VISION FOR 2050

A STUDY INTO THE NEEDS AND CHALLENGES ASSOCIATED WITH CONVERTING TO HYDROGEN-POWERED AVIATION

ABOUT US

THE MEMBERS OF 6061CONSULTANCY ARE STUDYING THE THEORY AND APPLICATION OF HYDROGEN POWER SYSTEMS AT THE UNIVERSITY OF CINCINNATI

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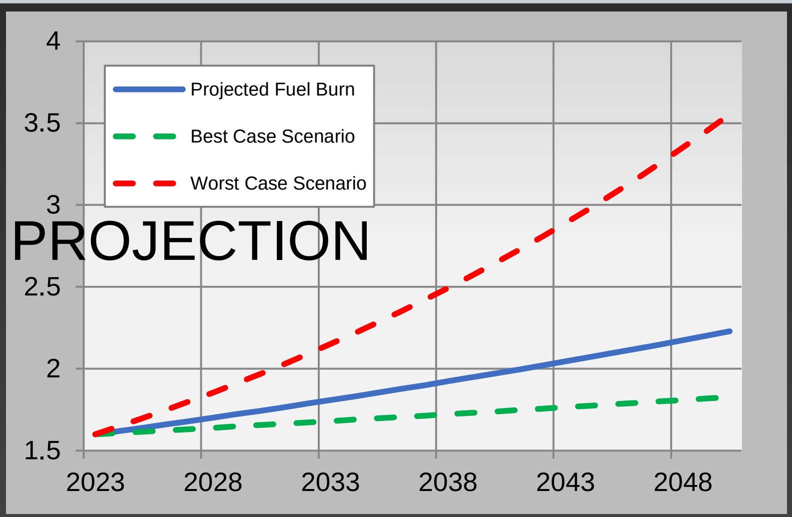
INTRODUCTION


PROJECTION
Projected Fuel Burn
Best Case Scenario
Worst Case Scenario
4
3.5
3
2.5
2
1.5
2023
2028
2033
2038
2043
2048


HYDEOGEN&
ELECTRICITY
NEEDS

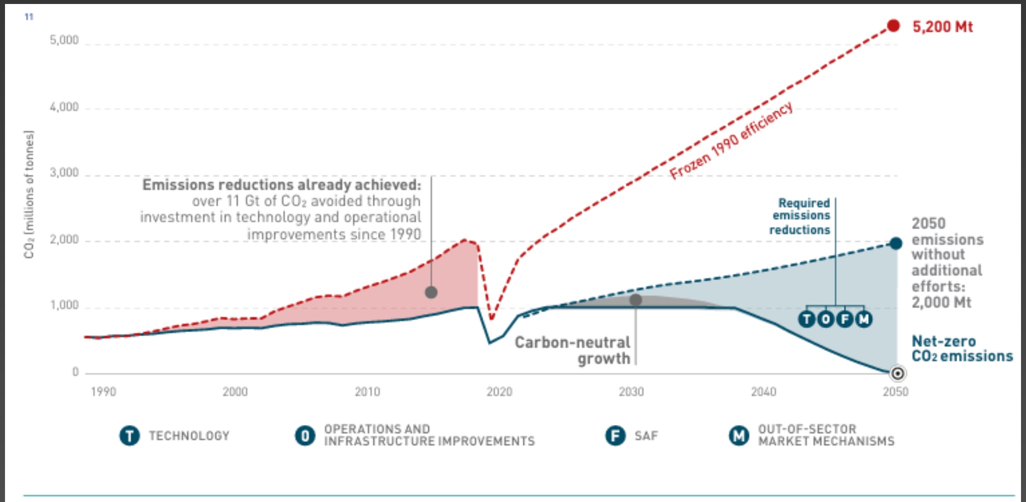

GREEN
ENERGY
SCALE UP


HYDROGEN PRODUCTION


SUMMARY &
CONCLUSION

INTRODUCTION

Air Transport Action Group (ATAG) April, 2023



http://atag-beginners-guide-to-saf-edition-2023.pdf (aviationbenefits.org)

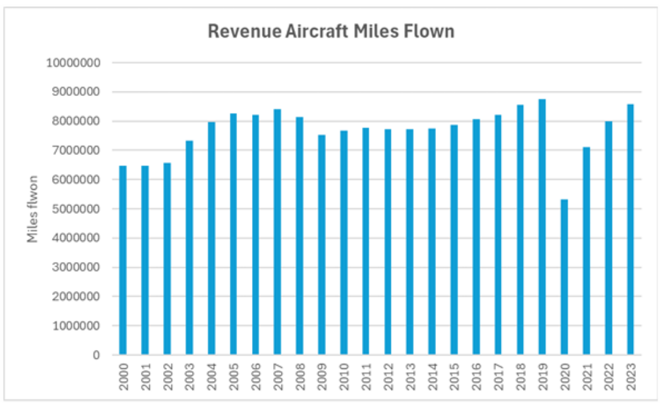
Hydrogen is the only identified option with the potential to achieve zero CO_2 emissions

