Life Cycle Assessment of Sulfur Iodine Process

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Steps in life Cycle Assessment*

- Purpose and Goal
- System Boundary Definition
- Life Cycle Inventory
- Life Cycle Analysis
- Life Cycle Interpretation

* ISO 14011 – International Standard for Environmental Life Cycle Assessment

Why Hydrogen?

- Replacement for fossil fuels (oil)?
  - Past peak oil production?
- Reduce greenhouse gas emissions?
  - Replace anthropogenic source of CO_2
- Promote energy independence?
  - Politics of Middle East
- Economical energy carrier?
  - Oil > $90.00 US/barrel

Purpose and Goal

- Interpretation of results of LCA in context of Goal:
  - Assess S-I cycle with respect to other thermochemical processes.
  - Assess nuclear hydrogen production with respect to current technology.
- What is purpose of this assessment?
  - Evaluate S-I process for environmental impacts on significant environmental aspects.
  - Raise awareness of factors involved in LCA.

System Boundaries

- Nuclear heat source, including:
  - Nuclear fuel cycle
  - Construction, operation and decommissioning of physical plant.
- Hydrogen Production Plant, including:
  - Production of raw materials
  - Construction and operation of physical plant.
- Does not include distribution of hydrogen product or end-use.

Other studies

- GREET Study[1]
  - System boundary includes entire nuclear fuel cycle, H_2 production, transportation and distribution of product, and fuel-cell vehicle operations (well-to-wheels).
  - Does not include He coolant.
- ISPRA Mk-9[2]
  - System boundary includes entire nuclear fuel cycle and H_2 production.
  - Excludes storage, transportation, distribution of product and end-use.

1. Wu, et al., Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Hydrogen Produced with Nuclear Energy. *Nuclear Technology*, 2006, **155**, 192-207
2. Utgikar and Ward, Life Cycle Assessment of ISPRA Mark 9 Thermochemical Cycle for Nuclear Hydrogen Process, *J.Chem Tech and Biotech*, 2006, **81** (11) 1753-1759.

Other Studies (cont'd)

- High-Temperature Electrolysis (3)
  - System boundary includes entire nuclear fuel cycle and H_2 production.
  - Excludes storage, transportation, distribution of product and end-use.
- Steam Reforming of Natural Gas (4)
  - Included as an example of non-nuclear hydrogen production.

3. Thiesen and Utgikar. Life cycle assessment of high temperature electrolysis for hydrogen production via nuclear energy. *International Journal of Hydrogen Energy*, 2006, **31**: 939-944.

4. Spath and Mann. Life cycle assessment of hydrogen production via natural gas steam reforming. NREL/TP-570-27637. February 2001

Other Studies (cont'd)

- Torness Advanced Gas Reactor (5)
  - Includes full nuclear fuel cycle, physical plant construction, operation and decommissioning, and electrical power generation.
- Examples illustrate the need to set LCA boundaries as discrete modules to provide meaningful comparison.
  - e.g., nuclear fuel cycle; physical plant construction, decommissioning; plant operation; product storage; transportation; distribution; end-use.

5. British Energy. Environmental product declaration of electricity from Torness Nuclear Power Station. AEA Technology. May, 2005.

Assumptions for LCA

- Reference nuclear heat source is 600 MWth high-temperature gas-cooled reactor (HTGR)
- Plant life is 30 years.
- All 600 MW heat is transferred to hydrogen production.
- Assume nuclear fuel enrichment is 100% centrifuge vs gaseous diffusion.
  - (Currently 45% is centrifuge; factor of 40 more efficient).
- 10% I_2, He, and H_2SO_4 makeup/year.

Significant Environmental Aspects

- Climate change (GWP = gCO_2-eq/kg H_2)
- Acidification potential (AP = gSO_2-eq/kg H_2)
- Critical resource usage, i.e., He, I_2
- Land area use

Life Cycle Inventory: Nuclear Plant

- Material and energy for construction of physical plant
  - Assume construction similar to current plant: Torness AGR
  - Reactor vessel liner – 76 E+03 kg steel.
  - Reactor vessel shell – 47 E+06 kg pre- stressed concrete.
  - Materials for balance-of-plant equal to above.
- Nuclear fuel
  - Initial loading 4000 kg
  - Refuel ¼ inventory/year
- Reactor coolant
  - Helium (alternately molten salt)
  - Compare to Ft St Vrain – 3.685 ton He
- Power to operate plant

Life cycle inventory: H2 Plant

- Material and energy for construction of physical plant and process equipment
  - Assume equal to BOP for nuclear plant
- Energy and raw materials for SI cycle
  - 2120 tons I_2, $13-14 /kg
  - 100 tons H_2SO_4
- Material and energy for Intermediate Heat Exchangers (IHX)
- Material and energy for heat transfer fluid
  - Helium (assume equal to mass of primary coolant)
  - Molten salt (no calculations for this analysis)

