Energy Safety Management
A Training Model to Improve Flight Safety

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Abstract  Failing to properly manage an airplane’s energy state can be unforgiving. Mismanagement of mechanical energy (altitude and/or airspeed) is a contributing factor to three common types of fatal accidents in aviation: loss of control in flight, approach and landing accidents, and controlled flight into terrain. Recognizing the importance of energy management, the Federal Aviation Administration has incorporated new elements into the Airman Certification Standards, emphasizing knowledge of energy management concepts and the consequences of mishandling an airplane’s energy state. Unfortunately, no adequate guidance has been available in terms of defining key energy management concepts or suggesting how these should be taught to the average pilot and applied to everyday flying. This article introduces energy safety management (ESM) as a best practice for incorporating energy management into pilot training. First, ESM integrates three well-tested energy management theories developed independently in engineering, military science, and biology. Second, ESM relies on the power of simple analogies and a pilot-oriented approach to make energy management principles accessible and practical to any airplane pilot operating standard propulsion/flight control systems and existing cockpit displays. Third, to organize and optimize learning, ESM incorporates a well-known human performance framework that establishes how humans learn to perform new tasks. In sum, this article offers both the rationale and the road map for an outside-the-box instructional approach illustrating how established complex scientific concepts can be taught to any pilot. The ESM training model has successfully been applied to design a new college course and, in collaboration with the Federal
Aviation Administration, is being used to support and develop new energy management guidance materials for pilots.

**Keywords** altitude-speed map, energy control rules, energy distribution, energy error, energy exchange, energy height, energy management, energy reservoir analogy, energy safety management, energy state, energy system, Federal Aviation Administration, irreversible deceleration, irreversible sink-rate, kinetic energy, money analogy, mountain analogy, pitch and power, potential energy, power available, power required, specific excess power, top-down approach, total mechanical energy

**INTRODUCTION**

A substantial number of fatal aircraft accidents have been associated with mismanagement of altitude (potential energy) and/or airspeed (kinetic energy). A pilot’s (or autopilot’s) failure to properly manage the energy state of the airplane is a contributing factor to loss of control in flight, the top leading cause of fatal accidents in aviation (Boeing, 2023; Carbaugh & Rockliff, 2004; Jacobson, 2010; NTSB, 2021). In general aviation alone, encompassing all U.S. civil aviation operations, 43% of 2,269 fatal accidents between 2012 and 2021 were caused by loss of control in flight (NTSB, 2021). Poor energy state awareness or management can also lead to unstabilized approaches that may result in runway excursions, undershoots, overshoots, or abnormal runway contact during landing (Airbus, 2005). By phase of flight, approach and landing accidents accounted for 19% of all fatal accidents in general aviation between 2012 and 2021 (NTSB, 2021). Another cause of fatal accidents involving lack of energy state awareness is controlled flight into terrain, in which an airworthy airplane is unintentionally flown into the ground (Boeing, 2023; NTSB, 2021). In the same period of time, 7% of all fatal general aviation accidents involved controlled flight into terrain (NTSB, 2021).

Given the potential deadly consequences of mismanaging the airplane’s energy state, the Federal Aviation Administration (FAA) Airman Certification Standards (ACS) now require that pilot applicants (from private pilot through airline transport pilot) be taught energy management (FAA, 2023a, 2023b, 2023c, 2023d, 2023e). Recognition by the FAA of the importance of teaching energy management to pilot candidates is a welcome development. Unfortunately, until recently, neither the ACS documents nor the references listed in them have provided adequate guidance on
relevant energy management concepts or how they should be taught to and demonstrated by pilot candidates (Merkt & Sizoo, 2019). However, using the novel approach described in this article, Merkt and Sizoo have collaborated with the FAA to start developing basic energy management guidance materials for pilots (Merkt, 2020; Merkt & Sizoo, 2019). This collaboration has included writing the first-ever chapter on energy management for the Airplane Flying Handbook (FAA, 2021). The training approach is being evaluated and refined through a course in safety principles of aircraft energy management offered to flight students at Embry-Riddle Aeronautical University since 2018 (Merkt, 2023).

This article then provides the rationale for the approach being used to develop guidance materials and offers a road map for integrating energy management into pilot training. The simplistic view of pitch + power = performance is not enough to improve the way pilots think of energy. What is needed is a practical application of basic knowledge, rules, and skills for safely managing the airplane’s energy state.

In sum, this article proposes energy safety management (ESM) as a best practice for incorporating energy management into pilot training. The ESM training approach is founded on three building blocks: (1) integration of three well-known energy management theories, (2) reliance on a pilot-oriented approach for conveying energy concepts, and (3) incorporation of a human performance framework for mastering the piloting knowledge, rules, and skills to manage an airplane’s energy state effectively and safely. Following a brief description of these building blocks, the article expands on the knowledge, rules, and skills needed for managing the aircraft energy state. At the end, the article provides a road map that outlines four steps for incorporating energy management into pilot training.