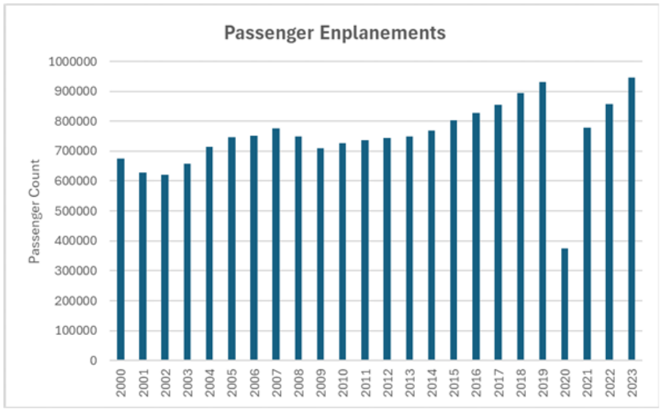
INTRODUCTION

The aviation sector is a significant contributor to greenhouse gas emissions, necessitating a shift towards sustainable fuel alternatives. Green hydrogen has emerged as a promising candidate due to its potential for zero emissions when produced through renewable energy sources. This feasibility study aims to assess the viability of meeting U.S. commercial aviation fuel needs with green hydrogen by 2050. Key areas of focus include projected aviation volumes, hydrogen production requirements, and the necessary growth in renewable energy capacity. Given the increasing urgency of climate action, transitioning to green hydrogen is not only desirable but essential for the aviation industry's long-term sustainability. This report will explore the technological, economic, and environmental implications of such a transition, highlighting both opportunities and challenges. By analyzing current trends and projecting future needs, this study will provide a comprehensive overview of how green hydrogen can serve as a viable alternative to conventional aviation fuels.

Viswanathan Hariharan/Rohit Mallela

BASELINE

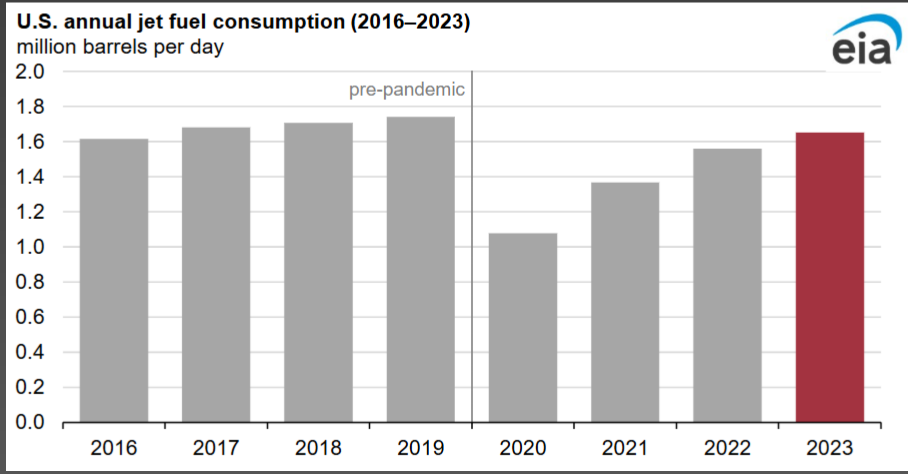




https://www.transtats.bts.gov/traffic/

Passengers and Miles

The trends described in both graphs are analyzed, based on the number of passengers and miles flown over the years in the commercial and cargo aviation sectors. For the analysis of the trend lines, which will be used to estimate the values for the year 2050, the years affected by the global COVID-19 pandemic (specifically 2019 to 2023) have been excluded. This is because during these years, the number of miles flown and passengers deviates significantly from the clearly established trends observed in the previous 18 years of analysis.



Fuel Consumption

As reported by the U.S. Energy Information Administration, jet fuel consumption in 2023 was about 1.60 million barrels per day

https://www.eia.gov/todayinenergy/detail.php?id=62443

Tom Bulabois, Jon Riloba, Amaia Diaz

PROJECTION

Growth Factor: CAGR

- The compound annual growth rate (CAGR) reflects how the demand for air travel is expected to increase over time.
- For U.S. aviation, a reasonable estimate is about 2 – 3 % per year, as suggested by the Federal Aviation Administration (FAA) and other aviation forecasts. This captures the increasing number of passengers and flights.
- The formula for the growth component is: $(1 + r_{growth})^{t}$
- Where:
  - r_{growth} is the growth rate.
  - t is the number of years from 2023 to 2050.

Efficiency Improvement Factor

- Fuel efficiency improvements reduce the amount of fuel burned per kilometer flown.
- Technological advancements in aircraft and operational improvements (e.g., better air traffic management) have historically contributed to a 1-1.5% annual efficiency improvement.
- It is acknowledged that hydrogen will pose new technological challenges, so the worst case assumption is zero efficiency improvement
- The formula for efficiency improvements is: $\frac{1}{(1+r_{efficiency})t}$
- Where:
  - $r_{efficiency}$ is the annual fuel efficiency improvement rate.

