Renewable Natural Gas from Biomass Gasification via Fluidized-Bed Methanation

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- The environment for the production of RNG in California
- Research to improve the technology for the production of RNG
- Economics of RNG commercialization

California Green House Gas Policy related to RNG

AB 32 The Global Warming Solutions Act of 2006

A comprehensive program to reduce greenhouse gas (GHG) emissions in California

Governor's executive order S-3-05 (6/2005)

- 2020 - reduce GHG emissions to 1990 levels (429 MMTCO2e/yr)
- 2050 - reduce GHG emissions to <80% 1990 levels (86 MMTCO2e/yr)

Governor's executive B-30-15 (4/2015) and SB 32 (9/2017)

- 2030 - reduce GHG emissions to <40 % 1990 levels (258 MMTCO2e/yr)

Governor's executive B-55-18 (9/2018)

- 2045 - state wide carbon neutrality (0 MMTCO2e/yr)

California Renewable Portfolio Standard (RPS)

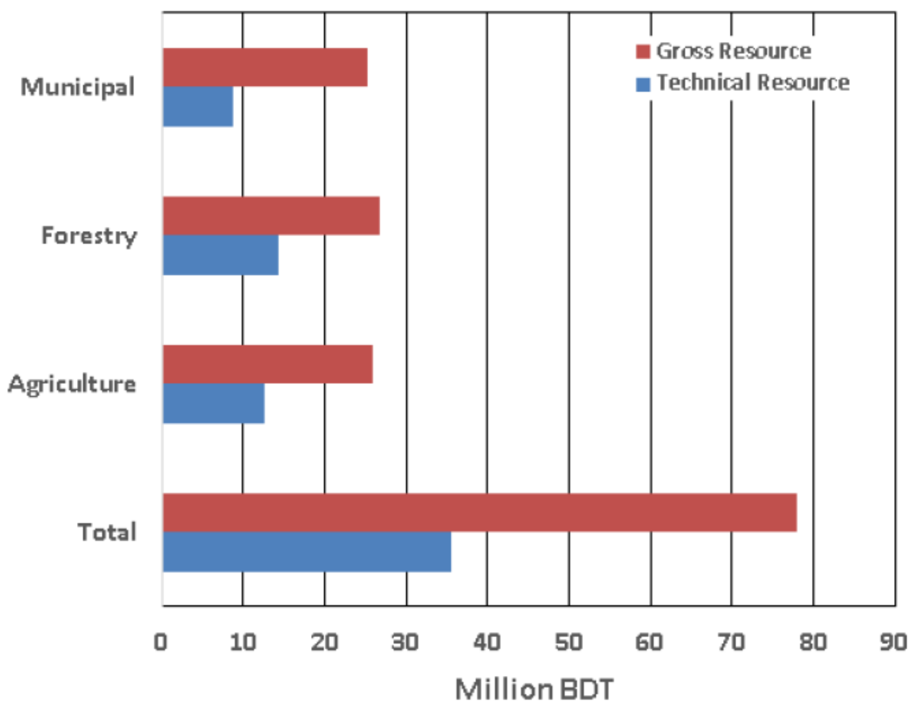
- 2020 - 33% renewable power
- 2030 - 50% renewable power
- 2045 - 100% renewable power – eliminates natural gas from power (44% in 2018)

California Low Carbon Fuel Standard (LCFS) (2010 Baseline Gasoline 95.61 gCO2e/MJ)

- 2020 - reduce Carbon Intensity 10% below 2010 level (86 gCO2e/MJ)
- 2030 - reduce Carbon Intensity 20% below 2010 level (76.5 gCO2e/MJ)

(Natural Gas 68 gCO2e/MJ)
(RNG 15 gCO2e/MJ)

