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Renewable Natural Gas Research Center Project

October 2019

A Research Report from the National Center for Sustainable Transportation

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National Center for Sustainable Transportation

UCR | College of Engineering- Center for Environmental Research & Technology

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16. Abstract

Renewable Natural Gas (RNG) is an important alternative fuel that can help the State of California meet several greenhouse gas (GHG) reduction and renewable energy targets. Despite considerable potential, current RNG use on national and state levels are not significant. RNG production potential in California through thermochemical conversion was evaluated as part of this project by assessing technical biomass availability in the state. Biomass feedstocks are defined broadly and include most carbonaceous matter including waste. The types of waste biomass available in the state are classified into three categories: municipal solid waste (MSW), agricultural residue and forest residue. A total of 32.1 million metric tonnes per year (MMT/year) of biomass is estimated to be technically available in the state. The energy content of this biomass is equivalent to approximately 602.4 million mmbtu/year. A survey of current renewable electricity generation and curtailment trends in California was conducted. Real-time data show significant curtailment throughout the year totaling more than 1,300 GWh from 2016 to early 2019. Power to gas and other forms of long-term storage integrated into the electric grid can mitigate these losses and enable smooth integration of additional renewables into the grid. Oxygen/air blown gasification, hydrogasification and pyrolysis are the three major technology options available for thermochemical biomass conversion to a gaseous fuel, including RNG. Although there are no commercial thermochemical biomass to RNG conversion facilities in operation, a number of gasification and pyrolysis technologies are undergoing pilot scale demonstration and development. Design basis for two thermochemical and power to gas conversion projects were developed as part of this project. Life cycle and economic analysis were conducted for the recommended processes.

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Renewable Natural Gas Research Center Project

A National Center for Sustainable Transportation Research report

October 2019

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EXECUTIVE SUMMARY

Renewable Natural Gas (RNG) is an important alternative fuel that can help the State of California meet several greenhouse gas (GHG) reduction and renewable energy targets. Despite considerable potential, current RNG use on national and state levels are not significant. As part of this grant, the University of California, Riverside (UCR) has established a research center dedicated to the development of technologies that will enable RNG production and use in substantial quantities in California and elsewhere. The new center, referred to as the Center for Renewable Natural Gas (CRNG), leverages on-going research and collaborations at the Bourns College of Engineering – Center for Environmental Research & Technology (CE-CERT) at UCR to maximize the impact.

RNG production potential in California through thermochemical conversion was evaluated as part of this project by assessing technical biomass availability in the state. Biomass feedstocks are defined broadly and include most carbonaceous matter including waste. The types of waste biomass available in the state are classified into three categories: municipal solid waste (MSW), agricultural residue and forest residue. A total of 32.1 million metric tonnes per year (MMT/year) of biomass is estimated to be technically available in the state. The energy content of this biomass is equivalent to approximately 602.4 million mmbtu/year. A survey of current renewable electricity generation and curtailment trends in California was conducted. Real-time data show significant curtailment throughout the year totaling more than 1,300 GWh from 2016 to early 2019. Power to gas and other forms of long-term storage integrated into the electric grid can mitigate these losses and enable smooth integration of additional renewables into the grid.

Oxygen/air blown gasification, hydrogasification and pyrolysis are the three major technology options available for thermochemical biomass conversion to a gaseous fuel, including RNG. A literature survey of available thermochemical conversion technologies was conducted. Although there are no commercial thermochemical biomass to RNG conversion facilities in operation, a number of gasification and pyrolysis technologies are undergoing pilot scale demonstration and development. Design basis for two thermochemical and power to gas conversion projects were developed as part of this project. Life cycle and economic analysis were conducted for the recommended processes. Significant research, development, and deployment efforts are necessary to achieve successful commercialization of thermochemical RNG production. Outreach and education activities including a ribbon cutting ceremony for the Center for Renewable Natural Gas and an RNG themed symposium were also conducted as part of the project.

Introduction

Background

Renewable Natural Gas (RNG) is pipeline quality gas that is fully interchangeable with fossil natural gas but is produced from a renewable feedstock and can be used as a 100% substitute for, or blended with, conventional natural gas. RNG is an important alternative fuel that can help the State of California meet several GHG and renewable energy targets. As a transportation fuel, RNG can result in approximately 90% reduction in GHG emissions.

Despite considerable potential, current RNG use on national and state levels are not significant. A concerted effort by all the stakeholders is needed to fully realize the potential of RNG. As part of this grant, the University of California, Riverside (UCR) has established a research center dedicated to the development of technologies that will enable RNG production and use in substantial quantities in California and elsewhere. The new center, referred to as the Center for Renewable Natural Gas (CRNG), leverages on-going research and collaborations at the Bourns College of Engineering – Center for Environmental Research & Technology (CE-CERT) at UCR to maximize the impact.

The report evaluates RNG production potential in California and includes a survey of thermochemical conversion technologies available for RNG production. Outreach and education activities including a ribbon cutting ceremony for the Center for Renewable Natural Gas and an RNG themed symposium were also conducted as part of the project.

Renewable Natural Gas Potential Evaluation

Biomass Resources

Biomass resources are primarily products of natural systems. However, within the energy resource assessment context, biomass is defined broadly and includes most carbonaceous matter including waste. The types of "waste" biomass available in the state are classified into five categories: agricultural residue, food and fiber processing, animal manure, forest residue and municipality solid waste (MSW). These resources do not include energy crops. Of these five categories, food waste and animal manure are converted into biogas through anaerobic digestion in many cases. Due to feedstock availability, conversion efficiencies and other factors, anaerobic digestion is the preferred pathway for these resources and it is assumed that these resources are unavailable for thermochemical conversion. Currently, biomass is primarily used for electricity generation in California with at least 30 generation facilities in operation [1–3]. From the renewable natural gas (RNG) perspective, biomass presents a significant opportunity to convert localized, distributed resources into a very low carbon intensity fuel.