Tom Bulabois, Jon Riloba, Amaia Diaz

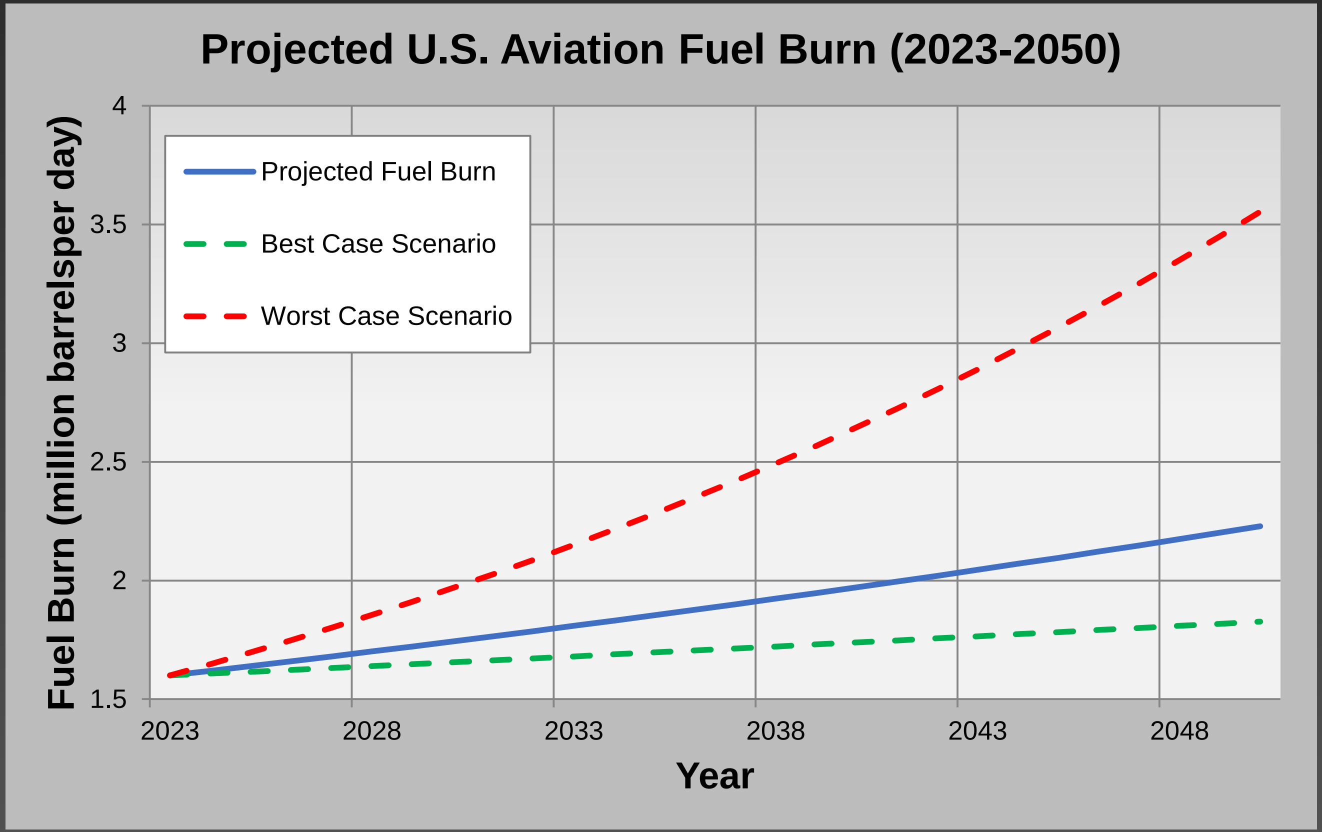
PROJECTION

Combining Both Factors

- To estimate the predicted fuel burn for U.S. aviation by 2050, combine the growth and efficiency factors, as follows:

$$F_t^{US} = F_0^{US} \cdot (1+r_{growth})\, t \cdot \frac{1}{(1+r_{efficiency})t}$$

- Where: • F_0^{US} = 1. 6 million barrels per day: is the initial fuel consumption in 2023.

