Technology Assessment

- Assess availability of production technologies for commercial deployment
  - 5, 10, 20 year timeframes

- Life Cycle Assessment of select technology pathways
  - CA-GREET Tier 2 model
  - Distributed and centralized pathways
  - Energy use, GHG & criteria pollutant emission estimates

- Economic analysis of select technology pathways
  - H2A model
  - Distributed and centralized pathways
  - Cost of production for select technology pathways

Technology Categories

- Thermal processes
  - Biomass gasification and pyrolysis
  - Bio-derived liquids reforming
  - Biogas reforming
  - Thermochemical water splitting

- Electrolytic processes
  - Electrolysis using grid and renewable power

- Photolytic processes
  - Photobiological, photoelectrochemical & photofermentation processes

- Biochemical processes
  - Dark fermentation

Technology Categories

- Biomass gasification
    - Directly heated gasifiers and indirectly heated gasifiers
    - Supercritical gasification; plasma gasification
    - Direct pyrolysis not considered
    - TRL-7
- Bio-derived liquids reforming
    - Aqueous processing or flash pyrolysis followed by reforming
    - TRL-4~5
- Biogas reforming
    - WWTP, animal waste digesters, and landfill gas upgrading
    - Technology integration challenges
    - TRL-8
- Thermochemical water splitting
    - Thermal energy from renewable sources, ex. concentrated soar power
    - TRL-4~5

Technology Categories

- Electrolytic processes
  - Renewable power and grid electricity mix
  - Alkaline and PEM electrolyzers
  - Technology components available; integration and capital cost barriers
  - TRL-8
- Photolytic processes
  - TRL-1~3
- Biochemical processes
  - TRL-1~3

Pathway List

Near Term Pathways – 5 years (commercial by 2020)

1. Water electrolysis
    a. Renewable power
    b. Electricity from the grid
2. Biogas reforming (biogas sources: a. Landfill gas, b. Waste water treatment facilities, c. Dairy digesters)

Mid Term Pathways – 10 years (commercial by 2025)

1. Biomass gasification
2. Bio-derived liquids reforming

Long Term Pathways – 20 years (commercial by 2035)

1. Photolytic conversion
2. Dark fermentation

Baseline: Natural gas reforming

Technology Availability

	Technology	TRL	Commercialization Timeframe
1	Water electrolysis	8	N
2	Biogas reforming	8	N
3	Biomass gasification	7	M
4	Bio-derived liquids reforming	4-5	M-L
5	Thermochemical water splitting	4-5	M-L
6	Photolytic conversion	1-3	L
7	Dark fermentation	1-3	L

Note: N: Near term; M: Mid term; M-L: Mid to long term; L: Long term
TRL 3 – experimental proof of concept; TRL 5 – validated in relevant environment; TRL 7 – prototype demo in operational environment; TRL 8 – system complete and qualified; TRL 9 – actual system proven in operational environment

Techno-economic Assessment - Pathways Studied

Near Term Pathways – 5 years (commercial by 2020)

1. Water electrolysis
   a. Renewable power
   b. Electricity from the grid
2. Biogas reforming (biogas sources: a. Landfill b. Waste water treatment facilities c. Dairy digesters)

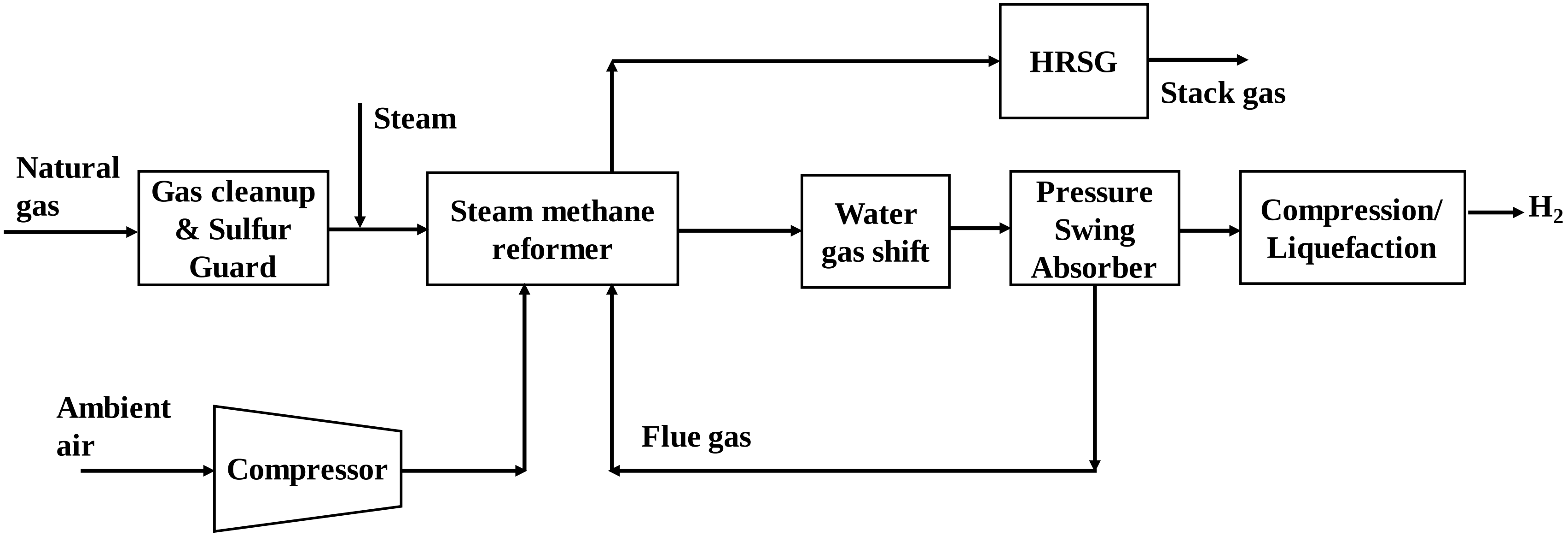
Mid Term Pathway – 10 years (commercial by 2025)

