTERA, which is much higher than the TERA's MTOW of 6850 lb. This means the larger an aircraft, the higher the current and/or voltage it will need for an identical flight segment. SBMs often ignore this element, although some may introduce a battery SP to account for the potential power available from the ESS. The use of an SP can improve accuracy, but it does not account for the decay in power availability to the same level of fidelity as a PBM. This is due to the term's dependency on an SOC, and therefore it would not be directly applicable to different mission segments with varying SOC. To model the temporal voltage behavior without the use of a PBM, terms to represent the temporal peak power decay during the mission and lifetime would be needed, and these terms would still gloss over the implications of a higher voltage or current system.

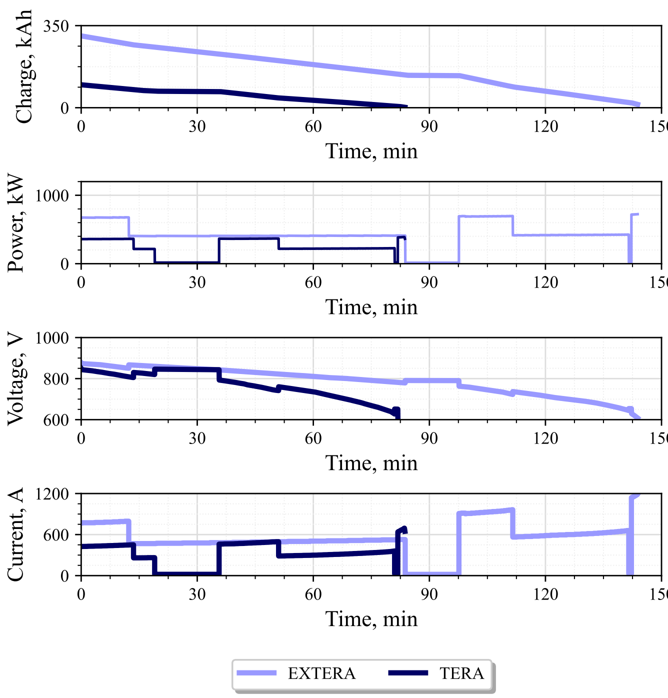

Fig. 5 800 Wh/kg pack discharge behavior for the TERA and EXTERA.

C. Lower State-of-Charge Limit

1. Parametric Battery Model SE and Current

One of the most important aspects of this PBM is finding the lower SOC limit that represents the true usable charge of a battery. A fully electric RAM aircraft with a higher SOC limit will have less usable charge and a reduced cruise range. A lower SOC limit for the standard mission represents the SOC at the end of the descent segment, and Fig. 6 shows how this lower SOC limit changes with varying amounts of reserve segments. To be explicit, the charge below the arbitrary 10% lower SOC limit was used for the reserve segments in every analysis in this study. If the charge below this unsubstantiated charge limit was left unused, then the usable capacity would be up to 10% less for all results.

There are a considerable number of variables within a PBM that can affect the usable SOC. Figure 6 shows the relationship between two of these variables, the SE and current, with values swept to show their effects on the lower SOC limit. From left to right, the missions shown in the contour plots require more reserve segments: from none, to a single balked landing, to both balked landings and a reserve. The current values selected in this study are only relevant for the respective voltage and power values of the EXTERA aircraft. The TERA is not used for this study because it had a cell-limited pack current below 800 A due to its lower quantity of battery cells. The constraining current level for each aircraft also changes as a function of system voltage or total number of cells, so it is essential to understand the correlations between variables rather than focus on the individual values.

The primary mission (consisting of only cruise, climb, descent) is flown until the commonly implemented 10% lower SOC limit. A lower SOC limit of 10% in Fig. 6 means that the entirety of the capacity exceeding this value was used for the standard mission. As the lower SOC limit increases, the usable capacity of the battery decreases for the standard mission, and any SOC limit higher than 80% in Fig. 6 means that the mission was infeasible. Without the need to store energy for any reserve or balked landing (BL) requirements (far left), the lower discharge limit remains at the predetermined minimum SOC, except for when pack current is below 1000 A and SE values are under 250 Wh/kg. The results for the mission with only balked landing are driven by current and almost completely independent of SE, as the balked landing is both low energy and high power.

