Hydrogen for Hypersonic Civil Transportation

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Outline

- Vision
- Environment
- Performance
- Cost
  - Fuel
  - Infrastructure
  - Operation
- A way forward

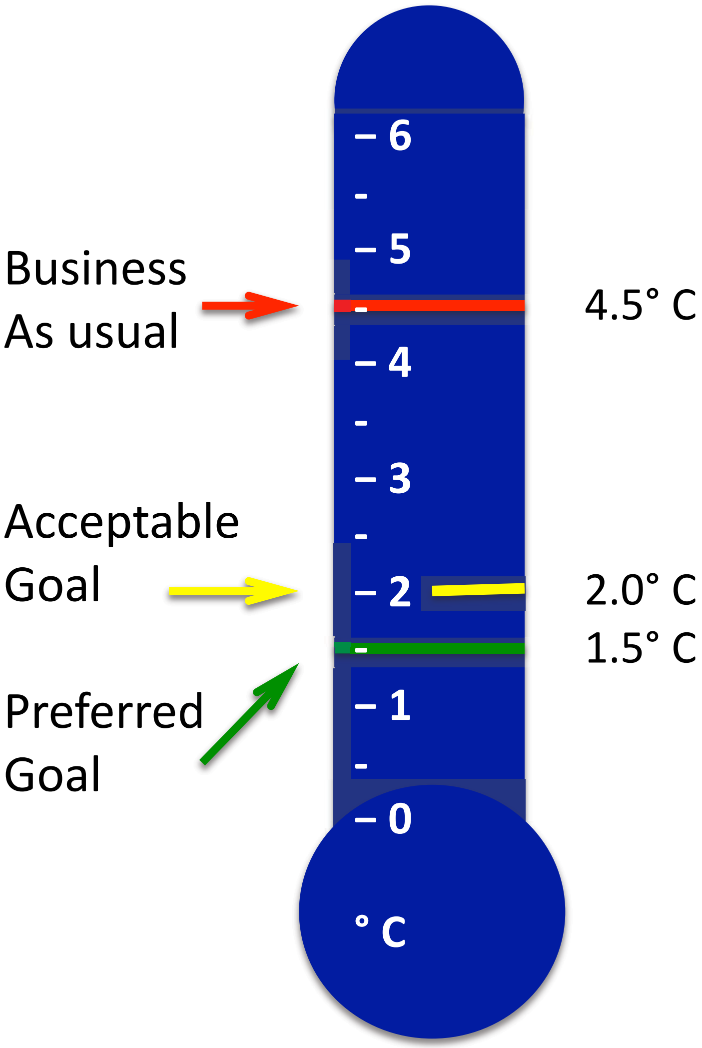
Vision and Fuel Choice

- Hypersonic air-breathing propulsion would revolutionize high-speed transportation through atmosphere:
  - Long distances transport on Earth
  - Transport of medium-weight payloads between Earth and low Earth orbit
- From the perspective of environment and performance, hydrogen is the perfect fuel for:
  - Turbo/ramjet engines
  - Dual-mode ramjet/scramjet engines
  - Rocket engines
  - Combinations of these engine types

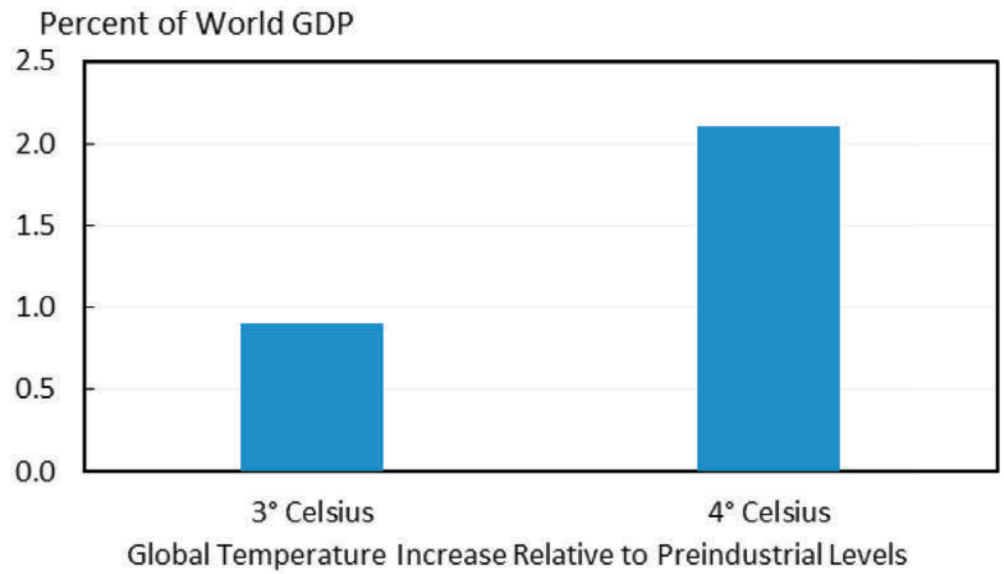
Environment

UN Climate Pledge Analysis

Increase in Global Temperature by 2100



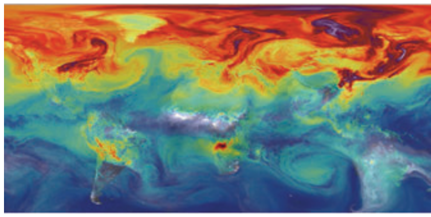
Economy Damage from Temperature Increase Beyond 2° C



Credit: Nordhaus (2013) and Council of Economic Advisers (CEA) calculations.