1. Biomass gasification

Baseline: Natural gas reforming (centralized & distributed)

Natural gas reforming

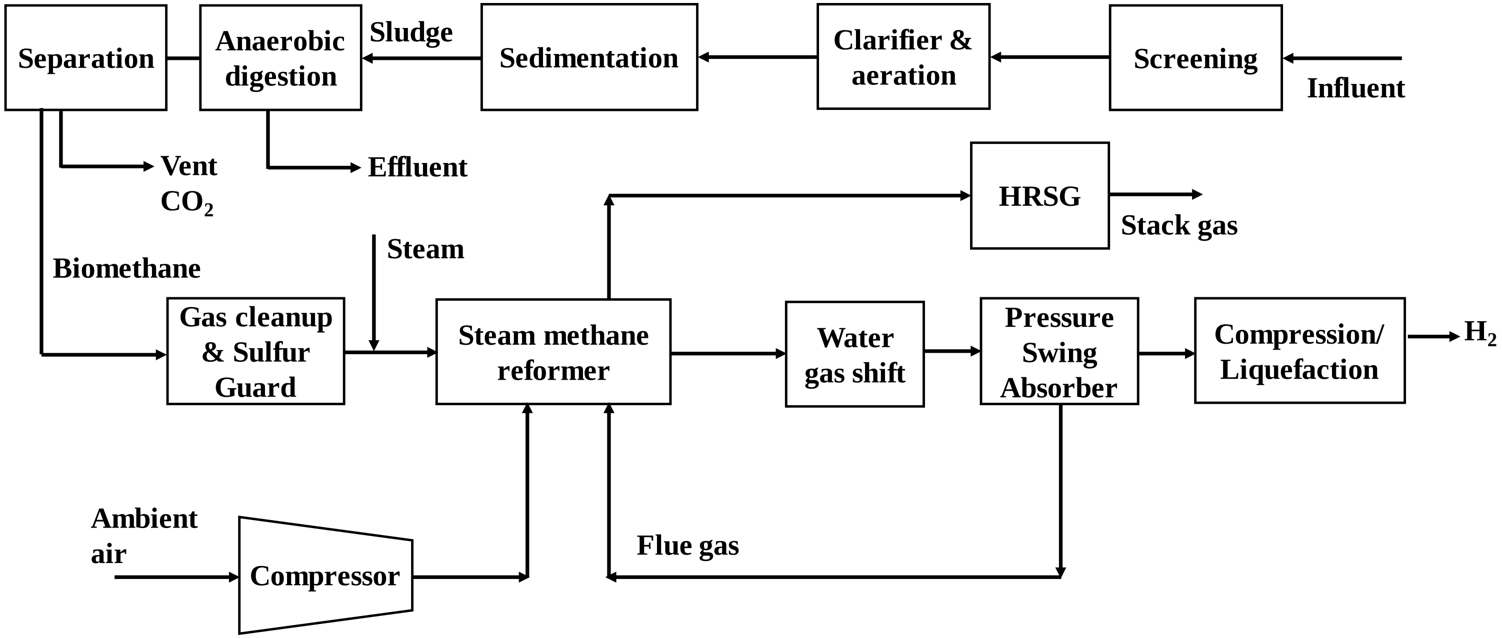
- North American natural gas feedstock
- Centralized and distributed pathways
- Gaseous hydrogen production with 72% thermal efficiency
- Reforming temperature: 800°C – 1,000°C
- Purified, compressed and/or liquefied as required



Hydrogen production via steam reforming of natural gas (HRSG: Heat Recovery Steam Generator)