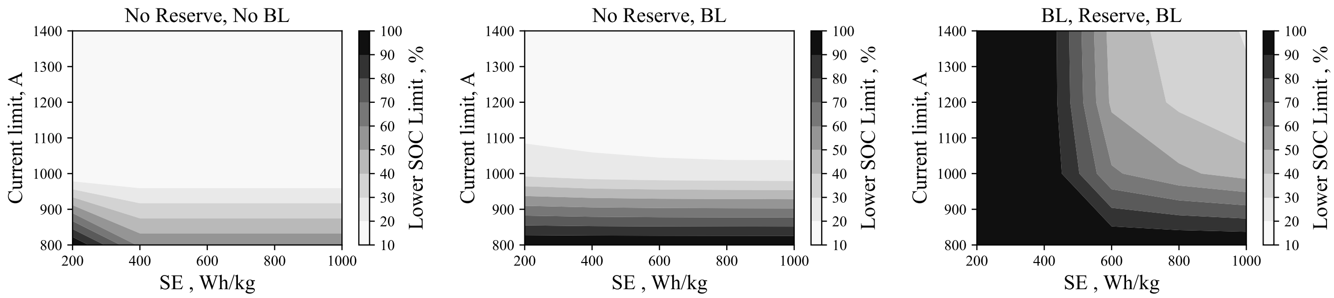

Fig. 6 Lower charge limit of PBM model with varying SE and current.

The mission with all reserve requirements (far right) is infeasible with a pack SE below 600 Wh/kg, hence the lower discharge limit of 100%. There is an artifact from the interpolation showing the contour falling below this value, but the trend between current and SE is valid: as SE increases, then the current is less constraining. As SE increases, the portion of battery that must be used for all reserve missions makes up a lower percentage of the total battery capacity. This means that as battery technology improves, lower SOC limits become less constraining. Furthermore, as long as there is enough current or voltage available at EOM, SOC limits set by power can be less constraining as well. For example, the lower SOC limit of a battery with an SE of 600 Wh/kg is highly dependent on current; a high pack current limit could result in a lower SOC limit of 30%. Another important result is that the lower charge limit does not fall below 20% for the EXTERA aircraft with any SE when including all reserve segments. This high limit is due to the combination of the energy requirement of the VFR reserve cruise segment and the power requirement of the balked landing segment. This highlights the importance of modeling the exact power and energy requirements of the reserve mission to determine the actual usable battery capacity.

2. Parametric Versus Simple Battery Model

The most notable differences between a PBM and SBM occur when one of the parameters in a PBM clearly constrains the mission. At the same SE there can be a sizeable difference between the two models if the underlying parameters for high power are not modeled. Figure 7 illustrates this, showing a cruise range disparity between the PBM and SBM of 68 nmi for a 400 Wh/kg battery pack and 128 nmi for an 800 Wh/kg battery pack.

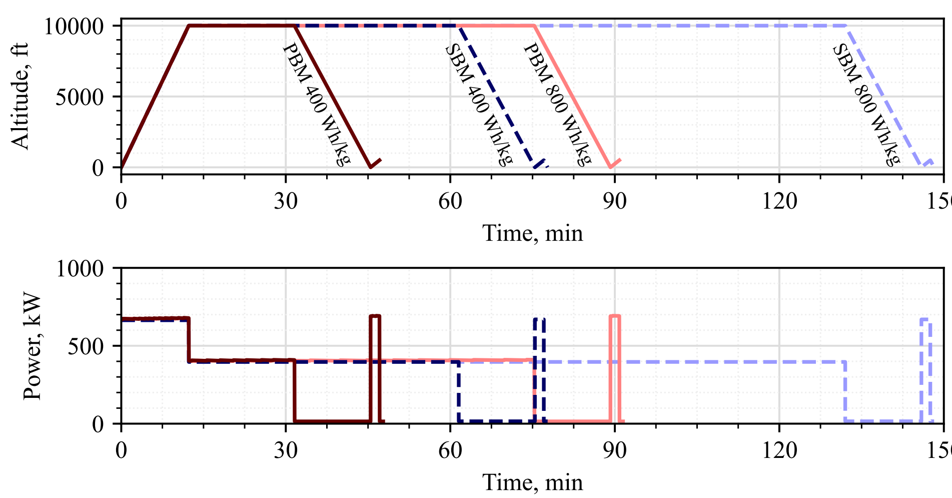

Fig. 7 PBM at 900 A versus SBM for an EXTERA mission with a single balked landing and no reserve segment.

