Life Cycle Assessment of Liquid Hydrogen In Aerospace Application

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Key Points

- Since 1960, energy carrying liquid hydrogen has been used primarily as fuel for rocket programs

- Logistic concerns associated with liquid hydrogen as a fuel source are substantial

- Can a hydrogen fuel economy improve the pollution, inefficiency of mechanical operations and environmental degradation are all consequences that we face in our carbon based economy ?

Where are we today ?

- An era of modern industry and production contributing to the scientific application of new technologies
- Emergence of the unparalleled anthropogenic influence upon the planet
- Technologies and advances owed to the global carbon based fuel infrastructure
- High emissions, high environmental impact, not sustainable

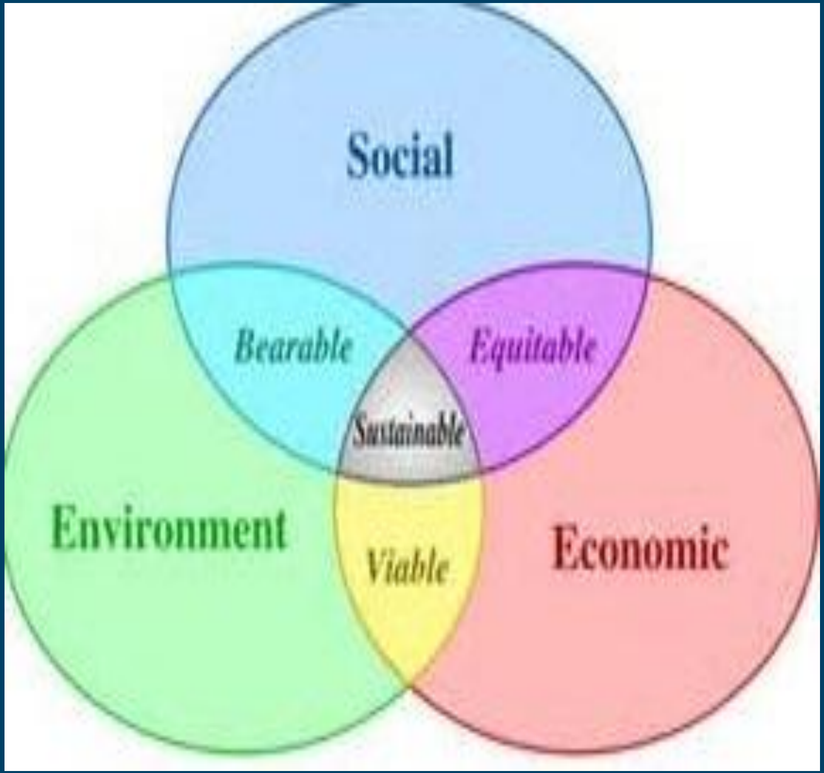
What constitutes sustainability?

What types of fuels are considered sustainable?

Sustainability

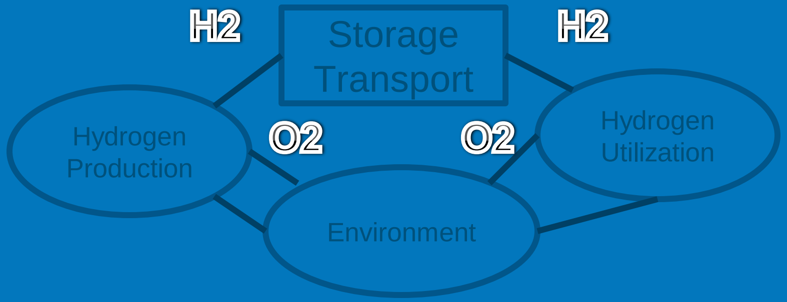
Two working definitions:

1. Refers to the renewability of an energy resource.
   - Energy sources that are delivered and captured upon a constant and extended duration.
   - Usually natural processes from the Earth
2. Refers to an energy resource that is not drastically harmful to the surrounding environment, atmosphere, ecological systems, etc.



