



# Future Fuel Scenarios and Their Potential Impact to Aviation

*Robert C. Hendricks  
Glenn Research Center, Cleveland, Ohio*

*David L. Daggett and Peter Anast  
The Boeing Commercial Airplane Group, Seattle, Washington*

*Nathan Lowery  
Princeton University, Princeton, New Jersey*

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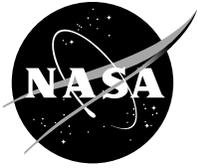
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Glenn Research Center, Cleveland, Ohio*

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Princeton University, Princeton, New Jersey*

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National Aeronautics and  
Space Administration

Glenn Research Center  
Cleveland, Ohio 44135

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Robert C. Hendricks  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135

David L. Daggett and Peter Anast  
The Boeing Commercial Airplane Group  
Seattle, Washington 98124

Nathan Lowery  
Princeton University  
Princeton, New Jersey 08544

## Abstract

In recent years fuel prices have been growing at a rapid pace. Current conservative projections predict that this is only a function of the natural volatility of oil prices, similar to the oil price spikes experienced in the 1970s. However, there is growing concern among analysts that the current price increases may not only be permanent, but that prices may continue to increase into the future before settling down at a much higher level than today. At high enough fuel prices, the aircraft industry would become very sensitive to fuel price. In this paper, the likelihood of fuel price increase is considered in three different price increase scenarios: “low,” “medium,” and “high.” The impact of these scenarios on the aviation industry and alternatives are also addressed.

## Introduction

According to the Boeing Current Market Outlook, air travel is projected to continue expanding at an average growth rate of about 5 percent per year. Underlying this projection of continued growth is an assumption that the industry will not be constrained by petroleum-based fuel availability. The purpose of the present discussion is to assess the validity of this assumption. If fuel is not available from various energy sources [1–4] in quantities required for such growth, alternative technologies for fuel and improved aircraft efficiency will need to be considered.

Over the past 40 years, airplane fuel efficiency has improved dramatically (Fig. 1).

However, the current rate of gains in efficiency will be outpaced by the projected growth in traffic, and the aircraft industry will thus require an increasing amount of fuel. This is

true not only of the aviation industry, but of worldwide transportation energy uses in general (Fig. 2).

Existing markets for energy use will not be the only source of increased demand for petroleum-based fuels. Growing economies in emerging nations—especially in Asia, Africa, and Latin America—will put an even tighter constraint on worldwide fuel supply (Fig. 3).

With a growing gap between the growth rate of petroleum energy production and demand, it is imperative that the aircraft industry investigate issues related to fuel availability and possible technologies for alternative fuels and improved aircraft efficiency to offset the potentially devastating effects that would be encountered by a future scenario in which jet fuel availability is not sufficient to meet demand and prices skyrocket.

## Discussion

When dealing on a global scale the word speculation takes root. While analysts may not agree when we will run out of “cheap-oil,” they all agree that we eventually will run out. Crises and fuel prices have fluctuated over several years (e.g., 1970s), but in the past few years there are trends that indicate a different scenario. The projected energy demands of India, Russia, and China—especially China and India—for fuel are acute. Resources are being gobbled up, and deals for future fuels are being consummated amid concerns of foreign debt.

### Future Fossil-Oil Fuel Availability

Before proceeding, a distinction needs to be made between fuel, an energy-storage medium, and petroleum energy sources (derived from oil). As inexpensive petroleum energy sources

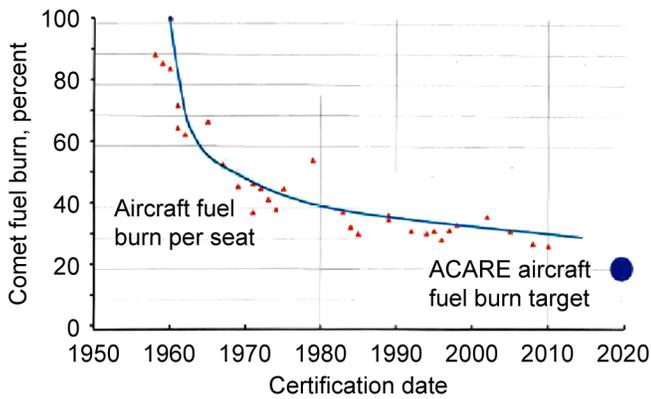


Figure 1.—Fuel efficiency improvement of long-range transport aircraft (Smith, Colin (2005) *The Environmental Challenge, Bringing Technology to Market. ISABE-2005-1008*).