In this case, there is an EOM high power requirement and the pack current is the constraint for power availability. The SBM does not account for the power requirement or the decay in voltage that leads to the maximum current limit.

An SP term could bring the results of the SBM closer to those of the PBM, but again, the SP term is defined at a specific SOC and therefore would incorporate further inexact approximations into the model. This gap between models at insufficient pack current levels only widens as the SE of the battery increases, and this disparity further accentuates the need for the accurate modeling of high system current or voltage implications. Note that the SE values for the PBM are calculated from a constant discharge rate of 10 A. When non-constraining values are given to the parameters such as maximum current or voltage, the results of the two models converge on a similar solution. In the case of maximum current, this trend can be seen in Fig. 8, which is similar to Fig. 6 except the difference in lower charge limit between the PBM and SBM is shown. The SBM lower SOC limit for the standard mission usable capacity varies with the SE of the battery, since this determines how much of the battery energy is required for the reserve mission. The PBM lower SOC limit is dependent on the current, SE, and reserve power requirements.

Figure 8 represents the stark contrast between the SBM and PBM when variables such as current are modeled. When computed with a high battery SE, a high current limit, or low reserve requirements, the models do not differ. The same trends are visible in Fig. 8 as in Fig. 6, but these plots highlight where the SBM and the PBM results disagree the most.

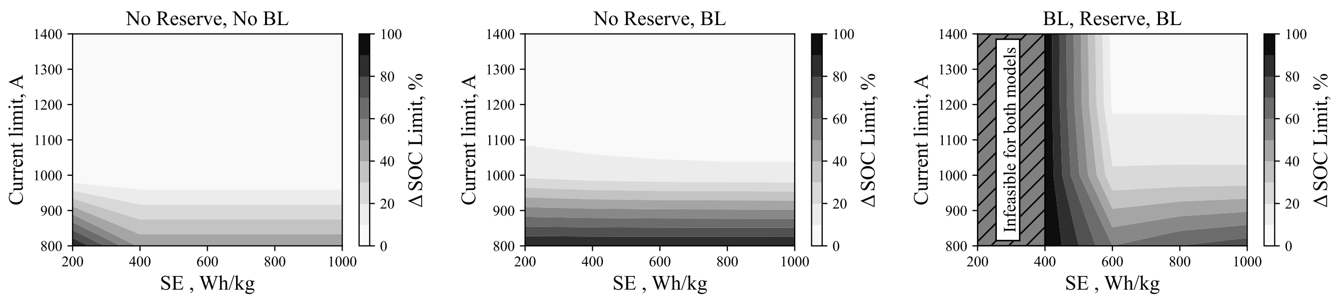

Fig. 8 Lower charge limit delta of PBM vs SBM with varying SE and current for EXTERA.

The lower SOC limit differs between the two models for the mission without any reserve (far left) when the current or SE values are excessively low due to the high power required for climb. A 100% ΔSOC limit means that the SBM was able to fly the mission but the PBM was not. For the standard mission the PBM accounts for the high power requirement of cruise with its low current availability and is unable to meet the mission requirements, whereas the SBM only uses energy. The difference between the two SOC limits is the greatest for late mission segments where high power requirements are introduced and the pack voltage is at a minimum. The power-limited mission with only a balked landing segment and no reserve mission incurs a power penalty without introducing extra battery energy required for a reserve segment. The difference between this mission and that without any reserve segments is due to the introduction of a high power requirement that the PBM considers; the SBM optimistically assumes that the power required for balked landing is always available. For the full reserve and balked landing segment (far right), the infeasible region of lower SE previously seen in Fig. 6 is labeled in Fig. 8. When the VFR reserve is introduced along with balked landings, both models must accommodate the extra energy of the lower power VFR reserve mission in addition to the balked landing. As SE increases, the low current end of the plot illustrates where a mission was feasible with the SBM but not with the PBM, due to the pack current limit. This results in the PBM being unable to fly the mission at lower SEs due to the VFR reserve climb and cruise power requirements that the SBM does not consider.

D. Aircraft Range with the Parametric Battery Model

As stated previously, the SBM is essentially an optimistic PBM, and the parameters that are ignored in the SBM must be accounted for and their effects well documented. This paper has already discussed lower discharge limits, but now the trends that impact the range of the aircraft will be investigated with the PBM. The maximum range mission was used in this analysis, which will result in a more optimistic range than a higher-powered, faster mission. Figure 9 shows the range for an EXTERA aircraft with the three types of reserve missions discussed in the preceding sections. These plots show the relationship between pack current limit and feasible cruise range specifically for an aircraft with a BMF of the EXTERA (29%), and will change greatly with BMF. The mission-limiting trend of low current and low SE can be observed in all missions via cruise range. Also, a low-weight method of storing the energy for reserve segments can result in substantially more range for an EXTERA-sized aircraft.

