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Introduction to Sustainable Aviation

ALLISON TSAY

Notes on the AIAA short course (Dr. Marty Bradley)
**All images taken from the course

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Overarching Themes and Topics

- Motivation for achieving sustainability
- Emissions
- Fuels
- Electrics, Hybrids
- Noise reduction

Aviation's Environmental Impact

Aviation activity results in…

CO2 Emissions

Contrail Formation

Product of hydrocarbon and water vapor

Formed ice crystals persist for a ***LONG TIME and contribute to climate warming***

The Problem

More than **90%** of CO2 emissions from global commercial aircraft operations are generated by large aircraft (twin-aisle and single-seater airplanes with > 100 passengers)

20% of total lifecycle CO2 is emitted **<u>before</u>** the plane is fueled (purely from extraction, transport, and refining)

Sustainable Aviation

Sustainable Aviation Fuels (SAF)

- Biofuels
- Synthetic Fuels
- Methane

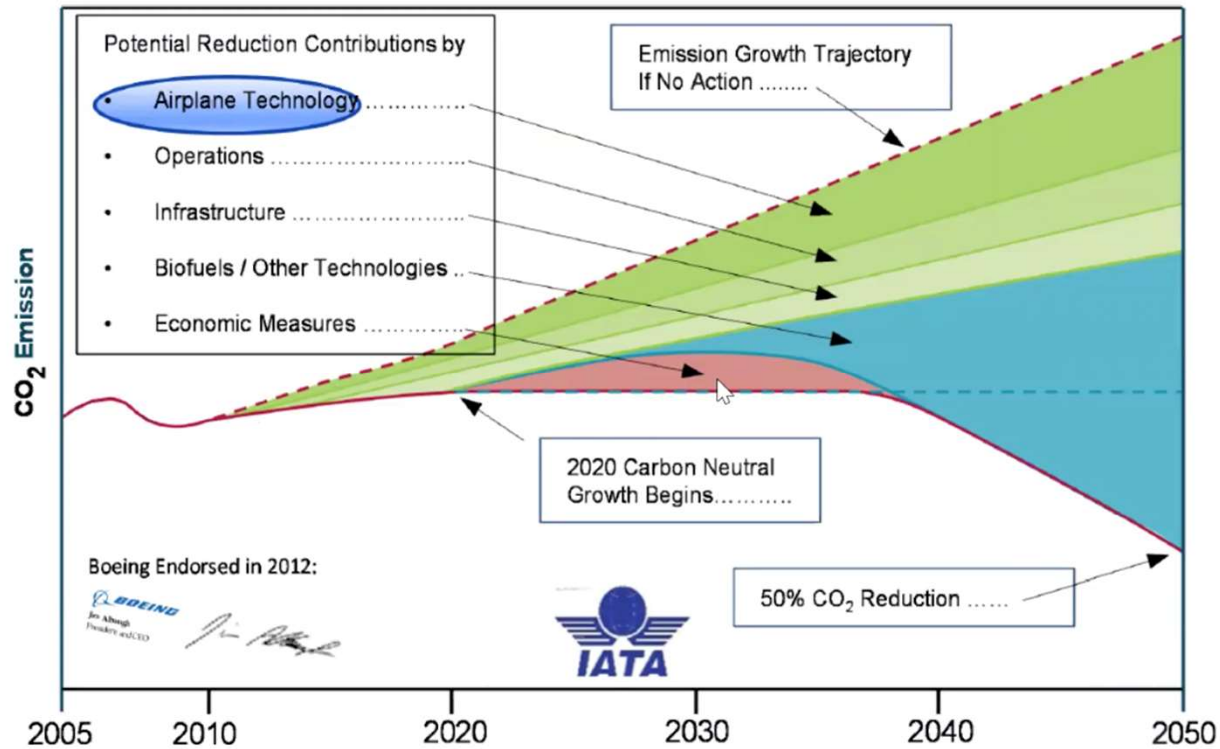
Electrics

Hydrogen

The Solution

Industry Goals

- Reduce CO2 by 50% by 2050
- Carbon neutral growth by 2020
  - Aside: I wonder if COVID-19 has helped achieve this goal at all…



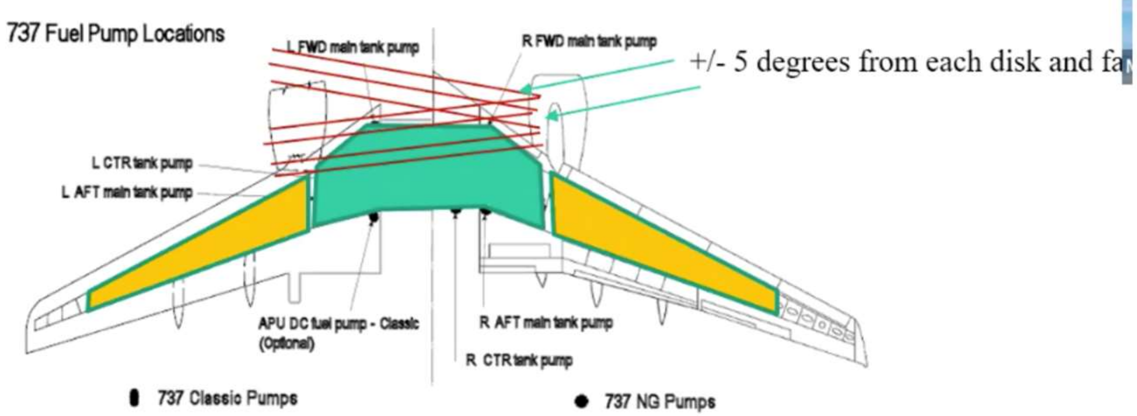
How do we achieve this?

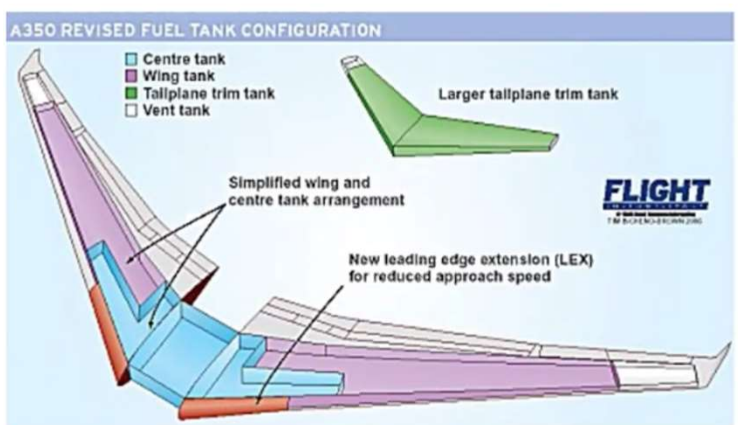
- Alternative Fuels
- Hydrogen Fuel Cells
- Electrification
- Aircraft structures
- Closing the carbon cycle/loop
- ***Some combination of all of the above***

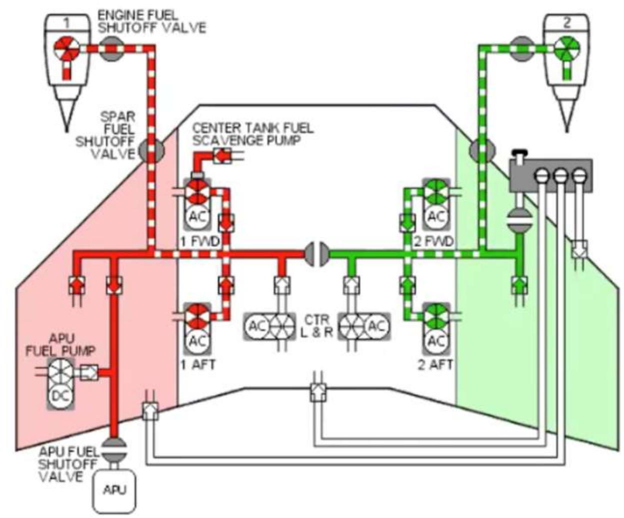
Sustainable Aviation Fuels

Fuel Distribution

- Planes typically distribute fuel between 3 different tanks
    - Tanks are arranged in a way that minimizes punctures in the case of engine failures