Primary Energy
Alternative: Renewable

- Solar
- Wind
- Geothermal
- Tidal/Wave
- Hydroelectric
- Biomass



Hydrogen as a Secondary Fuel:

- Functions as an energy carrier
- Generated by conversion from primary energy resources
- Depending on the primary energy source, can be processed sustainably

The Curious Case of Hydrogen as Energy Carrier

- Hydrogen has valuable potential for integration into an already vast energy economy.
- Characteristics of hydrogen as a fuel source(secondary)
- Alternative energy resource
- Technically sustainable, though not necessarily in practice
- Does undergo combustion with LOx to release energy

Unique type of combustion reaction which results in distinctly different products than that of fossil fuels. $2H_2 + O_2 \rightarrow 2H_2O$

Methods

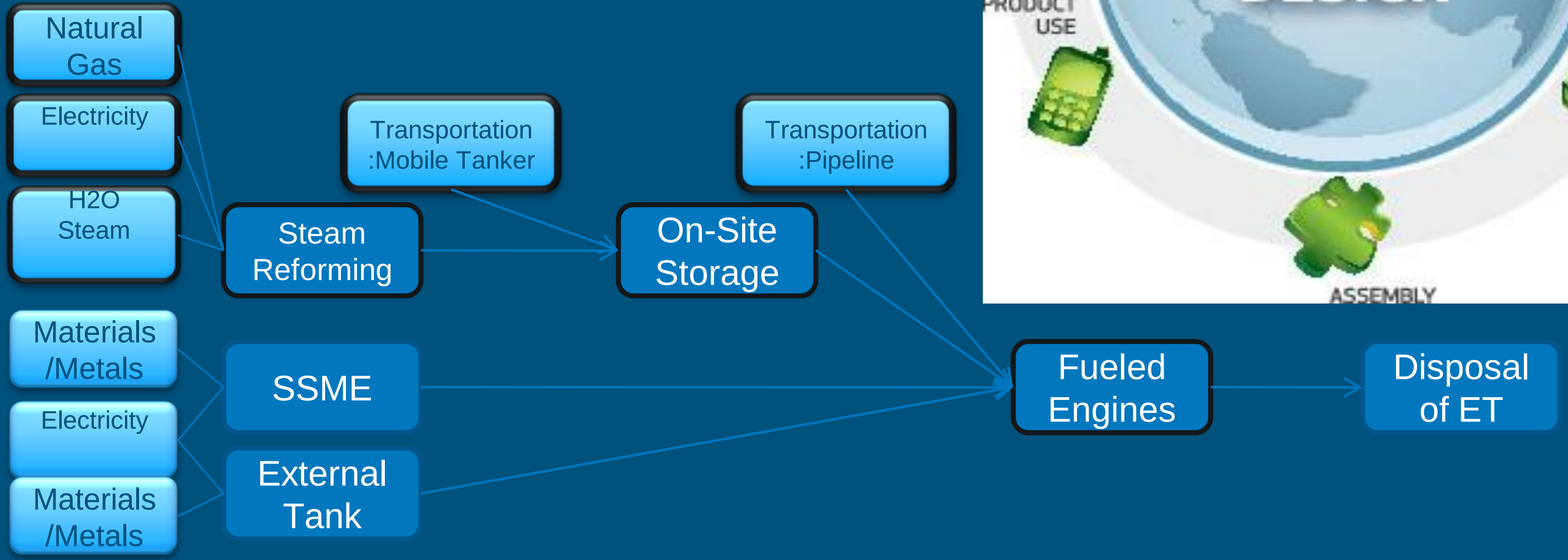
- Conduct a Life Cycle Assessment (LCA) on liquid hydrogen energy application potential.
    - An LCA: overview of material and energy inputs/outputs of a specific process, product, waste.
    - Scope/Goal Setting, Inventory Analysis, Impact Assessment, Interpretation.
- Literature review of existing hydrogen applications. Reviewed scholarly articles pertaining to different methods of production, storage, transportation.
- Connect information regarding logistics of LH2 in rockets with data obtained from LCA software. Complete and analyze a thorough understanding of how LH2 can be used for widespread application.