A number of California biomass availability assessments are available in the literature with a range of estimates based on the assumptions and the types of feedstocks included [4]. Biomass units used in calculations in this report are bone dry tons (BDT). Other units such as metric tonnes or short tons are used where literature data does not specify feedstock details such as the moisture content.

Jenkins et al., conducted a study assessing the potential of biomass utilization to meet the national bioenergy targets and estimated that the state produces roughly 30 million tons per year of biomass [5]. These resources are equivalent to more than 2 billion gasoline gallon equivalents (GGE) of energy. A study conducted by Milbrandt et al., for the National Renewable Energy Laboratory (NREL) estimated the net amount of biomass resource available in U.S.. To be 423 million metric tonnes per year (MMT/year) and in California to be 13.4 MMT/year [6–8]. Other reports estimate the range to be 35-40 million bone dry tonnes per year (MMBDT/year) of technical biomass availability in the state [9–12].

A 2014 report by the Bioenergy Association of California reported that the state has the potential to generate about 284 billion cubic feet (bcf) of renewable methane from organic waste [13]. This is equivalent to approximately 2.2 billion gasoline gallon equivalent (gge) of transportation fuels and can account for more than 10% of California's total natural gas consumption. Krich et al., estimated that the state has the potential to produce 23 bcf of methane per year from biodegradable sources, and the feedstock from dairies can alone produce 14.6 bcf per year [14]. A 2016 study by Parker et al., estimated a gross RNG potential of 90 bcf per year from anaerobic digestion of wet feedstocks and landfill gas upgrading. Description of the biomass resources potentially available in the year of 2000 for energy production in the state of California is given below.

Methodology

This section addresses the potential feedstock available in the state of California. Much of the information required to construct the biomass availability assessment in California was obtained from publications by California Energy Commission (CEC), California Integrated Waste Management Board (CIWMB) and the California Biomass Collaborative (CBC). The assessment includes estimates of the total biomass generated in California and also the technical values of the amount that can be effectively be utilized for fuel purposes. The gross amount of available biomass is calculated based on biomass source population and a source specific production factor.

Agricultural residue: Agricultural residues make up approximately 20.6 million dry tons of the total biomass available in California. However, only 8.6 million tons can be effectively used for energy purposes. The components of agricultural residues include sources from animal manure, orchard and vine, field and seed, vegetable, and food processing. The top contributor of agriculture residues is animal residues obtained from beef cattle, dairy cows, and poultry farms with a technical value of 3.5 million tons that can be used annually. Following animal manure is field and seeds at 2.1 million dry tons, orchard and vine at 1.7 million dry tons, food processing at 1.2 million dry tons and vegetables at 1.6 million dry tons per year. The planted area of orchard and vineyard, field and seed, and vegetable crops in 2013 was about 9.4 million acres [5]. Fresno, Kern and Tulare counties are the main areas for orchard and vine crops. Yield factor data for different types of biomass ware obtained from report published by Knutson and Miller [15] and by the California Energy Commission [5]. The food processing values refer to wastes from the food industry that include but not limited to: nut shells, fruit pits, rice hulls, cotton gin trash, meat processing residues, grape and tomato pomace, cheese whey and beverage waste.

Forest residue: Mill wastes from commercial logging and lumber manufacturing around forest areas are an important source of biomass. The four main categories of forestry biomass are logging slash, mill residues, biomass from forest thinning and stand improvement operations, and chaparral [12]. Excess forest biomass is often a wildfire hazard if not removed promptly. Estimates of forest residues from logging slash, thinning's, and chaparral etc. are based on data from the California Department of Forestry and Fire Protection (CDFFP) [5]. There is approximately 26.8 million dry tons of forestry biomass produced each year. However, only 14.3 million dry tons can be effectively used for energy purposes [16]. Forestry biomass includes mill residues, forest thinnings, logging slash and chaparral with effective values of 3.3 million, 4.1 million, 4.2 million and 2.6 million dry tons per year

MSW: MSW includes municipal waste, sewage and bio-solids from waste water treatment facilities. Municipal solid wastes in California are either landfilled or diverted. Diverted MSW refers to non-landfilled wastes. The state of California passed an assembly bill (Assembly bill 939) stating that all jurisdictions are required to achieve a diversion rate about 50 percent in 2000. The MSW data is acquired from the CIWMB and California Biomass Collaborative through a combination of commercial and household data. In some instances, the original data was in wet tons.

The amount of MSW landfilled exceeds that of the MSW diverted with the total values of 18.3 million and 16.6 million tons per year respectively. However, the effective values are projected to be 9.1 million for MSW biomass landfilled and none for the biomass diverted in MSW. The MSW that is diverted is usually sent for recycling or composted [17]. The major components of MSW that are landfilled include paper and cardboard and are projected to effectively supply 4 million dry tons per year for energy purposes. Following this value is commercial and demolition (C&D) lumber which accounts effectively for 1.8 million dry tons per year. Other organic materials contributing to MSW that is landfilled food, leaves and grass, prunings, trimmings, branches and stumps.

Energy Content: Heating value of biomass is the energy available when biomass is burned and varies depending on the feedstock. In this study, the MSW based biomass energy content is used as 5580 BTU/lb [18]. The energy content for agriculture residue is taken as 7007 BTU/lb [19]. The forest residue based biomass energy content taken for this study is 8450 BTU/lb [20].

Dead Trees: Forest residues cause serious wildfire hazards and the recent drought in California has led to a tree mortality rate epidemic, prompting an executive order by the Governor to expedite the removal of dead and dying hazardous trees [21]. The U.S. Department of Agriculture (USDA) estimates that there are more than 102 million dead trees in California [22], caused by the drought and the severe bark beetle infestation. The drought led to 62 million dead trees over 7.7 million acres of forest in 2016 alone. Most of the dead trees are located in 10 counties in the southern and central Sierra Nevada region. The dead trees are not considered as part of the annual supply estimates presented in Table 1. Based on U.S. Forest Service estimates of standing dead tree volume and weight, the Beck Group estimated that the 102 million dead trees equal 178 MMBDT of biomass [72]. This is approximately equal to 40 years of California timber harvest supply assuming 2015 levels of timber harvesting [72]. However, full utilization of the dead trees is not possible due to limited access and transportation challenges, wood quality degradation, and other issues.