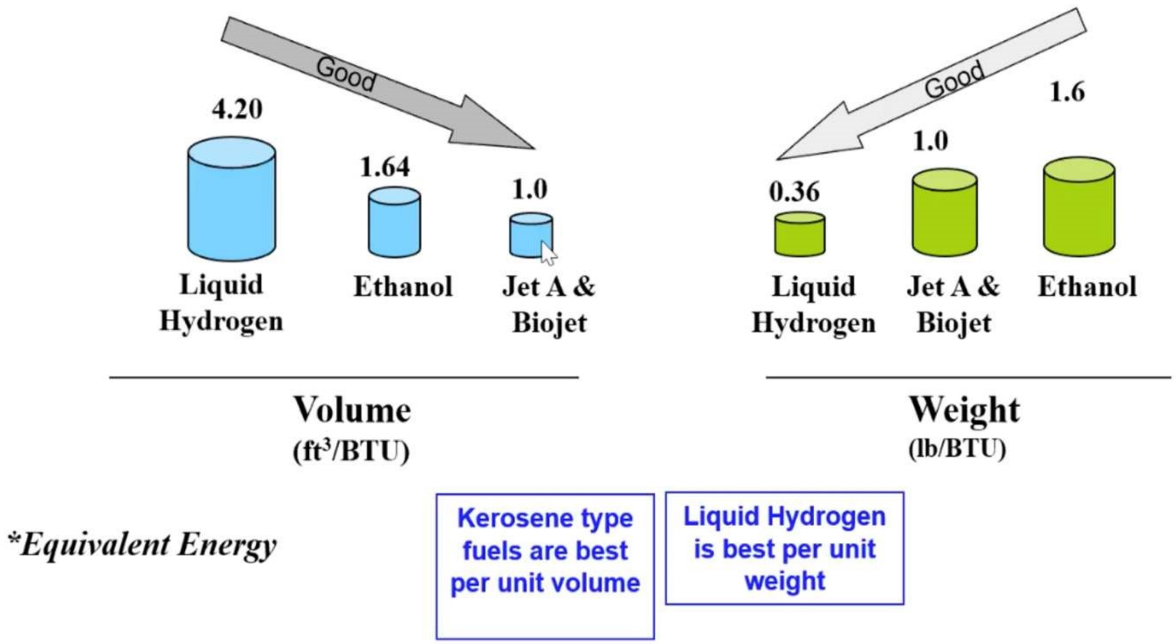






Fuel Basics

- Conventional Jet Fuel: $C_{12}H_{24}$
- Methane: CH_4
- Hydrogen: H_2



Key metrics:

- Fuel Density
- Energy/Weight
  - Liquid fuels have terrific energy/weight
  - Esp. H2 and batteries?
- Energy/Volume
  - Jet fuel has the best energy/volume
  - H2 E/V could offset benefits of E/W

Methane

- Cleaner than pretroleum-based jet fuel
- Fewer molecules = fewer contaminants
- Higher H:C ratio means more H2O byproduct and less CO2
- Could have low Nox emissions (via lean burning combustors, geometric configuration)

Biofuels and Synthetic Jet Fuels

AT7

Pure biofuel is **<u>not naturally compatible</u>** with jet engines.

Fuel must be modified to follow constraints:

1. **Sulfur content limits** (freezing point, viscosity, and thermal stability)
2. Limited to **50% biofuel 50% Jet-A blends**

Fischer-Tropsch Process:

Process in which metal catalysts are used to convert CO and H2 gas into liquid hydrocarbons (synthetic fuels)

**costly energy expenditures to create fuel can offset energy provided by fuel

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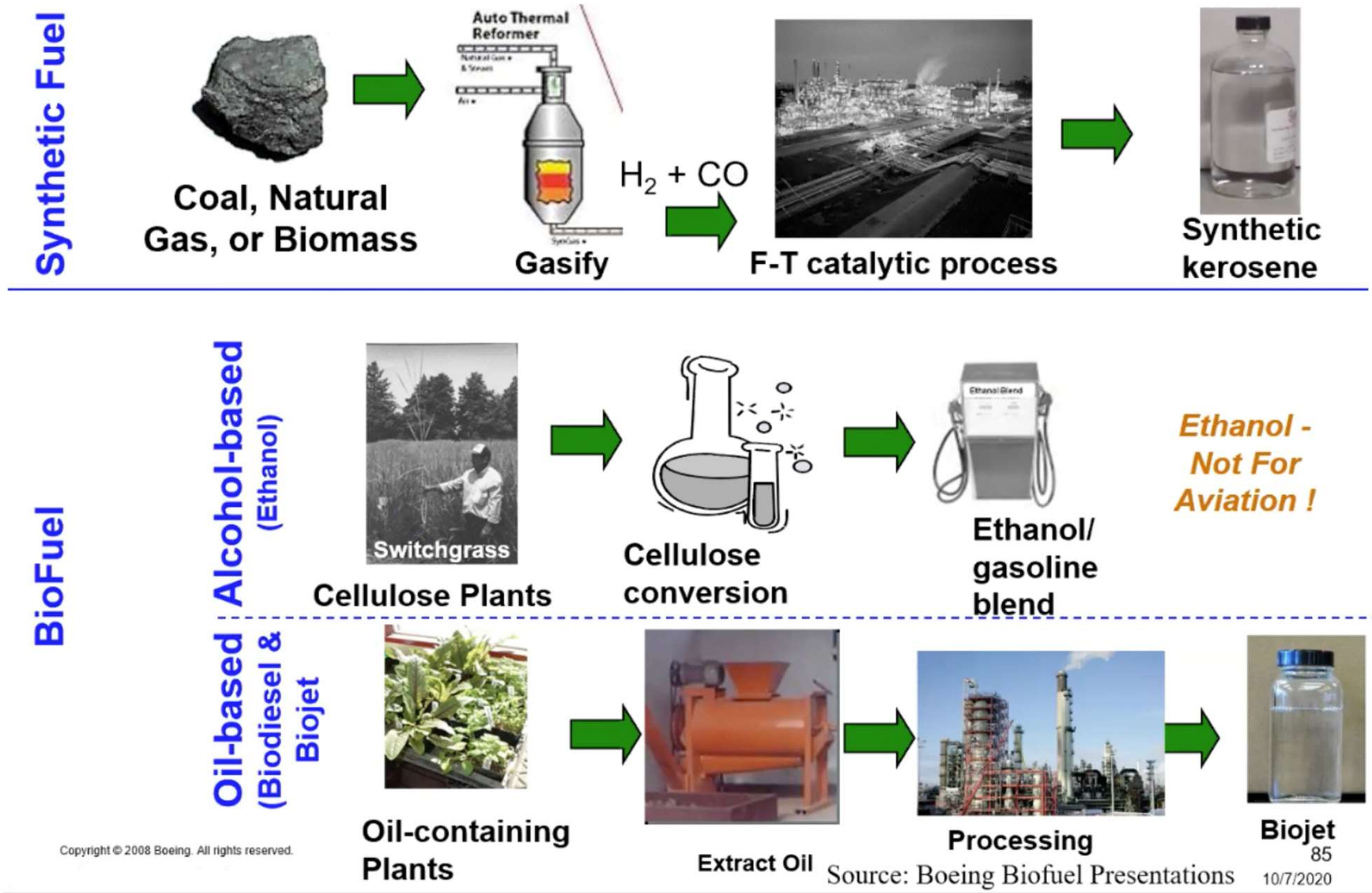
AT7 how is this related to the other concepts?
Allison Tsay, 11/15/2020