Waste-stream Biomass Resources in California

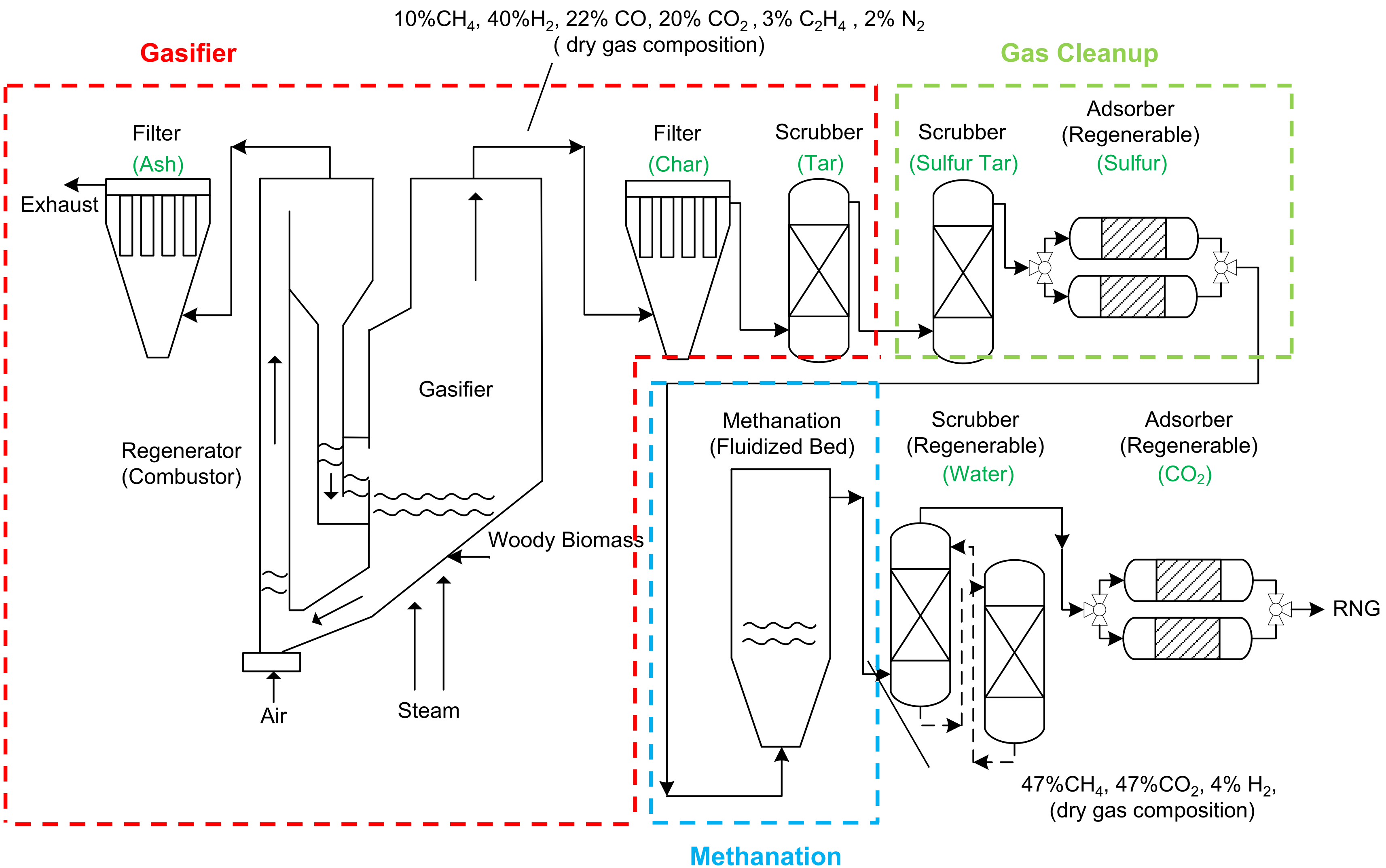


The difference between technical and gross resources arises from inaccessible or sensitive areas, losses from harvesting , and maintaining soil quality.

Source: Williams, R. B., B. M. Jenkins, and S. R. Kaffka (2015). An Assessment of Biomass Resources in California, 2013 Data. CEC PIER Contract 500-11-020, California Biomass Collaborative.

Gross annual biomass production in California and sustainable technical production. Total sustainable: 36 million BDT, 500 trillion BTUs, reduction of 26 MMT CO_2e.

Research on the Technology for the Production of RNG



- Dual-Fluidized Bed Gasifier (FICFB Design from TU Vienna/Güssing)
- Fluidized-bed material in Europe Olivine sand (Mg,Fe,SiO4) trace Ni and Cr contaminates ash – High attrition replaced weekly
- Fluidized bed material Woodland 400 micron dia. alumina ceramic.
- Indirectly heated, air-blown, ambient-pressure design.
- Low nitrogen producer-gas, acceptable tar levels.
- Good gas composition for chemical synthesis: 40% H_2, 10% CH_4, 22% CO, 20% CO_2, 3% C_2H_4, 2% N_2, and H_2/CO= 1.82
- Cold-gas efficiency > 70%