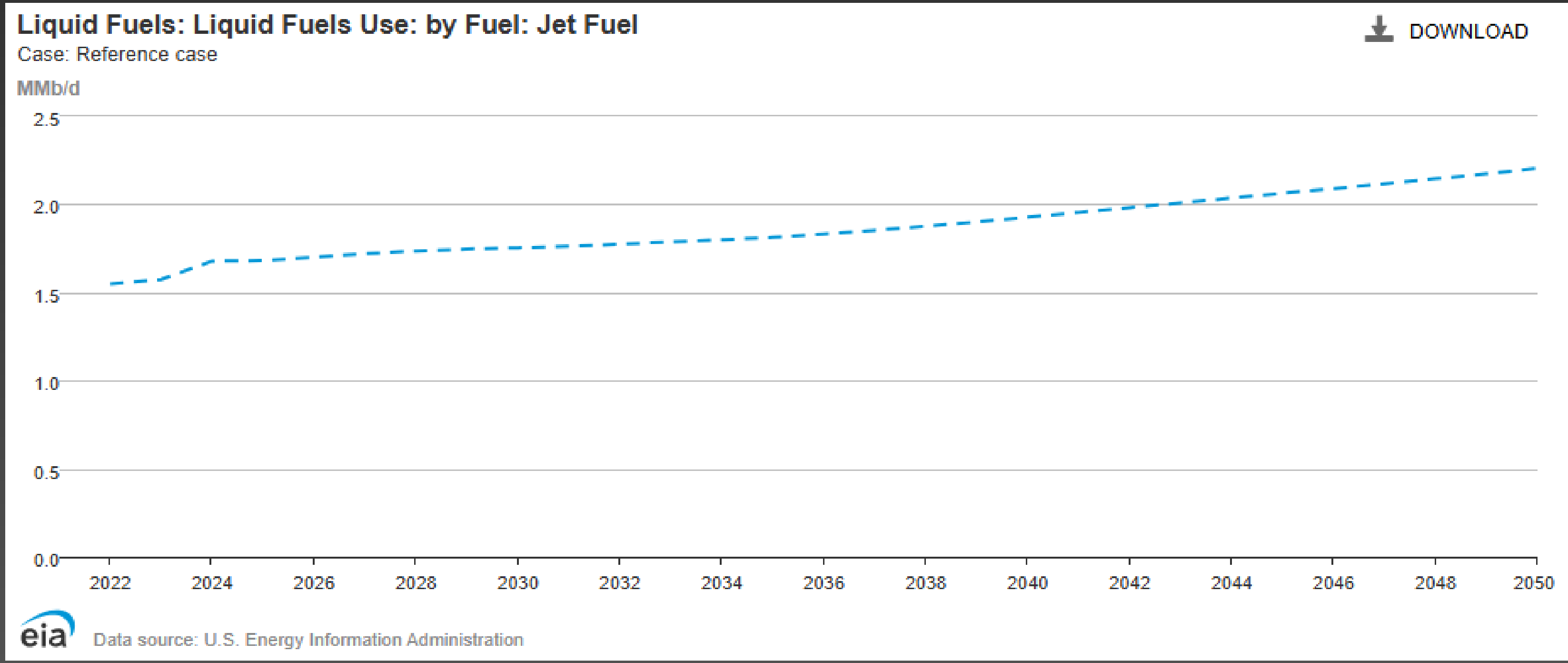


- In blue: $r_{efficiency}$ =0.0125 r_{growth} =0.025
- In green: $r_{efficiency}$ =0.015 r_{growth} =0.020
- In red: $r_{efficiency}$ =0.0 r_{growth} =0.030

Tom Bulabois, Jon Riloba, Amaia Diaz

VALIDATION

- Analyzing the previous graph, the nominal scenario projects a consumption of 2.3 million barrels per day by 2050.
- In comparison, the EIA forecast estimates a slightly lower figure of 2.2 million barrels per day for the same year.
- This close alignment between the two values suggests that the calculations are valid.



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HYDROGEN NEEDS

	Heat value
Hydrogen (H_2)	120-142 MJ/kg
Jet-A (Kerosene)	43 MJ/Kg

Figure 4: 20 m diameter LH_2 storage tank in NASA Kennedy Space Centre, Courtesy of NASA

Total Energy Requirement

The total energy requirement is based on 2.3 million barrels a day or 893 million barrels per year which translates to 4.6×10^{12} MJ

$$893 \times 10^6 \frac{barrel}{year} \times 127.7 \frac{Kg}{barrel} \times 43 \frac{MJ}{Kg} = 4.61 \times 10^{12} MJ$$