AT3


Synthetic Fuel
Coal, Natural Gas, or Biomass
Auto Thermal Reformer
Gasify
H_2 + CO
F-T catalytic process
Synthetic kerosene
BioFuel
Alcohol-based (Ethanol)
Switchgrass
Cellulose Plants
Cellulose conversion
Ethanol/ gasoline blend
Ethanol - Not For Aviation !
Oil-based (Biodiesel & Biojet
Oil-containing Plants
Extract Oil
Processing
Biojet
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Source: Boeing Biofuel Presentations
85
10/7/2020

Slide 13

AT3 Need takeaway slide
Allison Tsay, 11/15/2020

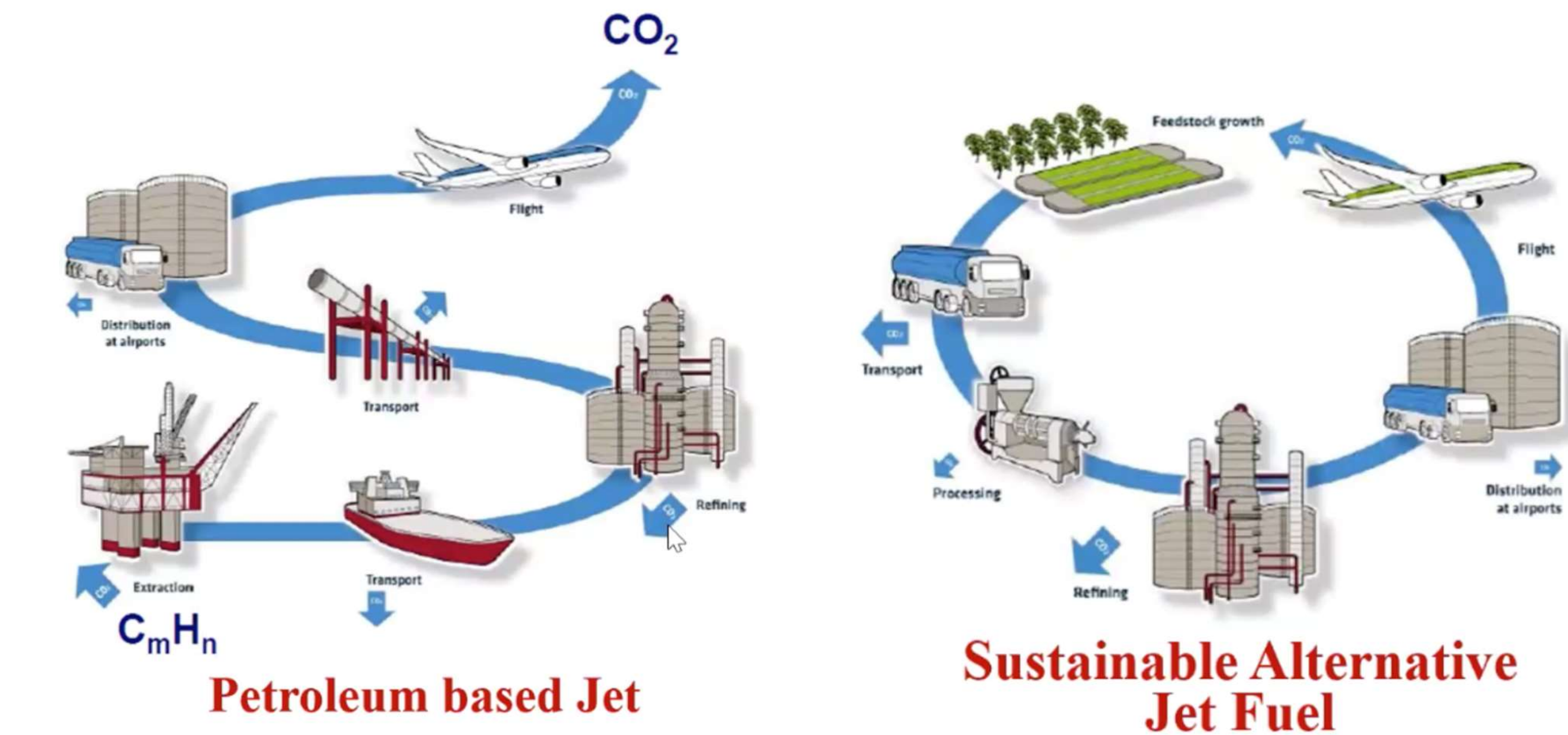
Biomass Sources

- **Soybean Feedstock**
  - Not sustainable, unable to meet aviation fuel demand
  - Requires land size of Europe
- **Jatropha (Saltwater plant)**
  - 322 billion liters of biojet fuel (total world usage)
  - Requires farm size of France

- **Algae**
  - Sewage water input to grow algae
  - Harvest, discharge clean water
  - Refine into biocrude / sustainable biofuel
  - Require algae pond the size of Belgium

Biofuels still emit carbon, but lifecycle carbon is greatly reduced

Biofuels still emit carbon, but lifecycle carbon is greatly reduced

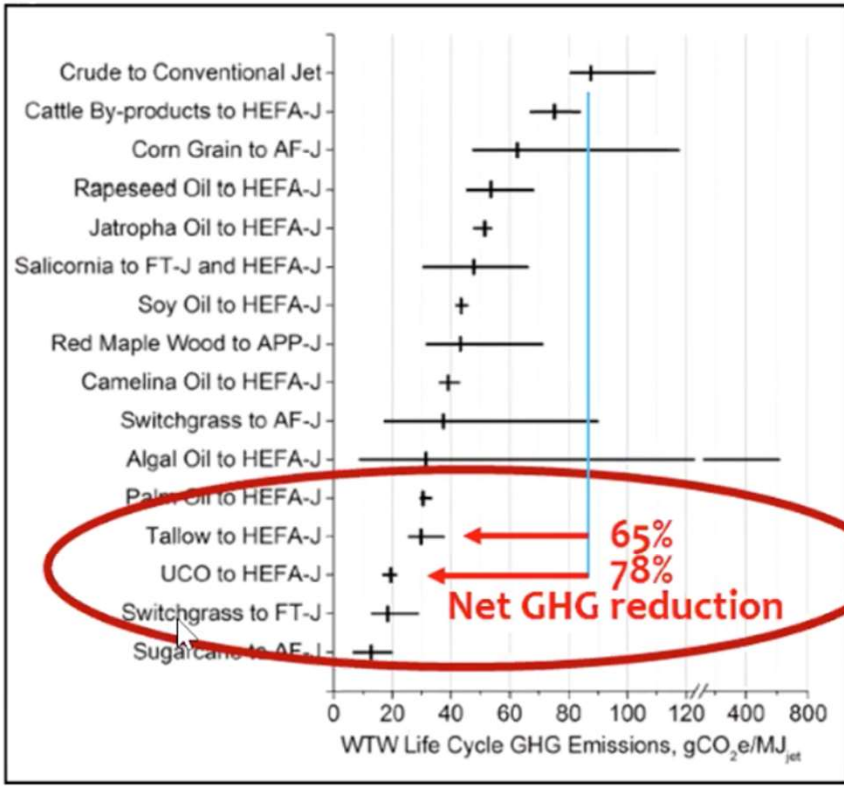


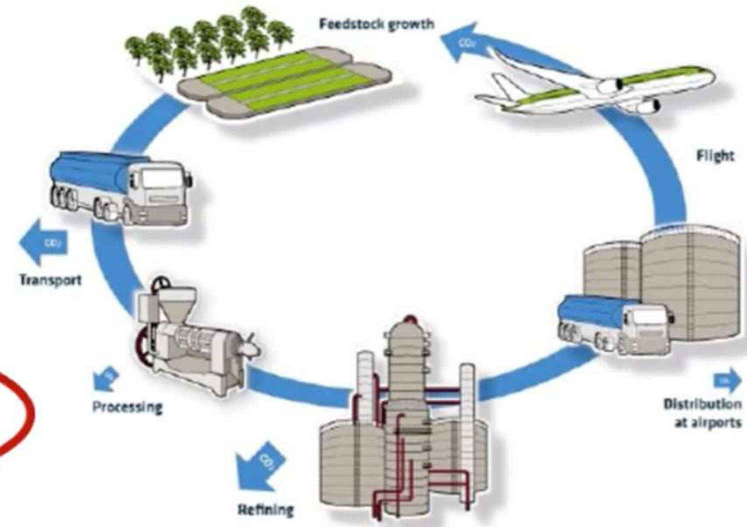
20% of the total CO2 is emitted before the plane is fueled (purely from extraction, transport, and refining)