INTEGRATION OF THREE ENERGY MANAGEMENT THEORIES

ESM integrates three energy management theories that have been successfully applied for solving motion-related problems: (1) total energy control system (TECS) theory designed to enhance automated flight control systems (Lambregts, 1983), (2) energy maneuverability (E-M) theory developed to assist fighter pilots in optimizing aircraft maneuvering and performance in air combat (Boyd et al., 1966), and (3) bioenergetics of locomotion (BEL) theory elaborated to appraise the amount of energy spent by animals as they move around (Schmidt-Nielsen, 1972). All three theories are founded on Newton’s laws of motion and the law of conservation of energy (Anderson, 2016; Cengel, 2008; Coopersmith, 2015; Feynman, 1985; Goodman & Warner, 2001; Merkt, 2013; Rutowski, 1954).
TECS is an integrated approach for controlling vertical flight path (altitude) and airspeed using total energy principles. TECS control laws have been applied successfully to design and test experimental energy-based automated flight control systems (Lambregts, 1983) and have inspired energy-augmented cockpit displays (e.g., Amelink et al., 2005). TECS principles clarify the role of the propulsion/flight controls for managing the airplane’s energy state, defined as the total amount and distribution of mechanical energy over altitude and airspeed.

Energy maneuverability (E-M), on the other hand, shows how an aircraft’s specific energy state (energy height) and energy rate of change (specific excess power) can be manipulated to optimize maneuvering and performance within the aircraft’s energy envelope. E-M theory has been instrumental for enhancing air combat tactics (Boyd et al., 1966; Shaw, 1985) and improving fighter aircraft design (Coram, 2004). E-M principles dictate how the pilot can “move” the airplane effectively from one energy state to another and maneuver within its altitude-airspeed envelope.

Finally, bioenergetics of locomotion (BEL) integrates the mechanics and energetics of movement to determine and compare energy costs of different modes of animal locomotion, including bird flight (Schmidt-Nielsen, 1972). One of the main themes that has emerged from biological studies is that motion control and performance are tightly integrated through common mechanisms governing the use of locomotive forces and energy transfer, exchange, and storage (Dickinson et al., 2000). In addition, in contrast to the traditional bottom-up approach used to teach flight theory (e.g., Anderson, 2016; Hurt, 1965), biologists use a top-down research approach to study locomotion that is ideally suited for teaching energy management and its underlying principles to pilots (Merkt, 2013; see also the section “The Top-Down Approach” in this article).

RELIANCE ON A PILOT-ORIENTED APPROACH FOR CONVEYING ENERGY CONCEPTS

The energy concepts that pilots need to understand and put into practice have already been developed and applied by engineers, military scientists, and biologists, as outlined in the previous section (Amelink, et al., 2005; Anderson, 2016; Boyd et al., 1966; Cliff, 1998; Dickinson et al., 2000; Lambregts, 1983; Lambregts et al., 2008; Schmidt-Nielsen, 1972). Unfortunately, most published work on energy concepts is written in math, the language of physics. But the goal of ESM is to teach energy management to an average general aviation pilot who may not have the science background of a flight control engineer, a fighter pilot, or a bird biologist to understand the advanced math and physics involved. Thus, ESM not only integrates key TECS, E-M, and BEL concepts but also transforms them into simple, intuitive,
and practical principles that all pilots can understand and use. The problem, then, is not so much what concepts to teach to pilots but rather how to convey them.

ESM solves this problem by employing simple analogies, plain language, and a learner-centered, top-down, pilot-oriented approach that uses standard propulsion/flight control systems and existing cockpit displays to convey energy management principles. As part of the pilot-oriented approach and as shown later in this article, a few simplified equations can be introduced to complement associated analogies and clarify the relation between key energy-relevant quantities. Figure 1 summarizes the

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Figure 1. ESM Learning Tools Used to Convey the Knowledge, Rules, and Skills Necessary to Safely Manage The Airplane’s Energy State (see the Section “Incorporation of a Human Performance Framework” below).
analogies and other learning tools that can be used to grasp key energy concepts. The application of these tools is illustrated throughout the article using selected examples that show how established scientific energy concepts can be taught to any pilot. For a more in-depth demonstration of how these tools can be applied, see Amelink et al. (2005), Aviation Safety (2021), FAA (2021), and Merkt (2013, 2015, 2020).

INCORPORATION OF A HUMAN PERFORMANCE FRAMEWORK

To organize and optimize learning, ESM incorporates Rasmussen’s skills-rules-knowledge conceptual framework for classifying human task performance (Rasmussen, 1983). According to the skills-rules-knowledge taxonomy, human tasks (e.g., playing a game or a sport, driving a car, or flying an airplane) can be performed at the skill-, rule-, or knowledge-based levels of operation (Rasmussen, 1983). Under this framework, learned tasks are ranked based on how much cognitive (mental) effort they take to perform, with knowledge-based–level tasks requiring the most mental effort and skill-based–level tasks requiring the least (Lewis-Evans, 2010).