Biogas reforming

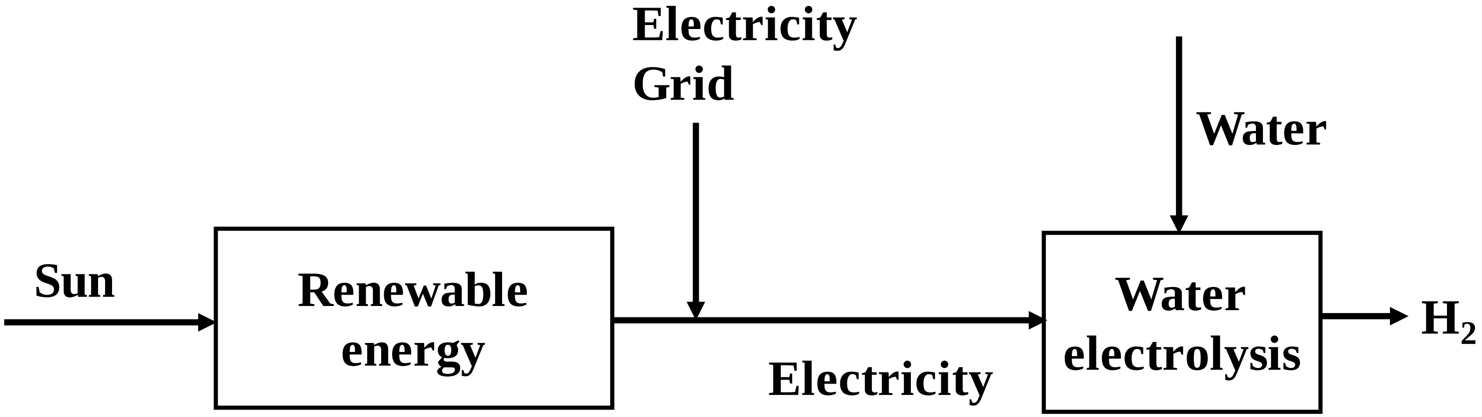
- Biogas source: WWTP or animal manure digester; landfill gas
- Biogas upgrading to methane followed by steam reforming
- Distributed pathway
- Hydrogen production from methane follows steam reforming pathway



Hydrogen production via steam reforming of biogas produced from a WWTP

Electrolysis based pathways

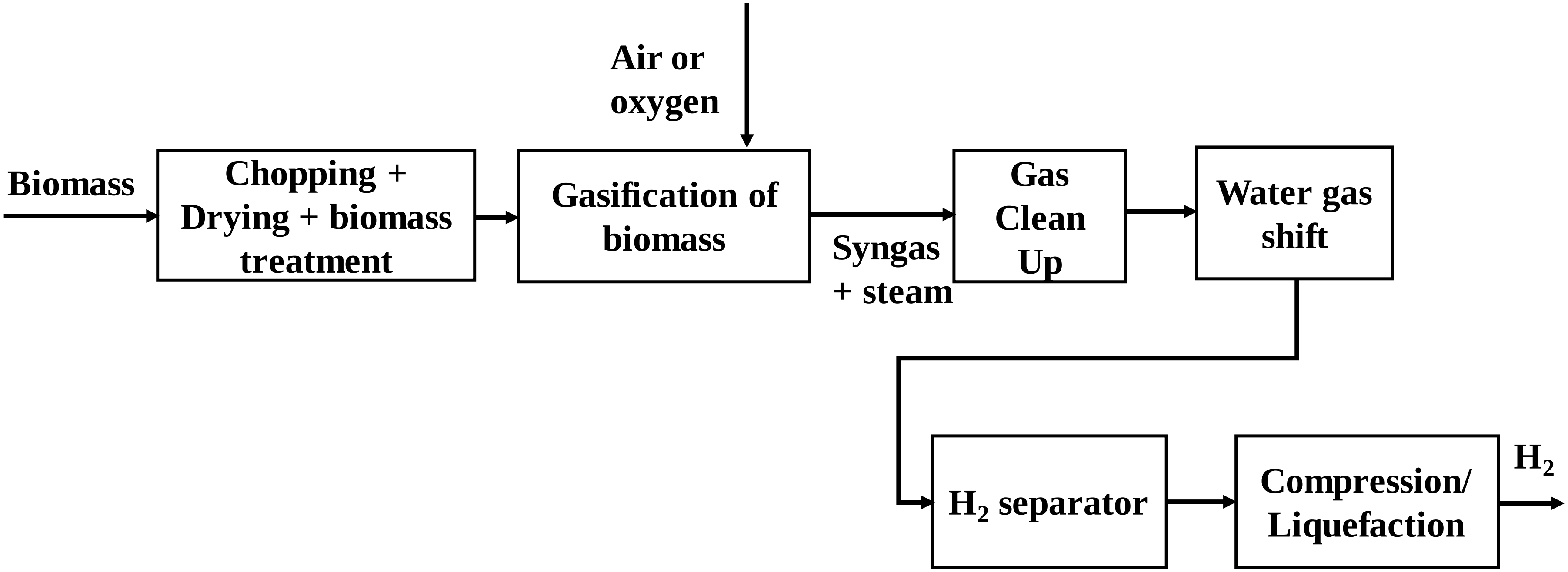
- Process thermal efficiency: 66.8%
- High purity water source
- Centralized or forecourt facilities
- Electricity from
  - CAMX grid mix – distributed pathway
  - Solar PV power – centralized pathway



Hydrogen production via water electrolysis using renewable power

Biomass gasification

- Process thermal efficiency: 57%
- Feedstock: biomass harvested from a 50 mile radius
- Partial oxidation gasification followed by syngas upgrading