Woodland, CA
~1 MW_{fuel}
Ceramic bed material

Research
Pilot Plant

Burgeis, Italy
~2 MW_{fuel}

CHP

Gussing, Austria
~8 MW_{fuel}

CHP

Senden, Germany
~16 MW_{fuel}

CHP

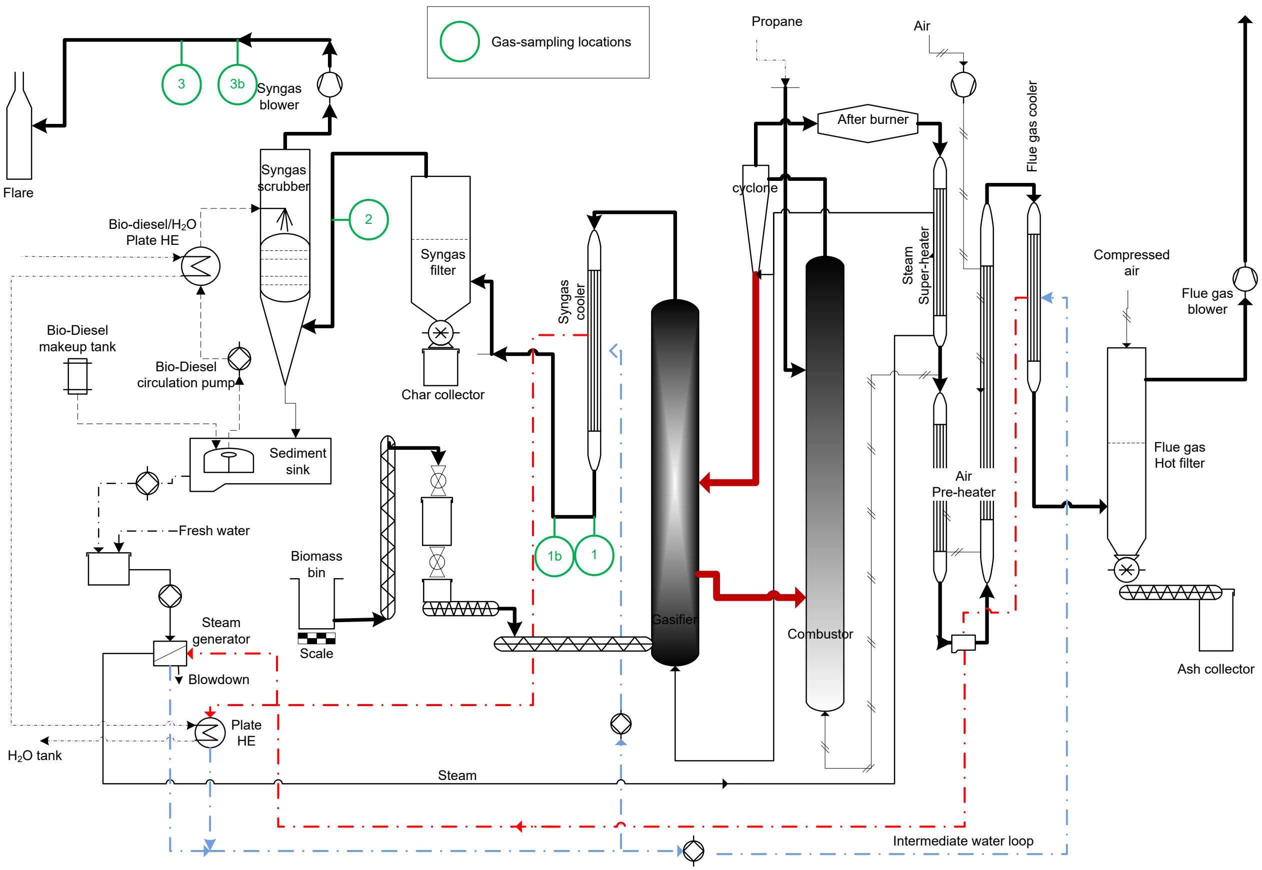
Gothenburg, Sweden
~32 MW_{fuel}

RNG

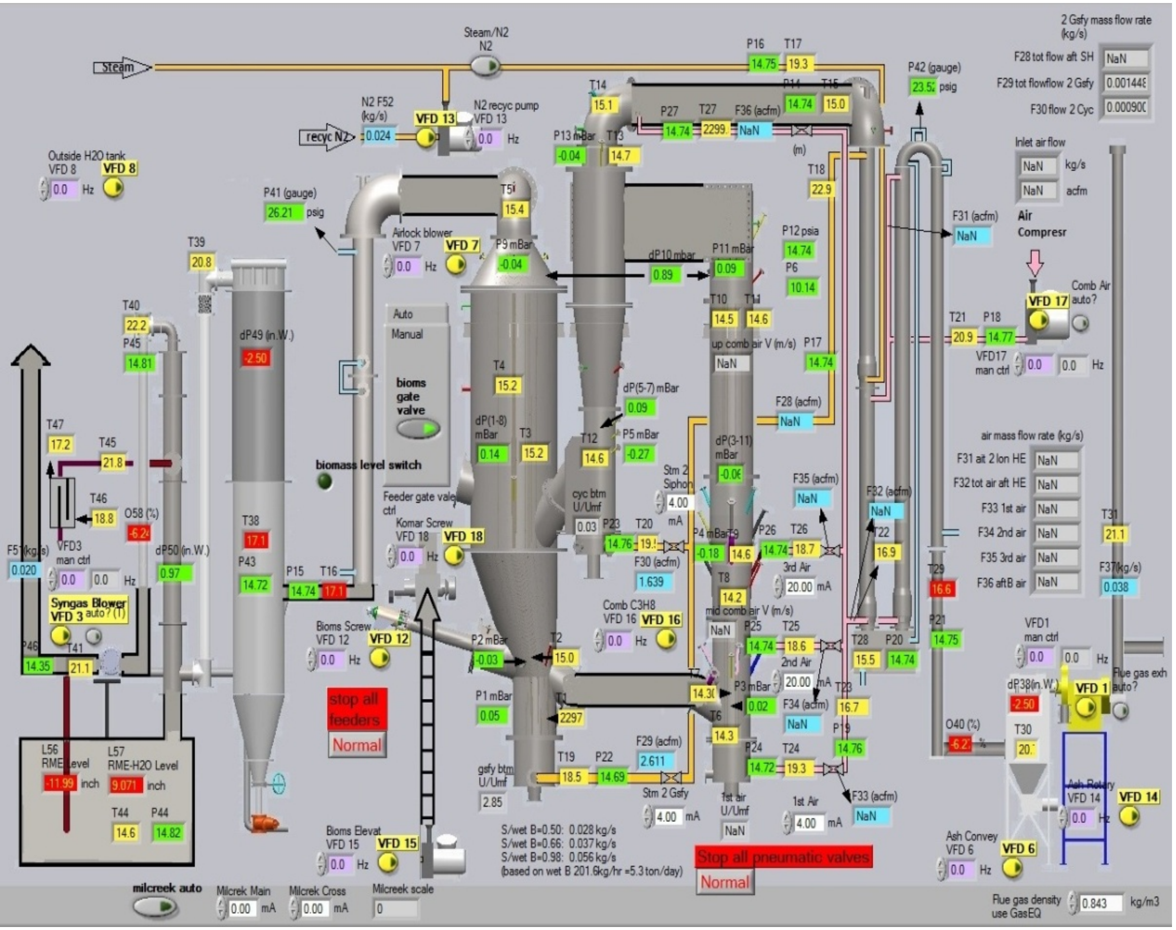
CHP…Combined Heat and Power, RNG…Renewable Natural Gas

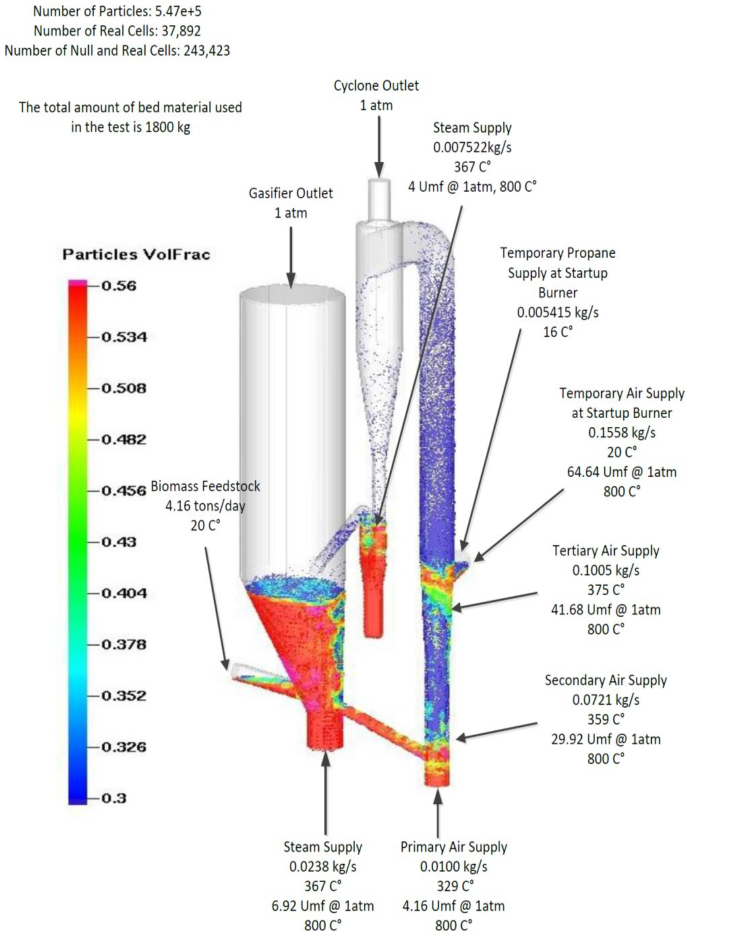
West Biofuels FICFB Pilot Plant 1MW$_{fuel}$, 6 tons/day

