EPIC
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Managing Range and Endurance of Battery-Electric Aircraft

A report by the Hybrid & Electric Propulsion Subcommittee of the GAMA Electric Propulsion and Innovation Committee (EPIC)

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1. Introduction

1.1. Foreword

Lithium-ion batteries were first commercialized three decades ago, resulting in a major technological shift in the mobile electronics industry. As battery technology has improved over the years, electric ground vehicles have become competitive with those powered by internal combustion engines. No longer a niche product, electric ground vehicles have become an appealing option for a growing number of consumers. Ongoing advancements in battery technology have also made electric aviation viable, with prospects of even greater energy density and cycle life in the future.

It may seem natural to compare an electric vehicle's battery pack to the fuel tank of a conventional vehicle. Like a conventional fuel system, an aircraft's high voltage energy storage system (HVESS) must be capable of supplying sufficient power to all essential loads during the intended mission.[1] While these two forms of energy storage have some similarities, they also have differences, which are especially significant for aviation. For fuel-based systems, a pilot simply needs an indication of fuel quantity to assess the present energy state and burn rate. For battery electric aircraft, an accurate assessment of a battery's remaining performance requires more than a single measurement, such as voltage. Manufacturers of these aircraft must provide clear and concise energy information so that pilots can make sound decisions.

This white paper aims to clarify the nuances of range and endurance management for battery-powered aircraft, including electric conventional takeoff and landing (eCTOL) and electric vertical takeoff and landing (eVTOL) variants. It highlights the differences pilots may encounter compared with the fuel-

[1] System power generation, storage, and distribution, 14 C.F.R. § 23.2525, 2023.

based aircraft with which they are familiar, even as the goal of safe flight and landing remains the same. By comprehending these intricacies, aviation professionals can effectively navigate this new and evolving landscape.

1.2. Executive Summary

GAMA recommends that civil aviation authorities acknowledge and assess the unique performance characteristics of HVESS. This evaluation is essential to fostering development of a performance-based regulatory approach to energy management, one that complements existing time-based rules and covers all aircraft types. Recognizing that electric aircraft do not have a single metric to assess battery performance, we propose a performance-based energy reserve concept. This approach calls for mission-specific energy hazard assessments, acceptable to civil aviation authorities, that incorporate the essence of time-based reserves into operational planning. The primary aim is to advance safety by identifying potential mission points where adequate margin for all foreseeable energy contingencies might be compromised.

2. Comparing Batteries to Conventional Fuel

2.1. Performance and Fuel Consumption

Both fuel-burning and electric aircraft depend on a powerplant and an inline energy storage system for propulsion. In a conventional fuel system, fuel tanks are responsible for energy storage, while the maximum flow rate of an aircraft fuel pump, or fuel lines, determines power capability (ignoring pressure altitude effects). In a high voltage energy storage system, however, energy storage and power capability are intrinsically linked within the battery itself (see Figure 2.1). The power capability of the HVESS is a function of many factors, including the energy state of the battery.

At constant pressure altitude, fuel-based systems can deliver constant power down to essentially the last drop of usable fuel. Moreover, there is a direct relationship between remaining fuel and endurance; at a constant power demand, there is a constant fuel consumption rate. Because fuel consumption rates are predictable based on conditions of operation, it is relatively easy for a flight crew to determine how much longer the aircraft can perform. While combustion engines are subject to additional factors that affect propulsion performance, the key factors and their relationships are relatively static.

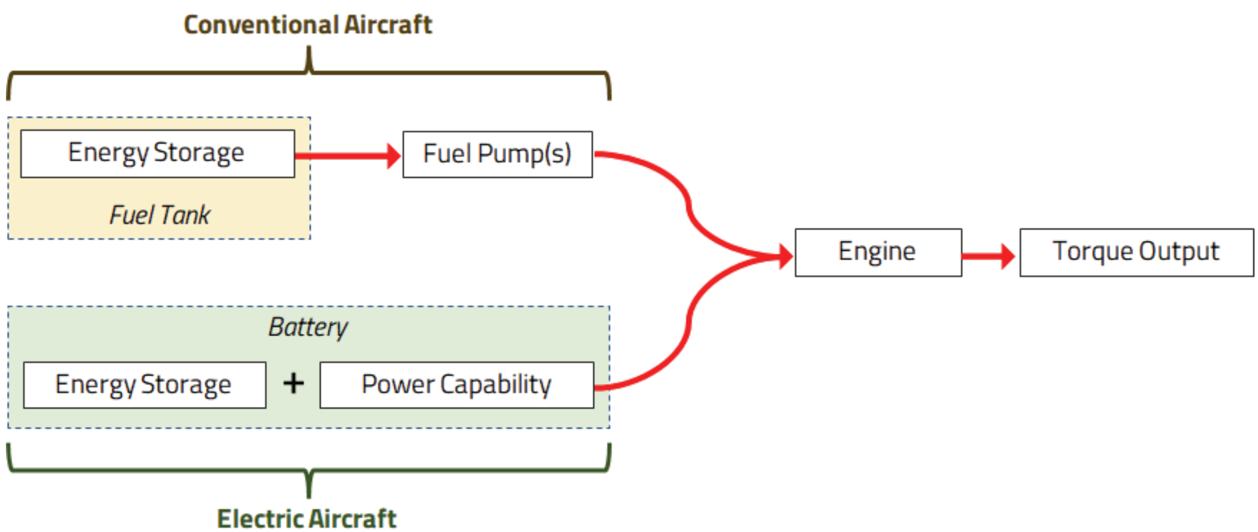

Figure 2.1 – Simplified schematic of path from stored energy to power output.

A battery's ability to deliver power, by contrast, diminishes as energy is removed from the system. Like a flashlight becoming dimmer as its batteries are depleted, an electric aircraft will lose some performance capability as the **state of charge** (SOC) of its batteries is reduced. One reason for this loss of system performance is that the maximum amount of electrical potential energy a battery can produce — its **open circuit voltage** (OCV) — decreases as its state of charge declines.

The equivalent of fuel exhaustion for a fully electric aircraft is when the open circuit voltage of the HVESS is no longer greater than the minimum voltage required to sustain flight, also known as the minimum bus voltage. Minimum bus voltage is the minimum voltage required for an electric propulsion system to function properly and provide torque through a motor.

For an eVTOL, minimum bus voltage may vary depending on whether the aircraft is in wingborne or thrustborne flight. This effect, illustrated in Figure 2.2, is particularly pronounced in — though not exclusive to — eVTOL aircraft, due to the significantly higher power demand for thrustborne compared with wingborne operations. As a result, an eVTOL may progressively lose operational capabilities as the energy state of the HVESS is depleted.