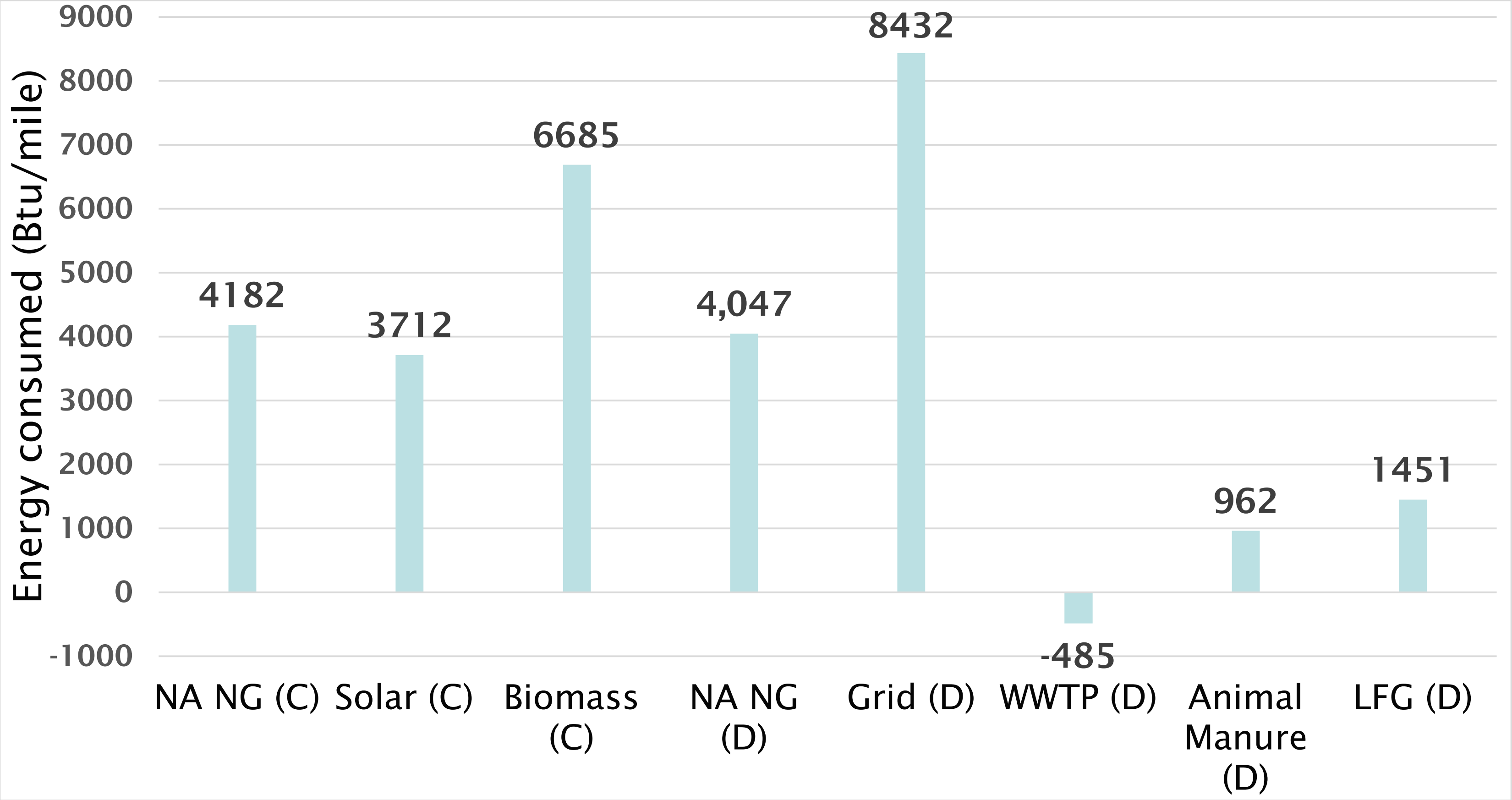
Hydrogen production via biomass gasification

Life Cycle Analysis - Assumptions

- CA-GREET Tier 2 model
- IPCC 2007 GWPs
- Analysis year: 2015
- Gaseous and liquid hydrogen production processes are considered
- Central or distributed pathways as stated
- CAMX grid mix
- CA Crude - regional crude oil use
- Final product hydrogen use: passenger car with 24.81 MPGGE
- NG transmission: Interstate pipeline: 1000 miles; Instate mile: 0 miles
- Electric Transmission and Distribution Loss: 6.5%
- Co-product credits: none; steam/electricity export credits: none