A Look into Life Cycle Assessment(LCA)

- openLCA software coupled with the Ecoinvent 3.1 database.

- Thorough modeling of material and energy inputs/outputs for described processes.
- Serves to collect and interpret background information and flows essential for the understanding of foreground processes.

Processes: As Defined by LCA



Scope/Goals Defined

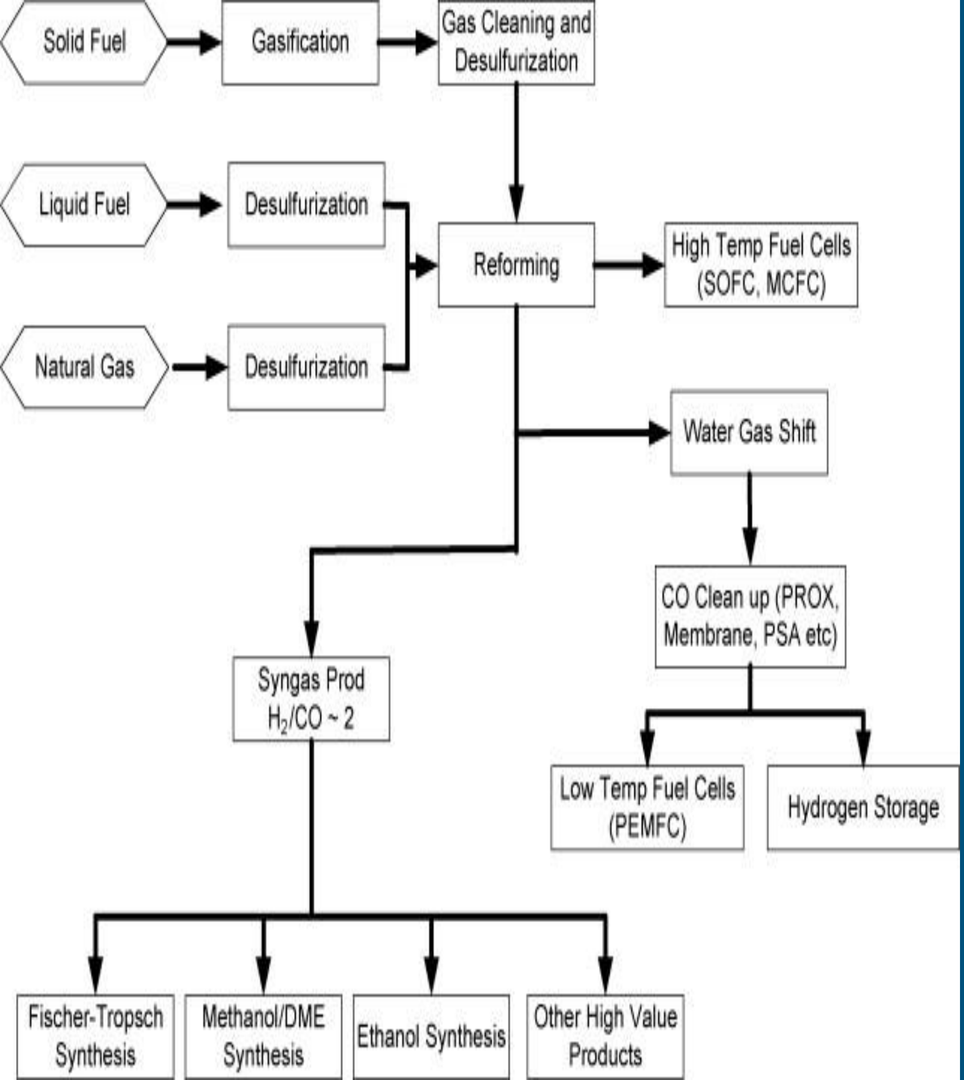
- **Scope:** observational limits of LCA model

  - Production of hydrogen through steam reforming

  - Transportation of hydrogen from manufacturing plants to on-site storage.

  - Transportation from on-site storage to external tank (ET) of the rocket

Goal: Through a thorough Life Cycle Assessment, determine various environmental impacts of LH2 as fuel in the context of aeronautical operations.