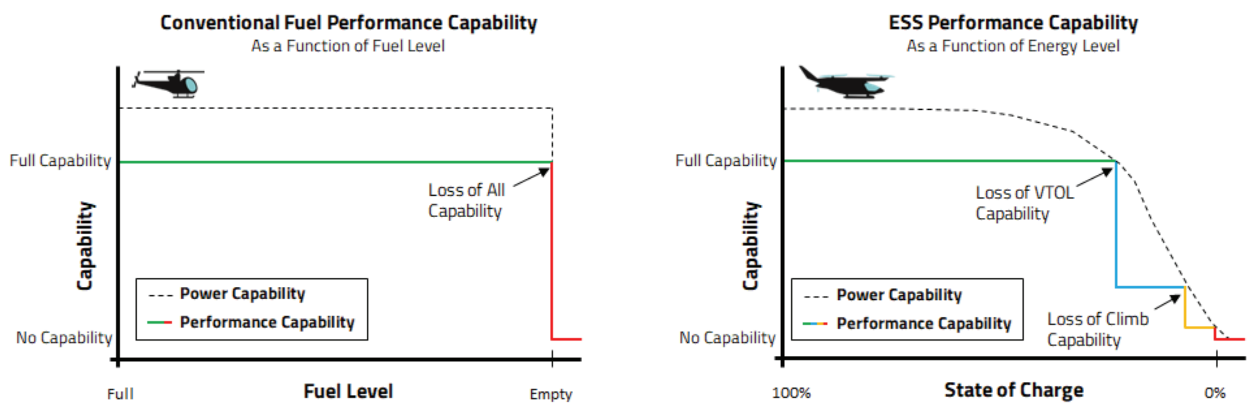

Figure 2.2 – Performance capability vs. energy state for fuel-based aircraft (left) and electric aircraft (right).

Another important distinction when considering an HVESS as the primary energy source is the difference between **total potential energy** and **usable energy**. Total potential energy represents all available electrochemical energy in the battery and depends only on the battery's state of charge, the health of its cells, and its operating temperature. From this total potential energy, there is **energy loss.** Some potential energy will be inaccessible because of impedances within the high voltage distribution system and electrochemical losses within the cells. The energy that remains after subtracting these losses is the usable energy that supports operation of the aircraft. Unlike total potential energy, usable energy is a dynamic value because energy loss increases with power demand due to higher electrical resistance and electrochemical dynamics (see Figure 2.3).

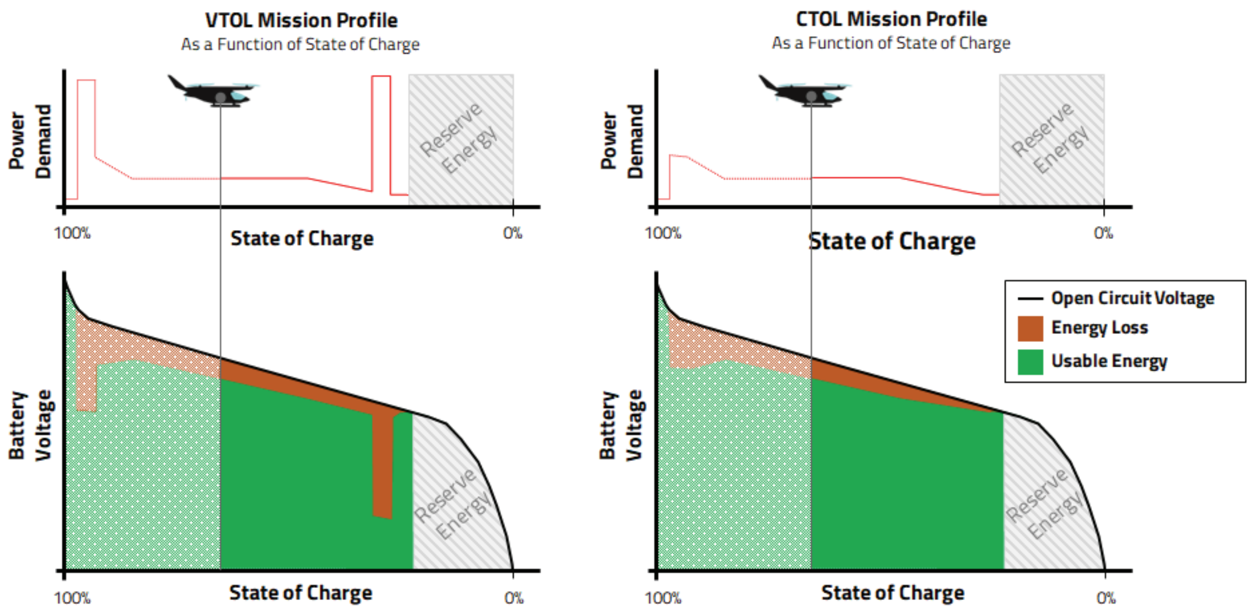

Figure 2.3 – The relationship between power profile and usable energy. eVTOL/eCTOL power profiles vary as they depend on specific aircraft design. These power profiles are purely illustrative.

Consider again the eVTOL and minimum bus voltage as the equivalent of fuel exhaustion, and the fact that many eVTOL aircraft have significantly higher power demands for thrustborne compared with wingborne flight. During cruise, the aircraft will deplete the energy state of the HVESS, reducing the open circuit voltage. A high-power thrustborne landing with a low HVESS energy state poses a critical situation: With low open circuit voltage and high energy loss, the minimum bus voltage for safe thrustborne flight may not be achieved. On the other hand, the low power demand of a wingborne landing may allow battery voltage to remain greater than minimum bus voltage deeper into discharge. As a result, a greater wingborne range would be possible (see Figure 2.4).

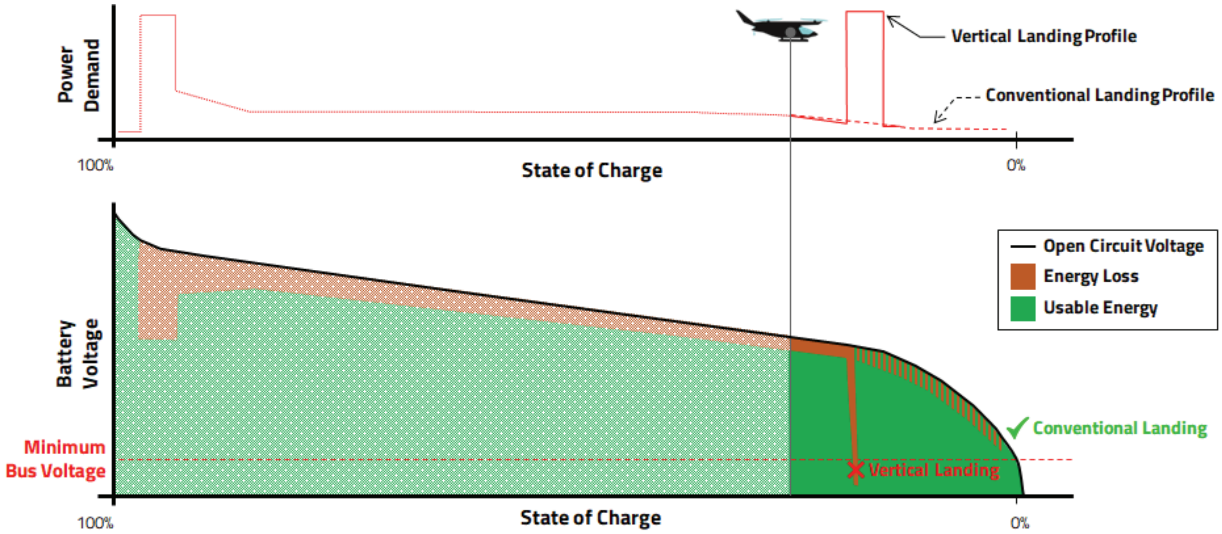

Figure 2.4 – Depiction of an approach to landing at a low energy state. Depending on energy state, battery health, and other factors, some power-demanding maneuvers, like vertical landing, may not be safe.