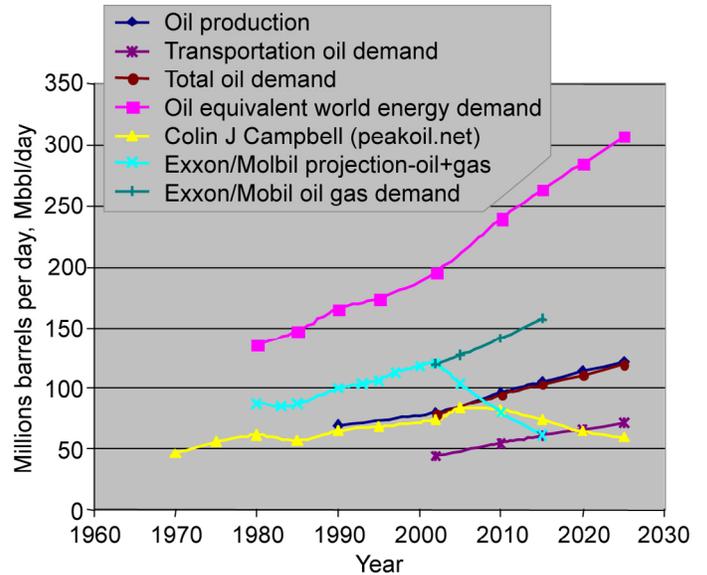


Figure 2.—World energy, oil, gas, and transportation consumption versus production reality ([www.eia.doe.gov/oiaf/ieo/pdf/ieooil.pdf](http://www.eia.doe.gov/oiaf/ieo/pdf/ieooil.pdf)).

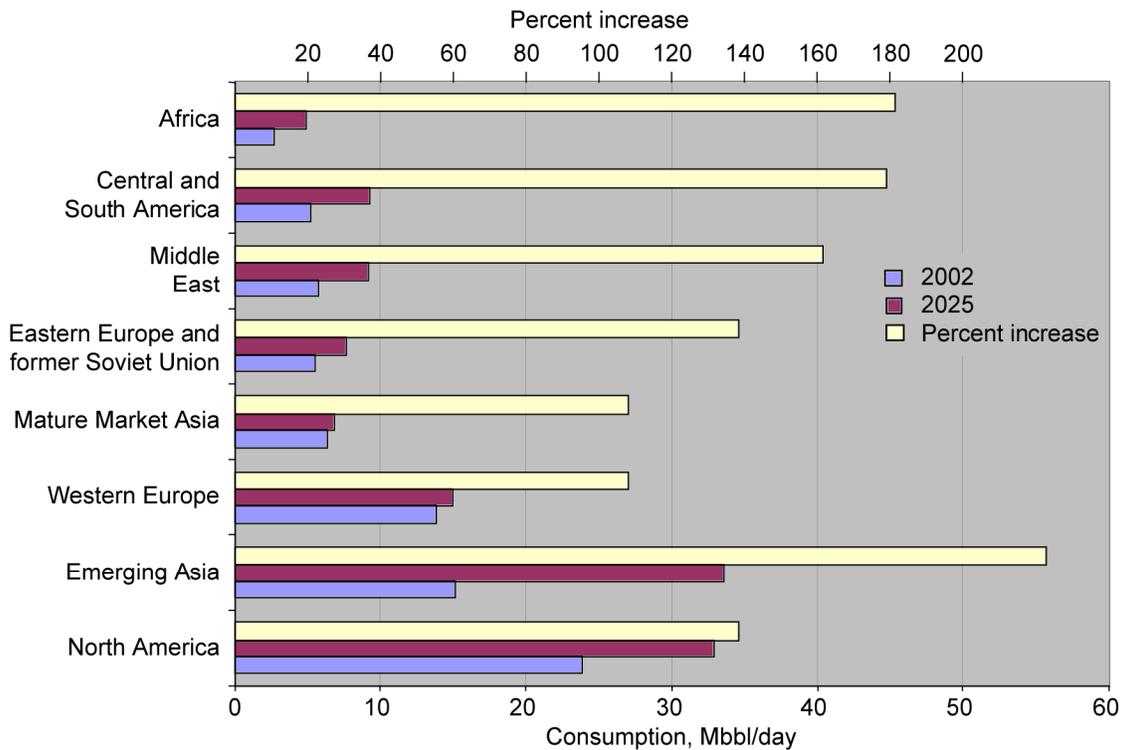
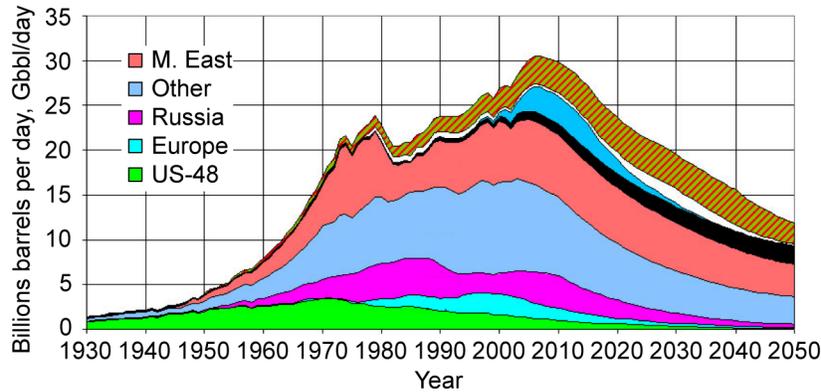


Figure 3.—World oil consumption by regions for year 2002 and projection for year 2025, with percent increase [(projected/current)100%] in consumption (<http://www.eia.doe.gov/oiaf/ieo/oil.html>).