Uses heat recovery for steam generation



California Energy Commission Report: CEC-500-2016-035,"Demonstration of Advanced Biomass Combined Heat and Power Systems in the Agricultural Processing Sector," M.D. Summers, C. Liao, M. Hart, R. Cattolica, R. Seiser, and B. Jenkins, June 2015.





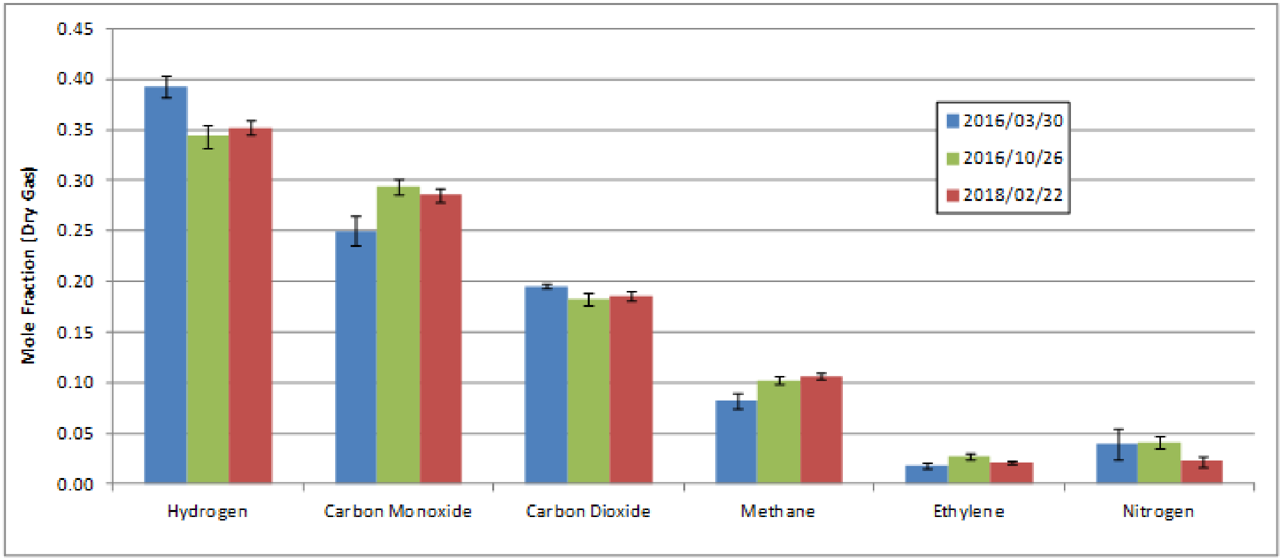
Integrated Biomass Gasification Plant with extensive distribution of sensors (52 temperature , 38 pressure, and 16 flow measurements)

Multiphase Particle-in-Cell Method (MP-PIC) Barracuda Code – CPFD software, LLC. *

*Hui Liu, Robert J. Cattolica, Reinhard Seiser, and Chang-hsien Liao, "Three-dimensional full-loop simulation of a dual fluidized-bed gasifier," Applied Energy, 160, 2015, 489-501.

Producer Gas Composition – Woodland Research Pilot Plant

- GC measurement of gas composition.