Knowledge-based performance is best suited for dealing with unforeseen and unfamiliar situations requiring conscious reasoning and strong foundational knowledge (e.g., a good mental model of the system) to solve problems never encountered before. Thus, in terms of how often it is used, knowledge-based performance sits at the bottom of the hierarchy, since it is used least frequently and only for dealing with unusual conditions (Lewis-Evans, 2010). An example of a knowledge-based action is troubleshooting an engine problem in flight, which requires good knowledge of engine systems and their operation.

At the other extreme, skill-based “muscle-memory” performance, heavy on memorization and fine-tuned through practice and experience, requires the least amount of mental effort. Thus, skill-based performance is used most frequently to efficiently accomplish routine and repetitive tasks (Lewis-Evans, 2010). Seamless coordination of aileron, rudder, elevator, and throttle inputs when entering a level turn is an example of skill-based performance.

Rule-based performance, sitting in the middle between knowledge- and skill-based performance, is used primarily for recognizing familiar patterns. This level of performance is best represented by general “IF, THEN” rules that require some level of memorization and can be applied to quickly make proper decisions before resorting to knowledge-level operations (Lewis-Evans, 2010). An example of a rule-based flight operation is performing a crosswind landing: IF you experience a crosswind,
THEN bank into the wind by an amount as necessary to prevent drift AND apply opposite rudder by an amount as necessary to align the fuselage with the runway.

Applying these three levels of human performance to learn new tasks can assist in organizing a training program, from required knowledge to skills, and can also help in developing effective learning objectives and training methods (Fleming & Pritchett, 2016). The next three sections elaborate on the knowledge, rules, and skills needed for safe management of the airplane’s energy state and illustrate specific learning tools that can be used at each level.

MASTERING KNOWLEDGE OF THE AIRPLANE AS AN ENERGY SYSTEM

Even though energy is a subtle and complex concept (Coopersmith, 2015), we can use the power of simple analogies to help us comprehend it (Wormeli, 2009). The goal is for a pilot to understand, monitor, and control the airplane as an energy system. Various analogies can be used as simplified ways to visualize and define the airplane as an energy system.

The Money Analogy

Just as with money, energy can be earned, spent, saved, withdrawn, and even transferred between energy “accounts.” In this analogy, the airplane is an energy bank, and the pilot owns the bank accounts. The pilot’s goal is to manage each energy transaction competently and, most importantly, avoid energy bankruptcy (Merkt, 2020).

Expanding on the money analogy (Figure 2), an airplane has two “savings” accounts where mechanical energy can be stored. In one account energy is stored as altitude (potential energy), and in the other account energy is stored as airspeed (kinetic energy). While flying, the airplane earns energy from engine thrust \( T \) and spends energy on aerodynamic drag \( D \). The “net income” \( T - D \) determines whether total mechanical energy (the savings) increases, decreases, or remains the same (Merkt, 2020).

When energy income exceeds the expense \( T - D > 0 \), the pilot can use the surplus energy and save it as the airplane gains altitude or airspeed. If the pilot places the surplus energy into altitude, the airplane can climb at a constant airspeed. If the pilot instead places the surplus energy into airspeed, the airplane can speed up while maintaining a constant altitude. When energy income is insufficient to pay for drag \( T - D < 0 \), the pilot must withdraw energy from the savings accounts. The pilot may...
decide to descend at a constant airspeed or slow down while maintaining a constant altitude as energy is withdrawn from one of the savings accounts to make up for the deficit. When energy earned and spent break even \((T − D = 0)\), all thrust is used to pay for drag, and the airplane can maintain a constant altitude and airspeed. Finally, just as with money, energy can be transferred between saving accounts by trading altitude for airspeed or vice versa (Merkt, 2020).

The money analogy is an excellent way to visualize a fundamental principle in energy management: the airplane’s energy balance (Equation 1). The left side of the equation, a function of the difference between thrust and drag \((T − D)\), controls the net transfer of energy into or out of the airplane, while the right side controls the distribution of the resulting change in total mechanical energy between altitude and airspeed (Merkt, 2020). More importantly, the difference between energy gain and loss on the left side is always matched by an equal change in the airplane’s total energy on the right side. Like money, the left side represents the airplane’s energy net income, while the right side reflects matching changes to its energy savings accounts (Figure 2).

\[
\dot{E}_{T−D} = \dot{E}_{pot} + \dot{E}_{kin}
\]

Where
\[
\dot{E}_{T−D} = \text{rate of change of total mechanical energy (a function of thrust minus drag)}
\]
\[
\dot{E}_{pot} = \text{rate of change of potential energy (a function of changing altitude)}
\]
\[
\dot{E}_{kin} = \text{rate of change of kinetic energy (a function of changing airspeed)}
\]
Understanding the airplane’s ability to earn, spend, save, withdraw, and exchange energy is a first step in developing an accurate mental model of the airplane as an energy system. The next step is to visualize the airplane’s ability to move from an initial altitude and airspeed to any other target altitude and airspeed within its flight envelope. A map analogy helps to visualize this process.