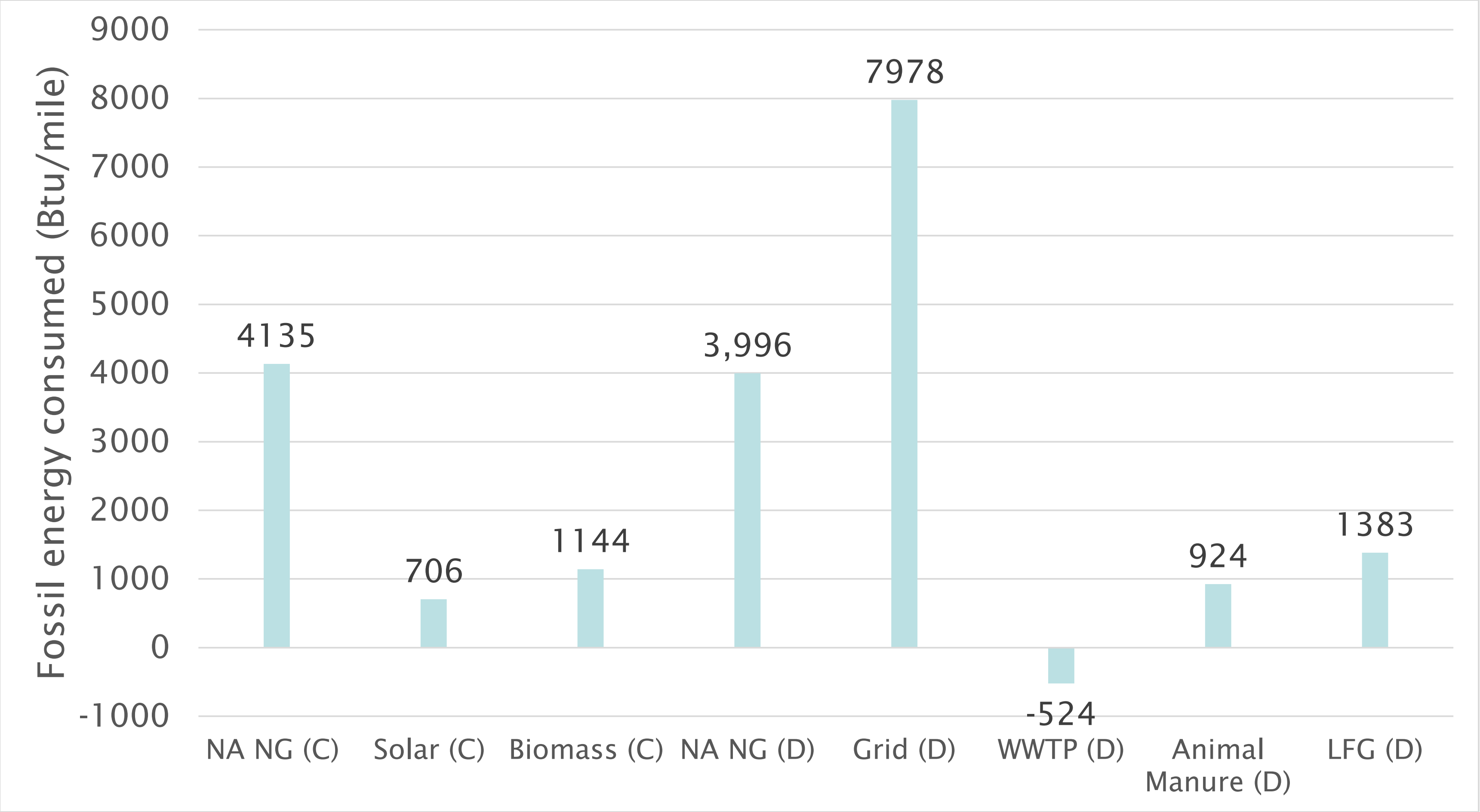
GHG Name	100 Year GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
Chlorofluorocarbons(CFC-12)	10,900
Hydrofluorocarbons (HFC-134a)	1,430

LCA results – total energy consumption for gaseous hydrogen production



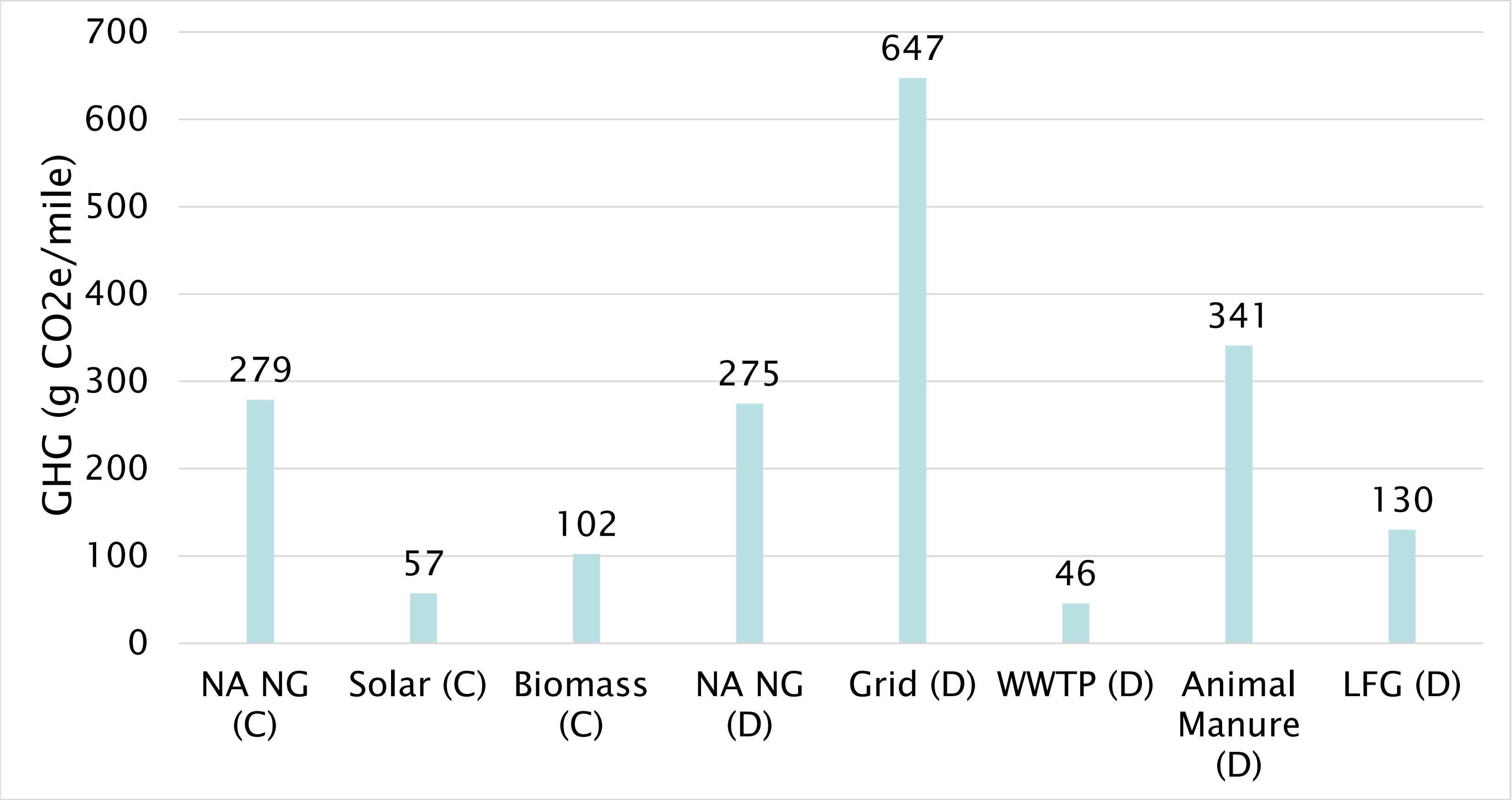
C - Centralized production pathway; D - Distributed production pathway