2.2. Other Factors Affecting Battery Performance

As batteries age, their energy capacity and ability to deliver power decreases with time and usage. Active ions in the cells' electrolyte become depleted, which is the primary driver of fading capacity. As the surfaces of the cell electrodes become less permeable to active ions, more energy is lost within the cells during charge and discharge. Manufacturers and aircraft operators must consider these effects, which comprise the **state of health** (SOH) of the battery.

There are parallels in conventional fuel-based aircraft. Though a fuel tank does not lose energy capacity as it ages, valves and other fuel system components degrade, which can decrease maximum fuel flow, and thus power delivery. Design and maintenance can mitigate the effects of this degradation.[2] Electric aviation original equipment manufacturers (OEMs) can deploy similar strategies to account for reductions in energy and power density and optimize the useful life of battery packs.

[2] Federal Aviation Administration, *Certification of Transport Category Rotorcraft*, AC 29-2C, 2018.

Temperature is another factor that causes battery performance to vary. Performance typically tends to improve as cell temperature increases and the chemistry within the cell becomes more energetic. This change in cell energy can affect the amount of usable energy available to the aircraft. Cold batteries, for example, have decreased power capability within their cells and may not be able to deliver what is needed for certain high-power phases of flight.

As a battery cell is discharged, it will naturally heat up as a function of both the discharge rate and its own intrinsic properties. Managing battery temperature to take advantage of higher efficiency at warmer temperatures while not exceeding safe operating limits is an important design consideration, and accounting for battery temperature is a crucial aspect of any energy management system.

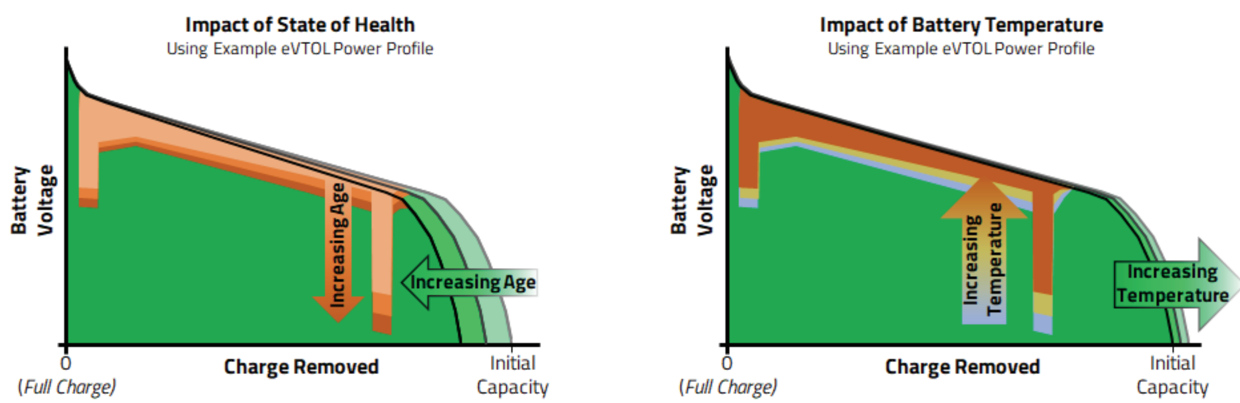

Figure 2.5 – Impact of state of health (left) and battery temperature (right) on battery performance.

Figure 2.5 summarizes the impacts of state of health and temperature on the overall electrical performance of a battery pack. Note that the term **Charge Removed** is used on the horizontal axis, rather than State of Charge, so that capacity can be more accurately represented. As capacity diminishes, the state of charge will decrease from 100% to 0% more quickly under the same load.

3. Performance Modeling and Indication Systems

Safe flight of an electric aircraft depends on thorough pre-flight planning, just as it does with a conventionally fueled one. This planning should include compliance with regulatory requirements; comprehensive evaluation of weather, air traffic, and airport conditions at the departure, destination, and alternate airports; and consideration of the mechanical condition of the aircraft. Pilots use the information they obtain during preflight planning to determine the fuel quantity or charge state needed for the flight. It is the pilot's responsibility to monitor the condition of the aircraft as it proceeds toward its destination and to confirm that sufficient range and endurance remain to complete the flight safely.[3]

For a conventionally fueled aircraft, the measurement of remaining fuel quantity and burn rate can typically support a reasonably straightforward estimation of remaining range and endurance. For electric aircraft that depend on batteries, indications of the remaining performance capability of the aircraft must be derived from inputs such as voltage, current, and temperature.

To support this computed solution, an accurate model of battery performance is required for all battery-electric aircraft. This underlying model plays a pivotal role in providing meaningful outputs that support range and endurance management. To develop accurate battery performance models, extensive testing is essential, and needed for aircraft type certification. During such testing, individual cells or modules are subjected to a variety of charge and discharge cycles under relevant environmental stresses. Multiple cycles of the same sample help inform the modeling of battery aging effects, which can vary based on the power profiles of the discharge cycles and other factors. Analysis of measurable parameters during testing provides the basis for developing performance models that can accurately predict the behavior of batteries in real-world applications. In many ways, the use of a performance

[3] ARAC Fuel Requirements Working Group, *Fuel Planning and Management*, Oct. 25, 1993.

model for a battery management system would echo practices already established in aviation for certifying engines that rely on full authority digital engine control (FADEC).

Yet even with aircraft systems handling underlying performance calculations, the pilot needs information to make proper energy-management decisions. The information the aircraft provides must be sufficient for the pilot to plan and execute a mission with suitable contingency options and should support safe flight and landing during an emergency condition, such as loss of performance due to a battery failure. When the equivalent of a minimum fuel or emergency fuel scenario develops, the pilot should be able to declare the remaining endurance to air traffic control.

OEMs can take various approaches to prevent situations in which electric aircraft unexpectedly run out of usable energy and to provide pilots with adequate situational awareness for managing range and endurance. These approaches range from simple to complex; all involve some combination of effective mission planning and in-flight indications. A thorough human factors engineering process is vital to the design of effective display and indication systems that meet regulatory requirements. Given the many different system architectures and concepts of operations (CONOPS) in today's emerging fleet of electric aircraft, it would be inappropriate for this paper to suggest a one-size-fits-all approach to mission planning and performance indication.

4. Reserve Concepts

4.1. Overview

Even with proper preflight planning and enroute range and endurance management, flight crews may encounter circumstances — unanticipated air traffic, airport closings, aircraft routing, wind, and weather conditions — that cause more fuel or energy to be used than planned.[4] The purpose of reserves is to allow continued operation should unexpected situations like these occur. By preventing energy depletion, reserves provide an additional margin of safety. All flights should be planned so that the pilot can land with reserves intact. Reserves should be used to complete a flight only after all other alternative actions have been taken. While using reserves does not make completion of the flight unsafe, pilots should be prepared to decide when and under what circumstances this is appropriate.

We will examine two primary reserve methodologies, which both aim to maintain a level of safety equivalent to existing standards: (1) prescriptive time-based standards, and (2) a performance-based reserve approach based on mission-specific range and endurance hazard assessment. These concepts could be extended or adapted to various operational frameworks, including FAA Part 135.

We are not presenting a definitive alternative rule set. We are offering, instead, a foundation for further discussions about a performance-based operational reserve strategy. The proposed methodologies are applicable across aircraft types, including airplanes, helicopters, powered-lift VTOL, and other vehicles. Although the discussion could be pertinent to fueled aircraft, the energy estimation is mainly for those with HVESS.