The Map Analogy

In a navigation map, two variables (latitude and longitude) establish the geographic position of an airplane. Likewise, in an energy map, two variables (altitude and airspeed) establish the energy position of an airplane (Figure 3). More precisely, the position of the airplane in the energy or altitude-airspeed map is defined by its specific total energy, $E_{s}$, which is the total mechanical energy of the airplane (sum of...
its potential and kinetic energy) divided by its weight. Measured in units of height (e.g., feet), specific total energy is also known as energy height (Anderson, 2016). In addition to depicting an airplane’s energy state, the altitude-airspeed map is helpful in visualizing how an airplane can move from one energy state to another. The ability of an airplane to change its energy state involves two processes: energy exchange and total energy rate of change.

During energy exchange, the airplane moves along a given energy height line (an idealized trajectory) by exchanging airspeed and altitude while in the short term maintaining total mechanical energy constant (Anderson, 2016; Boyd et al., 1966; Cliff, 1998; Rutowski, 1954). As seen in Figure 3, an airplane flying at 6,000 feet and 100 knots in position 1 has a specific total energy of 6,500 feet. By trading altitude for airspeed, the airplane can move from position 1 along the energy height line to position 5 at 4,000 feet and 230 knots while maintaining the same specific total energy of 6,500 feet.

During total energy rate of change, the airplane moves across energy lines by adding or subtracting total energy while redistributing this change over altitude and airspeed. The rate at which the airplane’s total mechanical energy increases or decreases is determined by specific excess power \( P_s \), which is excess power divided by the airplane’s weight. As shown in Equation 2, specific excess power is a function of the difference between thrust and drag (Anderson, 2016; Boyd et al., 1966; Cliff, 1998; Rutowski, 1954).

\[
P_s = \frac{(T - D) V}{W}
\]

Where

\( P_s \) = specific excess power
\( T \) = thrust
\( D \) = drag
\( V \) = velocity (airspeed)
\( W \) = weight

Note that since specific total energy is expressed in units of height (e.g., feet), it follows that specific excess power \( P_s \) is expressed in units of height divided by units of time (e.g., feet/minute or feet/second; Anderson, 2016). As seen in Figure 3, the airplane in position 1 is flying at 6,000 feet and 100 knots with a total energy equivalent to 6,500 feet. Since positions 2, 3, and 4 are located at higher energy heights (11,000, 9,500, and 8,000 feet, respectively), the only way to reach them from position 1 is by increasing the airplane’s total energy \( P_s > 0 \). The reverse is also true. If the airplane is at position 2, 3, or 4, the only way for it to get back to position 1 is by decreasing its total energy \( P_s < 0 \).
The Mountain Analogy

In a geographical map (e.g., a sectional chart), contour lines add a third dimension (terrain elevation) to the two existing dimensions (longitude and latitude). These contour lines allow us to view rising and descending terrain. Likewise, in an energy map (Figure 4), we can use contour lines to add a third dimension (available specific excess power) to the two existing dimensions (altitude and airspeed). Measured at full throttle, the available specific excess power \( (P_s) \) contours determine the ability of an airplane to climb or accelerate from a given flight condition (Precourt, 2018). Just as terrain elevation contours in a sectional chart help us visualize a real mountain viewed from above, the \( P_s \) contours allow us to visualize how available specific excess power at full throttle goes up or down at different airspeeds and altitudes within the energy map (Anderson, 2016; Boyd et al., 1966; Cliff, 1998; Rutowski, 1954).

The mountain analogy also helps in visualizing the airplane’s sustainable energy state envelope. The bottom of the “mountain,” depicted by the \( P_s = 0 \) contour, Figure 4. The Mountain Analogy, Adapted from Boyd et al. (1966) and Rutowski (1954), Depicts Available Specific Excess Power (\( P_s \)) Contours (Shown Here in Feet/Minute) As Well As the Combination of Altitudes and Airspeeds That Can Be Attained and Sustained in Flight for a Hypothetical Aircraft.
represents the edge of the energy envelope, defining the airspeeds and altitudes where the airplane, at full throttle, can sustain level flight but is no longer able to increase its total energy to climb or accelerate. Anywhere inside the envelope, the airplane is capable of sustained level flight and, since available \( P_s \), at full throttle is greater than zero, is also able to climb and accelerate at varying rates depending on its current altitude and airspeed. Outside of the envelope where available \( P_s < 0 \), the airplane cannot sustain level flight, as its total energy decreases as it descends and/or decelerates at full throttle. Note that the actual shape and size of the envelope is airplane-specific (Anderson, 2016).