Energy Density of Hydrogen

The lower heating value (LHV) of hydrogen is approximately 120 MJ/kg

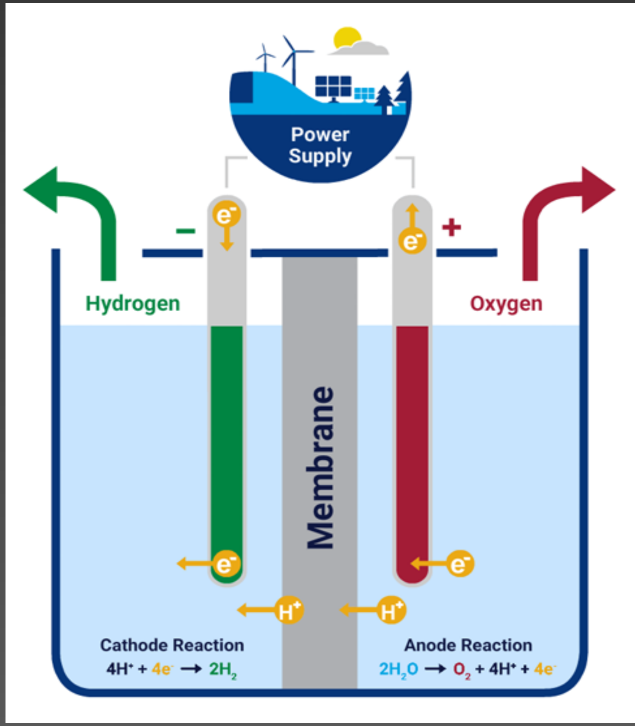
Calculation Steps

To calculate the equivalent mass of hydrogen required, the energy required must be converted into units of hydrogen mass. The annual mass of H2 required in 2050 is projected to be:

$$4.61 \times 10^{12} MJ/120 \frac{MJ}{Kg} = 3.84 \times 10^{10} Kg H_2$$

Maïeul RAVIER Quentin DEPEYROT Noé TRUBERT

ELECTRICITY NEEDS



Equivalent in electricity

Producing 1 kilogram of hydrogen via water electrolysis typically requires around 50 to 55 kWh (kilowatt hours) of electricity. The exact amount depends on the efficiency of the electrolyzer, which is usually between 60% and 80%.

For a breakdown:

- Lower efficiency electrolyzer (60%): Approximately 55 kWh is needed.
- Higher efficiency electrolyzer (80%): Around 50 kWh is sufficient.

Advances in electrolyzer technology are aiming to reduce this energy requirement further. For the purpose of this study, we assume 52.5 kWh of electricity per kg of Hydrogen:

$$3.84 \times 10^{10} Kg \times 52.2 \frac{kWh}{Kg} = 2.0 \times 10^{12} kWh = 2000\ TWh$$

Maïeul RAVIER Quentin DEPEYROT Noé TRUBERT

WATER NEEDS

Water Needs

- Following the previous electrolysis equation and using the molecular weight:
  - M(H) = 1 amu, M(O) = 16 amu
- Then, from the stoichiometry, 2 grams of hydrogen require 18 grams of water. Therefore, for every gram of hydrogen produced, 9 grams of water are needed. We will require:

$$3.84 \times 10^{10} \frac{Kg\ H_2}{year} \times 9 \frac{Kg\ H_2O}{Kg\ H_2} = 3.45 \times 10^{11} Kg\ H_2O/year$$

- The density of water is approximately 1 metric ton = 1 cubic meter (at 4°C and standard atmospheric pressure), therefore

$$Water\ required = 3.45 \text{ x } 10^8\ m^3\ H2O/year$$

- Comparing this value with total water used in the US in 2015, which was 449 x 10^9 m^3, the water needed to produce hydrogen is relatively small.
- In fact, the water needed for hydrogen production represents about 0.08 % of the total water usage in the US in 2015.

WIND LAND REQUIREMENTS

Alta Wind Energy Center (AWEC)

Reference Point

- For wind electrical production, to achieve this target, we evaluated the Alta Wind Energy Center (AWEC) in Tehachapi Pass, California.
- AWEC is the largest wind farm in the U.S. with a total installed capacity of 1,548 megawatts (MW) and producing about 4.75 TWh per year.

Calculating the area of required wind farms

- Assuming all 2,000 TWh of green energy is produced by wind:
- $\boldsymbol{Number\ of\ AWEC\ needed}$

  $$(2{,}000\ \boldsymbol{TWh/year})/(\boldsymbol{4.75\ TWh/year}) \approx 421$$
- Given that AWEC occupies approximately 130 square kilometers (km^2), the total land area required for 421 such wind farms would be:

  $$421 * 130\ km^2 \approx 55{,}000\ km^2\ \ (\approx 21{,}000\ miles^2)$$
- This area is approximately equivalent to the size of West Virginia.
- It is acknowledged that AWEC is sited in a location that is significantly windy. This study assumes that improvements in wind turbine efficiency will compensate for locations with less wind than Tehachapi Pass.

Vincent RISTIC, Alban HISSLER

SOLAR LAND REQUIREMENTS

Mount Signal Solar

Reference Point

- For solar electrical production, to achieve this target, we evaluated the Mount Signal Solar facilities in Imperial County California, with a capacity of 1.2TWh/year