Characteristics:

- Low ignition energy: 0.02 MJ
- High Heating Value(HHV): 142Mj/1kg
- Extremely low density
- Highest specific impulse of any known rocket propellant. (efficiency in relation to amnt. of propellant consumed).
- Cryogenic storage at -423F (-253C)

Production of Hydrogen

- There exist various production methods for hydrogen

- Conventional sources of fuel production

  -Hydrogen produced from steam reforming of natural gas

  -97% of all industrial hydrogen production comes from steam reforming (CH4)

- Hydrogen produced from renewable energy sources

  -Solar energy, using photovoltaics for direct conversion

  -From solar thermal energy

  -Wind power

  -Hydropower

  -Biomass

$$CH_4 + H_2O(g) \longrightarrow 3H_2 + CO$$

- $\Delta H = 206$ MJ

$$CH_4 + 2H_2O(g) \longrightarrow 4H_2 + CO_2$$

- $\Delta H = 165$ MJ

Steam Reforming Production

- Most industrially competent form of hydrogen production.
- Inventory Inputs: electricity, natural gas , metal for plant machines
- Processes involved: steam reforming followed by water gas shift conversion, and finally pressure swing absorption(PSA)
- Most realistic method of production in consideration for an industrial size fuel economy

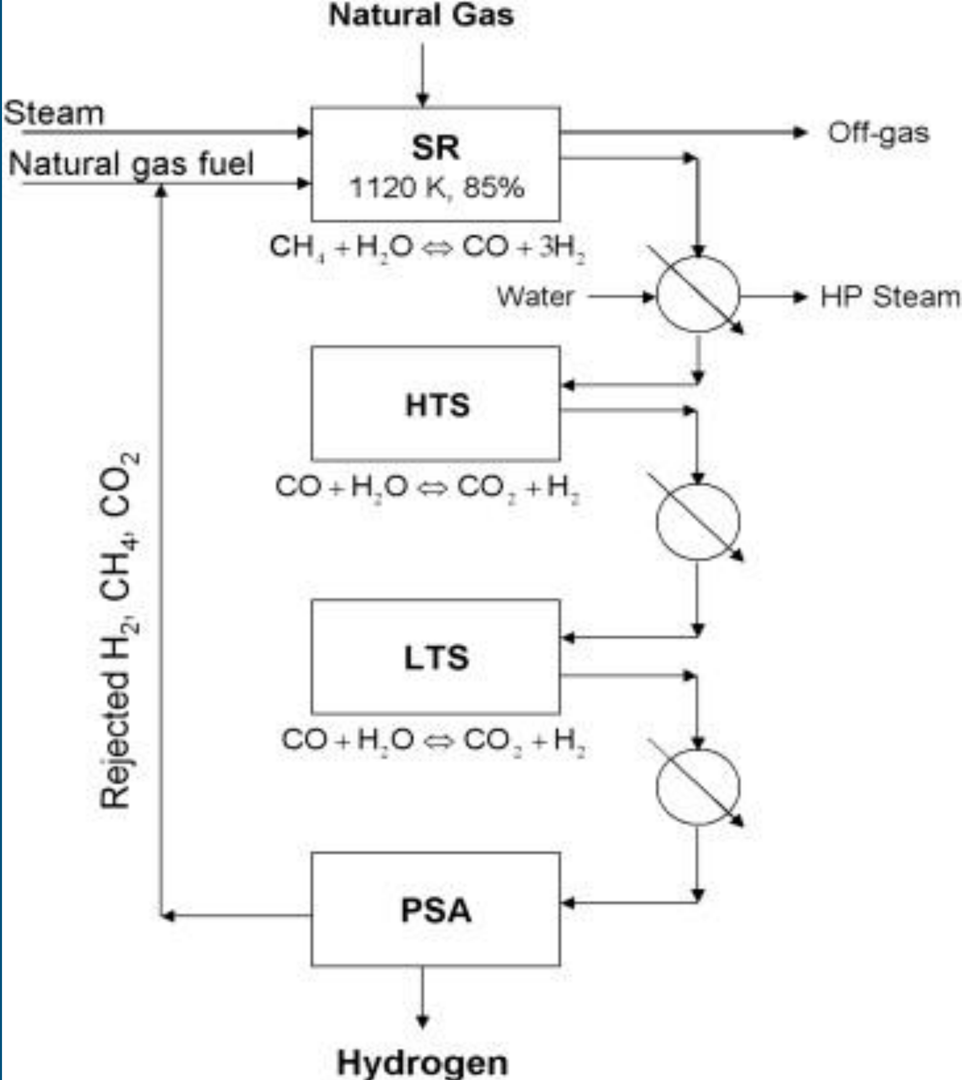


