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 solar 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

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

<table>
<thead>
<tr>
<th>Technology</th>
<th>TRL</th>
<th>Commercialization Timeframe</th>
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<tbody>
<tr>
<td>Water electrolysis</td>
<td>8</td>
<td>N</td>
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<tr>
<td>Biogas reforming</td>
<td>8</td>
<td>N</td>
</tr>
<tr>
<td>Biomass gasification</td>
<td>7</td>
<td>M</td>
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<tr>
<td>Bio-derived liquids reforming</td>
<td>4-5</td>
<td>M-L</td>
</tr>
<tr>
<td>Thermochemical water splitting</td>
<td>4-5</td>
<td>M-L</td>
</tr>
<tr>
<td>Photolytic conversion</td>
<td>1-3</td>
<td>L</td>
</tr>
<tr>
<td>Dark fermentation</td>
<td>1-3</td>
<td>L</td>
</tr>
</tbody>
</table>

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

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

Biomass → Chopping + Drying + biomass treatment → Gasification of biomass → Gas Clean Up → Water gas shift

Air or oxygen → Syngas + steam → H₂ separator

Compression/ Liquefaction → H₂
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

<table>
<thead>
<tr>
<th>GHG Name</th>
<th>100 Year GWP</th>
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<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>1</td>
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<tr>
<td>Methane (CH₄)</td>
<td>25</td>
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<tr>
<td>Nitrous Oxide (N₂O)</td>
<td>298</td>
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<tr>
<td>Chlorofluorocarbons(CFC-12)</td>
<td>10,900</td>
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<tr>
<td>Hydrofluorocarbons (HFC-134a)</td>
<td>1,430</td>
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</table>

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

- NA NG (C)
- Solar (C)
- Biomass (C)
- NA NG (D)
- Grid (D)
- WWTP (D)
- Animal Manure (D)
- LFG (D)

Fossil energy consumed (Btu/mile)

- 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

<table>
<thead>
<tr>
<th>Source</th>
<th>GHG (g CO2e/mile)</th>
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<tbody>
<tr>
<td>NA NG (C)</td>
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<tr>
<td>Solar (C)</td>
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<tr>
<td>Biomass (C)</td>
<td>193</td>
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<tr>
<td>NA NG (D)</td>
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<tr>
<td>Grid (D)</td>
<td>807</td>
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<tr>
<td>WWTP (D)</td>
<td>171</td>
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<tr>
<td>Animal Manure (D)</td>
<td>498</td>
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<tr>
<td>LFG (D)</td>
<td>264</td>
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</table>
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 H₂)
Sensitivity analysis – centralized natural gas reforming

Feedstock price (% of baseline) (70%, 100%, 130%)

Total Capital Investment ($275,468K, $393,525K, $511,583K)

Operating Capacity Factor (99%, 90%, 81%)

After-tax Real IRR (9%, 10%, 11%)

Total Fixed Operating Cost ($9,292K, $12,389K, $15,486K)

Plant Design Capacity (kg of H2/day) (416,900, 379,000, 341,100)

Utilities Consumption (% of baseline) (75%, 100%, 125%)
Sensitivity analysis – centralized biomass gasification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>2.09</th>
<th>2.49</th>
<th>2.89</th>
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<tbody>
<tr>
<td>Feedstock price (% of baseline)</td>
<td>(70%, 100%, 130%)</td>
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<tr>
<td>Total Capital Investment</td>
<td>($137,772K, $196,818K, $255,863K)</td>
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<tr>
<td>Operating Capacity Factor</td>
<td>(99%, 90%, 81%)</td>
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<tr>
<td>Total Fixed Operating Cost</td>
<td>($9,627K, $12,835K, $16,044K)</td>
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<td>After-tax Real IRR</td>
<td>(9%, 10%, 11%)</td>
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<tr>
<td>Utilities Consumption (% of baseline)</td>
<td>(75%, 100%, 125%)</td>
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<tr>
<td>Plant Design Capacity (kg of H2/day)</td>
<td>(171,111, 155,556, 140,000)</td>
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</tbody>
</table>

$0.0 $1.0 $2.0 $3.0 $4.0

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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 result in significantly reduced fossil energy consumption compared to baseline

- **Economic Analysis**
  - Centralized biomass gasification offers most cost effective approach for 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