Costs increase with the length of delay to stem climate change.*

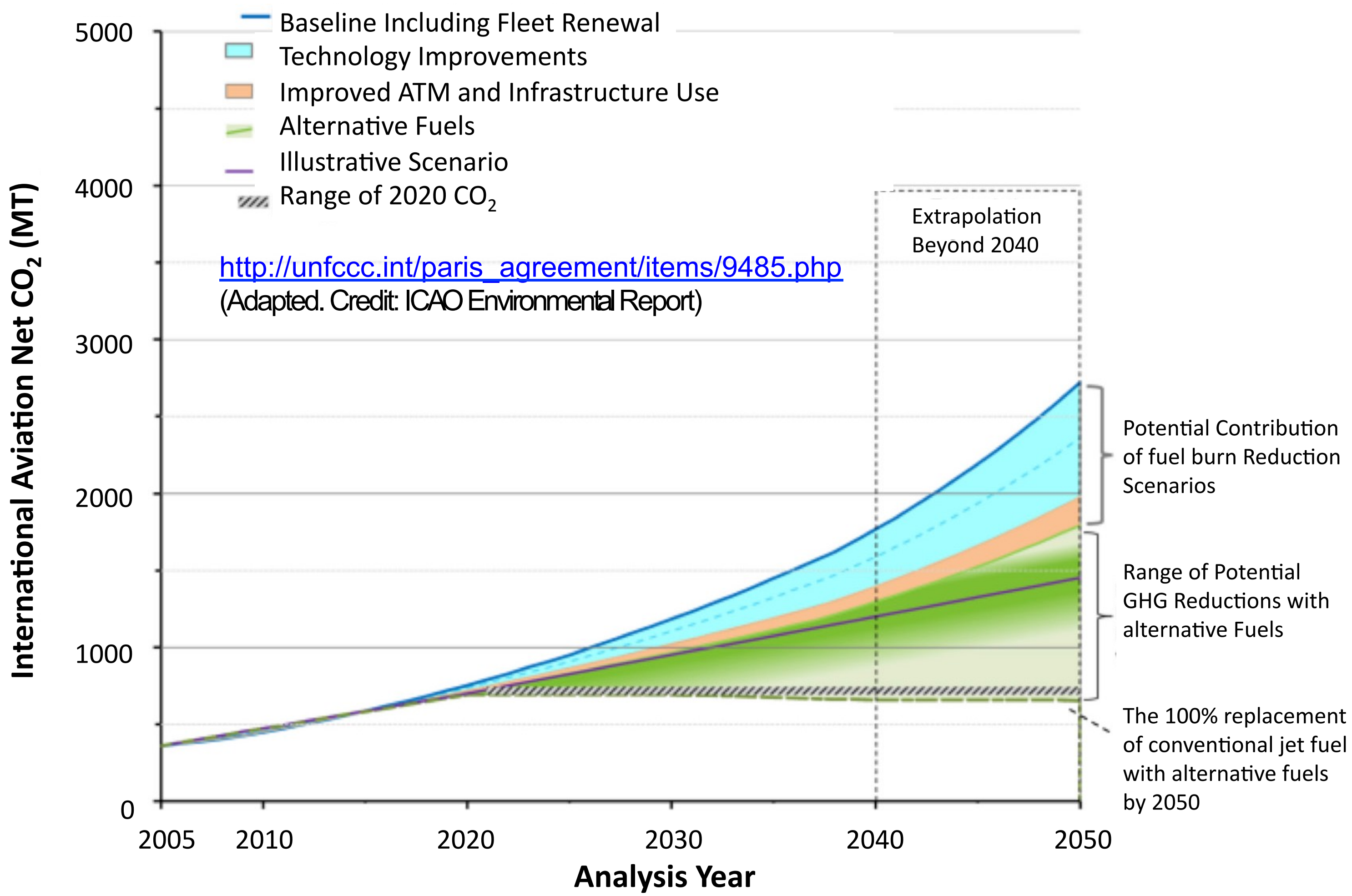
*The Executive Office of the President of the United States, *Cost of Delaying Action to Stem Climate Change,* July 2014.