Biomass Availability

The total biomass and technical biomass availability values are shown in Table 1 for the state of California. The technical amount of agricultural residue available is 8.6 MMBDT/year. The MSW is the largest biomass contributor in the state with approximately 18 MMBDT/year of technical production. Densely populated area like Los Angeles produces significantly higher quantities of MSW. Humboldt, Mendocino and Siskiyou counties are the primary areas for forest residue availability. The net forest residue available in California is about 14.3 MMBDT/year.

Table 1. California biomass availability

Units: kBDT/year	**Total biomass availability**	**Technical biomass availability**
Total Biomass	82,737	32,055
Total Municipal	36,000	18,000
Biosolids landfilled	123	0
Biosolids diverted	698	558
Total MSW biomass landfilled	18,300	9,077
Paper/Cardboard	8,000	3,993
Food	1,900	926
Leaves or grass	710	355
C&D lumber	3,600	1,785
Prunings. Trimmings, branches & stumps	2,256	1,127
Total MSW Biomass Diverted	16,600	0
Other MSW materials landfilled	18,400	0
Organic	5,700	2,850
Plastic	4,100	2,050

Units: kBDT/year	**Total biomass availability**	**Technical biomass availability**
Textiles	1,600	800
Inorganic	12,700	6,350
Other C&D	5,100	2,550
Metal	3,300	1,650
Other mixed & mineralized	3,300	1,650
Glass	1,000	500
Tires	127	63
Total Agricultural	20,562	8,615
Total animal manure	10,150	3,475
Total cattle manure	8,380	3,078
Milk cow manure	3,920	1,960
Total orchard and vine	2,492	1,744
Total field and seed	4,750	2,054
Total rice straw	2,220	1,110
Total vegetables	1,652	128
Total food processing	1,518	1,214
Total forestry	26,800	14,270
Mill residue	6,200	3,330
Forest thinning	7,700	4,110
Logging slash	8,000	4,250
Chaparral	4,900	2,580

Table 2 provides a summary of the available biomass by feedstock types. Biomass availability was mapped using the estimates. Total biomass availability in the state is shown in Figure 2. Significant quantities of biomass available in Los Angeles, Orange, San Diego, and Fresno counties.

Table 2. California biomass availability estimation summary

	MSW, kBDT/year	Agricultural residue, kBDT/year	Forest biomass, kBDT/year	Total, kBDT/year
Total availability	36,000	20,562	26,800	82,837
Technical availability	18,000	8,615	14,270	32,055