Calculating the area of required solar farms

- Assuming all 2,000 TWh of green energy is produced by solar:
- $\boldsymbol{Number\ of}$ Mt. Signal $\boldsymbol{needed}$

$$(2{,}000\ \boldsymbol{TWh/year})/(1.2\ \boldsymbol{TWh/year}) \approx 1667$$

- Given that Mt Signal occupies approximately 21 square kilometers (km^2), the total land area required for 1667 such wind farms would be:

$$1667 * 21\ km^2 \approx 35{,}000\ km^2 \ \ (\approx 13{,}500\ miles^2)$$

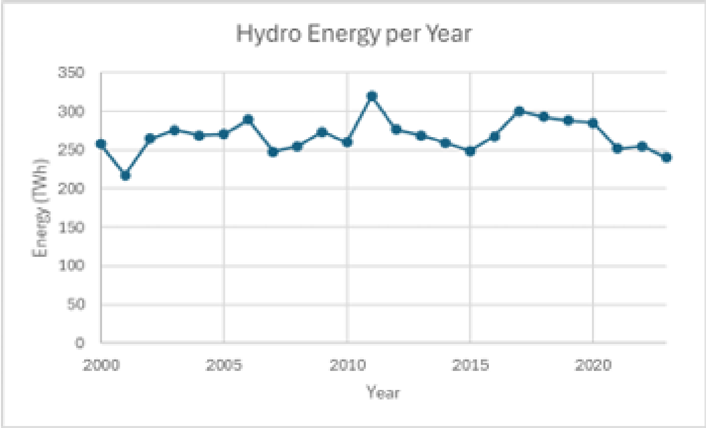
- This area is approximately equivalent to the size of Connecticut.
- It is acknowledged that Mt Signal is sited in a location that is significantly sunny with poor soil conditions for farming. This study assumes that improvements in solar panel efficiency will compensate for locations with less sun than Imperial County.