LCA results – fossil energy consumption for gaseous hydrogen production



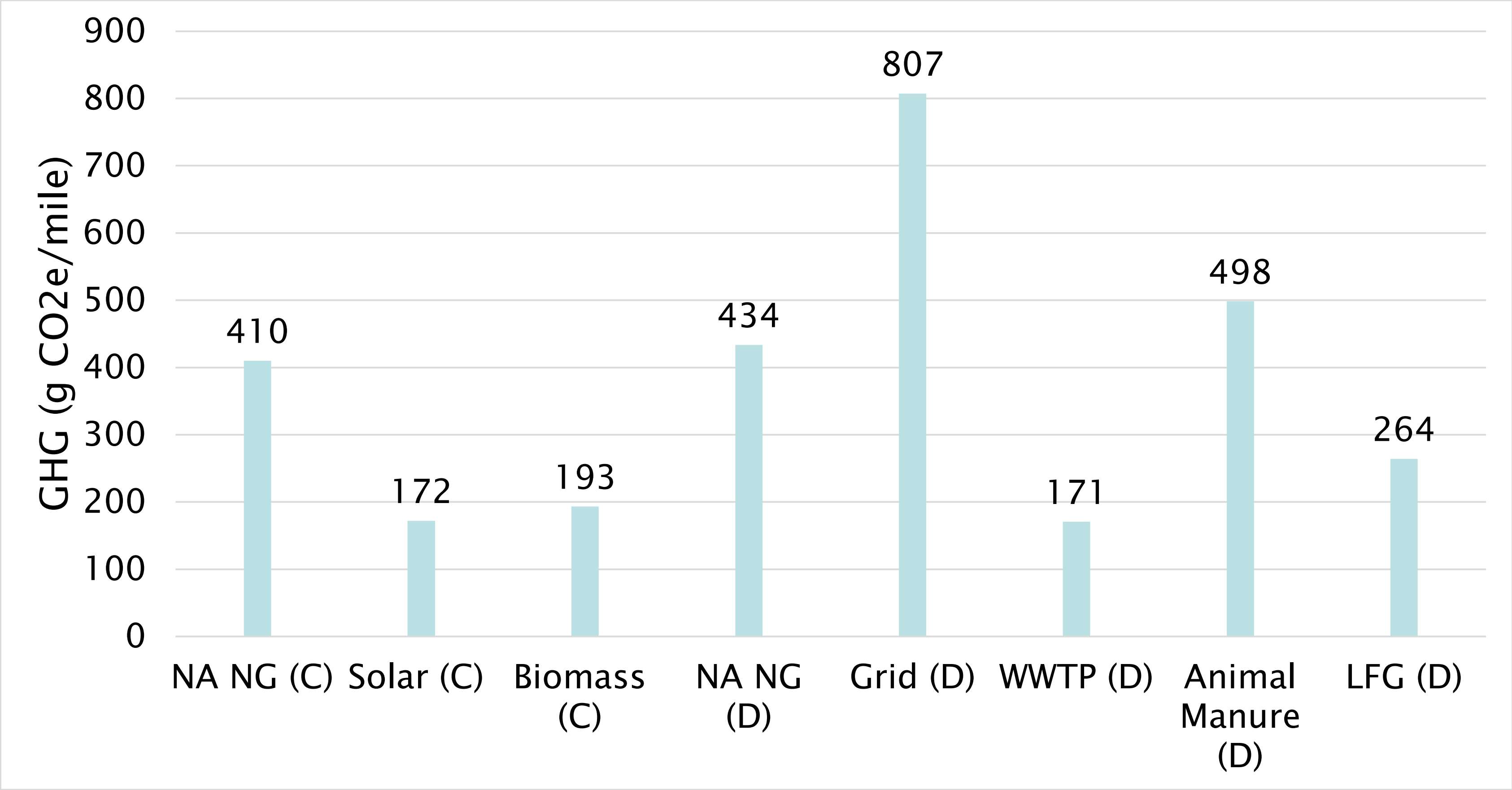
C - Centralized production pathway; D - Distributed production pathway