87 Source: National Academies Report

Achieving net LCA GHG reduction

Reduction in carbon being introduced to biosphere



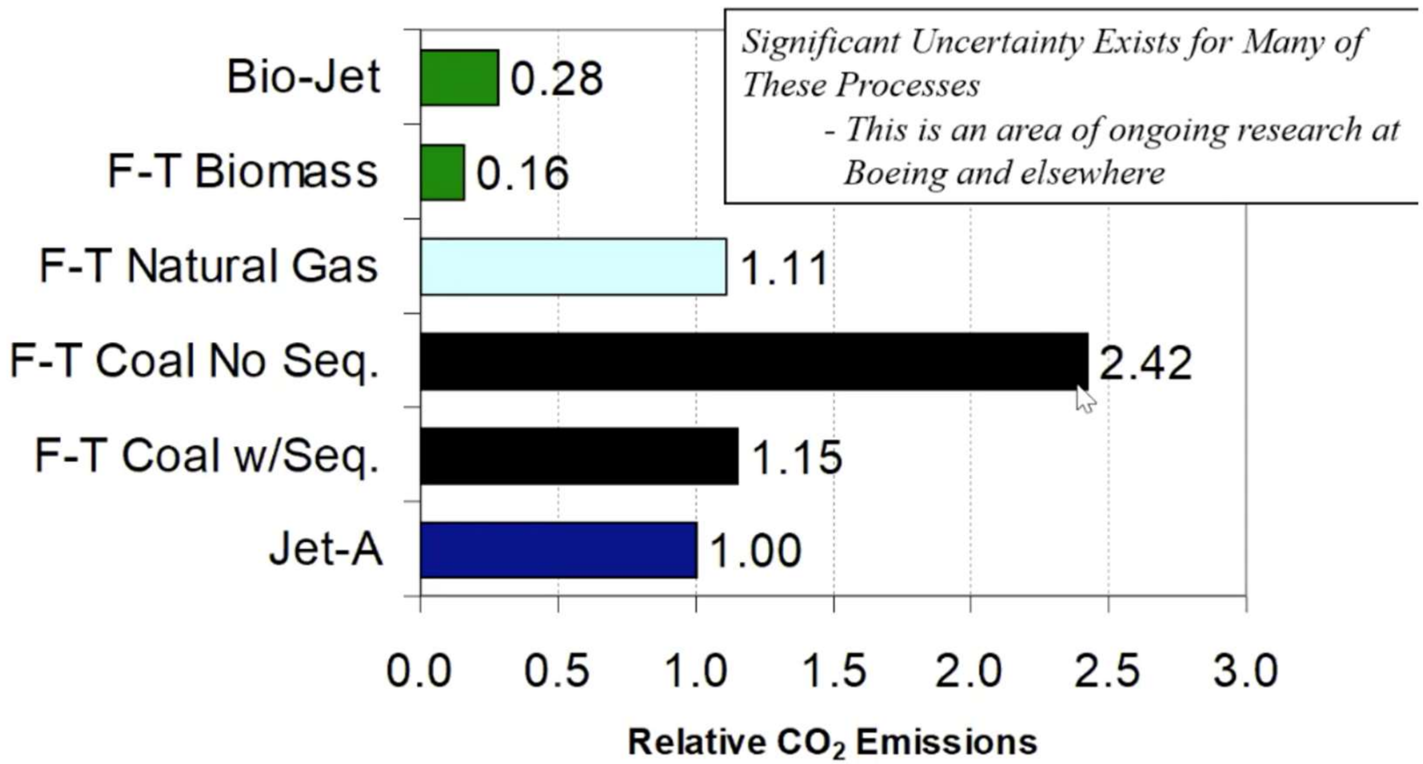


Sustainable Alternative Jet Fuel

Source: National Academies Report

AT4
AT8
AT9

Biofuel vs. Synthetic Fuel vs. Jet-A Conventional Fuel



1.0=Jet Fuel from Crude Oil

Biojet from Soybeans
F-T Biomass from Woody Biomass
Results sensitive to biomass source, co-generation, and other efficiency assumptions (ongoing research and analysis)

Results Using GREET 1.8b: Greenhouse gases, Regulated Emissions, and Energy use in Transportation

Slide 17

AT4 Need takeaways
Allison Tsay, 11/15/2020

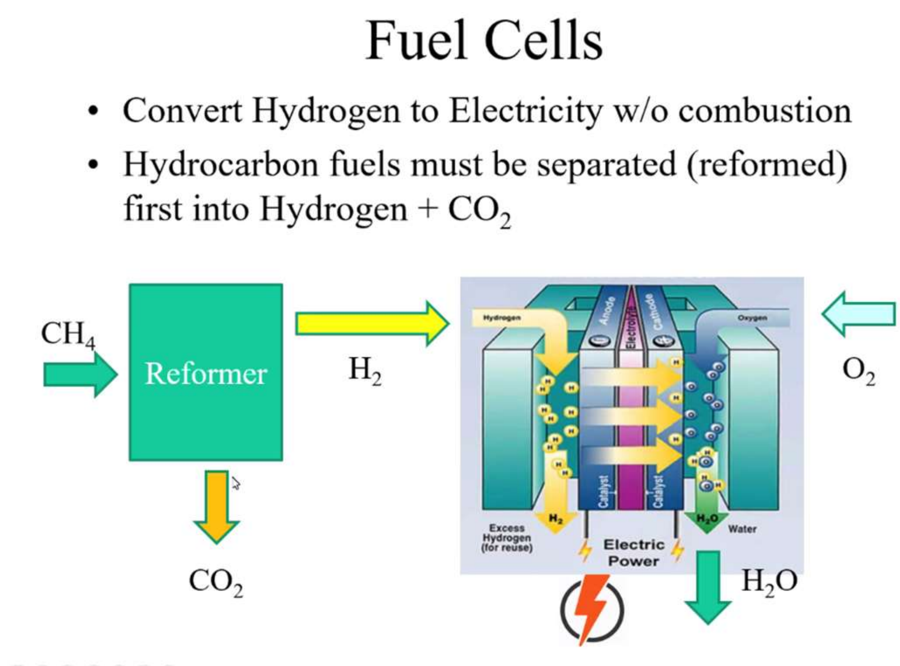
AT8 What is F-T Biomass vs. Bio-Jet?
Allison Tsay, 11/15/2020