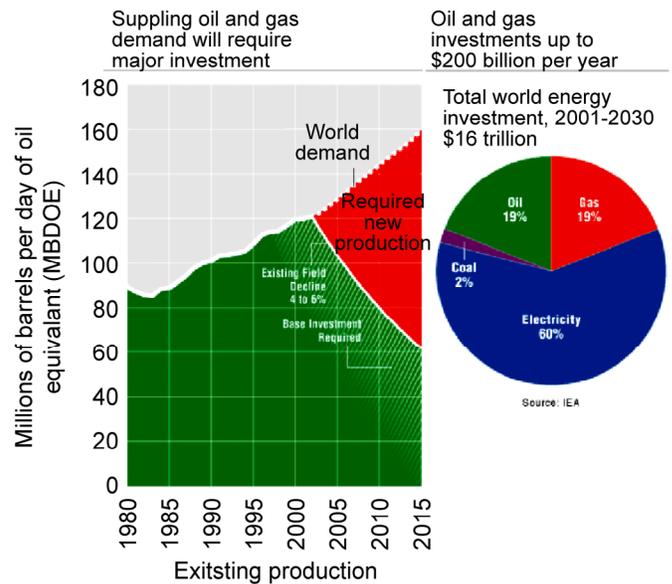
**Figure 4.—World oil consumption: oil and gas liquids, 2004 scenario**  
 (<http://www.peakoil.net/uhdsg/Default.htm>).

are exhausted, alternate energy sources will change the type of fuels available in the future, which in turn will impact the aircraft platform. A design using hydrogen will be very different from one using gas-to-liquid (GTL) derived fuels. These GTL fuels are usually environmentally cleaner—some can mimic Jet-A—and will enable new engine and aircraft technologies, yet will require major investments.

“Peak Oil” is a term that comes from the work of geologist M. King Hubbert, who correctly predicted the peak of U.S. oil production 15 years in advance. In the 1960’s, Hubbert predicted world oil production to reach a maximum around the year 2000. Ken Deffeyes reworked Hubbert’s calculations with updated data and places this peak somewhere around the end of 2005 or 2006 [5]. Still more experts [6] have done analyses of their own and made widely varying predictions of the timing of peak oil production. Colin J. Campbell of the Uppsala Hydrocarbon Depletion Study Group places the peak in oil at around 2008, and this study includes unconventional oil such as tar sands, deepwater oil, and natural gas liquids (see color bands of Fig. 4) [7]. Almost all experts in the field agree that petroleum is a non-renewable resource, and as such cannot be produced indefinitely. So the issue is not whether this peak will occur, but when? Many analysts think this peak will occur very soon.

As shown in Fig. 5, this peak in oil production will mean that, as demand continues to grow, the gap between production and demand will also continue to grow. If the region on the chart marked “required new demand” is not able to be met through increased production of alternative fuels, the price of all petroleum products worldwide will naturally increase as well.

The quantity of world oil that has been produced throughout the world as of 2005 has been estimated by Laherrere [8] to be just over 1 trillion barrels of conventional oil worldwide, with about 1 trillion more to be recovered. Cambridge Energy



**Figure 5.—World oil and gas production, demand, and investment.** <http://www.exxonmobil.com/corporate/Newsroom/Publications/eTrendsSite/chapter1.asp>.

Research Associates (CERA) claims that the capacity of oil production will outpace demand until at least 2010 and that the peak in oil production will occur no sooner than 2020 [9]. CERA, like the Department of Energy Energy Information Administration (DOE-EIA) forecast “assumes that OPEC will pursue policies intended to increase production, that sufficient resources exist, and that access and capital will be available to expand production.” [10]. However, respected energy industry analyst Matthew Simmons indicates that at least for the claims made by the Saudi Arabian government—the largest producer of oil worldwide with 2/3 of the world proven

reserves—oil reserves have been significantly exaggerated for political reasons, and Saudi Arabia is not in fact capable of stepping up production to meet future demands like its government has repeatedly claimed; a fact recently corroborated by the Saudis [11–13]. Based on current oil industry practices, Boone Pickens, a retired geologist from Mesa Petroleum, sets global oil production at 84 Mbbbl/day (million barrels per day) and does not expect increased production. This is based on the fact that we are currently consuming more than we are producing and are not replenishing our reserves [14]. With the peak of oil production imminent, it is useful to consider the possible effects of fuel availability on the cost of jet fuel, and, in turn, the effects of fuel costs on the aviation industry.

## Cost Scenarios

Projections have been made for the cost to industry to enhance production of conventional and unconventional fuels, as well as for the impact on the aviation industry and airline consumers, while indirectly considering the effects of greenhouse gases and the need for nonfossil fuels.

**Projected Industry Costs.**—With the dwindling supply of oil, it has been argued that unconventional oil sources such as shale oil and Canadian tar sands will be able to compensate. Even CERA, who conservatively places the peak in oil production in 2020, forecasts it will cost the energy industry \$4 to \$6 trillion to bring production of unconventional oil up to these levels [15]. A similar number (\$3 trillion) is cited by Klare [13] to enhance conventional oil production. In 2004, major oil companies spent about \$64 billion on new capital projects. Over 15—even 30—years this investment gap could be covered by governments worldwide, but the current U.S. Energy Bill includes only \$8 billion to encourage more energy research in all fields—nuclear, renewable and crude oil [16], and other governments worldwide cannot be relied upon to make up this deficit. International Energy Agency (IEA) estimates a total annual energy investment of about \$530 billion per year is required with 40 percent (\$200 billion

per year) required by the gas and oil industry. Placing these figures into perspective, the Gross Domestic Product of Norway is less than \$200 billion, and \$530 billion is greater than the 2004 U.S. defense budget [15].