[4] ARAC Fuel Requirements Working Group, *Fuel Planning and Management*, Oct. 25, 1993.

The examples provided in this section are solely for illustrative purposes. The performance curves used are notional, generalized assumptions and are not intended to prescribe a method to determine HVESS energy capability.

In summary, the objective of this section is to expand the discourse around energy management in aviation, particularly as it relates to ensuring adequate reserve energy. We hope this exploration of energy planning methodologies will contribute to more efficient operations.

4.2. Time-Based Reserve Concept

The intent of existing time-based reserve requirements is to provide energy contingency for unforeseen conditions, such as delays, energy monitoring accuracy issues, higher-than-anticipated energy consumption, wind corrections, navigation errors, human factors, route changes, go-arounds, loitering, and performance degradation. Regulations requiring reserves have existed for decades. Indeed, regulatory language used today in Part 135 regulations dates as far back as 1946:

> *A flight shall not be started unless the aircraft carries sufficient fuel and oil, considering the wind and other weather conditions forecast, to fly to the next point of intended landing and thereafter for a period of at least 30 minutes at normal cruising consumption.*[5]

The current reserve rule,[6] which specifies nearly the same parameters, was incorporated into the regulations in 1978.

When this rule was developed, a simple time-based energy planning procedure to account for complex variables was a pragmatic necessity. Fuel monitoring was crude, and weather forecasting capabilities were limited. Dead reckoning was often used for navigation, and most ops were calculated on paper. It

[5] Fuel Supply – (a) Flight under contact flight rules (CFR), 14 C.F.R. § 42.33, 1946.
[6] VFR: Fuel Supply, 14 C.F.R. § 135.209, 2023.

was not practical for flight crews to evaluate every contingency separately to adapt reserve needs for specific missions. To account for this, time-based reserves added a considerable margin to cover various contingencies, which made planning easier.

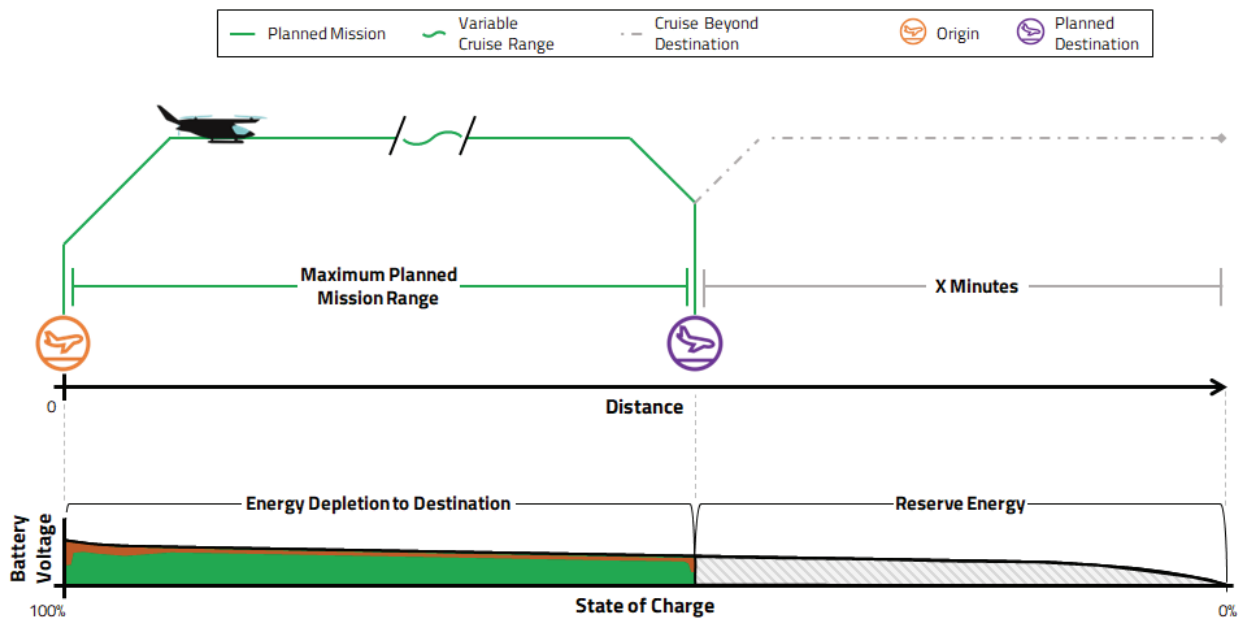

Figure 4.1 – A simplified illustration of time-based reserve energy planning.

Though time-based reserves still suffice for many operations, technologically advanced flight planning tools allow for significant improvement to this decades-old ruleset. Electronic flight bag (EFB) software is widely used, fuel/energy measurement is more accurate, weather forecasting is more sophisticated, and newer avionics have enabled precise trajectory planning. Modern systems can now account for the numerous considerations that time-based standards sought to address with a generous margin. Today, pilots can quickly project energy needs for go-arounds, unanticipated changes to flight speed, and range limitations due to degraded performance. While time-based rules generally account for such circumstances, they do not specifically address them.

The next section considers a methodology that incorporates the outcome of time-based contingencies directly into operational planning. Concepts that allow for unique mission characteristics and aircraft performance already exist, including Category A/B and ICAO performance classes for rotorcraft, ETOPS

(Extended-Range Twin-Engine Operations Performance Standards), and OpSpec B343 (Performance-Based Contingency Fuel Requirements for Flag Operations), as well as the upcoming EASA Part IAM. Our proposed reserve concept uses many of the principles from existing ops guides to show how a performance-based reserve approach can meet the safety intent of existing reserve rules for aircraft operating under FAA parts 91 and 135 or other civil aviation regulations.

4.3. Performance-Based Energy Reserve Concept

The performance-based energy reserve concept has the same overarching objective as the time-based reserve approach: to ensure a safe flight and landing. Yet while the time-based reserve is a general rule incorporated into operational planning, the performance-based concept is based on a mission-specific energy hazard assessment acceptable to the governing civil aviation authority. This assessment includes evaluation of performance-degrading conditions, environmental factors, and alternate landing sites, as well as aircraft-specific capabilities, as summarized in Figure 4.2. Ultimately, this establishes a structured approach for addressing the risk of inadequate margin throughout the flight.