Carbon Dioxide

- The atmospheric concentration of CO_2 has increased from 280 ppm in 1750 to 400 ppm in 2015.
- In 2015, global aircraft CO_2 emissions rank 7th – just behind Germany's total emissions for the same year, outranking 150 other countries.
- The atmospheric lifetime of CO_2 is 100 – 300 years.
- The supply of fossil (nonrenewable) energy is limited.
- We must develop fuels from renewable energies to:
  - Meet the growing demand for fuel.
  - Prepare for the expected exhaustion of fossil energy (by 2100).
  - Significantly reduce greenhouse gases (GHG).
- Solar energy + the availability of water ➔ hydrogen would:
  - Meet fuel demand.
  - Always be sustainable.
  - Eliminate CO_2 emissions.

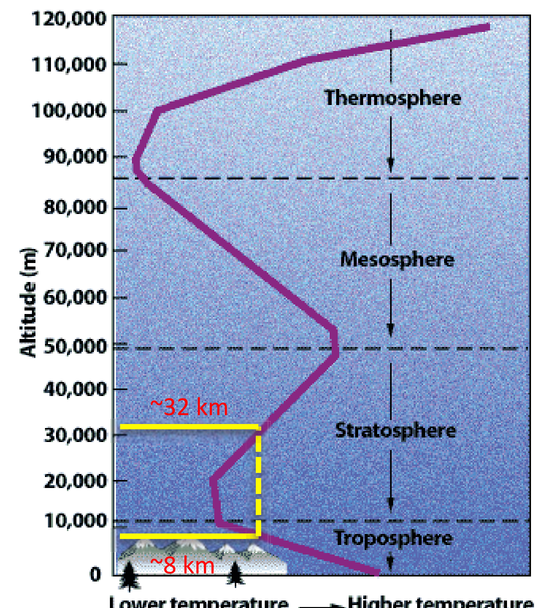
Alternative Scenarios: Global Aircraft Life Cycle CO_2 Emissions



- The conversion of many biofeedstocks to sustainable alternative jet fuels (SAJF) requires hydrogen, significantly increasing the conversion cost.

Performance With Liquid Hydrogen

- No lifecycle CO_2 emissions are produced by solar water splitting.
- A hydrogen-fueled aircraft is as safe as (or safer than) a hydrocarbon-fueled aircraft because hydrogen fires:
  - Burn rapidly
  - Rise up
  - Produce less smoke & noxious products than hydrocarbon fuels
- A hydrogen engine reduces NO_x emissions through:
  - Lean burning
  - Reduced reaction time scale
  - Specially designed combustor
- A hydrogen-fueled engine will produce ~2.5 times more water vapor than a hydrocarbon-fueled engine, and will not emit particulates.
- Higher cruise altitude to minimizes/eliminates contrails.
  - Contrails depend on the climate and latitude (air temperature).
    - No contrails below ~8 km in troposphere
    - No contrails above ~32 km within stratosphere
- A hydrogen leak is difficult to locate.
- Specific impulse, ignition speed, utilization Mach range, and cooling capacity are much higher with hydrogen than with hydrocarbon fuels.



Fuel, Infrastructure, and Operation Costs

Star-Raker_SSD_79-0082

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- Today, a large airport can consume over 3000 MT/day of hydrogen.
- Liquid hydrogen (LH_2) demands a high amount of electric power and requires additional land for hydrogen storage.
- At present, the lifecycle cost of hydrogen is very high compared to conventional jet fuel and other alternative aviation fuels (e.g. biofuel and liquefied natural gas).
- Extensive research and technology efforts are pursued to achieve economical methods for solar splitting of water.
- New technologies are developed to reduce infrastructure and operation costs.
  - At NASA Kennedy, zero boil-off of LH_2 has been accomplished—saving 1 dollar in hydrogen for every 20 cents spent on electricity needed to keep it cooled.

Some Relative Fuel Production Costs

Process	Input Fuel Cost	Output Fuel Cost	Technology Readiness	Lifecycle CO_2 Emissions
Crude Oil	Medium	Low	State of the Art	High
Synthetic Kerosene: Biomass Fischer-Tropsch (BLT) Process	Medium	?	Low	Medium to Low
Gasification of Coal (Non-Solar to Solar)	Low	Medium to Low	Medium	High
Steam Reforming of Natural Gas (Non-Solar to Solar)	Medium	Medium to Low	High	Medium
Gasification of Biomass (Non-Solar to Solar)	Medium	Medium to Low	Medium	Low
Water Splitting with Photonic Energy (e.g., photocatalytic water splitting)	Zero	?	Low	Zero

A Way Forward

- Use drop-in jet fuels for subsonic civil transportation, 2020 – 2045
- Demonstrate (efficient and affordable) solar water splitting technology ➔
    - Pilot solar water splitting factory ➔
        - Commercial solar water splitting factories near spaceports ➔
            - Hydrogen management capability at these spaceports
- Demonstrate a Mach 5.5 turbo/ramjet engine ➔
    - Flight test an X-plane ➔
        - Develop an operational civil hyperplane ➔
            - Hypersonic civil transportation