**Future Fuel Price Scenarios.**—Historical jet fuel prices are very closely correlated with the price of crude oil. With production restraints and “peaking” imminent, it is prudent to consider different cost scenarios for use in analyses of future technologies. The focus of this discussion is to consider three cases in which fuel prices rise over the long term, simply named the “low,” “medium,” and “high” fuel price scenarios, as shown in Fig. 6.

*Low-Price Scenario:* Data from The U.S. Bureau of Transportation Statistics (BTS) Airline Fuel Cost and Consumption (1977 to 2005) data tables (available from <http://www.bts.gov/>) were fitted from 1995 to 2003 and extrapolated to year 2020 giving the low-price scenario of \$1.33/gal. This assumes the recent upswing in price reverses and settles back down to the average growth trend experienced since approximately 1995 (after the Gulf War), as shown by the lower solid arrow on the chart. The DOE–EIA [10] provides several potential scenarios using data from 2003, yet greatly underestimates the prices that are being experienced in 2005. The DOE expects oil demand to jump from 77 Mbbbl/day in 2001 to 121 Mbbbl/day by 2025, a net increase of 44 Mbbbl/day. Over 1/4 of this additional oil—some 12.3 Mbbbl/day—is expected to come from Saudi Arabia, the only country that may be capable of increasing its output by this amount. Take away Saudi Arabia's added 12.3 Mbbbl/day, and there is no possibility of satisfying anticipated world demand in 2025, which is the reality of Figs. 1 to 5. One could, of course, suggest that some other oil producers will step in to provide the additional supplies needed, notably Iraq, Nigeria, and Russia; although these countries together would have to increase their own output by more than 100 percent simply to play their already assigned part in the DOE's anticipated global supply gain over the next two decades. This in itself may exceed their production capacities. To suggest that they could also make up for the shortfall in Saudi production is questionable. The DOE–EIA

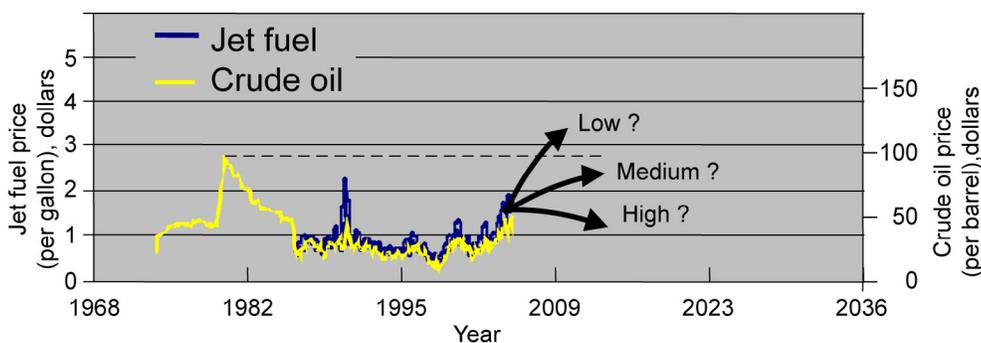


Figure 6.—Comparison of historical prices of crude oil to Jet-A fuel with future projections (<http://www.bts.gov/xml/fuel/report/src/tableversion.xml>).

report tacitly assumes OPEC and the non-Gulf 8<sup>1</sup> can and will meet energy demands. It was already noted though, that oil producing countries are too often mired in political strife and remain without sufficient infrastructure in place or plans to meet those demands [12–13].

CERA argues that alternative energy sources, especially unconventional oil will play a large role in allaying troubles arising from the depleting oil supply, making up almost 35 percent of world oil supply by 2020. The report claims that there are about 20-30 new major projects coming online before 2010, and these projects, combined with the increased capacity of current oil production sites, will produce about 17.7 Mbbbl/day of new capacity. This is an increase of about 20 percent over current oil productivity. Assuming a demand growth of 2.2 percent per annum (which CERA claims is rather strong), this amount of new productivity would still be well above demand and thus prices should re-stabilize in the short term and resume moderate historical growth trends.

This report paints an optimistic picture in the short to medium term and further asserts that when oil does peak, other conventional oil sources will have matured sufficiently such that there will not be a peak in oil, but more of a plateau that will be sustained until alternative energy (renewable, nuclear, unconventional oil, etc.) can replace oil almost entirely.

So, while the CERA report probably means good news for the short term—with more than 20 new large-scale projects coming online in the next 5 years—the need for investment in unconventional oil remains a large question in the long term. Because of this, the low-fuel price scenario seems to be a decidedly optimistic projection; in 10 to 15 years, the price will likely be much higher.

*Medium-Price Scenario:* The choice of the medium price, \$2.67/gal (twice the low price) in year 2020, also corresponds quite well to the historical maximum crude oil price at the height of the oil crisis following the war between Iran and Iraq in the 1970s. In this case, it is assumed that rate of current price increases will diminish and will eventually flatten out to about the same as the slope of increase since 1991; the low-price scenario plus a constant.