In sum, the money, map, and mountain analogies can help visualize the airplane as an energy system and how it can move effectively from one energy state to another. The next step is to understand the energy role of the controls and the simple rules for moving the airplane from one energy state to another within its energy envelope.

**RULES FOR CONTROLLING THE AIRPLANE’S ENERGY STATE**

Changing an airplane’s total mechanical energy is a function of both thrust and drag (Equations 1 and 2); however, changes in drag mainly occur long term due to airspeed changes or by using high lift/drag devices, such as flaps, that which increase drag (Amelink et al., 2005; Lambregts, 1983). Thus, changes in total mechanical energy are normally initiated not by changing drag but instead by adjusting thrust. Once the new target profile is achieved, the throttle sets engine thrust to match the total energy demanded by both vertical flight path and airspeed combined. Thus, the throttle is the total energy controller (Amelink et al., 2005; Lambregts, 1983).

In contrast, the elevator, which intrinsically does not contribute to total energy gain or loss, is an energy exchanger and a distribution device. The primary role of the elevator is to allocate changes in total energy between vertical flight path and airspeed by adjusting pitch attitude. Once the new target profile is accomplished, the elevator sets the proper pitch attitude to maintain the demanded distribution of total energy over vertical flight path and airspeed. The elevator then is the energy distribution controller (Amelink et al., 2005; Lambregts, 1983).

**The Reservoir Analogy**

The reservoir analogy (Figure 5) illustrates the primary energy role of the throttle and elevator for managing the airplane’s energy (Amelink et al., 2005). Throttling up so that thrust is greater than drag \( (T > D) \) makes the airplane gain total energy, while
throttling down so that thrust is less than drag \( (T < D) \) makes the airplane lose total energy. The elevator then redistributes this change in total energy between altitude and airspeed. Now, when the throttle adjusts thrust equal to drag \( (T = D) \), there is no change in total mechanical energy, but the energy stored in the altitude and airspeed “reservoirs” can be exchanged, adjusting pitch attitude with the elevator. The reservoir analogy is another great tool for visualizing the airplane’s energy balance (see Equation 1), with the throttle controlling energy transfer on the left side of the equation and the elevator controlling energy distribution on the right side. For a more detailed account of the energy reservoir analogy, see Amelink et al. (2005).

**Visualizing an Additional Role for the Elevator**

While the throttle and elevator perform their respective primary roles in most situations as described in the previous section, the reservoir analogy does not consider that drag varies with airspeed. Occasionally the elevator has a secondary role in energy management: assisting the throttle in altering \( T - D \) and \( P_s \) through energy exchange that results in changes in airspeed and thus drag (Merkt, 2023). The power curves and mountain analogy can help in visualizing this secondary role of the elevator (Figure 6A and 6B).
On the front side of the power curve (point 1, Figure 6A), at the maximum airspeed at the edge of the energy envelope (point 1, Figure 6B), the airplane cruises at low angle of attack (AOA) with little or no excess power or thrust. Here, pulling back on the yoke or stick (elevator up) will result in a brief energy exchange climb and a reduction in total drag, as the airplane slows down from 1 to 2 toward the center of the power curve (Figure 6A). The reduced drag will result in available energy in the form of positive excess power ($P_s > 0$), where thrust exceeds drag ($T > D$). With this excess power (point 2, Figure 6A and 6B) the airplane can now climb at a constant airspeed.

On the back side of the power curve (point 3, Figure 6A), at the minimum airspeed at the edge of the energy envelope (point 3, Figure 6B), the airplane flies at high AOA with...
little or no excess power or thrust. Here, pushing forward on the yoke or stick (elevator
down) will result in a brief energy exchange descent and a reduction in total drag as the
airplane accelerates from 3 to 4 toward the center of the power curve (Figure 6A). The
reduced drag will result in available energy in the form of positive excess power ($P_s > 0$)
where thrust exceeds drag ($T > D$). With this excess power (point 4, Figure 6A and
6B) the airplane can now climb while maintaining a constant airspeed. This secondary
role of the elevator is essential for preventing unwanted depletion of mechanical energy,
as shown later in the section “Visualizing Irreversible Deceleration and/or Sink Rates.”