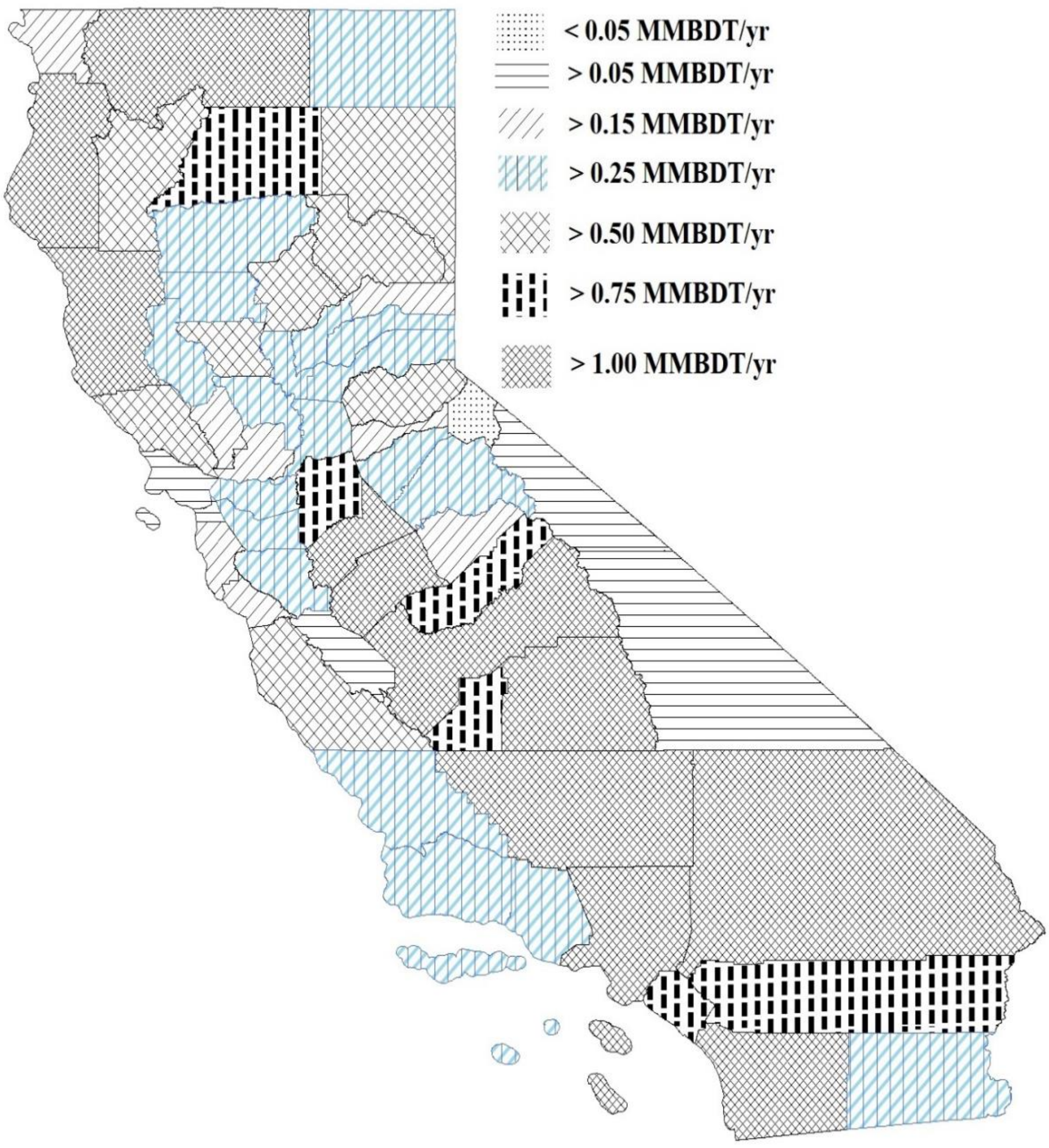

Figure 1. California biomass resource distribution

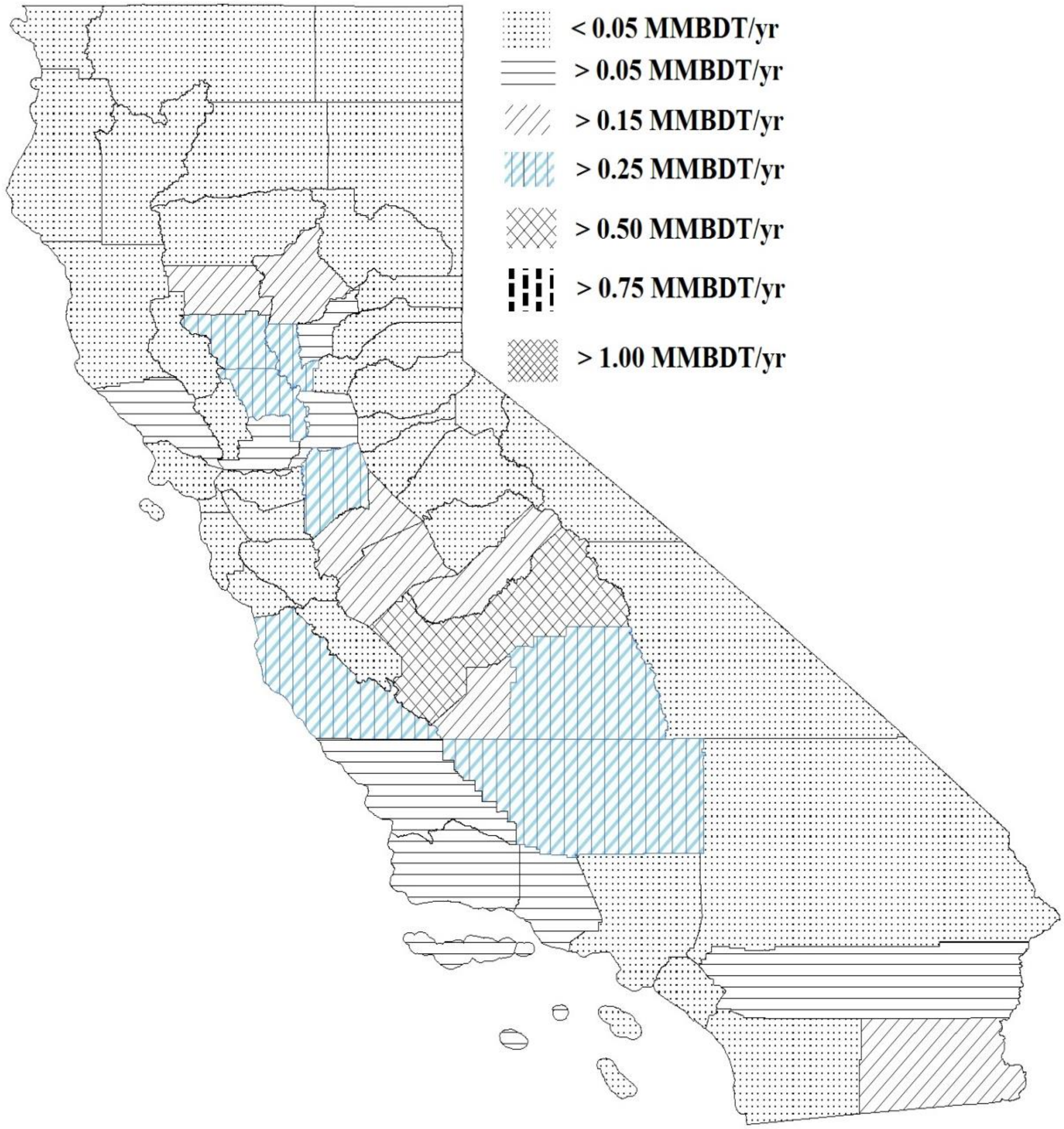

Figure 2. California biomass resource distribution (Ag residue)

Figure 2 shows the agricultural residue type biomass distribution is California. A comparatively high quantity of agricultural residue type biomass is available in Fresno.