The price reflects unconventional oil sources being online, but due to practical constraints such as limited capital and the inherent time required to build new facilities, production from these sources is not able to keep up with the demand as well as CERA projects that it will. As a result, fuel prices rise appreciably in the long term. Because of the uncertainty in trying to predict how quickly these relatively immature technologies will be developed, this seems to be the most reasonable prediction.

The DOE projection is predicated on technological advances and new energy sources. Hybrid- and diesel-powered automobiles are projected to enjoy an 11 percent market share by 2012, up from 4.8 percent in 2005 [18], and several fuel cell vehicles are currently in development. Cleaner synthetic fuels, such as gas-to-liquids (GTL) fuels, will also help alleviate the

strain of dwindling oil supply and could reach 1.5 Mbbbl/day by 2020 (Jeroen van der Veer, CEO of Shell) that represent roughly 1 percent of projected worldwide oil demand at that time. These alternative energy sources may be able to stabilize the energy market in the very long term; however, it is the short and medium terms that are uncertain.

Political factors are likely to manifest in the form of some type of rationing or nationalization of the industry. As supplies dwindle, and prices skyrocket, there will be more pressure on politicians and governments (domestically and internationally) to intervene and bring prices down. For example, the British Government in July 2005 began to discuss the idea of “Domestic Tradeable Quotas” of carbon, a type of personal carbon allowance [19]. Such a measure would ostensibly be implemented to manage carbon emissions, but would ultimately amount to a type of gas rationing, with low energy users selling part of their quotas to high energy users.

Unfortunately, the complexities of this issue make speculation about its specific effects a futile effort. One can expect though, that if governments intervene, it will be only in the case that prices are rising rapidly with no sign of coming down, and such policies will be used to force fuel prices to settle at a reasonable, midrange price.

The expectation of drastic price increases being slowed either by forces of the market or politics is the reasoning behind the “medium price” for U.S. Jet-A fuel being placed at about \$2.67/gal, which is the current domestic price in India. This price represents a relatively modest 5 percent increase compounded annually over each of the next 15 years. In this scenario, it is expected that either other technologies will come online just fast enough to keep oil prices from skyrocketing without bound, or if they do not, governments will intervene to keep prices down. Airlines and engine and aircraft manufacturers would have even greater incentive to improve fuel efficiency.

*High-Price Scenario:* The choice for the high-price scenario represents a projection based on BTS tabulated 2002 to 2005 fuel cost data and represents nearly a quadrupling of current fuel prices by 2020 to \$5.51/gal. Fig. 6 shows this would occur in the event that recent growth trends continue for several years and only slow gradually and asserts that global oil production has or is about to peak.

Pickens (Mesa Petroleum) claims that global production has already peaked [14], Deffeyes (updating of Hubbert’s work) cites 2005, Simmons places the peak sometime in the next 3 years [12], and Campbell (Uppsala Hydrocarbon Depletion Group) places the peak in oil at around 2008. Campbell’s work includes unconventional oil such as tar sands, deepwater oil, and natural gas liquids [7]. This is in contrast to the CERA report which argues that unconventional oil sources will constitute 35 percent of the world’s energy supply by 2020 and delay the peak of oil until long into the future.

If it is indeed true that oil production will peak within the next couple years, and that unconventional oil will do little to improve the situation, we can expect drastic increases in the price of oil until nuclear, alternate, and/or renewable energy is producing in large enough capacities to replace demand for oil.

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<sup>1</sup>This group comprises Mexico, Venezuela, Colombia, Russia, Azerbaijan, Kazakhstan, Nigeria, and Angola.

The EIA foresees these technologies growing only marginally by 2020: according to their numbers, nuclear power production will increase by 9 percent, hydropower by 17 percent and other renewables by 28 percent [20]. However, it should be noted that these power sources currently represent only about 15 percent of domestic power production, and even after these increases they will actually represent only 14 percent of the projected power demand in 2020, or a reduction in the overall contribution of these alternative power sources. This means that if—as Simmons writes in his book—the production of oil does not grow at the rate the EIA predicts, these other sources will have to increase at a much higher rate than current data suggests, or there will be a significant energy shortage, and prices will skyrocket.

Assuming that this actually happens, and that governments do not intervene to keep prices down, it is very difficult to determine a realistic oil price.

For example, what if oil prices continue to rise dramatically and Jet-A becomes \$5.51/gal, which is about four times current jet fuel prices? For the price to quadruple in 15 years, an annual increase of about 9.7 percent is required. This is a rather strong increase to sustain over such a long period, but it is much less than the current rate at which prices are growing. The average price in 2003 was 20 percent higher than in 2002. In 2004 the price increased another 36 percent, and the year-to-date average price as of July 2005 is another 28 percent increase over 2004 [20]. Thus, as a theoretical “high price” scenario, \$5.51/gal is not completely out of the question and in line with some 2005 European petrol consumer prices near \$5/gal. In a world where oil production has peaked and there are limited alternatives, the price of oil will increase without bound until alternatives are sufficient to slow its pace.

These projected scenarios are based on analysts views and speculation; it is true that any projection, be it scientific or otherwise, is speculation and often an analysts opinionated position for an ideology. There are very few absolutes. But these projections are, presently, the best that we can achieve while indirectly addressing the greenhouse gases (GHG) challenge of our planet with the acute need for nonfossil energy supplements.