LCA results – GHG emissions for gaseous hydrogen production



C - Centralized production pathway; D - Distributed production pathway

LCA results – GHG emissions for liquid hydrogen production

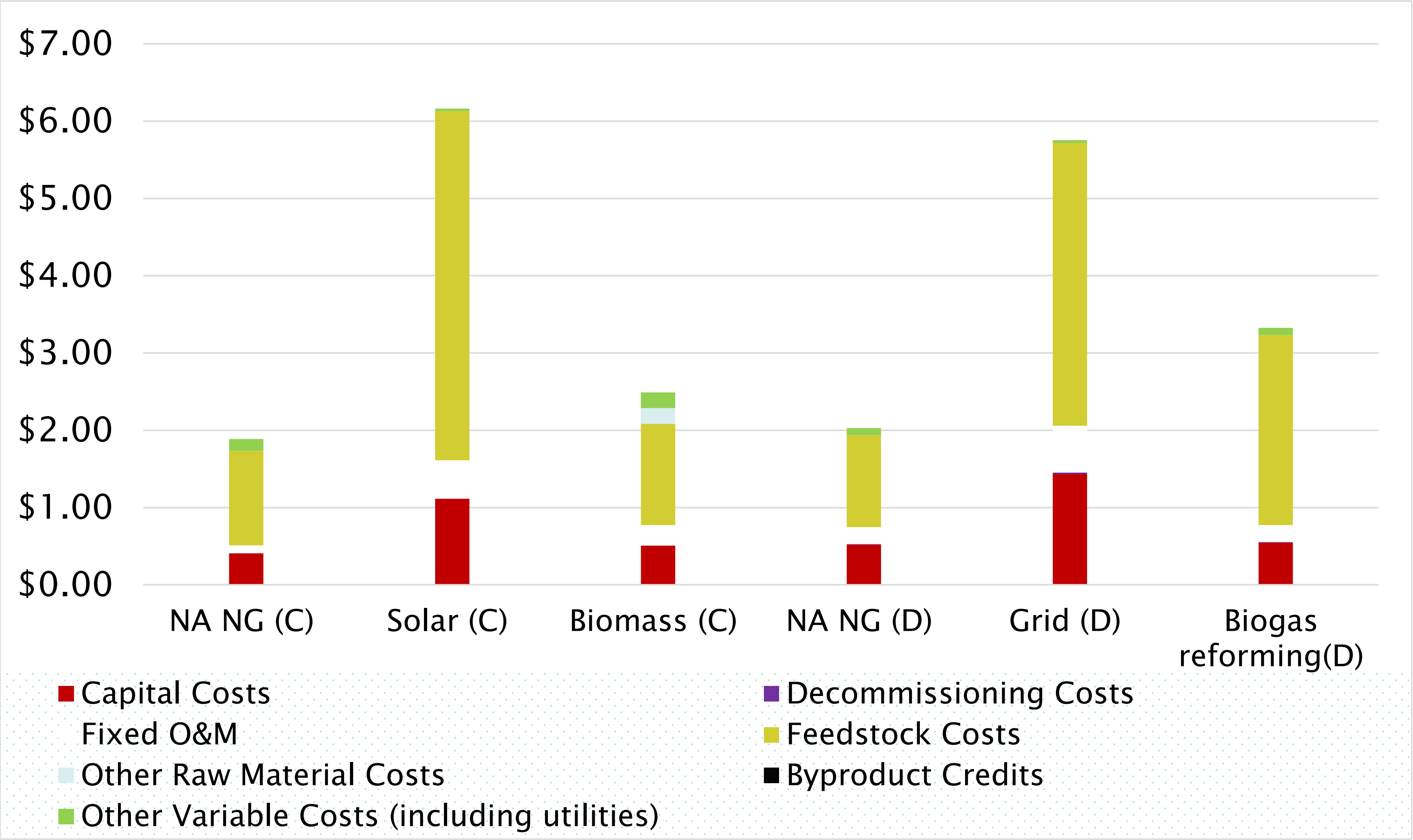


C - Centralized production pathway; D - Distributed production pathway

Economic analysis-assumptions

- H2A model (v3.1)
- Plant startup year: 2018
- Discounted Cash Flow (DCF) analysis
- Equity financing: 20%; debt: 80%; interest rate on debt: 6%
- Depreciation schedule length: 20 years
- Depreciation type: MACRS
- Decommissioning cost: 10 % of depreciable capital investment
- Salvage value: 10% of total capital investment
- Internal rate of return (IRR): 10%
- Inflation rate: 1.9%; total tax rate: 38.9%, sales tax not included
- Industrial electricity (US grid mix)
- Price Conversion Factor: 0.0036 GJ/kWh
- Price in Startup Year: 0.06714 $(2012)/kWh
- Industrial Natural gas
- Price Conversion Factor: 1.055 GJ/mmBtu
- Price in Startup Year: 7.65 $(2012)/mmBtu (EIA 2017)