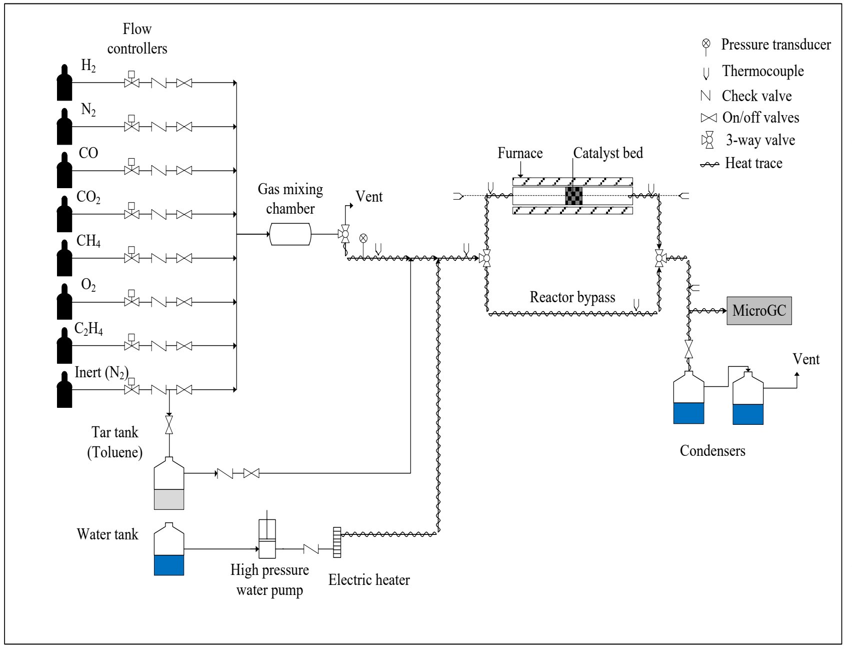


- Tar content from European tar protocol

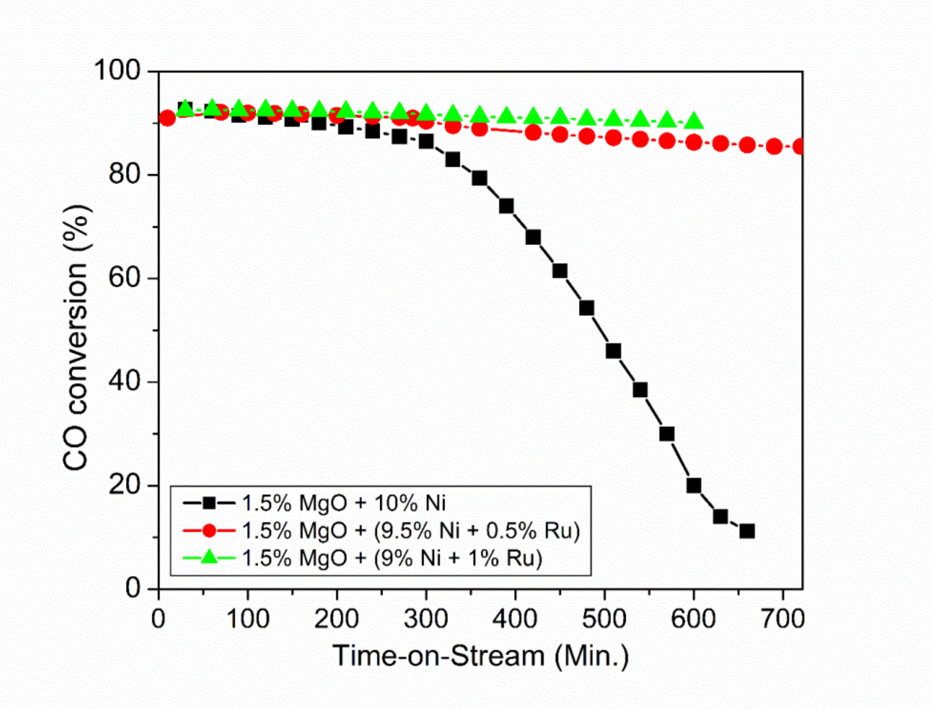
Biodiesel Scrubber (RME) - before 11.8 g/Nm^3
after 0.33 g/Nm^3

Methanation Catalyst Development

- Standard Ni-Mg methanation catalyst requires H_2/CO =3 for stable performance in fixed bed.
- Fluidized-bed methanation can operate at lower H_2/CO ratios due to catalyst circulation.
- Fixed-bed flow reactor study of Ni-Mg-Ru methanation catalyst at H_2/CO = 1.82
- Catalyst support – CoorsTek AD90 : ~200 micron Alumina, ~4 m^2/g



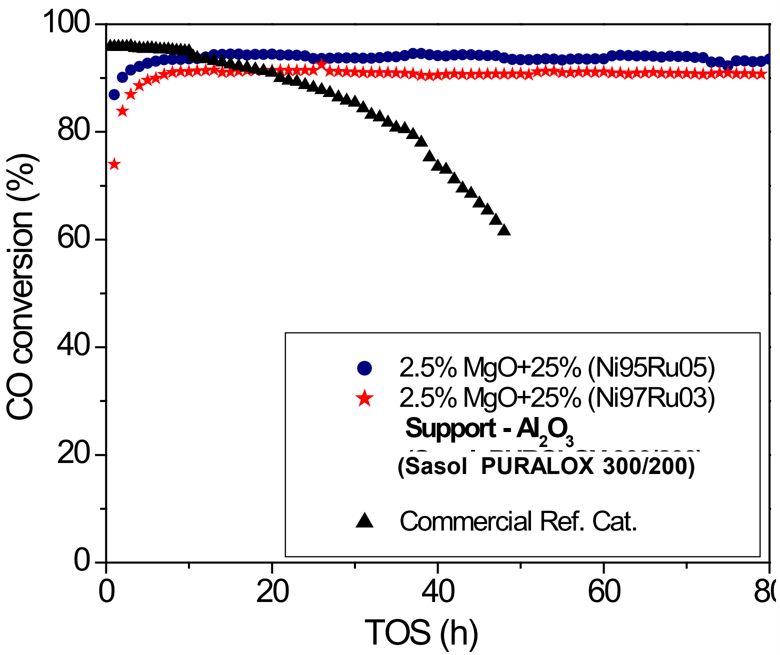
Fixed-bed flow reactor for catalyst development



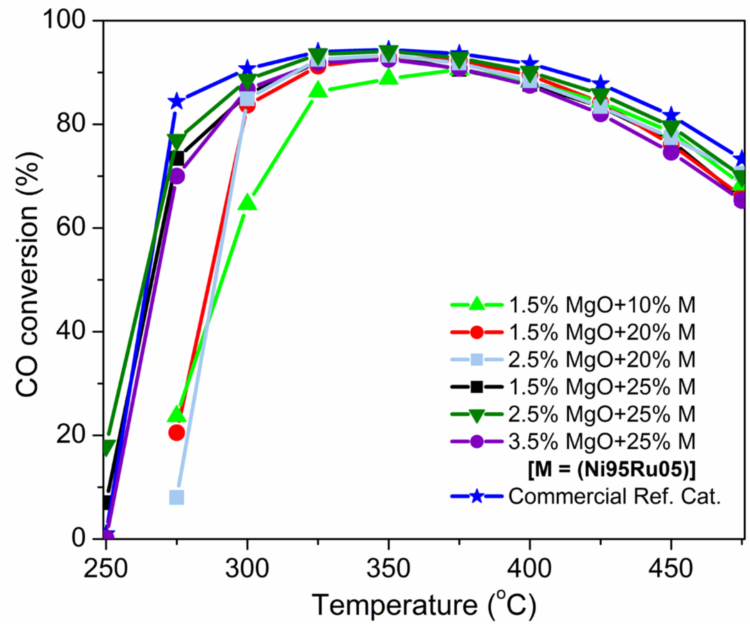
Time-on-Stream for methanation activity with 40% H_2 22% CO, 38% N_2 gas mixture with Ni-Mg and Ni-Mg-Ru catalysts at 425 °C ; GHSV - 96000 cc g_{cat}^{-1} h^{-1}