Table 1

Average air emissions from H_2 production by natural gas steam reforming [8]

Air emission	System total (g/kg H_2)
Benzene (C_6H_6)	1.4
Carbon dioxide (CO_2)	10662.1
Carbon monoxide (CO)	5.9
Methane (CH_4)	146.3
Nitrogen oxides (NO_x as NO_2)	12.6
Nitrous oxide (N_2O)	0.04
Non-methane hydrocarbons (NMHCs)	26.3
Particulates	2.0
Sulphur oxides (SO_x as SO_2)	9.7

C. Koroneos, A. Dompros, G. Roumbas, N. Moussiopoulos, International Journal of Hydrogen Energy 29 (2004) 1443–1450

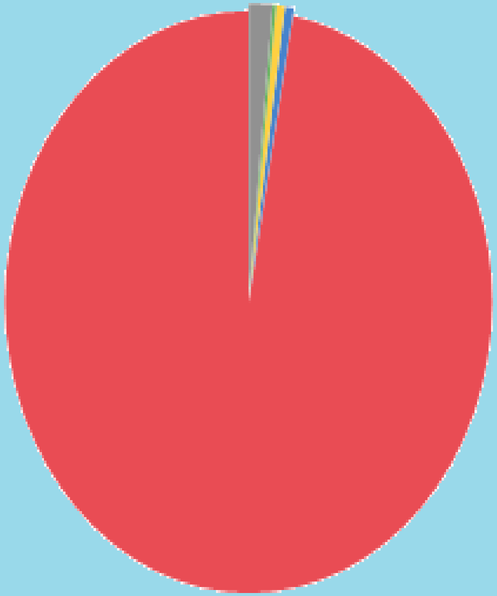
Transportation

- Via Mobile Tanker: Distance of 691mi (1112 km). Carried in 13,000 gallon mobile tankers
- Via Vacuum-Jacketed Pipeline: Distance of 0.2841mi (0.457 km). Dimensions of 10inches x 12 inches

Results of Life Cycle Assessment

- The production process for liquid hydrogen characterizes the largest impact of the life cycle

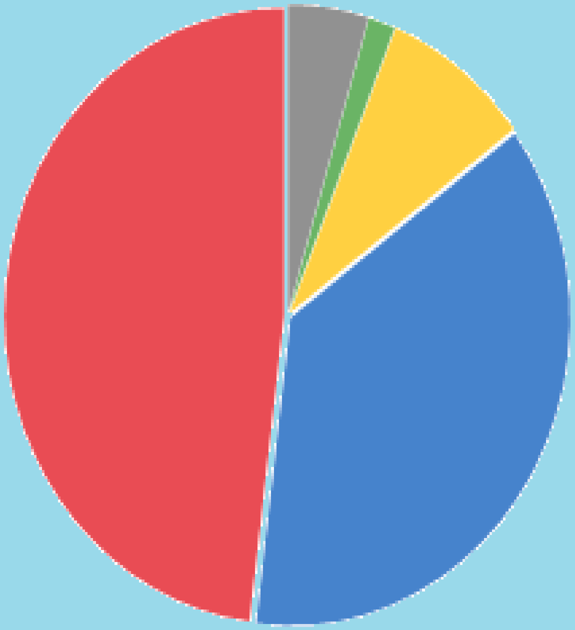
Climate Change GWP100



- 3.604E3 kg CO2 eq.: LH2 creation
- 21.318 kg CO2 eq.: electricity production, hard coal, cut-off, U - RFC
- 21.018 kg CO2 eq.: electricity production, hard coal, cut-off, U - SERC
- 8.981 kg CO2 eq.: electricity production, hard coal, cut-off, U - WECC, US only
- 56.770 kg CO2 eq.: Other