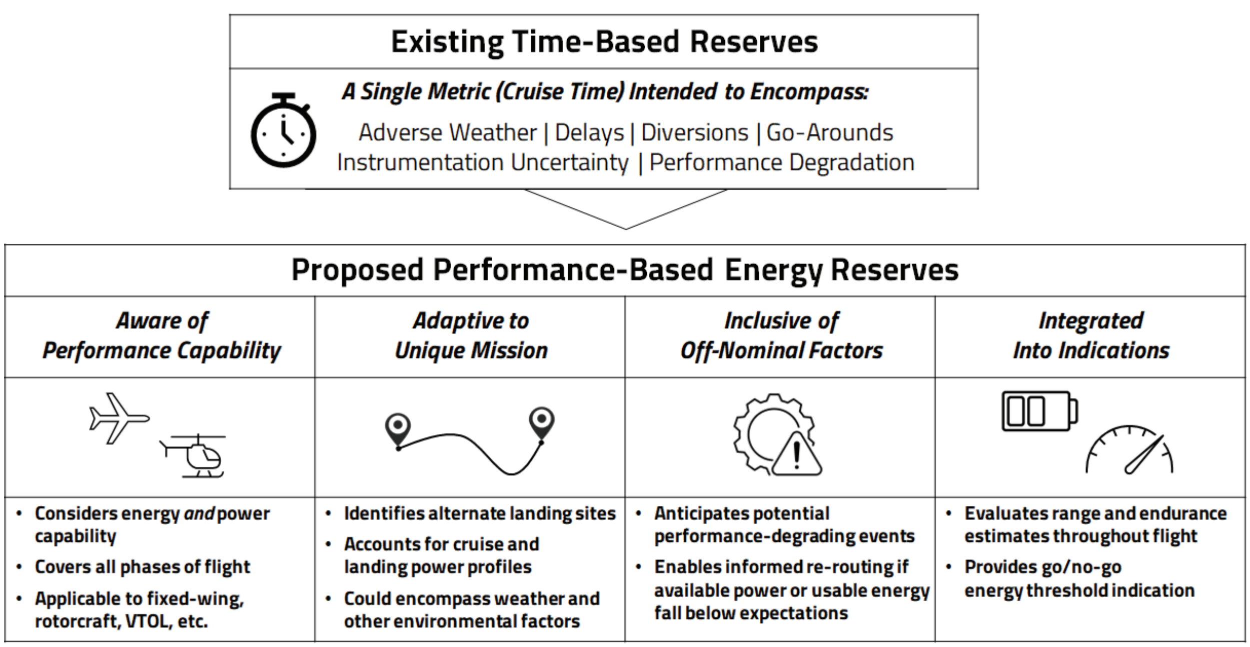

Figure 4.2 – Performance-based energy reserve planning elements.

4.3.1. Mission Energy Hazard Assessment

This assessment for the performance-based energy reserve builds on existing rules to evaluate energy contingency. By planning for alternate landing sites, monitoring in-flight energy, and evaluating aircraft-specific performance capability, this approach ensures the ability to reach the destination with the desired reserve intact should the mission proceed as planned. It also identifies contingency maneuvers, which the time-based reserve approach does not do. Moreover, off-nominal aircraft performance factors are evaluated throughout the mission.

Imagine that an aircraft could be flown over a continuous runway from its point of origin to its destination. If this were the case, the aircraft would always have landing access should a problem arise or the projected energy reserve fall below the desired level. Now suppose that instead of a continuous runway, there are multiple landing locations throughout the route. The mission could continue as planned if there is sufficient energy reserve to safely reach each alternate landing site. This is an underlying premise of the energy assessment. Evaluation and monitoring provide assurance to the pilot that sufficient energy remains for non-hazardous conditions all along the route.

The assessment would analyze the contingencies defined below, per specific aircraft and mission, to ensure a performance-driven energy reserve:

> **Energy Derating:** Any variability or uncertainty in the energy-gauging performance model and in energy consumption during flight. This value, most likely set by the OEM, in effect derates the capacity of the HVESS.
>
> **Nominal Performance Capability:** The expected HVESS energy and power capability for the given mission, including such factors as flight profile, route adjustments, takeoff weight (TOW), planned maneuvers, and environmental conditions.

Off-Nominal Performance Capability: The energy and power capability to reach a landing site with a non-hazardous performance-degrading condition at any mission point. Off-nominal factors would be aircraft-specific but could include, for example, partial loss of thrust or energy.

Nominal Capability Reserve: The operator's accepted energy margin relative to the lowest energy state at which the HVESS can provide sufficient power capability to successfully complete necessary landing maneuvers. This reserve should include energy for decision-making and go-around.

Critical Capability Reserve: The operator's accepted energy margin relative to the lowest HVESS energy state at which the aircraft can land with off-nominal performance. This reserve should include energy for decision-making and go-around in a performance-degrading state.

Alternate Landing Sites: En route or destination alternate landing sites that may be needed to ensure safe landing per the aircraft's capability and mission profile.

Energy Threshold(s): The planned and/or computed energy threshold(s), per the aircraft's capability and mission profile, for initiating a diversion or other action should the projected energy at the intended destination fall below the level deemed safe.

4.3.2. Usable Cruise Energy Estimation

Landing energy and power capability limits are critical because they ultimately dictate usable cruise energy. To determine the limits for a particular mission, the pilot operating handbook (POH), or equivalent, would provide energy performance plots or tables for given flight profiles and mission sets. An example is shown in Figure 4.3 below.

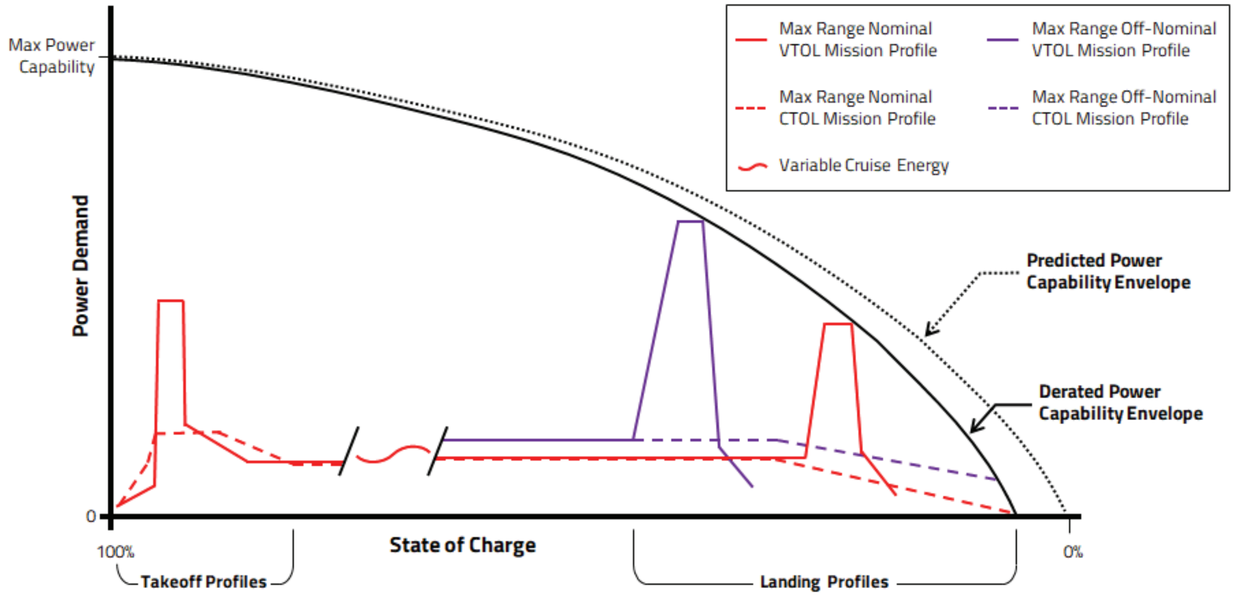

Figure 4.3 – Maximum-range power profiles based on power capability and anticipated power demand. A potential battery performance graphical aid that could be used as part of a mission energy hazard assessment.

The solid black curve in Figure 4.3 represents a derated HVESS power capability envelope that would serve as a reliable limit for operations. Potential landing profiles based on the aircraft's inherent operational capabilities, such as a conventional or vertical landing profile, are circumscribed within this envelope. The POH (or equivalent) would note the corresponding indication system limits for each landing profile. Figure 4.3 identifies several examples of such limits for conventional landing, vertical landing, and landing with off-nominal, performance-degrading conditions. With this information, operators can identify the last usable energy state for safe landing.