Critical Resource Usage

- For 600 MWth HTGR-SI cycle:
  - Requires 2120 tons I_2 (world annual production is 18,000 tons)
  - Requires 100 tons H_2SO_4
  - Platinum catalyst in H_2SO_4 decomposer
    - Assume technology eliminates losses.
  - 3.69 tons He coolant for reactor
  - Exotic high-temperature corrosion resistant materials (Incoloy, Hastelloy, SiC)

Land Area Usage

- Average nuclear plant occupies 4 km^2
- 100 m separation between HTGR and SI hydrogen plant.
  - Safety basis of nuclear plant
- Isolation of plant from population centers.
- Method of distribution – pipeline.
- Surface area of open pit mines for uranium, coal, iron ore extraction
  - difficult to quantify.

Analysis

- Hydrogen production = 200 ton/day
- For steel: energy requirement 25.9 GJ/ton
  - CO^2 = 0.50 tons carbon/ton
- Concrete: 5.6 GJ/ton
  - CO^2 = 0.12 tons carbon/ton
- Nuclear fuel: 2.28 g CO^2-eq/kWh
- Iodine extraction from brine: 88.21 kg CO_2/kg
- High purity sulfuric acid production: 8.10 lb CO_2/ton
- Helium fractional distillation from natural gas: 754 kg CO_2/kg

Analysis (cont"d)

- Steel: 1.74 E-2 g CO_2/kg H_2
  - Multiply by 3 for total plant = 5.21 E-2
- Concrete: 2.58 E-2 g CO_2/kg H_2
  - Multiply by 3 for total plant = 7.74 E-2
- Iodine: 118.8 g CO_2/kg H_2
  - alternate method, not validated (next slide)
- Helium: 999 g CO_2/kg H_2
  - Multiply by 2 for H2 plant
  - Alternate method, not validated
- Sulfuric Acid: 1.84 E-4 g CO_2/kg H_2
- Nuclear Fuel Cycle: 131.3 g CO_2/kg H_2
- TOTAL: 2250 g CO_2-eq/kg H_2

Analysis (cont'd)

- Method to determine GHG emissions when not otherwise specified:
  - Cost of commodity specified
  - Reduce by reasonable overhead costs and profit (40%).
  - Relate adjusted cost to cost of power (electricity @ $/kWh
  - Relate power requirement to GHG emissions from power generation (US mix of coal, nuclear, NG, etc.)
  - Divide by total H_2 production over the life of the plant to yield g-CO_2-eq/kg H_2

Example: Iodine

- Cost of iodine = \$17.03/kg
- Adjusted cost = 0.6(13.5) = \$10.25/kg
- Regional cost of electricity = \$.0560/kWh
- Power required = 10.25/.056 = 183 kWh
- GHG emissions (elect) = .610 kg CO_2-eq/kWh (1.341 lb/kWh)
- GHG emissions (I_2) = (.610)(183) = 111.6 kg CO_2-eq/kg I_2.
- For total plant load of 2120 tons (2.12E+06kg): (1.116E+02)(2.12E+06) = 2.36E+08 kg CO2-eq.
- To equate to H2 production:
  - (200 ton/day)(30 yr)(365d/yr) = 2,190,000 tons = 2.19E+09 kg
- GHG contribution = (2.36E+08 kg)/(2.19E+09 kg-H2) = 0.108 kg (108 g CO_2-eq/kg H_2)
- To allow for losses, make-up = (1.10)(108) = 118.8 <u>g CO_2-eq/kg H_2</u>

Comparison of Results

- ISPRA Mk-9:
  - 2368 g CO_2-eq/kg H_2
  - 1250 g CO_2-eq/kg H_2 due to nuclear plant
- High-Temperature Electrolysis:
  - 2000 g CO_2-eq/kg H_2
- Torness
  - 5.05 g CO_2-eq/kWh
  - Assumes centrifuge for enrichment
- GREET
  - 25-30 g CO_2-eq/km
- Steam Methane Reforming:
  - 9000 g CO_2-eq/kg H_2

Conclusions

- Compared to the current method of hydrogen production, ANY nuclear-based process emits approximately 20-25% GHG emissions.
- Although many studies have been performed, need to standardize results with respect to system boundaries and units;
- There is much variability in the quality of data used for LCA; and,
- There is a lack of data for certain key processes.
- The decision to use a particular process should consider the results of LCA, but not be based solely on results of LCA;
- LCA is only one of many factors to be considered.