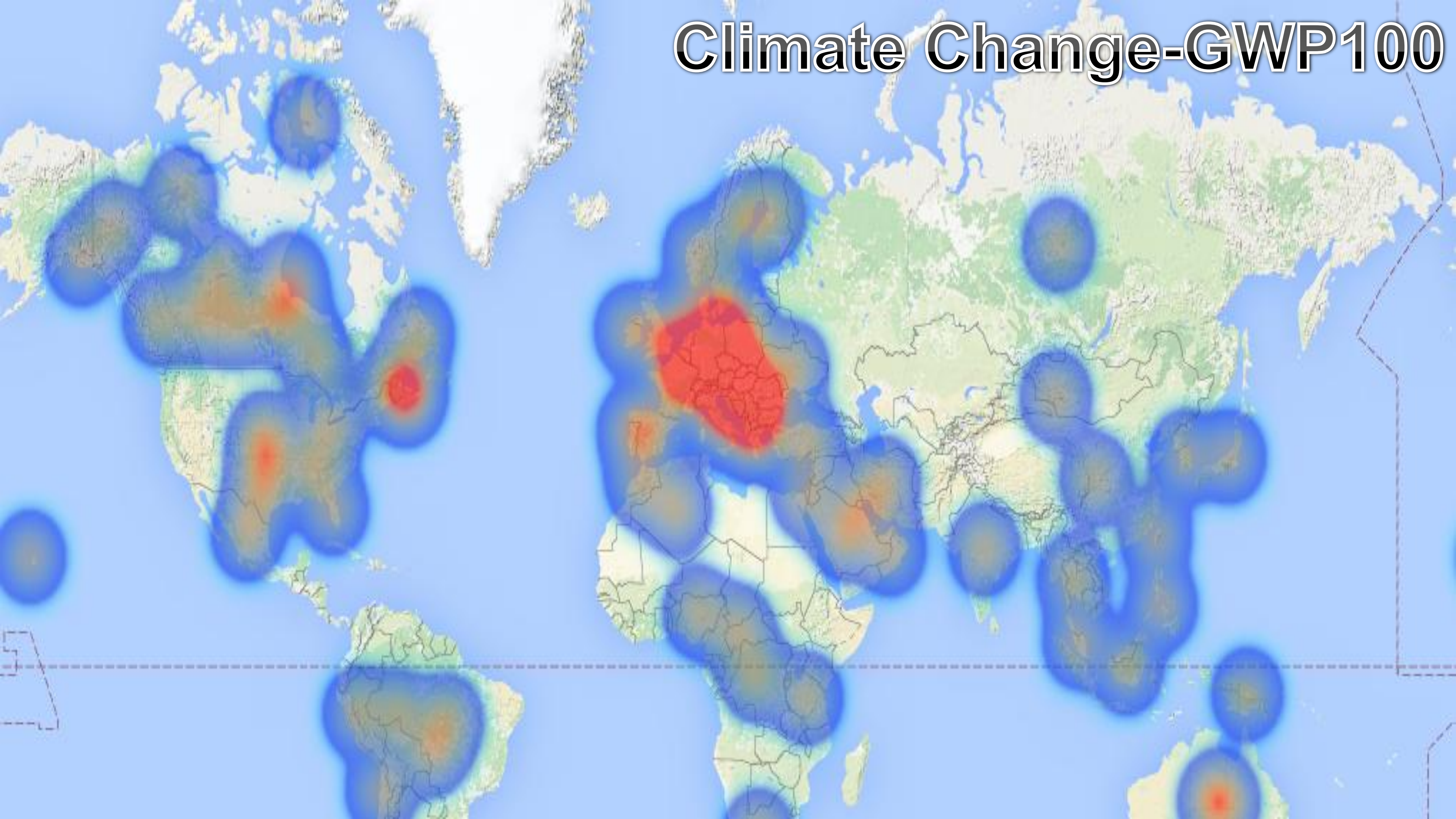
Results of Life Cycle Assessment

Depletion of Abiotic Resources: Fossil Fuels



- 9.867E2 MJ: petroleum and gas production, on-shore, cut-off, U - US
- 7.636E2 MJ: hard coal mine operation, cut-off, U - RNA
- 1.766E2 MJ: natural gas production, cut-off, U - US
- 31.945 MJ: sweet gas, burned in gas turbine, cut-off, U - RoW
- 95.362 MJ: Other