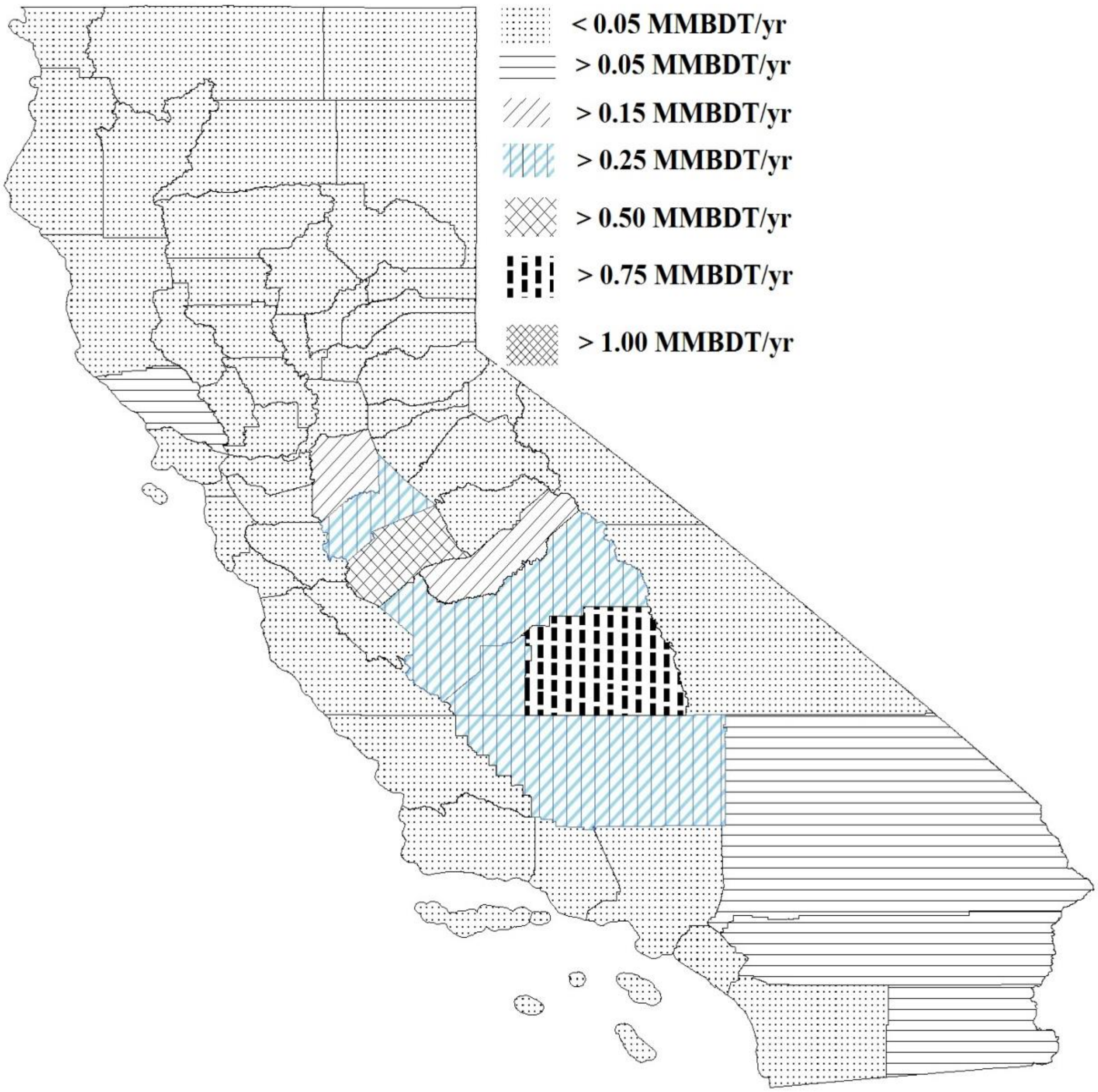

Figure 3. California biomass resource distribution (Animal manure)

Figure 3 shows the animal manure type biomass distribution is California. A comparatively high quantity of animal manure type biomass is available in Tulare.

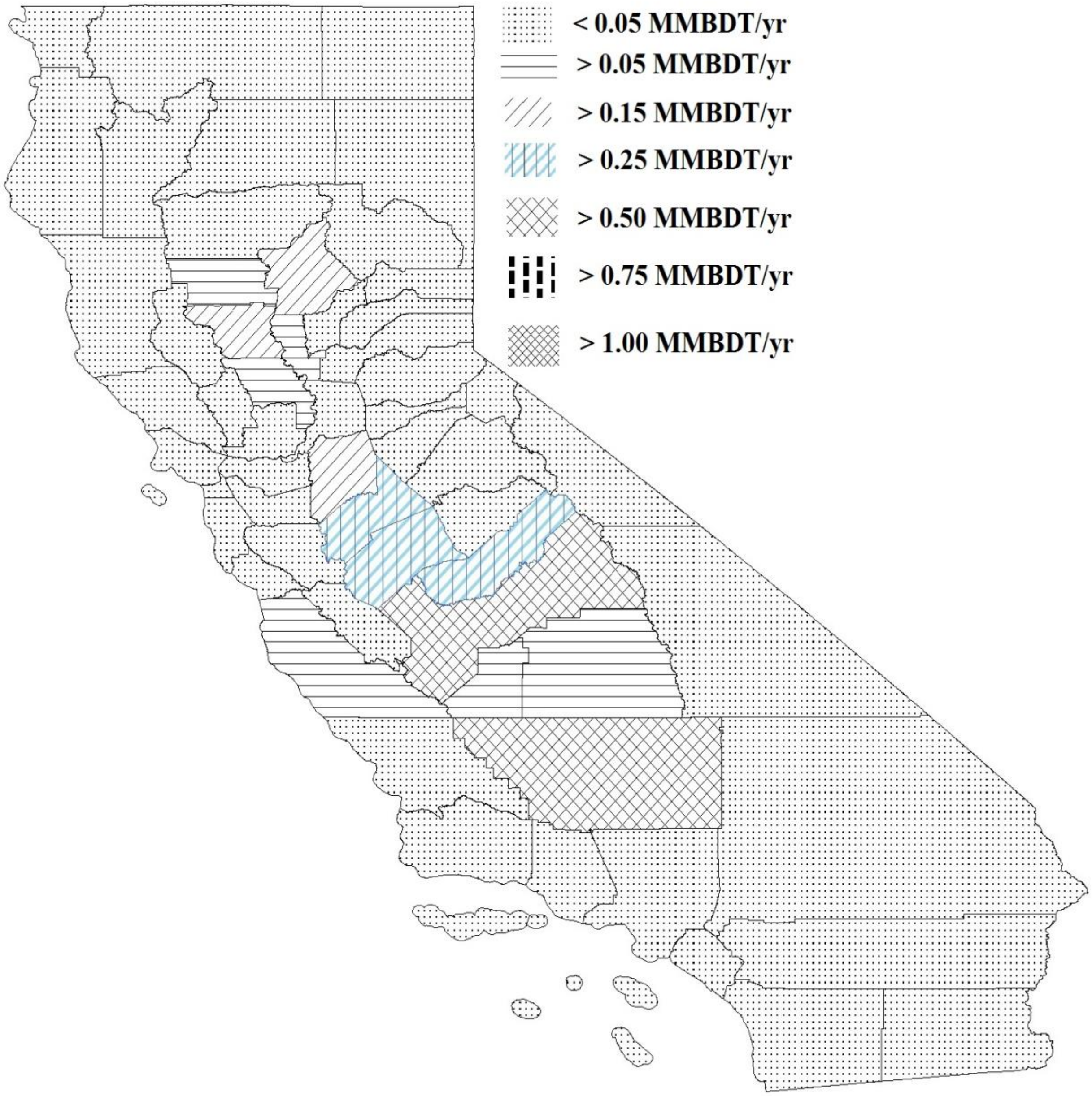

Figure 4. California biomass resource distribution (Food and Fiber processing residue)