Methanation Catalyst Development

- New Ni-Mg-Ru catalyst developed at UCSD prevents deactivation at low ratio H_2/CO= 1.82
- Catalyst support - Sasol PURALOX : ~300 micron Alumina, >100 m^2/g
- High surface area catalyst support allows for increase catalyst loading and resulting increase in activity at a lower operating temperature.
- Time on stream catalyst performance at 325 C and 1 atm on producer gas (40% H_2, 8% CH_4, 22% CO, 22% CO_2, 8% N_2)

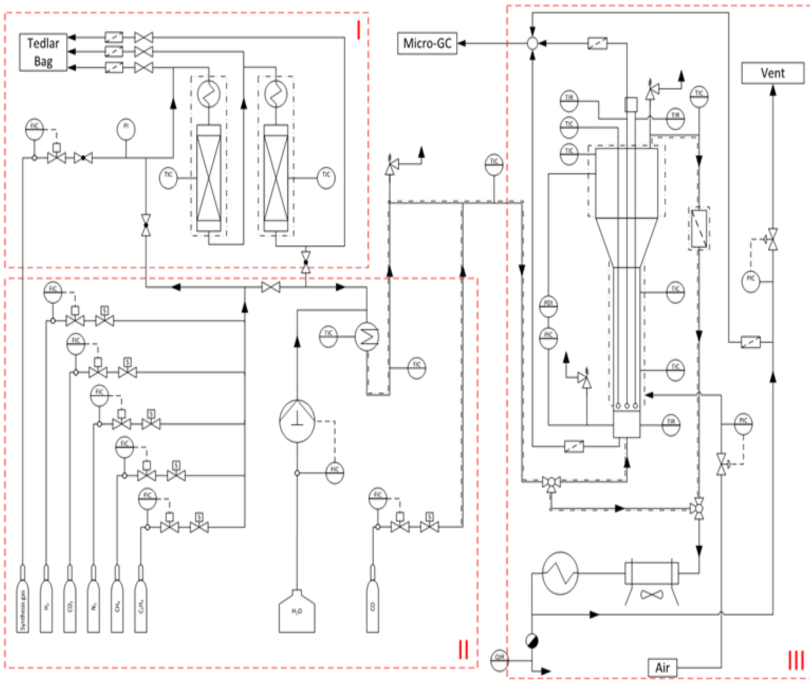


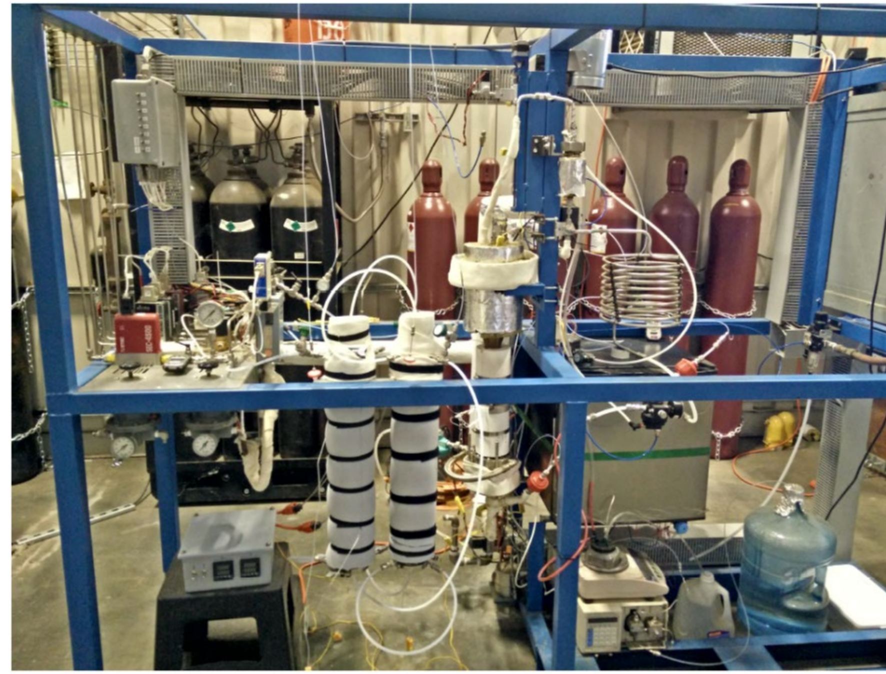
Time-on-Stream for CO conversion activity with producer gas for Ni-Mg-Ru catalysts and ref. catalyst at 325 C ; GHSV – 96000 cc g^{-1} h^{-1}



CO conversion in producer gas with Ni-Mg-Ru catalyst on Al_2O_3 (SASOL PURALOX 300/200) and ref. catalyst from 250 to 475°C; GHSV = 96,000 cc $h^{-1}g^{-1}$