AT9 Bio-Jet = blend of fuels
Allison Tsay, 11/15/2020

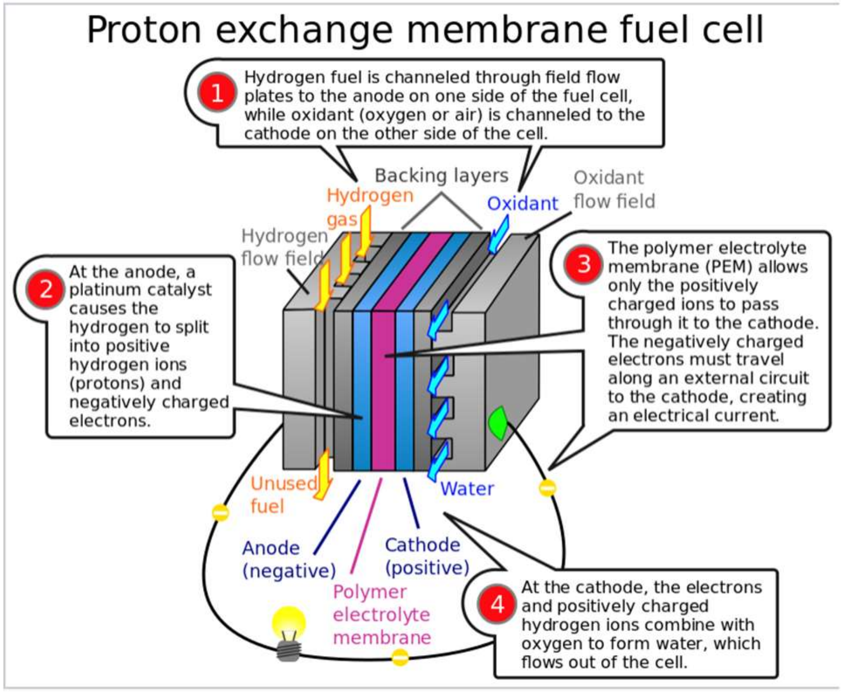
Fuel Cells

Fuel Cell Basics

- Natural gas, Hydrogen, etc.
- Methane can also be used directly (without reformation?)
- Convert input to **electricity w/o combustion**
- Hydrocarbon fuels must be reformed first into Hydrogen + CO2
- Water output can still contributed to contrail formation



Hydrogen Fuel Cells



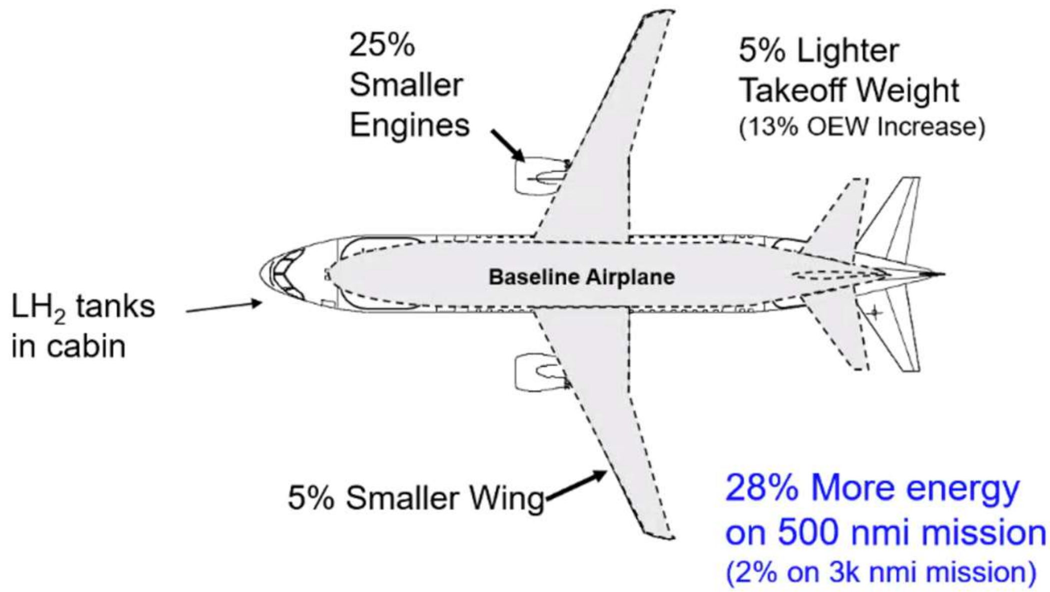
- Advantages
  - Stack Power / Weight ~ 1 kW/kg
  - Thermal efficiency ~ 60%
- Disadvantages
  - H2 molecules are much smaller, easy to leak out
  - Higher amount of H2O can exacerbate contrails situation
  - Balance of Plant & Parasitic Losses could be difficult

Studies

A hydrogen fuelled airplane would be efficient on long range missions

Engineering, Operations & Technology | Platform Performance Technology

Hydrogen Powered Airplane



OEW = Operating Empty Weight

Source: Boeing Biofuel Presentations

Studies

Hydrogen powered aircraft are not a near-term solution

Engineering, Operations & Technology | Platform Performance Technology

Advantages:

- Reduced emissions (CO_2)
- Crude oil independent fuel
- Long range fuel efficiency
- Engine design opportunities
- Enable new technologies; fuel cells

Challenges:

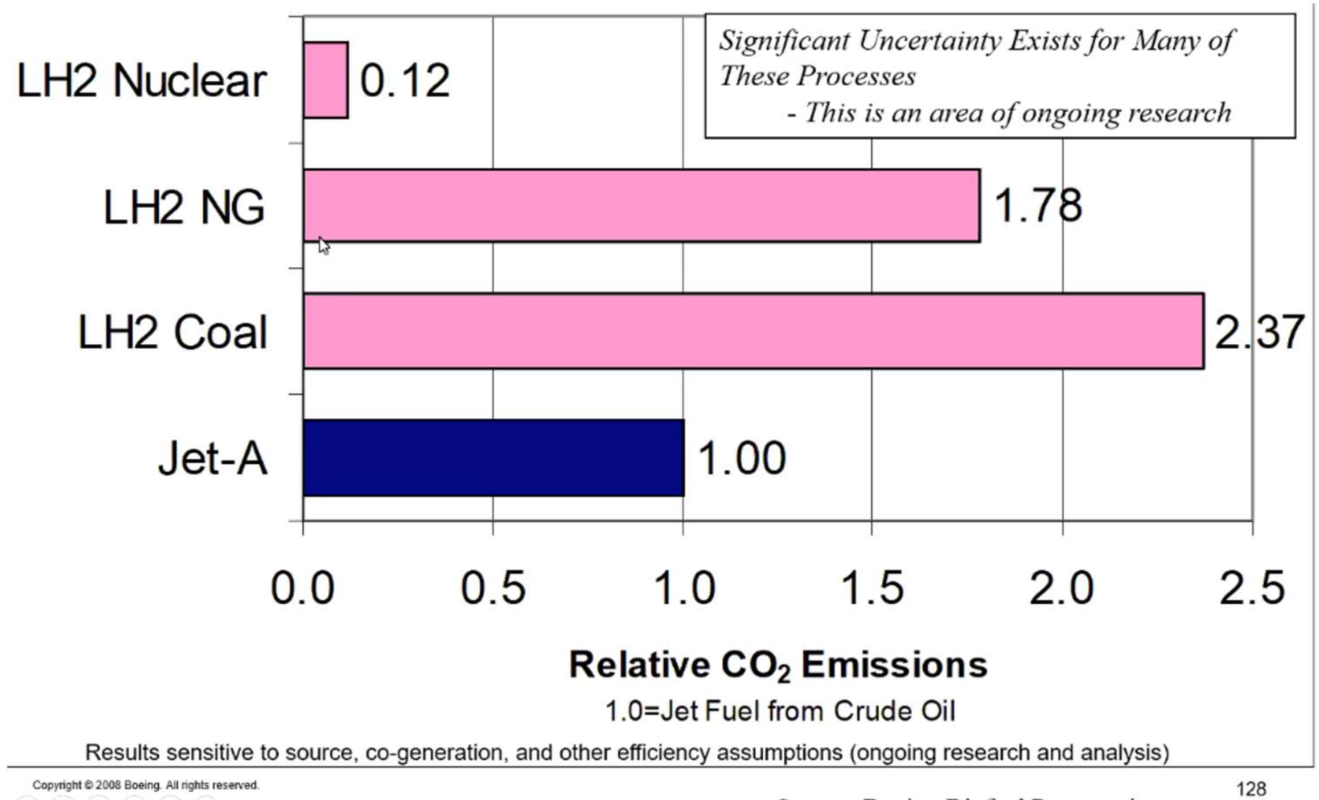
- Hydrogen production
- New infrastructure
- Passenger acceptance
- 4 times larger fuel tanks
- Technically challenging
- Impact of H_2O emissions
  - Contrails

Developing hydrogen airplanes and infrastructure will be a major undertaking that will require industry collaboration and government support.