Figure 4 shows the food and fiber processing residue type biomass distribution is California. A comparatively high quantity of animal manure type biomass is available in Kern and Fresno.

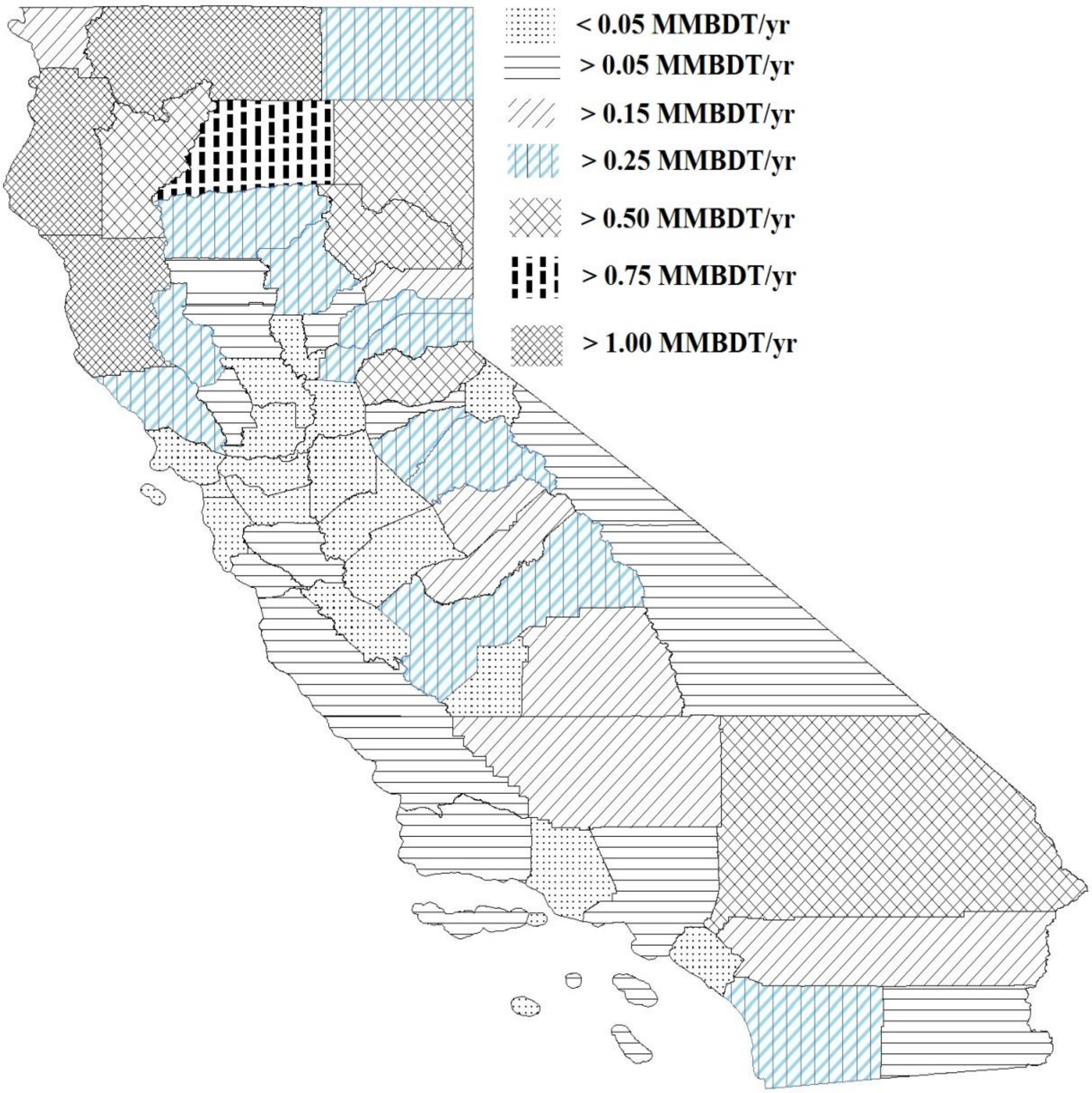

Figure 5. California biomass resource distribution (Forest biomass)

Figure 5 shows the forest biomass distribution is California. A comparatively high quantity of forest biomass is available in Humboldt, Siskiyou, Mendocino and Shasta.