Fluidized-Bed Methanation Experiment for Evaluating Sulfur Removal and Catalysts



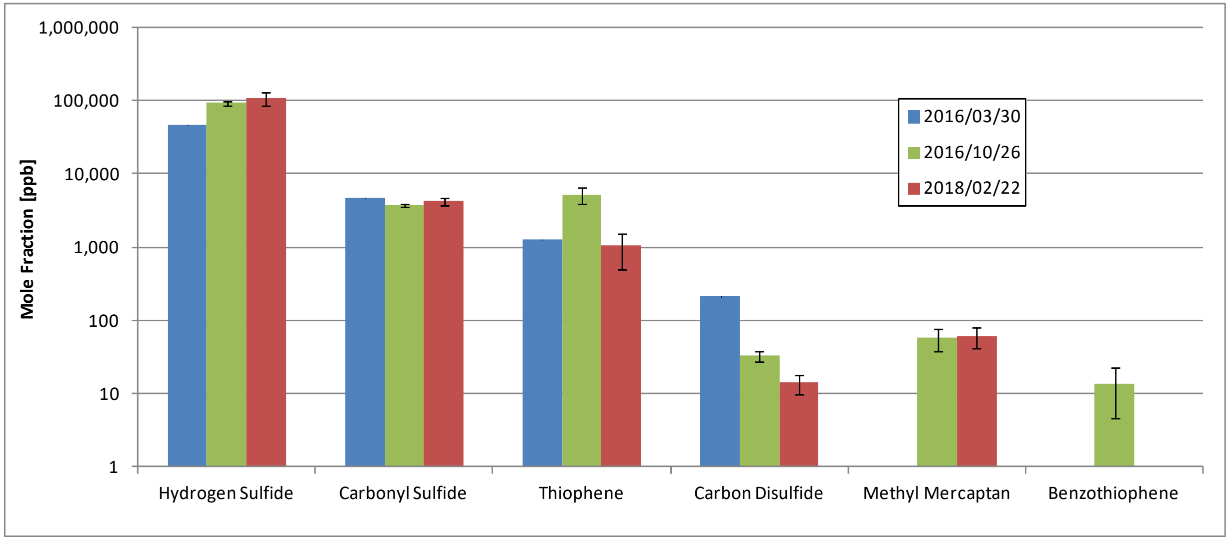


I sulfur adsorbent , II gas source, III Fluidized-bed methanation reactor.

- Composition profiles throughout the fluidized bed
- Operational parameters studies on: U/U_{mf}, H_2/CO ratio, steam addition, temperature, and pressure
- Catalyst stability, activity, and regeneration
- Sulfur removal with adsorbents in one or two stages before methanation.

Sulfur Compounds in Gasifier Operation

- Sulfur compounds after biodiesel (RME) scrubber



- Sulfur Clean Up

Sulfur removal using solid adsorbents*

- Evaluated 7 adsorbents.
- Tested for adsorption of sulfur compounds. Principally carbonyl sulfide (COS) and thiophene in the presence of benzene.

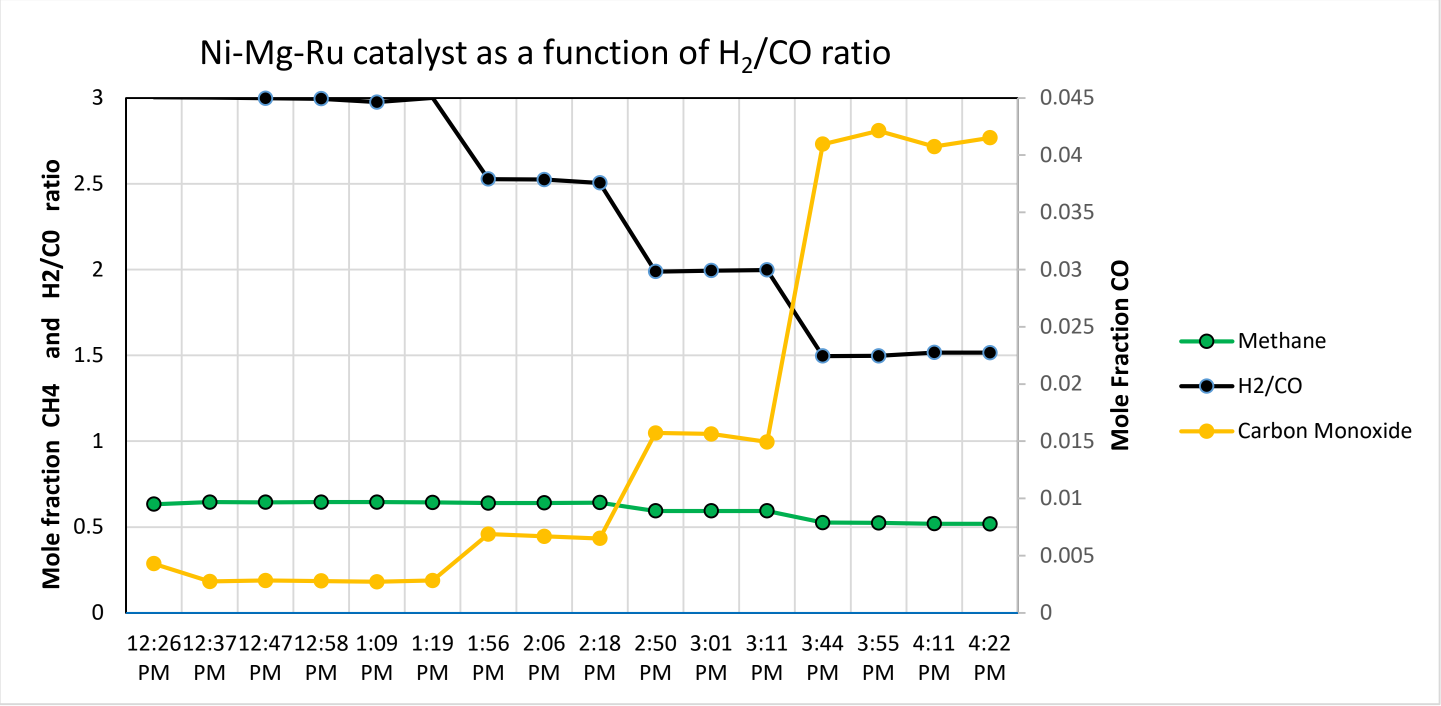
*California Energy Commission Report: "Renewable Natural Gas Production from Woody Biomass via Gasification and Fluidized-Bed Methanation,"UC San Diego, R. Seiser, R. Cattolica, and M. Long, April 2019.