Source: Boeing Biofuel Presentations

Life Cycle Analysis of Hydrogen Sources

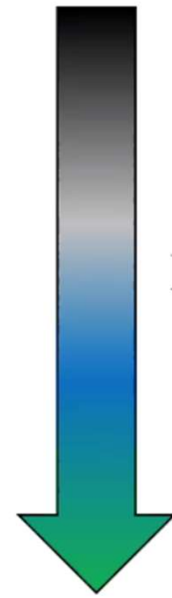
- Hydrogen generation method has undeniable impact on CO2 emissions.
- Moving forward, focus will be on sustainable H2 generation
- LH2 from Coal and NG fare worse than Jet-A



Source: Boeing Biofuel Presentations

"Colors" of Hydrogen

- "Black" Hydrogen – Steam reforming of coal feedstock
- "Grey" Hydrogen – Steam reforming of natural gas feedstock
- "Blue" Hydrogen – Steam reforming of natural gas, but with CO2 capture
- "Green" Hydrogen – Hydrogen made from electrolysis with renewable electricity



Reduced Lifecycle CO_2

Note: These definitions vary a bit in their details and there are a few others ways to make hydrogen

Hydrogen Storage

Pro: H2 energy/weight ratio is high
Con: H2 energy/volume ratio is low

- Liquid H2: Tank is 2-4x fuel weight
  - cooling process also adds energy costs
- Compressed Hydrogen Gas
  - Tank is 6-15x fuel weight (used in ground transit applications)
- Alternate Hydrogen "Carriers"
  - Ammonia NH4
  - Urea CO(NH2)2
  - Metal Hydrides (MgH2, NaAlH4, etc...)

Hydrogen Fuel Cell Summary

Hydrogen has potential for applications requiring high energy storage...

Hydrogen can be efficiently utilized in 2 ways

cleanly burned in aircraft gas turbines

processed by a fuel cell to create electricity to run electric motors

H2 is complex to handle due to cryogenic storage, leakage, and materials issues

To be environmentally friendly, hydrogen must be produced with renewable energy

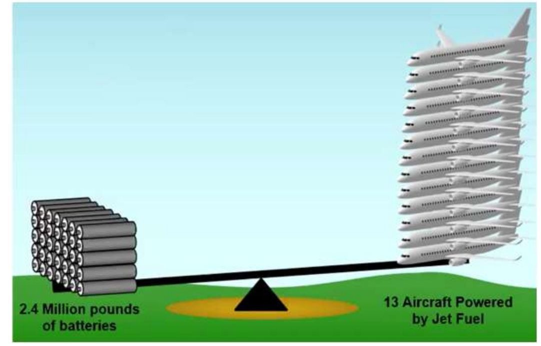
hydrolysis process is relatively efficient

from natural gas (is not)

Electrics

AT5

Electric Aircraft



Advantages

No direct CO_2 emissions

Reduced noise

Unique configurations: BLI, Distributed Propulsion

Multiple Power Schedules

Potential for Reduced Costs

Disadvantages

Low Energy power / density

Safety (high voltage, thermal management)

Ground operations

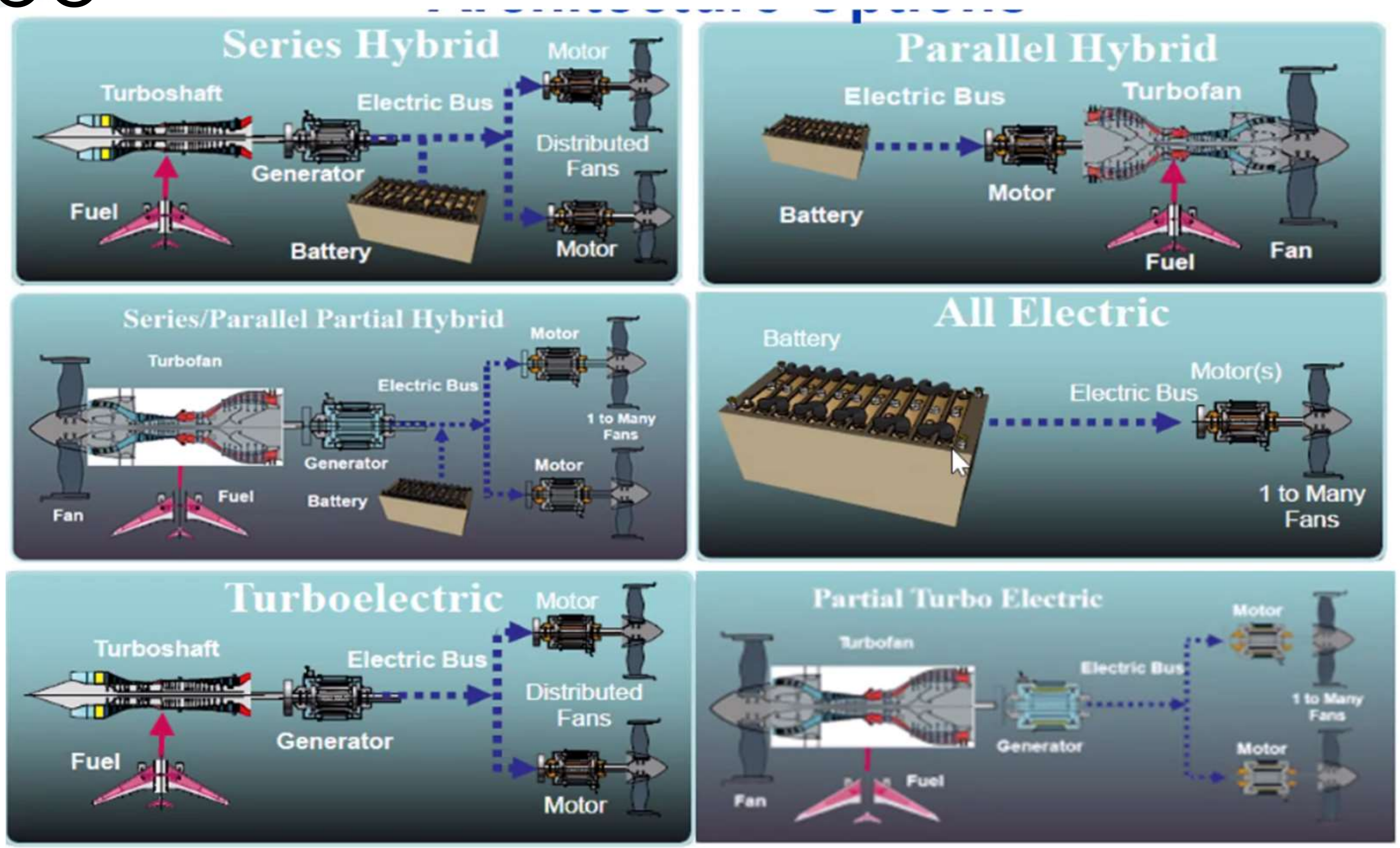
Certification processes

Weight: takes 2.4 million pounds of batteries to reach the same energy as 60,200 lbs of Jet-A