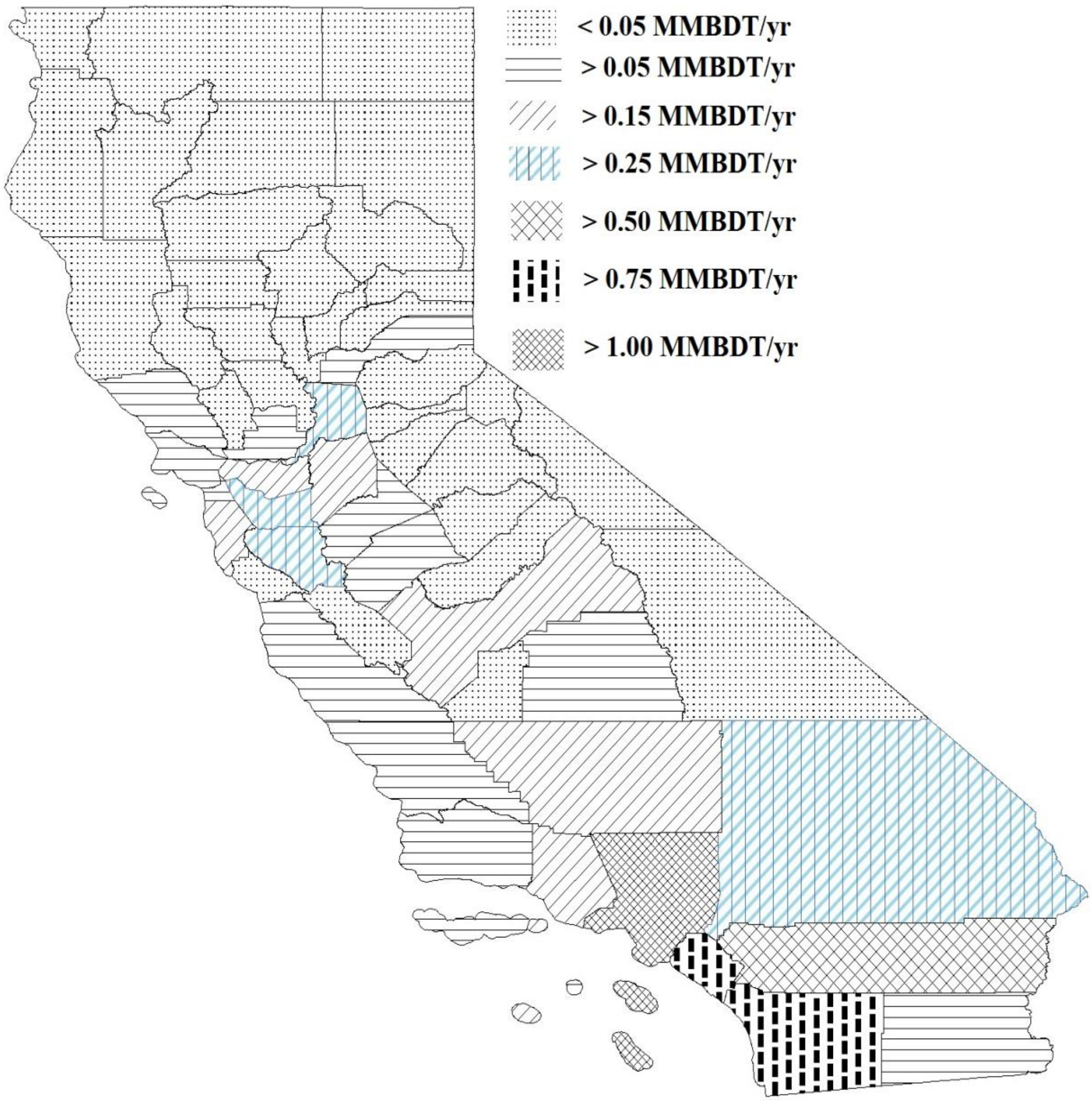

Figure 6. California biomass resource distribution (MSW)

Figure 6 shows the MSW distribution is California. A comparatively high quantity of MSW is available in Los Angeles County.

The energy content the available biomass in the state was calculated using the typical calorific value and moisture content of each feedstock. The results are shown in Table 3.

Table 3. Energy content of biomass available in California

Energy content of biomass (x 10^6 mmbtu/year)			
MSW	**Ag residue**	**Forest biomass**	**Total**
221.4	220.4	160.5	602.4

The biomass availability data demonstrate that it can play a meaningful role in improving domestic renewable production while addressing waste management, air pollution and GHG emission related challenges. Although statewide resource estimates are available as discussed earlier, the availability information is often based on countywide or regional waste stream approximations. There are studies available focused on specific cities or municipalities that collect real waste generation information. However, statewide and nationwide estimates often do not conduct detailed availability estimates and must rely on assumptions related to waste throughput based on population densities, agricultural activity, forest land characteristics, and other parameters. Viability assessments based on such data is unlikely to be meaningful since there are logistic, economic, and technological challenges unique to each site. In addition, existing conversion facilities for renewable methane or syngas production biomass are all based on biological pathways. The few thermochemical biomass conversion facilities in operation in California are designed for power generation. End use facilities that consume significant quantities of natural gas are connected to the pipeline infrastructure. Hence, the practical approach is to design projects based on specific local biomass generation data with the renewable methane product being injected into the pipeline either on the utility or the customer side. For these reasons, the research team did not create biomass availability map overlays of end users, facilities or infrastructure proximity.

The Southern California Gas Company (SoCalGas) supplies natural gas to more than 21 million customers and includes significant territory that offers a wide range of biomass resources. SCG's territory generates approximately 13 MMBDT/yr of biomass, representing about 37% of the total biomass available in California. This represents a significant resource and a renewable methane production opportunity. Countywide biomass availability is shown in Table 4. Availability data in some regions are approximated.

Table 4. Biomass availability in the SoCalGas territory

County Name	MSW	Ag Residue	Forest Biomass	Total	Energy content
	kBDT/yr	kBDT/yr	kBDT/yr	kBDT/yr	(× 10^6 MMBtu/yr)
Los Angeles	2404	6	125	2535	31.99
Fresno	188	1639	259	2086	32.46
Tulare	87	1375	200	1662	26.04
Kern	212	1205	232	1649	25.54
San Bernardino	438	139	640	1216	19.46
Orange	964	2	10	977	12.08
Riverside	502	175	229	905	13.14
Kings	23	734	1	757	11.64
Imperial	61	284	142	487	7.78
Ventura	222	92	34	349	4.79
Santa Barbara	102	120	83	305	4.65

Biomass Availability Summary

RNG production potential in California through thermochemical conversion was evaluated by assessing technical biomass availability in the state. Biomass feedstocks are defined broadly and include most carbonaceous matter including waste. The types of waste biomass available in the state are classified into three categories: MSW, agricultural residue and forest residue. MSW is the largest biomass contributor in the state with approximately 18.0 MMBDT/year of technical production. The availability estimates for agricultural residues (including animal manure, food processing and fiber based feedstocks) are 20.6 MMBDT/year and the technical availability is about 8.6 MMBDT/year. The net forest residue biomass available in California is about 26.8 MMBDT/year. A total of 32.1 MMBDT per year of biomass is estimated to be technically available in the state. The energy content of this biomass is equivalent to approximately 602 million mmbtu/year.