So why investigate the high, medium, and low fuel price scenarios? First, these factors illustrate the vulnerability of nations and industry to fuel prices and second, aircraft operation and design is greatly influenced by fuel costs. The aircraft design for the low-price fuel would be similar to that which is being designed and fielded today. However, the high fuel price would necessitate a new aircraft design philosophy and would be different than what is on the boards today.

### Impact on Airplane Operating Cost

Airline operating costs are currently dominated by flight crew costs, which represent about 33 percent of the total, as shown in Fig. 7(a). If one now considers the tenuous position of fuel availability and the high-cost scenario from above, with all other costs inflated nearly 1 percent/year, fuel costs are

projected to dominate with about a 50 percent share of the total cash airplane-related operating costs (CAROC) (Fig. 7(b)).

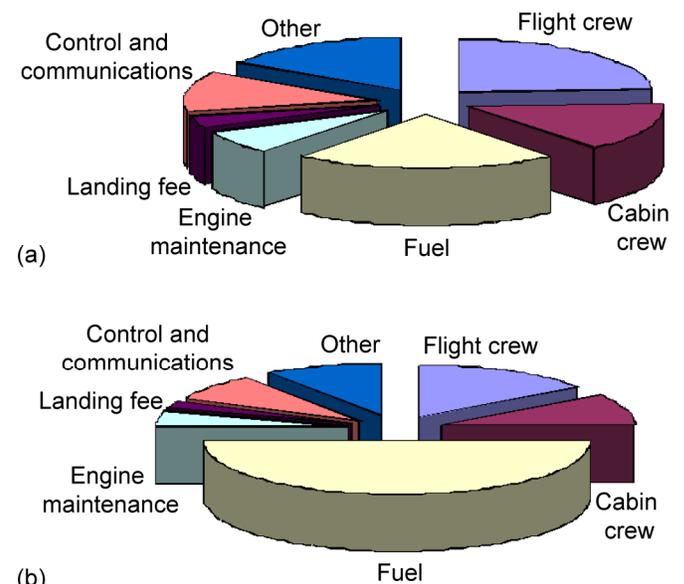
If fuel costs become the most important operating expense for aircraft, alternate fuel sources might become more attractive to the aviation industry. Alternative fuels would require significant changes to the design of current aircraft.

### Alternate Energy Sources for Fuels

As petroleum prices continue to increase, several alternative fuel sources will become price competitive with currently available energy sources. Synthetic fuels made from plentiful energy sources such as coal, natural gas, or other hydrocarbon feedstock show significant promise as fuels that could be easily integrated into today’s aircraft with little or no modification to current aircraft designs, yet may require additives. These synthetic fuels are most often referred to as “gas-to-liquid” or GTL fuels.

The market for GTL fuels is rapidly emerging. The process used to produce this synthetic fuel, which is sometimes called “Fischer-Tropsch” or “FT” fuel after its inventors, was developed in 1923 and put into use by Germany during WWII. The actual Fischer-Tropsch process refers to the conversion of synthesis gas, or “syngas,” into any of a variety of synthetic fossil fuels. Syngas is the name for a mixture of hydrogen and carbon monoxide gases that can be obtained through reformation of a number of feedstocks including coal, natural gas, or biomass.

Today, the most promising feedstock for use in this process is natural gas and coal because of the potential to make use of the large amounts of these energy sources available around the world. One potential source is the natural gas found in oil fields that is currently “flared” (burned) because no use can be found



**Figure 7.—Cash airplane-related operating costs (CAROC) for 747–400ER, 3000 nmi mission. (a) 2004 (from Daggett, D.L.: Water Injection Feasibility for Boeing 747 Aircraft. NASA/CR—2005-213656, 2005). (b) 2020 projected.**

for it. According to one source, the energy content of the natural gas flared each day (10 billion cubic feet worldwide) could provide 17 percent of the daily power demand in the United States [21]. More promising (yet less proven) energy sources in terms of the world's organic carbon are found in remote locations around the world (Fig. 8).

The so-called "stranded" natural gas reserves are reserves that have been located but are not economically exploitable because they are not located near a pipeline, and thus currently lay unused. Current figures place the total known amount of this stranded gas at about 14 quadrillion cubic feet. If this gas were able to be harvested and converted to synthetic fuel, it alone would supply the world's energy needs for 25 years [22]. Looking even further into the future, in addition to these known stranded gas reserves, there are tremendous amounts of natural gas in the form of methane hydrates that are found in permafrost regions and below the ocean floor (Fig. 9).

Until recently, there was no economically viable way of harvesting methane hydrates, but Syntroleum, Inc. (Tulsa, OK), received a patent in 1999 for a process that will allow them to recover this gas from the ocean floor. According to David Greene of the Oak Ridge National Laboratory, "worldwide estimates of the natural gas content of methane hydrates approach 400 quintillion cubic feet." [23]. This is 30 000 times the amount of known stranded natural gas. Given that there is enough stranded natural gas to supply energy for the world for 25 years, these methane hydrates represent the potential to supply the world's energy needs for the next 750 000 years. They also represent an environmental problem because methane, as a GHG, is 20 times worse than CO<sub>2</sub>.