Climate Change-GWP100



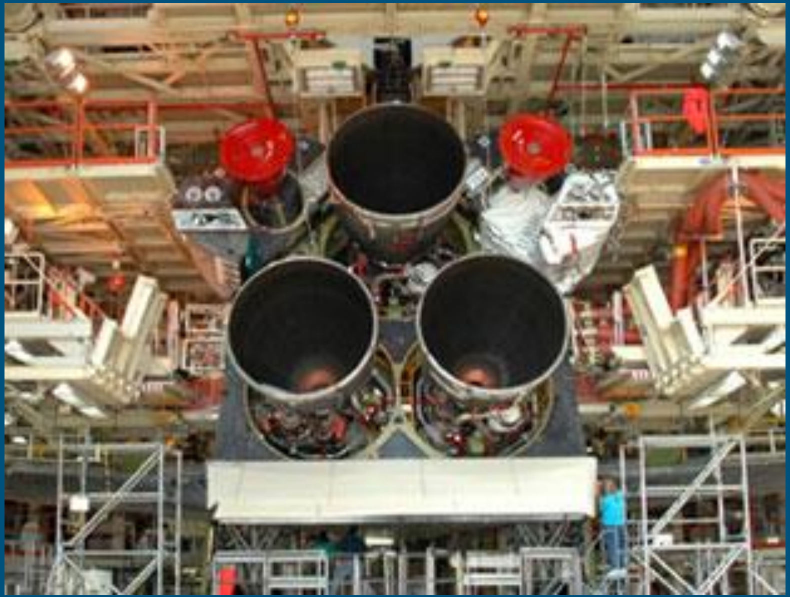
LCIA Results

Impact category	Result	Reference unit
Acidification potential - average Europe	0.64992	kg SO2 eq.
Terrestrial ecotoxicity - TETP inf	0.19057	kg 1,4-dichlorobenzene eq.
Marine aquatic ecotoxicity - MAETP inf	1.52363E5	kg 1,4-dichlorobenzene eq.
Climate change - GWP100	3712.18664	kg CO2 eq.
Photochemical oxidation - high Nox	0.10968	kg ethylene eq.
Human toxicity - HTP inf	38.25968	kg 1,4-dichlorobenzene eq.
Depletion of abiotic resources - elements, ultimate reserves	1.77355E-5	kg antimony eq.
Freshwater aquatic ecotoxicity - FAETP inf	25.66946	kg 1,4-dichlorobenzene eq.
Eutrophication - generic	0.15874	kg PO4--- eq.
Ozone layer depletion - ODP steady state	2.14048E-5	kg CFC-11 eq.
Depletion of abiotic resources - fossil fuels	2054.16453	MJ

Literature Review

- Purpose: To provide a more full understanding of the problems concerning liquid hydrogen in the context of rocketry.

- Boil-off and venting problems



-Selection of proper materials

http://www.nasa.gov/returntoflight/system/system_ET.html

Problems: Boil-off and Insulation

Passive boil-off: Associated primarily storage, transportation and handling. Heat leak boil off proportional of the surface area to the volume of the tank.