Profiles and limits would likely be presented with adaptations for HVESS state of health, TOW, and atmospheric conditions. These limits would be evaluated for each mission case, just as MTOW, endurance, and altitude are considered in flight planning for aircraft that use fuel.

4.3.3. Mission Capability Energy Limits

From the information obtained through the POH, the aircraft operator could then evaluate the maximum mission endurance. This requires identifying nominal and critical performance capability points and appropriate energy reserves so that the pilot can land at the destination and/or alternate before the last instant of remaining performance capability (Figure 4.4). Various frameworks could be used to determine energy margins; this paper does not specify them.

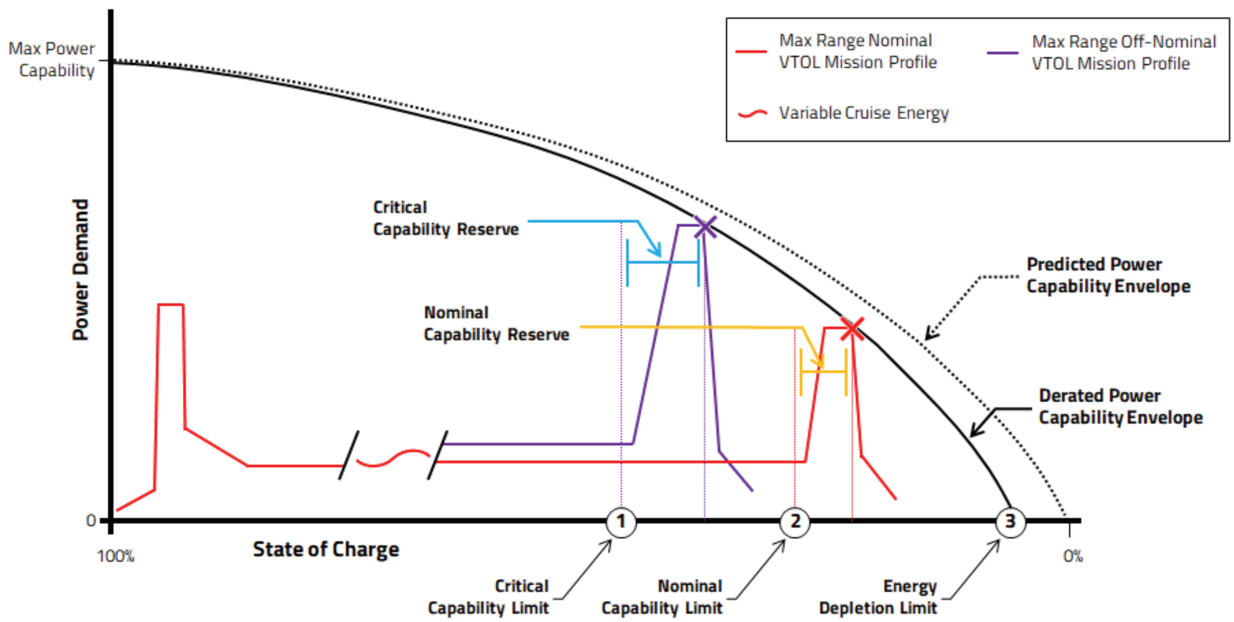

Figure 4.4 – Capability limits for a VTOL mission after accounting for adequate energy margins.

Key limits in usable energy are identified along the x-axis in Figure 4.4 (points 1-3) as follows:

1. **Critical Capability Limit:** The minimum energy threshold at the destination or destination alternate that ensures adequate endurance for contingencies like go-arounds, loitering, and off-nominal power performance. The critical capability limit is calculated by deducting the critical capability reserve from the energy the aircraft is expected to consume during a maximum-range off-nominal mission that accounts for the landing power profile. Flight planning should consider the risk of operating past this point. The pilot should not plan to

reach the destination or destination alternate (whichever is further) with remaining energy below the critical capability limit.

2. **Nominal Capability Limit:** The minimum energy threshold at the destination or destination alternate that ensures adequate endurance for contingencies like go-arounds and loitering if energy and power performance remain nominal throughout the mission. The nominal capability limit is calculated by deducting the nominal capability reserve from the energy that the aircraft is expected to consume during a maximum-range nominal mission that accounts for the landing power profile.

3. **Energy Depletion Limit:** The projected point at which the aircraft's derated HVESS energy model predicts that all usable energy would be consumed.

Figure 4.5 illustrates these endurance limits and corresponding performance-based energy reserves as they relate to maximum mission range.

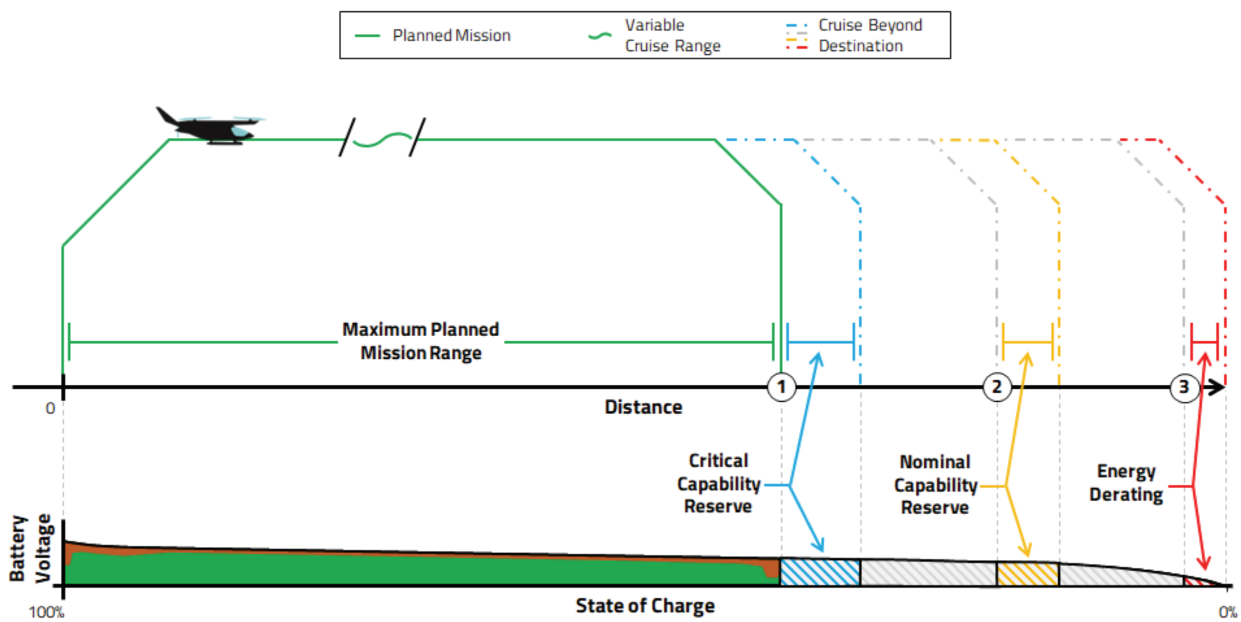

Figure 4.5 – Maximum usable mission capability for a given mission profile.
Points 1-3 correspond to the mission capability limits identified in Figure 4.4.