AT5 Add advantages
Allison Tsay, 11/15/2020

AT6

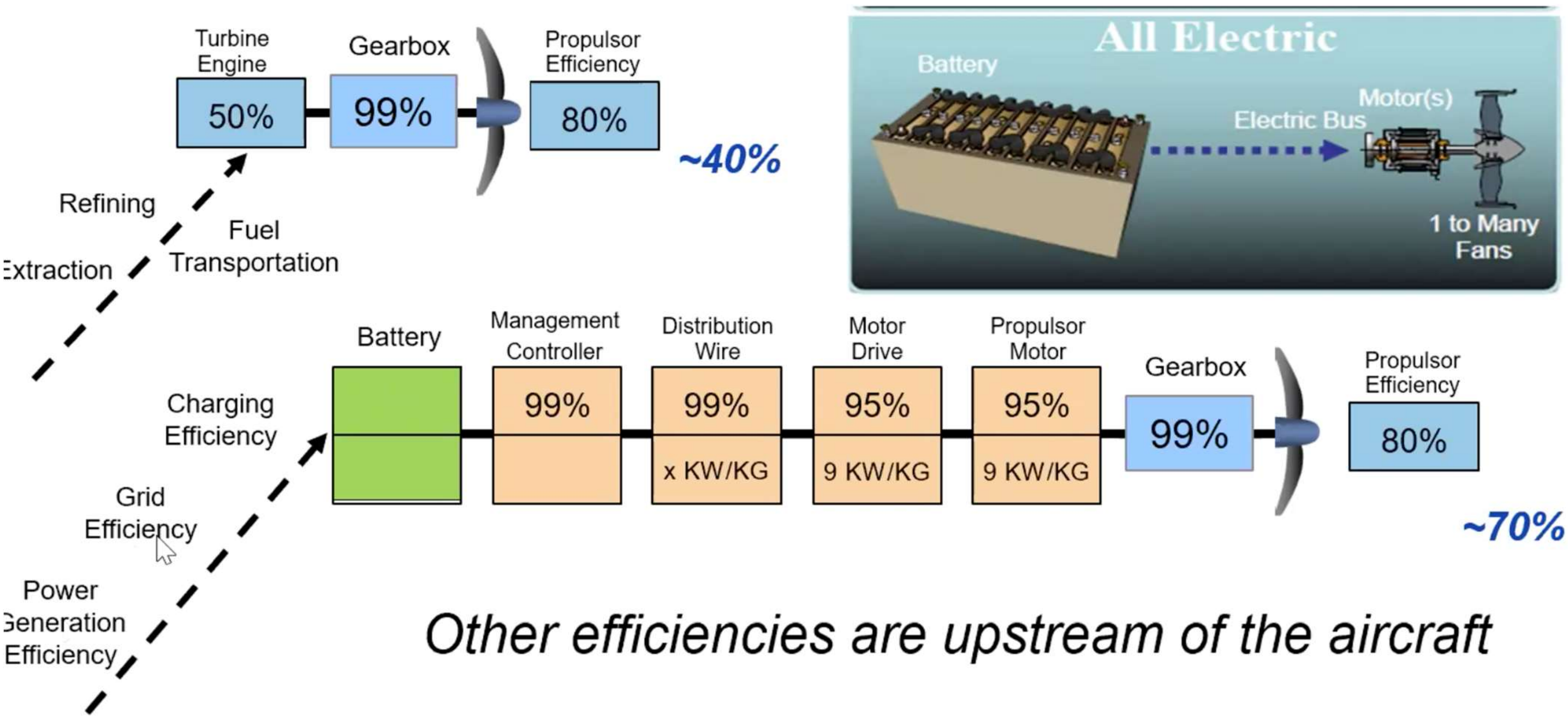
Architecture Options for Electric, Hybrid, Turbo



Images courtesy of Dr. Marty Bradley

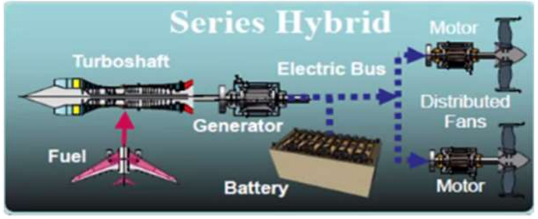
Slide 29

AT6 Needs explanation
Allison Tsay, 11/15/2020



Other efficiencies are upstream of the aircraft

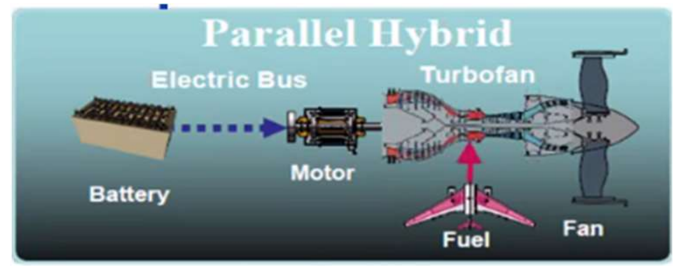
Series Hybrid



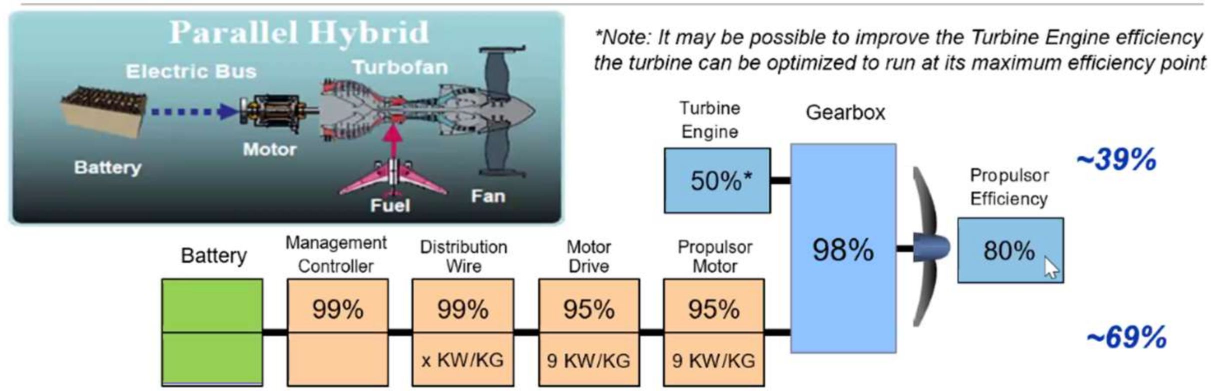
Images courtesy of Dr. Marty Bradley

- Long range efficiency
- Fuel Tank can be used as a reserve

Parallel Hybrid



- Long range efficiency
- Fuel Tank can be used as a reserve
- Gas turbine augmented with electric motor