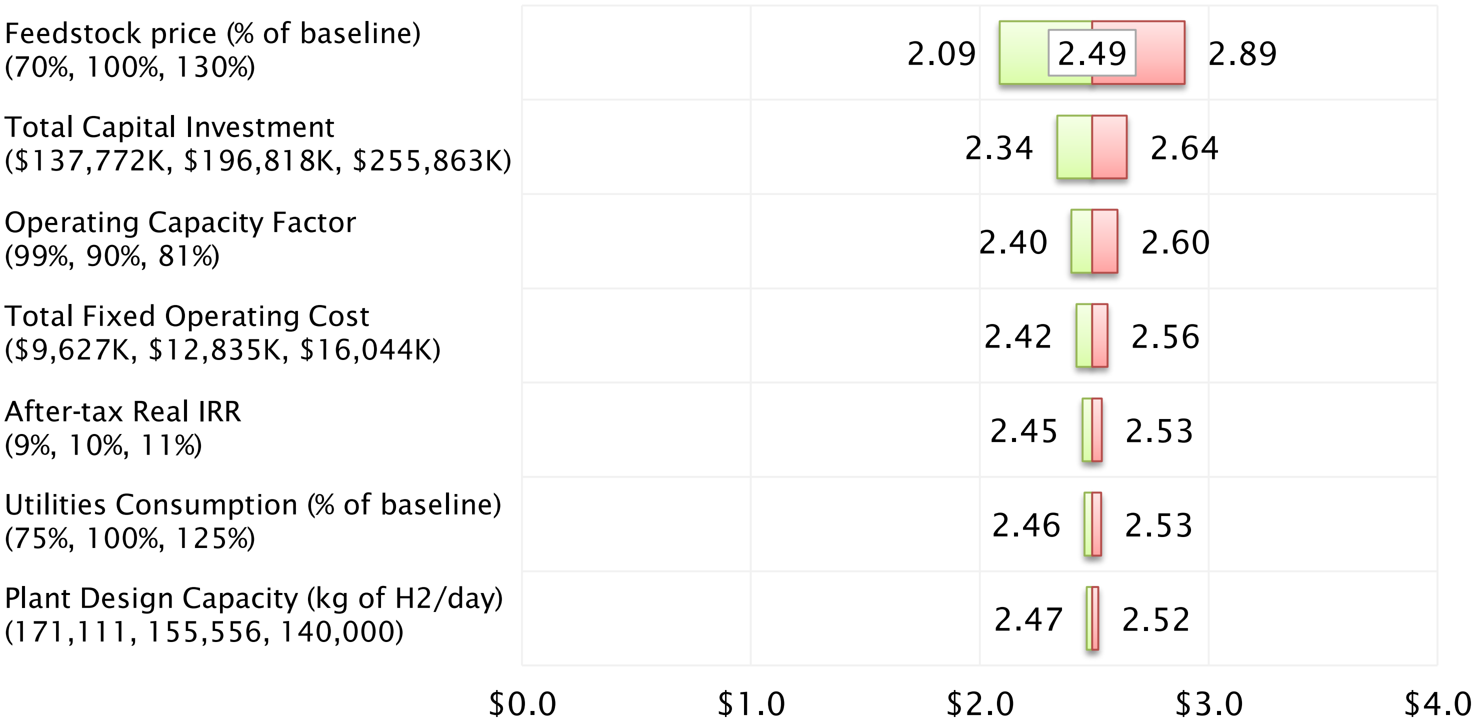
Economic analysis – gaseous hydrogen production cost



Real levelized production cost ($/kg H_2)

Sensitivity analysis – centralized natural gas reforming

Sensitivity analysis – centralized biomass gasification



Discussion – technology availability

- A range of technology options are under development for renewable hydrogen production
- Electrolytic and thermochemical conversion pathways are at the highest TRLs
- Market and regulatory environment will play a key role in commercial deployment
- Anticipated commercial availability -
  - Near Term: 5 years (by 2020)
    - Water electrolysis based hydrogen production (TRL 8)
    - Biogas reforming to hydrogen (TRL 8)
  - Mid Term: 10 years (by 2025)
    - Biomass gasification based hydrogen production (TRL 7)

Discussion – techno-economic assessment

- Life Cycle Analysis
- Biogas reforming pathway results in lowest GHG emissions
- Electrolysis using renewable power results in the lowest GHG emissions among centralized production pathways
- Total energy consumption is lowest for biogas reforming pathway
- All renewable pathways results in significantly reduced fossil energy consumption compared to baseline
- Economic Analysis
- Centralized biomass gasification offers most cost effective approach renewable hydrogen production
- Electrolysis based pathways result in high costs
- Feedstock costs are the largest contributor followed by capital expenses
- Centralized biomass gasification is most cost effective approach among renewable pathways

Discussion - recommendations

- Renewable pathways will be technologically feasible but commercial viability will likely be a challenge
- Targeted evaluation of most feasible commercialization approaches and regulatory support and incentives are necessary
- Focused analysis of specific technologies using data from demonstration projects or relevant commercial installations is necessary to assess RD&D and policy needs