There are several reasons GTL fuels are so attractive, not the least of which being the fact that current oil prices hover above \$60/barrel. According to the chairman of Syntroleum, "these projects would have been profitable with oil at \$25-30 a

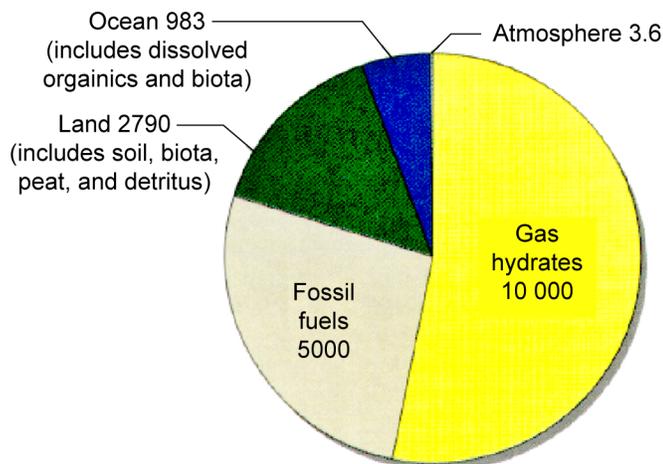
barrel" [24]. Since, according to Greene, GTL fuels cost about \$15-20/barrel to produce, there is a good business opportunity with this technology. Perhaps more significant for consumers, GTL diesel burns very cleanly [25]. There are only 1 to 15 ppm sulfur [26] and negligible amounts of aromatics and metals in GTL diesel [27]. In a study conducted by Shell, when used with a catalyzed diesel particulate filter, emissions of particulate matter from heavy-duty trucks were reduced by 97 percent. Better catalytic filters can be used with this fuel because of the low sulfur content of the fuel [24]. Finally, and most importantly for the short term, this fuel can be transported using current infrastructure and can be used in current diesel engines or mixed with "dirtier" diesel fuels with no modification to the engines. This means that with the tightening emissions regulations soon to go into place in Europe and eventually worldwide, GTL diesel can be used to improve the quality of current diesel inventories to bring them up to standards.

### Alternate Fuel Possibilities

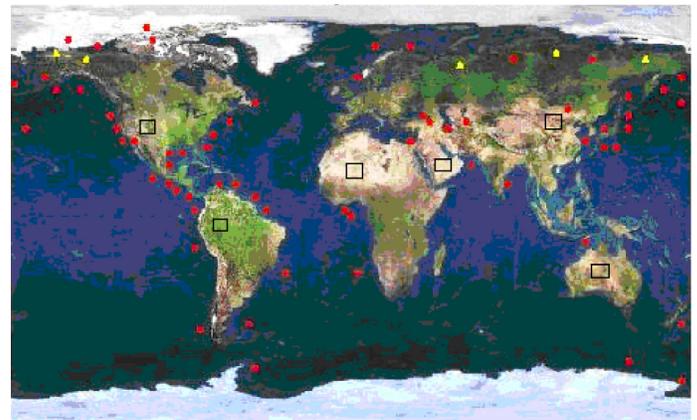
While our economy and security are currently dependent on inexpensive oil and other fossil-based fuels, there are alternatives, many of which have been discussed in the 1970s by Reed and Lerner [28], such as

(1) GTL biomass: a renewable source and more environmentally friendly in most applications including

- ethanol from corn, corn-stover, and grasses (e.g., switch grass)
- biodiesel from soybeans
- methanol from trees and wastes
- synthesis gases in general



**Figure 8.—Distribution of the organic carbon in Earth reservoirs, excluding that dispersed in rocks and sediments. Numbers are in 10<sup>15</sup> tons of carbon (<http://marine.usgs.gov/fact-sheets/gas-hydrates/title.html>).**



**Figure 9.—Global distribution of methane gas hydrates, illustrating (1) location of methane hydrates with large deposits about coastal America and Japan (e.g., off coastal Carolinas); (2) most likely desert areas for massive solar power developments (e.g., U.S. Southwest); and (3) land area for Smalley solar power generation, shown by boxes ([http://www.netl.doe.gov/scngo/Natural Gas/hydrates/databank/HydLocations.htm](http://www.netl.doe.gov/scngo/Natural%20Gas/hydrates/databank/HydLocations.htm)).**

(2) Solar and wind generation of electricity: also renewable and environmentally benign and can be used in fuels synthesis for transportation, see references 28 to 36, for example, and Fig. 9.

(3) Hydrogen: Today most comes from reformation of coal; as such, for heat engine applications, gas or liquid, the life cycle is not environmentally friendly. Yet other energy sources as solar, wind, or nuclear-electric electrolysis can be used.

## Alternate Fuel Use in Aircraft

There are aircraft challenges in implementing many of the alternate fuels (e.g. fuel freezing, thermal stability, sustainability, storage, safety, reliability, etc.).

While using Jet A-GTL mixtures or synthetic jet fuel (SJetA) will require qualification testing, including crash fire safety for example, and unexpected complications may arise, these fuels should become acceptable. On the other hand, there are many issues that need to fall into place prior to using biomass fuels (some of which apply equally to SJetA or mixtures).<sup>2</sup> A few examples are listed here:

(1) Assurance of supply and consistency of biofeedstocks (switchgrass, soybeans, rapeseed, stover, trees, wastes)

(2) Need for new more efficient methods and cycles for biostock to fuel conversion and waste disposal.