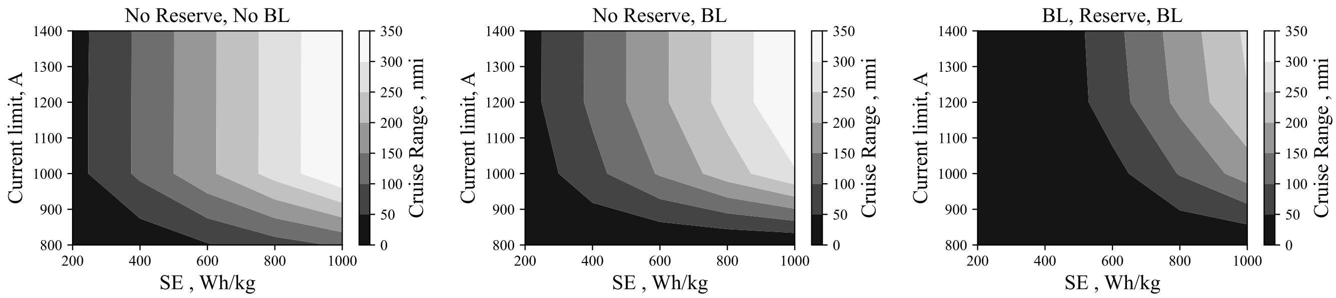

Fig. 9 Cruise range of EXTERA with varying SE and current.

With a pack SE of 400 Wh/kg, the RAM retrofit aircraft modeled in this paper flying only the primary mission at maximum L/D can achieve a cruise range of 100 nmi, given that the battery has sufficient pack current. In the event that the aircraft needs to use the same ESS for its reserve segments, the primary mission cannot be completed. When the battery is tasked with the energy storage for reserve segments, the cruise range drastically drops for the EXTERA. For an aircraft with a lower BMF such as the TERA, this is even more hindering, with over 750 Wh/kg required to have a cruise range greater than zero. The use of high current or voltage systems could help alleviate the challenge of such a high SE requirement, but their impact has yet to be modeled.

V. Conclusion

There are many more variables and intricate relations within this model to investigate, but overall this study has shown that the detailed modeling of battery parameters has the potential to more accurately define the mission capabilities of RAM aircraft. Using specific attributes such as voltage and current, this study has explained the use of a battery model for RAM aircraft and compared various aircraft, battery SEs, ESS requirements, and battery model fidelities. This study has compared the range of two simplified retrofit RAM aircraft with varying lower SOC limits and shown that when accounting for reserve missions, the aircraft are limited by both energy and power. For mission planning purposes, the unusable amount of energy in the battery is set by the balked landing power requirement. The often-implemented lower SOC limit of 10% does not provide enough energy to meet all reserve requirements, but this study has shown that some of the charge below this limit can be used for a portion of the reserve mission energy requirements, even with an EOM high power requirement. Both the SBM and PBM show that the portion of a battery's capacity required for reserve or balked landing mission segments is inversely related to the SE of a battery ESS, but identifying the key drivers of this minimum SOC is critical to advancing fully electric aircraft.

The use of a separate emergency ESS, or the main ESS in tandem with a parallel-hybrid reserve architecture, are viable options for unlocking more energy for RAM operations while remaining capable of performing reserve segments. Overall, the PBM tracks closely with the SBM under the condition that the pack current and voltage do not constrain the vehicle's battery operation. If the electric powertrain and battery are not designed with these implications in mind, then an SBM will not accurately model the capabilities of the aircraft. The inaccuracies of an SBM will only increase with the higher voltage and/or current of larger aircraft; therefore, it is vital that the potential impact of a system is correctly modeled. Additional research is warranted for PBMs to investigate the interrelationships between the numerous parameters not highlighted by this study, such as the effects and implications of pack and cell voltage, SP, MTOW, and aircraft configuration. This battery model also enables co-optimization of mission climb gradients and speeds with the battery ESS, which can be used to maximize the performance of fully electric RAM aircraft.

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