4.3.4. Diversion Landing Assessment

To account for variable energy use and potential off-nominal conditions, diversion locations should be integrated into mission planning that follows an accepted risk-management process. The aircraft operator should identify anything that could expose the mission to a less-than-adequate energy reserve with no planned landing location. One option to address this kind of situation, shown in Figure 4.6, is to add alternate destinations so a landing site would be available if an off-nominal issue emerges partway through the mission or if the performance capability at mid-flight is lower than anticipated.

Alternates should be chosen based on the aircraft's ability to land safely under various power states. This may include using alternates when transitional lift is available in a low-energy state. Given the wide range of mission types and aircraft performance capabilities, multiple factors will figure into assessing diversion locations.

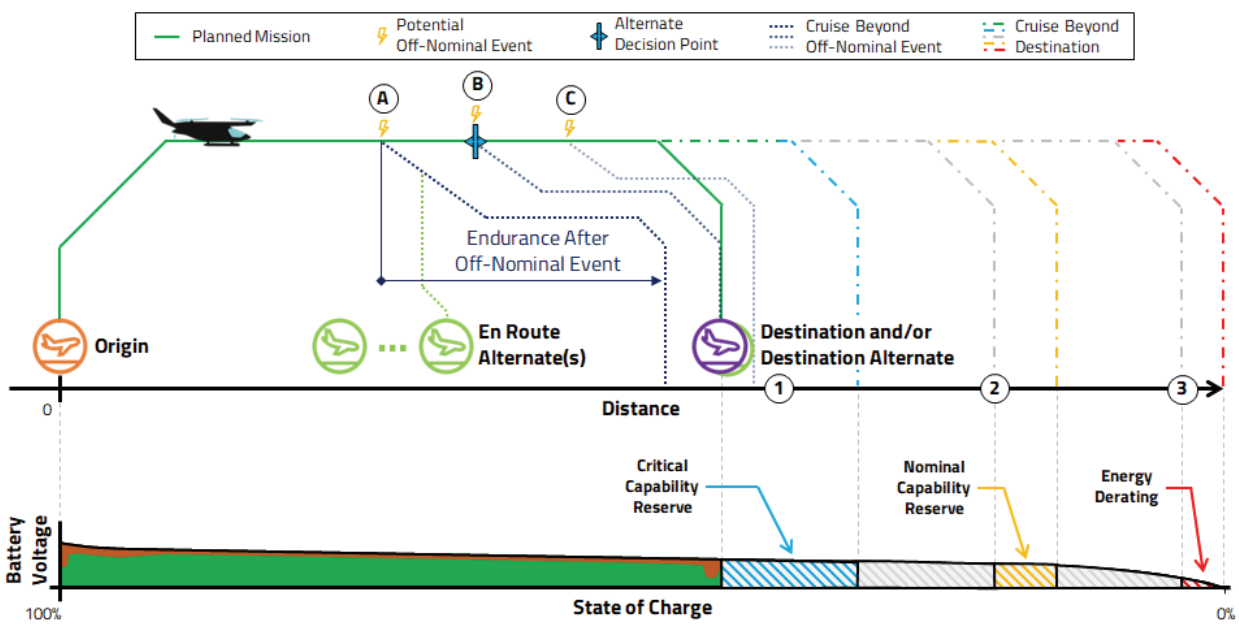

Figure 4.6 – Mission planning with diversion landing assessment. Points A-C are defined below.

For example, if the intended landing location is likely but not guaranteed, perhaps due to weather, selecting a destination alternative as a backup would be wise. In some cases, the operator may choose a mix of conventional and vertical landing sites. In these cases, the operator would evaluate the mission energy hazard assessment for both landing profiles and set energy limits based on which has the highest energy requirements. The pilot must be aware of any performance capability limitations they may encounter if the mission progresses beyond the critical capability limit.

In the event that a pilot encounters performance-degrading conditions, with available energy falling below expectations, an alternative landing site along the intended route might be the best option for both safety and convenience. If the performance-degrading event occurs at a point where the off-nominal distance capability of the aircraft is insufficient for safely reaching the intended destination (point A in Figure 4.6), this alternate destination would be used instead. On the other hand, if the performance-degrading event occurred at or beyond the point where the energy margin provides sufficient off-nominal capability to reach the planned destination (points B and C, respectively, in Figure 4.6), no re-routing would be necessary.

4.4. Performance–Based Energy Reserve Example Mission

To put the energy planning assessment methodology into perspective, consider how the energy evaluation steps we have detailed could be used to plan a VFR mission in the Los Angeles area (Figure 4.7). This is an example of how an energy planning assessment would apply to a real route.

4.4.1. Mission Vector and Alternate Planning

The route between KSNA (John Wayne/Orange County Airport) and KSMO (Santa Monica Municipal Airport) is a busy one that involves flying around Class B airspace. Three alternate landing sites and four alternate decision points have been selected along the flight route; these are indicated in Figure 4.7. Though there are dozens of airports and heliports in the area, the alternates picked are all municipal airports, which offer clear advantages: they provide a common traffic advisory frequency (CTAF) for communicating priority needs, they can accommodate both conventional and vertical landings, and the sites are relatively easy for a pilot to spot. Though en route alternates were selected, a destination alternate was not seen as useful for this mock mission hazard assessment.

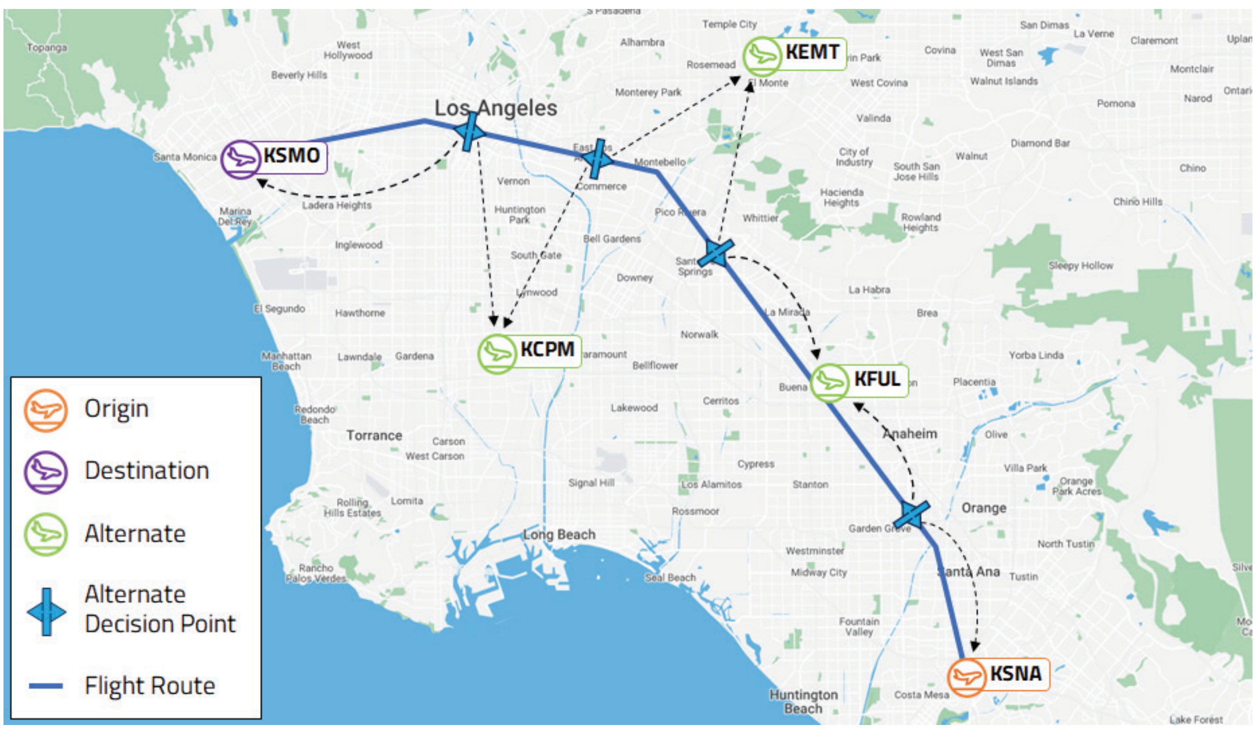

Figure 4.7 – A mission from KSNA to KSMO, with alternate landing sites and decision points along the way.