(3) Need to determine how current systems and components must be altered, such as fuel metering, fuel injection, storage, handling, and transfer systems; safety; anthropogenic emissions (combustion, production, propulsion, and flight); standardization of fuel heating values and constituents; thermophysical properties measurements and fundamental equation or equation of state predictors; long-term storage separation and stratification; long- and short-term corrosion and materials compatibility; fuel thermal stability for Bio-Jet (fails JFTOT test, ASTM D 3241 (Jet Fuel Thermal Oxidation Tester)), poor lubricity for GTL-Jet; heat of combustion content of the fuels (not too bad for Bio-Jet or GTL-Jet fuels); life cycle emissions impact; and fuel cost impact, to name a few.

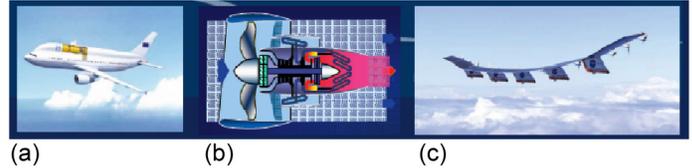
(4) For aviation applications, low temperatures at altitude engender fuel viscosity and freezing issues that require resolution. Standardization of the percentage fossil-fuel to bio-fuel blends becomes necessary and to determine if EJ15 is better suited for aviation than EJ10 or EJ50? Or could EJ100 be used? Here EJ15 implies 15 percent ethanol + 85 percent Jet-A by volume.

<sup>2</sup>Typical heat content of Jet-A is 18,500 BTU/lb. The density varies but is around 6.74 lb/gal or 124,690 BTU/gal. Seattle to Washington DC is 2325 statute miles. If the aircraft consumes 25,000 lbs of fuel, seats 162 passengers (737-800) with a passenger load factor of 80%, this will give a fuel mileage of 81.5 passenger miles (pmi) per gallon, which provides for an energy requirement of 1,530 BTU/pmi.

Note: Lufthansa (year 2003) fleet average 4.31liter/100 pkm (passenger kilometer)

$$= \left[ \frac{4.31 \text{ liter}/100 \text{ pkm}}{3.78 \text{ liter}/\text{gal}} \right] \times [1.60934 \text{ km}/\text{mi}]$$

$$= 1.846 \text{ gal}/100 \text{ pmi or } 54.2 \text{ pmi}/\text{gal or } 2301 \text{ BTU}/\text{pmi}$$



**Figure 10.—Possible future aviation projects (from Szodrich, ref. (37)). (a) Hydrogen fuels. (b) Intercooler or Recuperator. (c) Solar electric or fuel cell.**



**Figure 11.—Vision of future aircraft configurations powered by turboprops (lower and slower concepts) (from Broichhausen, ref. (38)).**

Assuming that these factors can be resolved, fuel type, cost, and availability could now drive design of the engine and airplane configuration (Figs. 10 and 11).

Hydrogen bulk density is low, necessitating large storage volumes. Engine efficiency enhancements through intercooling of the compressor and recuperating heat from the turbine exhaust represent major design challenges. Unmanned ultrahigh altitude solar electric and fuel cell communications platforms present new opportunities for flight propulsion and aircraft integration [37].

Fuel savings of lower altitude and lower cruise Mach number may also become interim solutions to the high cost of fueling. For example, turboprop aircraft and ocean skimmers are envisioned, illustrated in Fig. 11 [38].

## Preparing for the Future

While hydrogen-fueled systems represent our nation's long-term goal, this goal appears further into the future than anticipated. To alleviate potential shortages and enhance our ability to grow aviation, research and development needs to be done for all alternate fuels and not just hydrogen.

## Conclusions

With rising fuel prices, improving airplane energy efficiency becomes an increasingly important driving factor in new aircraft design. If prices reach and sustain levels near the medium- or high-price scenarios discussed above, it will not be sufficient to continue with incremental improvements to aircraft efficiency. Instead, fundamental aircraft technologies will need to be reconfigured for more fuel-efficient designs.

Another factor of rising fuel prices that will indirectly affect the aviation industry will be the introduction of alternative

fuels into the market. The development of these fuels will be driven by the price of crude oil and will help to stabilize the long-term price of jet fuel. However, most experts agree that there will be a long and difficult transition period in which prices will remain high and place considerable constraint upon the aviation industry.

Aside from helping to stabilize the price of fuel, alternative fuels offer other benefits to the aviation industry. Most of these alternative fuels, such as biodiesel and in the longer term, hydrogen, are best used in the ground transportation sector. With the increased use of these fuels, a greater portion of a barrel of crude oil can be used for producing jet fuel, because aircraft are not as fuel-flexible as ground vehicles. However, the aviation industry would of course have to pay a significant premium to increase its share in the overall consumption of petroleum. This provides further incentive to design more fuel-efficient aircraft.

Much work remains to be done to bring alternate fuels into more widespread use, both within the aviation industry and outside of it. Questions have been raised about the energy needed to produce some of these fuels compared to the energy that they provide. Further life-cycle analyses need to be performed to verify the practicality of using these fuels in the entire transportation sector.

Finally, because of the ease with which it can be integrated into current aircraft, GTL fuels show significant promise to transition the aviation industry from traditional petroleum-based jet fuel to other sustainable fuels in the long term.

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