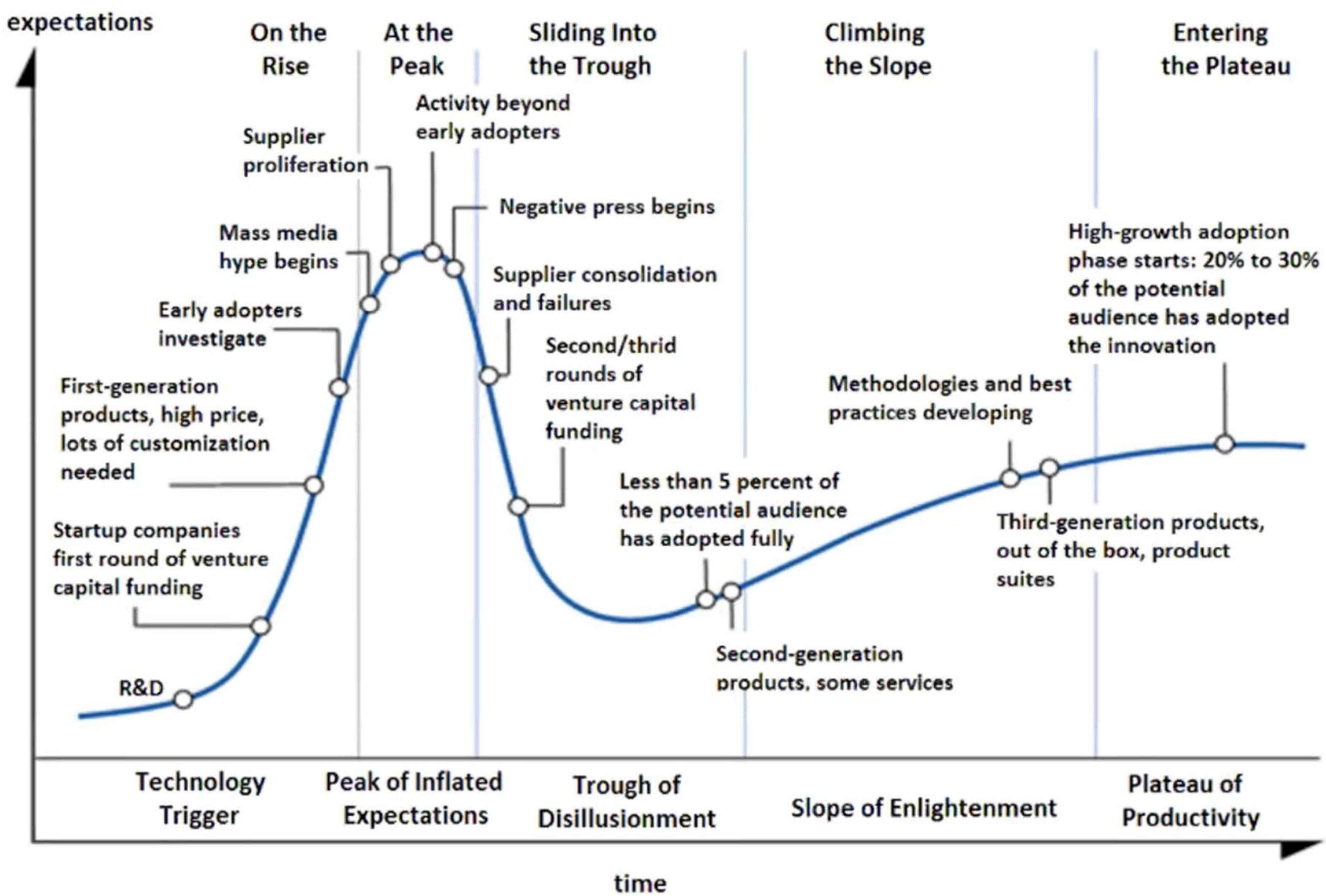


- *Potential flexibility to improve system by:*
  - *Using fuel to achieve long range*
  - *Using fuel for reserve range instead of heavy batteries*
  - *Downsizing turbine by assisting with electric motor*
  - *Optimizing operating points for turbine for higher efficiency* *
  - *If motor/generator is used, then batteries can be recharged in flight*

Images courtesy of Dr. Marty Bradley

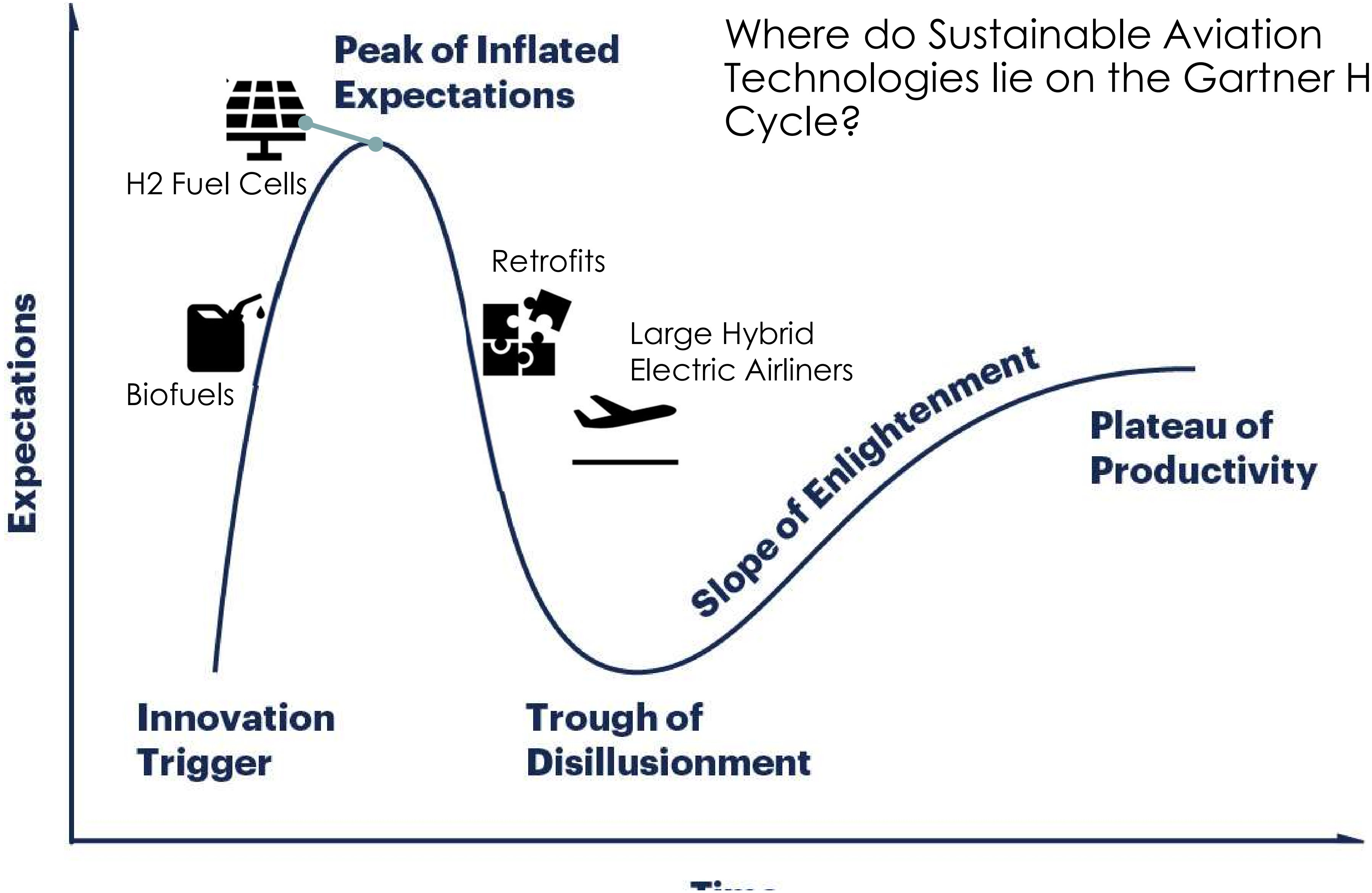
Design Challenges

- Integrated Energy Storage is misaligned with improvement predictions
  - New chemistries
  - Aviation not well-funded by DOE
- Factors reducing available energy
  - Thermal safety protection
  - Discharge limits
  - Battery life



The Gartner hype cycle (Wikimedia Commons)

Where do Sustainable Aviation Technologies lie on the Gartner Hype Cycle?



Summary

Wrap Up – Technology Matrix

Technology	Opportunity	Challenges
Electric	• No Direct CO_2 • No Direct Emissions	• Battery specific energy – reduced range • Battery safety • Component power and specific power • Thermal management • Airport electrical infrastructure
Hybrid Electric	• Reduced Direct CO_2 • Reduced Direct Emissions	• Battery specific energy • Battery safety • Thermal management • Airport electrical infrastructure
Biofuels	• Reduced Life Cycle CO_2 • Drop-In Fuel • Reduced Contrails?	• Sustainable biomass supply • Production cost • Legacy aircraft fuel system compatibility
Synthetic Fuels	• Reduced Life Cycle CO_2 • Drop-In Fuel • Reduced Contrails?	• Production cost • Legacy aircraft fuel system compatibility • Sustainable electricity
Methane	• Slightly Reduced Life Cycle CO_2 • Low Cost	• Methane leakage • New aircraft needed • Airport infrastructure
Hydrogen	• No Direct CO_2 • Reduced Direct Emissions (except H_2O)	• New aircraft needed • Sustainable production (CO_2 & cost) • Airport infrastructure • Contrails?

Image courtesy of Dr. Marty Bradley