The Energy-Control Rules Map

By applying the respective role of the controls to manage the airplane’s energy
state, we can develop a set of basic rules for proper throttle-elevator coordination
to effectively control altitude and airspeed. An energy-control rules map helps
visualize the basic energy control rules (Figure 7). This map illustrates not only

![Figure 7: The Energy-Control Rules Map, Adapted from Lambregts et al. (2008), Illustrates Not Only the Trajectories of an Airplane Transitioning from an Arbitrary Initial Energy State (1) to Other Target States (2, 3, 4, 5, 6, and 7), but Also the Changes in Energy Caused by the Throttle (Blue/Red Arrows) and the Elevator (Green Arrows).]
the trajectories of an airplane moving from an initial energy state (1) to other desired states (2, 3, 4, 5, 6, and 7) but also the changes in energy caused by the throttle (blue and red arrows) and the elevator (green arrows). Thus, the throttle increases (blue arrow) or decreases (red arrow) the total energy as demanded by the new target energy state by acting across energy height lines, while the elevator (green arrows) redistributes the change in total energy between altitude and airspeed by acting along energy height lines. By balancing the concurrent actions of the throttle and the elevator, the airplane can fly along the selected energy trajectory. The basic energy control rules for moving an airplane along the trajectories depicted in Figure 7 are summarized in Table 1.

The rules in Table 1 can be expressed using the “IF, THEN” format explained in the section “Incorporation of a Human Performance Framework.” For example, the rule
for the first trajectory \((1 \rightarrow 2)\) can be stated as this: “IF you want to climb at a constant airspeed, THEN throttle up to increase total energy AND pitch up as needed to allocate the surplus energy into altitude while maintaining airspeed constant.” Likewise, the rule for the second trajectory \((1 \rightarrow 3)\) can be stated as this: “IF you want to accelerate at a constant altitude, THEN throttle up to increase total energy AND gradually pitch down to allocate the surplus energy into airspeed while maintaining altitude constant.” Note that in both cases the throttle controls the change in total energy, while the elevator controls the distribution of that change over altitude or airspeed. The remaining rules could likewise be expressed using the “IF, THEN” format.

The airplane’s energy balance equation (see Equation 1) is another great tool for elucidating the general rules for controlling altitude and airspeed. Any desired change in altitude and/or airspeed demands the throttle to manipulate total energy on the left side of the equation and requires the elevator to adjust pitch attitude accordingly to redistribute total energy over altitude and airspeed on the right side. Having established the roles of the throttle and the elevator and the general energy control rules for moving the airplane within its energy envelope, let us focus on how the pilot can put these rules into practice and develop skills necessary to mitigate energy crises in flight.

**SKILLS FOR MITIGATING RISKS OF MISMANAGEMENT OF ENERGY**

In addition to proper use of the controls during normal flight operations, pilots must acquire “defensive” skills to mitigate two major risks associated with mismanagement of energy: (1) unintentional departure from the desired energy state and (2) irreversible deceleration and/or sink rate causing unwanted depletion of mechanical energy (i.e., a crash). The first risk is associated with unintended altitude-airspeed deviations (see the section “Energy Error Diagram” below). The second risk involves excessive loss of airspeed and/or altitude coupled with insufficient excess power in a given flight condition (see the section “Visualizing Irreversible Deceleration and/or Sink Rates” below).

**Energy Error Diagram**

Pilots need to develop skills to recognize, correct, and prevent altitude-airspeed deviations. Although the goal is to minimize deviations in altitude and airspeed, the pilot is actually controlling the airplane’s energy state (Amelink et al., 2005). Thus,
it is important to translate altitude-airspeed deviations into energy errors. Since total mechanical energy is distributed over altitude and airspeed, energy errors fall under two categories: (1) total energy errors and (2) energy distribution errors (Amelink et al., 2005). The pilot can recognize these two types of energy errors by monitoring the altimeter (or other flight path reference) and the airspeed indicator. A total energy error means that the airplane has too much or too little energy; thus, altitude and airspeed deviate in the same direction (lower and slower or higher and faster). In contrast, in energy distribution errors the total energy may be correct, but its distribution over altitude and airspeed is not, and thus altitude and airspeed deviate in opposite directions (higher and slower or lower and faster).

Another extension of the map analogy, the energy error diagram (Figure 8), is an excellent tool for illustrating energy errors and the skills needed to correct them. Consider three scenarios (B, C, and D) where an airplane has unintentionally descended below its intended altitude or flight path. Since the goal is to return the airplane to its correct energy state (A), should the pilot pull up, add power, or both? The answer depends on the airspeed. Compared to the target airspeed, the actual airspeed may be slower (B), on target (C), or faster (D).

Lower and slower (B) is different from lower and faster (D). The former requires adding power to regain total energy, while the latter requires pulling back on the yoke to nullify the energy distribution error (Amelink et al., 2005; Merkt, 2015). Now, look at C in Figure 8, where the airplane is lower than desired but is at the correct airspeed. Here the pilot faces a combination of total energy and distribution errors.
Regaining altitude while keeping airspeed constant calls for adding power while easing aft on the yoke. Put differently, decoupling altitude and airspeed (i.e., changing one while constantly maintaining the other) requires using both controls simultaneously (Amelink et al., 2005; Merkt, 2015).