Catalyst Performance in Fluidized-Bed Methanation

- Fixed-Bed methanation catalyst requires $H_2/CO = 3$ (H_2=75% CO = 25%)
- Fluidized-bed methanation with Ni-Mg-Ru catalyst is stable at $H_2/CO = 1.5$ (H_2=60% CO = 40%)

Fluidized-Bed Reactor Methanation Experiments with H_2 and CO using Ni-Mg-Ru (9.5%,1.5%,0.5%)

- Catalyst support: CoorsTek AD90, alumina, ~200 micron, ~4 m^2/g
- Experiments conducted at a temperature of 380 C, 1.3 atm, U/U_{mf}= 4



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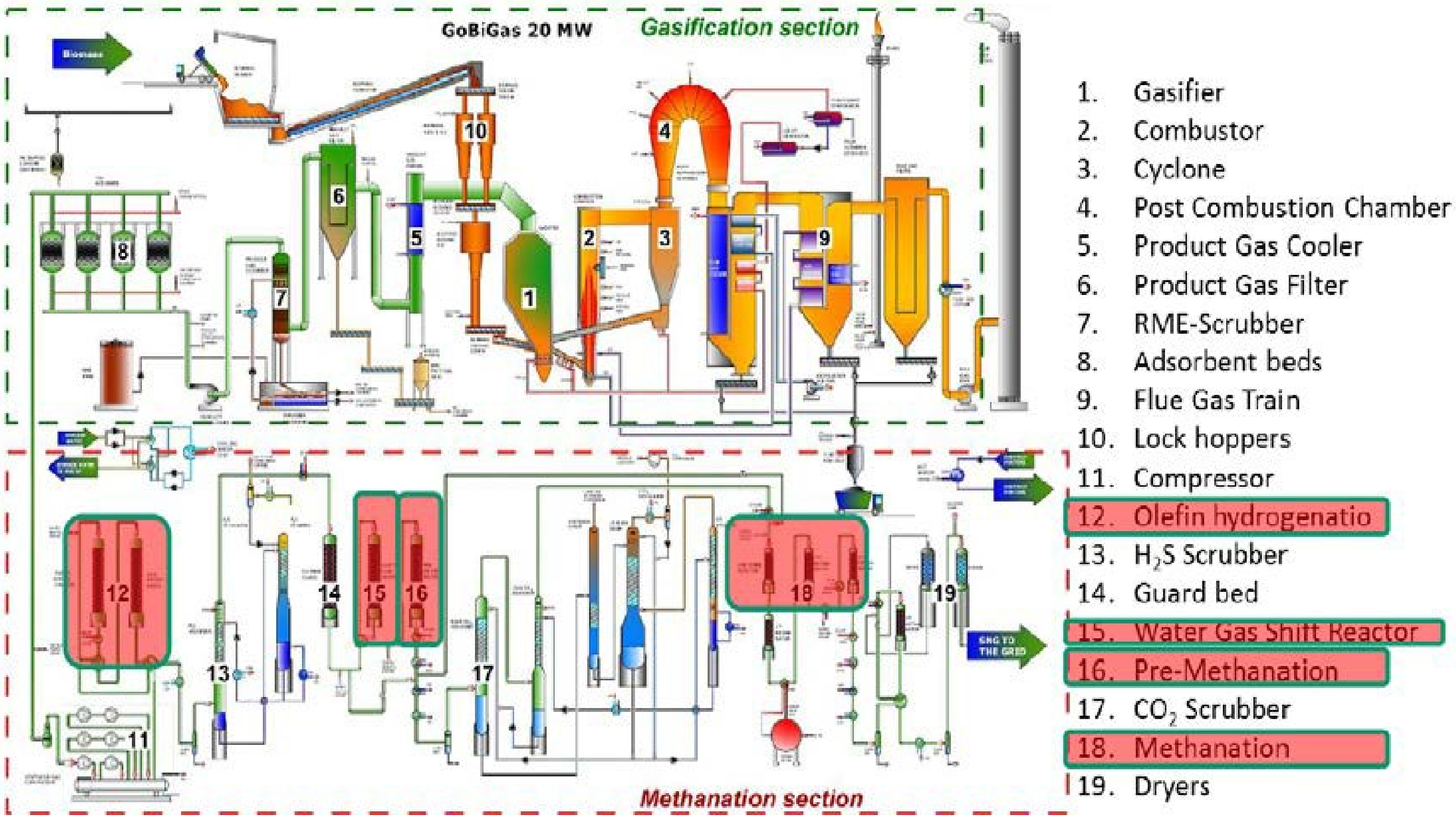
GoBiGas plant (32 MW_{fuel}/20MW_{RNG}/160 tons biomass/day), Gothenberg, Sweden



Fluidized-bed methanation eliminates three processes steps: Olefin hydrogenation (12), Water Gas Shift (15), Pre-methanation (16) and reduces Methanation reaactor (18) from 3 to 1.

Economics of RNG Production

($100\ MW_{th}/60\ MW_{RNG}/\ 500$ MT/day)

RNG Production Cost*

Capital Cost	$166 M
Debt	60%
Debt Interest	4%
Equity	40%
ROI Equity	10%
Lifetime	20
Levelized Cost RNG	$26.42

RNG Revenue in Transportation Market (fossil fuel replacement)

	Average 2018	August 2019
Henry Hub Natural Gas ($/mmBTU) ($/gal gasoline equivalent)	**$3.17** $0.36	**$2.22** $0.26
California LCFS ($/MT CO2e) For RNG ($/mmBTU)	$155 **$13.08**	$190 **$16.04**
Federal D3 RINS ($/gal Ethanol) For RNG ($/mmBTU)	$2.34 **$27.43**	$0.70 **$8.21**
Total RNG Revenue ($/mmBTU)	**$43.68**	**$26.47**

*Black & Veatch study in California Energy Commission Report:
"Renewable Natural Gas Production from Woody Biomass via Gasification and Fluidized-Bed Methanation," UC San Diego, R. Seiser, R. Cattolica, and M. Long, April 2019.

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