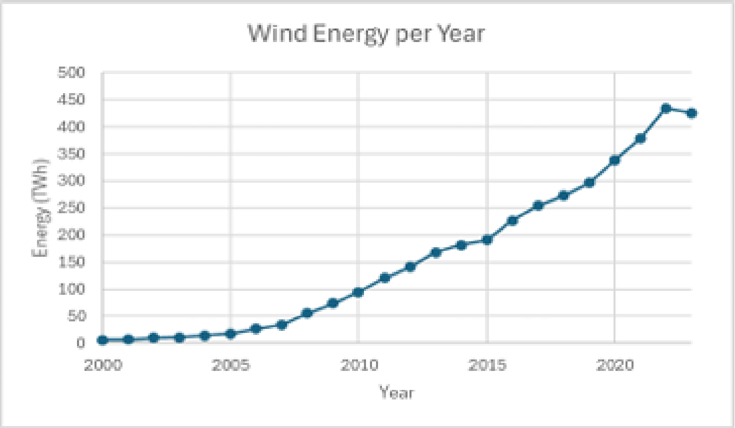
Vincent RISTIC, Alban HISSLER

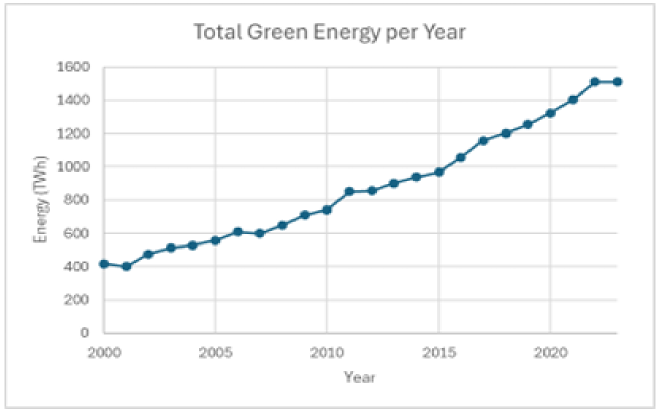
GREEN ENERGY PRODUCTION

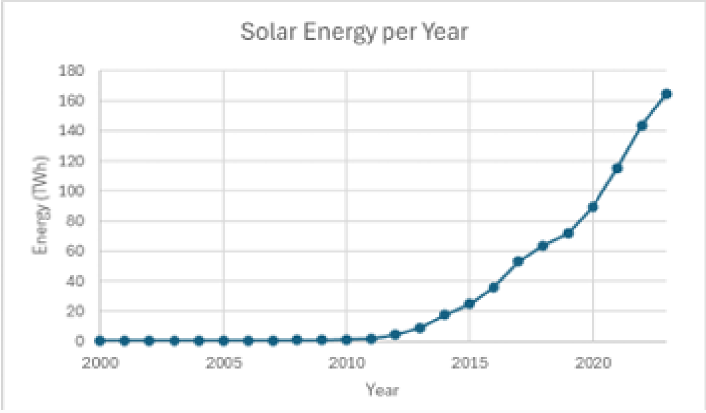
2000-2023 U.S. Installed Base

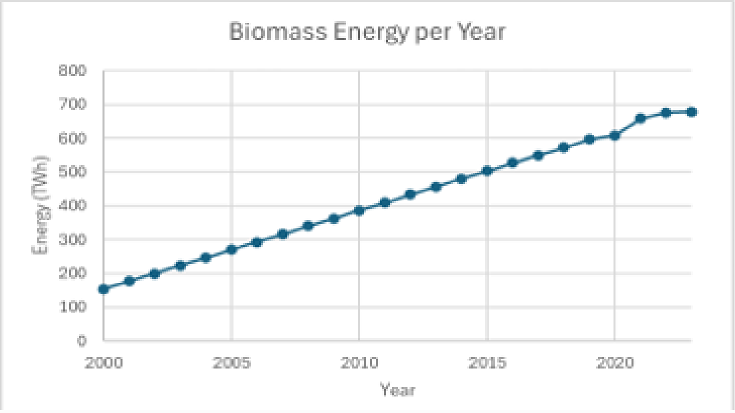
- Biomass Plants
  - 2023 Plants: 630
  - Avg Yearly output per plant: 1.078 TWh
- Solar Farms
  - 2022 Farms: 5,000
  - Avg Yearly output per Farm: 0.0329 TWh
- Wind Turbines
  - 2022 Turbines: 90,000,
  - Avg Yearly output per Turbine: 0.0047 TWh