With adequate practice and experience, pilots can learn proper coordination of control inputs to correct energy errors by referring to existing cockpit instruments (Aviation Safety 2021; FAA, 2021; Merkt, 2015). However, the task may be facilitated by pilots having a display showing energy errors directly. Research on the effectiveness of energy-augmented displays for correcting energy errors has shown promising results (Adami et al., 2014; Amelink et al., 2005; Lambregts et al., 2008). Adoption of such displays would facilitate the effort of incorporating ESM into pilot training and operations (see the section “A Road Map for ESM Training”).

Visualizing Irreversible Deceleration and/or Sink Rates

The pilot must also be aware of the risk of unwanted depletion of the airplane’s mechanical energy, especially as the airplane approaches the edges of its flight envelope where excess power is zero. It is normal for an airplane to encounter negative energy rates (negative specific excess power, or \( P_s < 0 \)) while slowing down at a constant altitude or descending at a constant airspeed; these are intended negative energy rates. The problem occurs when the airplane experiences unintended, irreversible negative energy rates resulting from excessive deceleration or sink rates with no available excess power at full throttle under a given flight condition and insufficient altitude to recover (Precourt, 2018). No matter what the pilot does in that situation, the airplane will crash.

The map and mountain analogies can help visualize the risk of irreversible negative energy rates as well as the skills needed to mitigate it (Figure 9). The risk may be greatest when handling the airplane near the edge of its energy envelope in low-altitude slow airspeed maneuvers such as takeoffs, landings, go-arounds, and slow maneuvering in the traffic pattern, where available \( P_s \) at full throttle may be close to zero (0) under certain flight conditions. Any attempt to gain altitude by trading airspeed would result in excessive speed loss or a stall, making the situation even worse. As illustrated in Figure 9, the quickest and most effective action for mitigating this risk is to rapidly move the airplane from position 1 to position 2 toward the center of the energy map by pushing the stick/yoke forward. In this new position, positive excess power (\( P_s \)) is available, allowing the airplane to climb at a constant airspeed, position 3 (Figure 9).

This recovery maneuver is a carefully developed skill. It may seem counterintuitive in flight, since the pilot must unload and push the yoke/stick forward so that the airplane is accelerated by exchanging energy just enough to the correct
airspeed (e.g., best rate of climb airspeed, or \( V_y \)) where available excess power is maximized. Thus, underaccelerating to an airspeed short of \( V_y \) or overaccelerating to an airspeed above \( V_y \) results in an insufficient increase in available excess power, making the airplane unable to recover from excessive negative energy rates and possibly resulting in a crash.

### The Top-Down Approach

Mastering the ability to identify, assess, and mitigate the risk of unrecoverable deceleration and/or sink rates requires a deeper understanding of “edge of the envelope” maneuvers. In such maneuvers, three factors—energy errors, poor AOA control, and deteriorated flying qualities—can dangerously converge increasing the risk of unintended energy depletion (crash) in flight. The ability to promptly
correct destabilizing energy errors without exceeding the wing’s critical AOA can enhance safety. However, during these low and slow maneuvers pilots must also be aware of the difficulty in controlling flight path and airspeed as determined by flying qualities, an umbrella concept that encompasses aircraft stability, control, and handling qualities (Kolano, 2000).

To gain insight into the intimate connection between energy management, AOA control, and flying qualities, these factors can be examined in the context of accomplishing a specific maneuver or task, such as transition to slow flight (Figure 10). This is best done by breaking the maneuver down into distinct processes, or levels, starting with top consequences and working our way down to the underlying causes of energy and aerodynamic processes as the airplane transitions from its initial state to the target energy state at the same altitude but a slower airspeed (Figure 10). Note that deterioration of flying qualities, making it harder to control flight path and airspeed as the airplane transitions to slow flight, may occur at each level as it enters the back
side of the power curve (Merkt, 2023). Such deterioration includes speed instability at the energy level, reduced yaw/roll stability at the force and moments level, less responsive flight controls at the airflow level, and occasionally uneven pressure changes along the wing at the air properties level (Figure 10).

One benefit of the top-down approach is that underlying principles only emerge in the context of the big picture presented at the top energy level (Merkt, 2013). The distinct levels in Figure 10 do not reflect different methods for controlling flight path and airspeed. They simply reveal diverse ways of explaining the same action by the pilot and complement each other. Instead of having conflicting explanations, the pilot now has a coherent story in which all the pieces of the puzzle fall into place to form a complete clear picture of the maneuver and how to perform it safely.

The top-down approach is ideal for examining risk factors involved in performing critical maneuvers such as slow flight, takeoffs, approach to landing, go-arounds, and steep turns. Instructors can use this approach not only in the classroom but also during in-flight demonstrations of safe flight path and airspeed control. An integrated training approach designed to enhance energy management, AOA control, and flying quality awareness can be an effective training solution for mitigating the risk of crashing from unrecoverable depletion of mechanical energy. This is especially true when the pilot must take the airplane near the edge of its energy envelope.