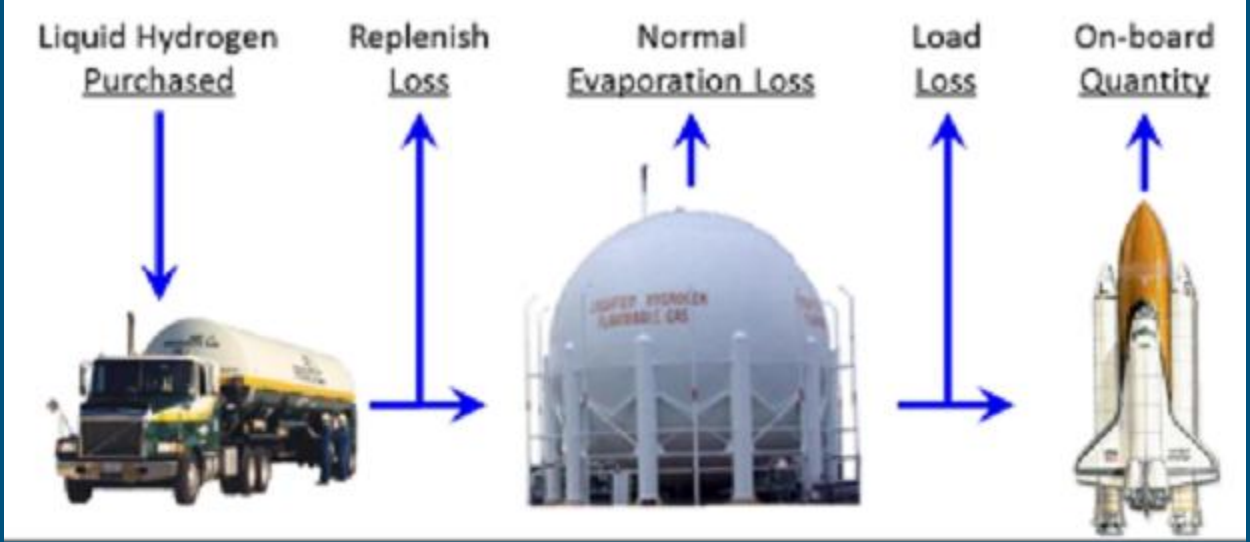
•Consequence of heat leaks, sloshing, flashing , ortho-para conversion

-Can accumulate to 40% loss of available combustion energy.

•Total boil off rate from tanks reach up to 600,000 LPY (liters per year).

Solutions: -Sufficient insulation of vessels to reduce heat influx

-Selection of optimal tank sixe and shape. Consideration of (S/v)



- All stages are subject to inherent losses from boil-off
- Different stages are subjected to different amounts of boil-off occurring. Due to,
  - -Differences in amounts of insulation at each stage
  - - Amount of time hydrogen is contained in each stage

https://indico.cern.ch/event/244641/session/25/contribution/323/attachments/418276/580937/O10-4_ICEC-Notardonato_140709.pdf

Problems: Proper Selection of Materials

Materials Selection:

- Significant consideration because of susceptibility to hydrogen environment embrittlement (HEE) and low temperature embrittlement.
- Attention to materials can reduce problems in other areas of concern like boil-off and venting problems

Solutions: -Use metals specifically resistant to cryogenic temperatures (Austentic Stainless Steels 300 series metals/ aluminum alloys for ET)

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Conclusions

•Liquid hydrogen has limitations as an energy carrier (i.e. few realistic options for production, highly specific requirements of associated materials, major technical problems related to storage/transportation)

•The most significant impact of liquid hydrogen clearly comes from the production process through steam reforming.

•LH2 has significant potential for uses as propellant although its application for domestic uses will be difficult.

•Despite observed environmental impacts, hydrogen still remains extremely valuable for its clean burning properties. As a supplement for current energy economy, LH2 is a viable option.

Limitations of Study

- Life cycle assessments are inherently complex studies. Important factors could be un-modeled due to the large amount of variables

- openLCA software is only as functional as the database its associated database

  -Ecoinvent v3.1database supplies regional information

- Minimal consideration of materials included in engine and external tank parts

- Lack of openLCA ability to model the important output of H20 from the combustion of LH2 and LOx

Future Research

- Inclusion of liquid oxygen to the LCA calculations. (Lox)
- Extend the scope of study to cover the production and transport of External Tank and Space Shuttle Main Engines.
- Include in LCA calculations GHG emissions of H2O


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