Global electricity generation by source 2023 | Statista

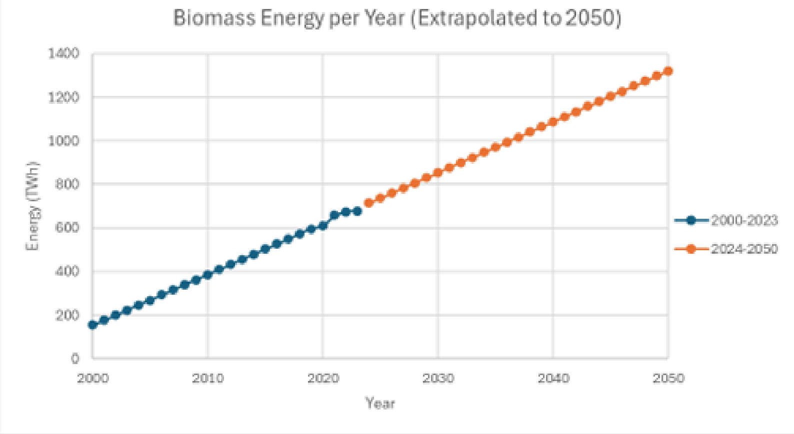
Jack DeVita and Kevin Schaffer

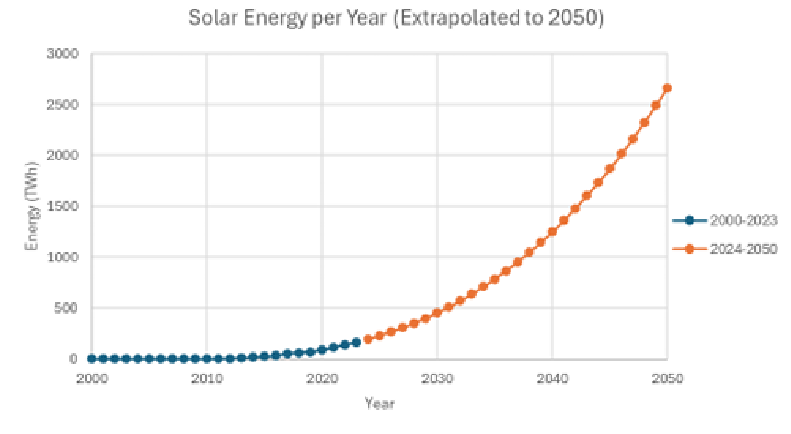
GREEN ENERGY PRODUCTION

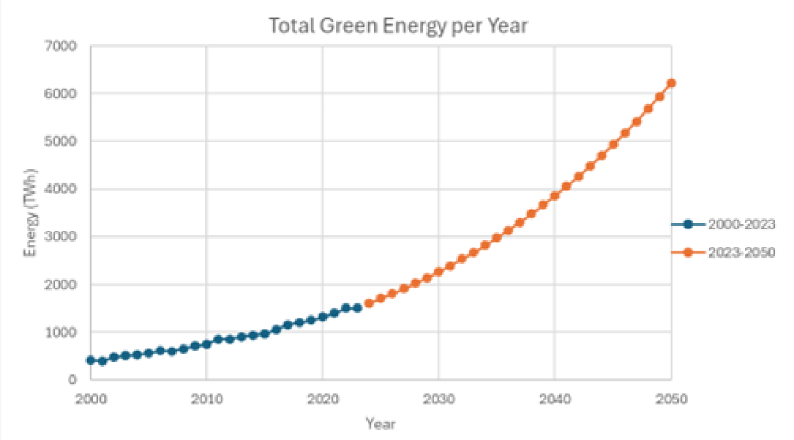
Projection to 2050

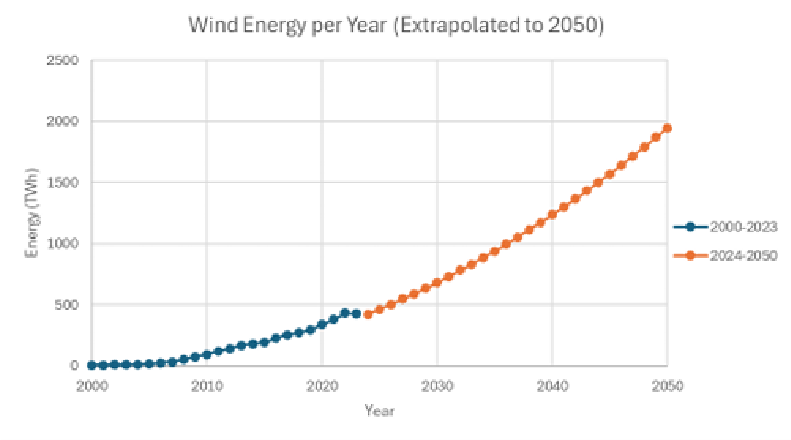
- Scaled each energy source independently, based on growth from 2000-2023
- Scaling Methodology:
  - Biomass: Linear Scaling
  - Solar: 3rd Order Polynomial Trend
  - Wind: 2nd Order Polynomial Trend
- Projected 2050 Capacity:
  - Biomass: 1320 TWh
  - Solar: 3030 TWh
  - Wind: 1890 TWh
- Total: 6240TWh

Aviation's green energy needs of 2000 TWh could be met, if exponential growth in wind and solar is maintained









Global electricity generation by source 2023 | Statista

Jack DeVita and Kevin Schaffer

HYDROGEN PLANT

Plug Power Camden County, Georgia

Shubham Uday Dhadhal Connor Nielsen Ruchir Ravishankar

Reference Point

- Plug Power announced the plan to establish a green Hydrogen plant in Camden County, Georgia.
- We can take this as a reference to get an approximate estimate of the total amount of investment required to produce the amount of green Hydrogen to satisfy the projected aviation industry requirements.

Investment Cost

- Plug Power invested $84 million into building a facility that is capable of producing 15 imperial tons of green LH2 every day.
- Upon conversion, we can assume that an investment of $16.91 is required to produce a production capacity of 1 kg of green H_2 per year.

Total H_2 Plant Investment

- To produce of the required production capacity of LH2 in 2050, a total investment is:

$$3.84\text{X}10^{10}\text{Kg/year} \times \$16.91/\text{Kg} = \$649\text{B}$$

- This equates to roughly $24 Billion p/a

Plug Power Inc. | Plug Power Announces Green Hydrogen Plant in Camden County, Georgia

TOTAL H2 INVESTMENT

Solar

- Again, referring to the Mount Signal Solar facilities in Imperial County California, investment cost was reported to be $636M. If all of the green H_2 needs in 2050 were produced from solar power: Total cost = 1667 * $636M = $1.06T

Wind

- Alternatively, if all of the Green H_2 Needs in 2050 were produced from wind power, we refer to Alta Wind Energy Center, which cost $2.875B: Total cost = 421 * $2.875B = $1.21T

Bringing it together

- Assume 50% Solar and 50% Wind:
  - Energy production investment = $1.13T
  - H_2 plant investment = $0.65T
  - Total H_2 investment = $1.78T OR $71B/year

Reality Check

- $71B represents ~ 1% of the U.S, Government's annual budget of $6.1T

Shubham Uday Dhadhal Connor Nielsen Ruchir Ravishankar

AIRCRAFT REPLACEMENT

A320

- About 11,000 in service currently
- At max production rate of 64 per month, it will take 15 years to replace the current fleet
- Need to begin placing into service green hydrogen replacement aircraft in 2035 to fully replace Jet-A powered A320's by 2050

Fleet Implications

- Assume production rates for other aircraft can likewise replace the existing fleet in 15 years
- Typical timeframe for Launch to Entry-in-Service for a new aircraft type is 10 years

World aircraft fleet could be hydrogen-powered by 2050, but new aircraft need to be launched now

Olla Al Mutawa & Emma Ochs

SUMMARY & CONCLUSIONS

Summary

- Projecting historic rates of growth in travel and efficiency, need equivalent of 2.3 million barrels of jet fuel/day in 2050
- 2,000 TWh of green electrical generating capability is required
- Need to begin shipping green hydrogen replacement aircraft in 2035
- Total green electrical and H_2 investment = $1.78T OR $71B/year

Conclusions

- Conversion to non CO_2-emitting H_2-powered aircraft by 2050 is feasible, with the following observations:
  - A significant investment in green energy and hydrogen production is required, on the order of 1% of the US Government's annual budget per year
  - The current exponential growth rate in wind and solar generation could satisfy the green energy needs of 2000 TWh in 2050
  - Significant land will need to be set aside, whether wind or solar farms are utilized
  - A 15 year overlap period will be required to phase out Jet-A and phase in Hydrogen


VISION FOR 2050
Thank You