A ROAD MAP FOR ESM TRAINING

The training approach outlined in this article is a first step for incorporating energy management into pilot training as required in the FAA ACS. As part of this first step, an operational definition of aircraft energy management can now be offered (Aviation Safety, 2021; FAA, 2021; Merkt, 2023): Aircraft energy management is the process of planning, monitoring, and controlling altitude and airspeed targets in relation to the airplane’s energy state as appropriate to (1) attain and maintain desired path-speed profiles; (2) detect, correct, and prevent unintentional altitude-airspeed deviations from the desired energy state; and (3) prevent irreversible deceleration and/or sink rate.

Note that this definition is concerned with managing mechanical energy (altitude and airspeed) and addresses the safety (flight control) side of energy management. It does not address the efficiency (aircraft performance) side of energy management, which is concerned with how efficiently the engine generates mechanical energy from fuel and how efficiently the airframe spends that energy in flight (Rutowski, 1954). Thus, even though the training approach outlined in this article focuses on the safety side of energy management, future studies could evaluate the effectiveness
of energy management as a training tool to integrate flight safety and efficiency (Merkt, 2022).

The second step is to collaborate with the FAA to support and develop appropriate energy management guidance in FAA handbooks and other reference materials. This effort, already under way (Merkt, 2020; Merkt & Sizoo, 2019), has included writing the first-ever chapter on energy management for the Airplane Flying Handbook (FAA, 2021). Chapter 4 (Energy Management) in the Airplane Flying Handbook lays out the essential knowledge, rules, and skills for safely managing the airplane’s energy state during flight (FAA, 2021).

The third step, already in progress at Embry-Riddle Aeronautical University, is to provide practical hands-on guidance for integrating energy management into a pilot training curriculum that will meet and exceed the appropriate FAA standards outlined in the ACS. The ground portion of the training is being evaluated through an academic course on safety principles of aircraft energy management being taught at Embry-Riddle since 2018 (Merkt, 2023). Integration of ESM principles into flight training is planned following additional research that will involve flight data monitoring (FDM). The first part of the research will measure “energy-based metrics” (Puranik et al., 2017) to evaluate FDM as a tool for detecting and analyzing anomalous energy states during flight. The second part will involve using FDM to assess, validate, and verify the effectiveness of ESM training for mitigating anomalous energy states and enhancing flight safety. Expected outcomes from ESM training (both on the ground and in flight) include:

- Improved mental model of the airplane as an energy system;
- Heightened awareness of the consequences of mishandling an airplane’s energy state during critical phases of flight such as takeoff, landing, go-around, and low-altitude maneuvering;
- Effective coordination of pitch and power inputs for achieving and maintaining vertical flight path and airspeed targets in any phase of flight; and
- Enhanced stick-and-rudder energy skills to correct path speed deviations and avoid irreversible deceleration and/or sink rates.

The fourth and last step will be to develop and implement energy-based cockpit displays that provide direct information on the energy state of the airplane to the pilot. Awareness and management of the airplane’s energy state may be enhanced by coupling ESM with energy-augmented displays. Experimental energy management displays have been researched and evaluated in academia (Amelink et al., 2005; Atuahene, 2009; Lambregts et al., 2008; Van den Hoven et al., 2010). The FAA has already sponsored research to explore the feasibility and practical use of energy...
displays in general aviation aircraft (Adami et al., 2014; Silver et al., 2020). Additional research, coupling ESM training with energy-based displays to evaluate any increase in safety and/or reduction in pilot workload, may justify implementation of such displays in the future.

CONCLUSION

Pilots are energy managers. The goal of ESM training is to help pilots master the knowledge, rules, and skills necessary to effectively manage altitude and airspeed in any airplane or phase of flight as well as mitigate the consequences of mishandling the airplane’s energy state. ESM accomplishes this goal by using a novel approach in flight training — teaching pilots to fly the airplane as an energy system — using simple analogies, plain-language rules, and appropriate piloting skills. As an added benefit, it is anticipated that incorporation of ESM into pilot training will not only increase flight safety but also improve training efficiency by making it easier for new pilots to master vertical flight path and airspeed control.

NOTES

1. Vertical flight path defines the altitudinal (as opposed to lateral) direction of flight. Here, the angle between the flight path and the horizontal determines whether the airplane is maintaining a constant altitude (flight path angle = 0), gaining altitude (flight path angle > 0), or losing altitude (flight path angle < 0). Due to their close relation, the terms “vertical flight path” and “altitude” are used interchangeably in energy management literature (e.g., Amelink et al., 2005; Lambregts, 1983; Merkt, 2013) and in this article.

2. Note that this simplified equation does not account for changes in total mechanical energy caused by the continuous reduction in aircraft weight, as fuel is gradually burned in flight. Although the effect of weight loss is negligible when applying the energy approach to solve short-term control problems, it becomes critical when solving long-term performance problems such as those involving range calculations (Rutowski, 1954).
REFERENCES