4.4.2. Energy Evaluation

Figure 4.8 illustrates the energy overhead through the entire mission via the remaining cruise distance capability of the aircraft. By strategically selecting alternate landing sites along the flight path, the pilot can expect the distance to the nearest potential landing site to remain below the available endurance from departure to arrival, even in off-nominal conditions.

Note the locations of each decision point along this route. Most are equidistant (or equal in energy consumed) from two potential landing sites, so the pilot could land at the nearest should an adverse event occur. The only exception is the final decision point, which is where the aircraft could still reach the last planned destination with endurance after an off-nominal event. Beyond this point (equivalent to point B in Figure 4.6), no re-routing would be necessary even if there were an adverse event.

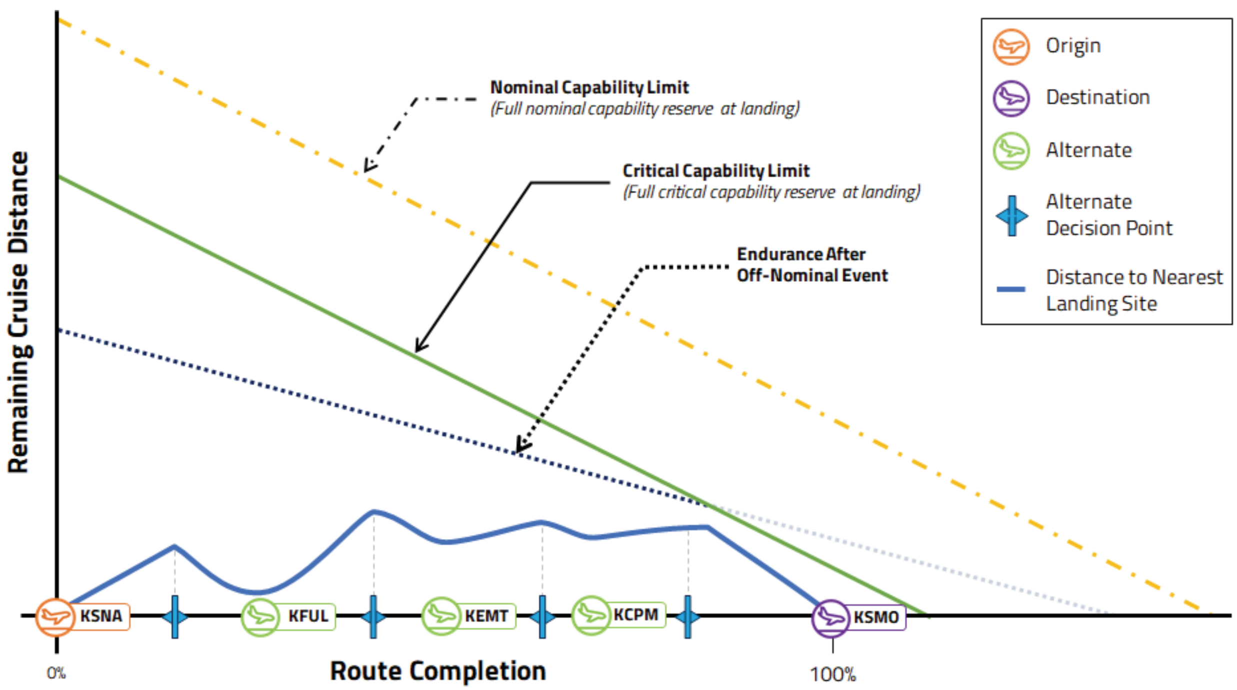

Figure 4.8 – Remaining cruise distance to nearest landing site throughout the mission.

4.4.3. Inflight Monitoring

For pilot decision-making, energy reserve factors must correlate with inflight indication systems. Figure 4.9 depicts one potential display, with three primary indication metrics:

1. The off-nominal performance capability from the aircraft's current location.
2. The projected remaining endurance expected at the last planned destination, assuming none of the critical capability reserve is consumed.
3. The projected remaining endurance expected at the last planned destination, assuming the nominal capability limit is reached but none of the nominal capability reserve is consumed.

Figure 4.9 – KSNA-KSMO enroute energy indications.

Though there are undoubtedly other ways to convey this information to the flight crew, this example provides indications that would inform pilot decision-making by enabling easy monitoring of the energy limits established in flight planning. Indicating the endurance from the current location should a performance-degrading event occur would heighten awareness of whether an alternate landing site is within reach. Displaying endurance beyond the destination to the critical capability limit would enable the pilot to understand if they can handle an off-nominal situation at the intended landing site, and showing the additional endurance beyond the destination to the nominal capability limit would highlight the full performance capability envelope of the aircraft.

4.5. Summary

The example in Figure 4.9 helps visualize how a performance-based energy reserve concept would work in practice, using evaluation of various factors to adapt energy margins to unique missions. Much of the proposed framework depends on the accuracy of energy planning and indication systems, and on setting performance limits. Indeed, embracing a performance-planning reserve approach will require OEMs to demonstrate that their energy measuring, planning, and indication systems and/or processes can achieve sufficient accuracy.

5. Conclusions

This white paper encompasses the collective considerations of an industry committee with expertise in battery-electric propulsion systems, aircraft performance, and flight operations. To address the fundamental differences in battery energy systems, the group has taken a holistic approach to energy management for battery-electric aircraft. In this paper, we have focused on (1) describing novel energy characteristics inherent in HVESS compared with conventionally fueled propulsion systems; (2) establishing the need for battery performance models and human factors engineering to support the design of indication systems; and (3) calling for performance-based energy reserves that directly account for circumstances that can affect flight risk and safe landing. These three building blocks of our approach provide a performance-driven framework that meets the safety objectives of prescriptive time-based requirements while clearly describing the hazards and risks of individual mission profiles.

We believe there is a paramount need to inform the broader industry about battery energy systems. For aircraft that use these systems, traditional fuel management may not always result in safety equivalence. In developing the methodologies presented in this paper, the members of the drafting committee consistently considered safety as if our own families were the passengers. Our hope is that we have laid a stepping stone on the path toward advancing energy management for both HVESS and traditional aircraft. This paper does not offer rigid directives but rather aims to invite insights, foster discourse, and adapt over time. Feedback and contributions are encouraged and can be directed to comments@gama.aero. Your input will play a vital role in shaping the evolution of this initiative.