Power-to-Gas Resources

The Power to Gas (P2G) pathway converts excess renewable electricity into hydrogen that can then be stored, or used as a fuel or converted into RNG and injected into the gas pipeline. This approach can produce hydrogen or RNG while also addressing shortcomings related to renewable electricity production and storage. Converting excess renewable electricity into a gaseous fuel such as hydrogen or methane is very attractive since it offers a means to increase the renewable energy content of the pipeline infrastructure while addressing the well-known grid capacity and curtailment problems associated with electricity transportation. Since methane, and to some extent hydrogen, can be reliably stored for long periods using the existing infrastructure, Power to Gas can significantly 'decarbonize', i.e., reduce the GHG footprint of the natural gas supply while enabling increased renewable energy use in all major sectors including commercial, residential, and transportation [77].

California's renewable portfolio standards (RPS) require the state's electricity grid to incorporate significant renewable generation over the next few decades. Current standards mandate that 33% of the state's electricity supply be derived from renewable sources by 2020 and 50% by 2030 [23]. SB 100, recently signed into law by the Governor, accelerates and expands the RPS targets to 60% by 2030 and 100% by 2045 [24]. The three largest investor owned utilities companies collectively supplied about 49% of the state's electricity in 2015 with 27.6% of that supply coming from renewables [25]. As shown in Figure 7, the state's power mix consists of a number of renewable sources with solar and wind power accounting for more than 75% of the total renewable generation [26].

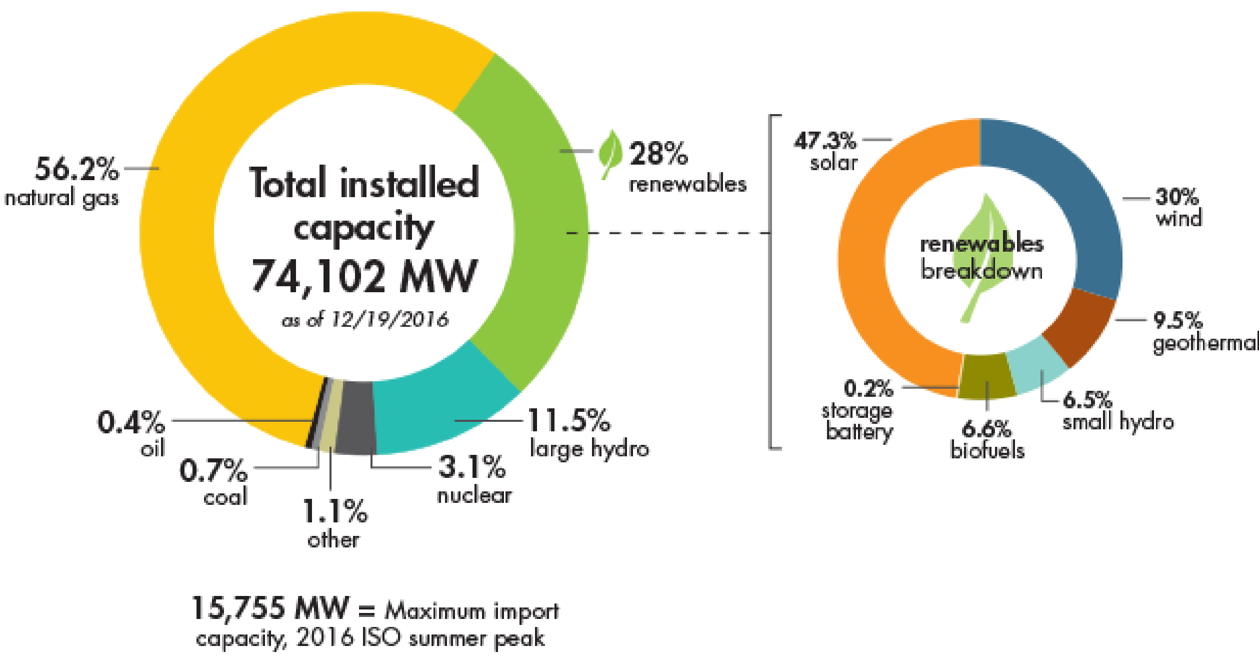

Figure 7. California electricity power mix by fuel type [1]

The solar generation includes both solar PV and concentrated solar thermal power plants. The solar thermal facilities are primarily located in the Mojave Desert area [27] whereas the solar PV generation facilities are distributed throughout the state [28]. Solar based facilities produced 15,811 gigawatt-hours (GWh) of energy in 2015 with an installed capacity of 7560 MW [27]. California generated about 12,180 gigawatt-hours (GWh) of electric power from wind energy in 2015 with a total installed capacity of 5,998 megawatts [29–31].

The significant increase in renewable generation is becoming an increasingly important aspect of grid management and leads to well-known supply and demand issues. Unlike fossil fuels, most renewable energy sources perform poorly in providing a continued, 'baseline' output and increased renewable energy generation targets create a need for efficient, reliable energy storage methods. As more renewable power plants are integrated into the grid, there is an increasing 'mismatch' between generation and demand that affects grid reliability. The Power to Gas pathway can help address many of these challenges while increasing the renewable energy utilization levels. Converting excess renewable electricity into hydrogen or methane essentially allows this energy to be stored safely and efficiently with little loss over long periods.

Currently, the challenges are managed by using peaker plants or by curtailment. The peaker plants are natural gas powered generating stations that help stabilize the power supply and to meet peak demand [32]. California Independent System Operator (CAISO) has published data of overgeneration due to increased renewable sources. The result is the well-known duck curve, shown in Figure 8 [33].

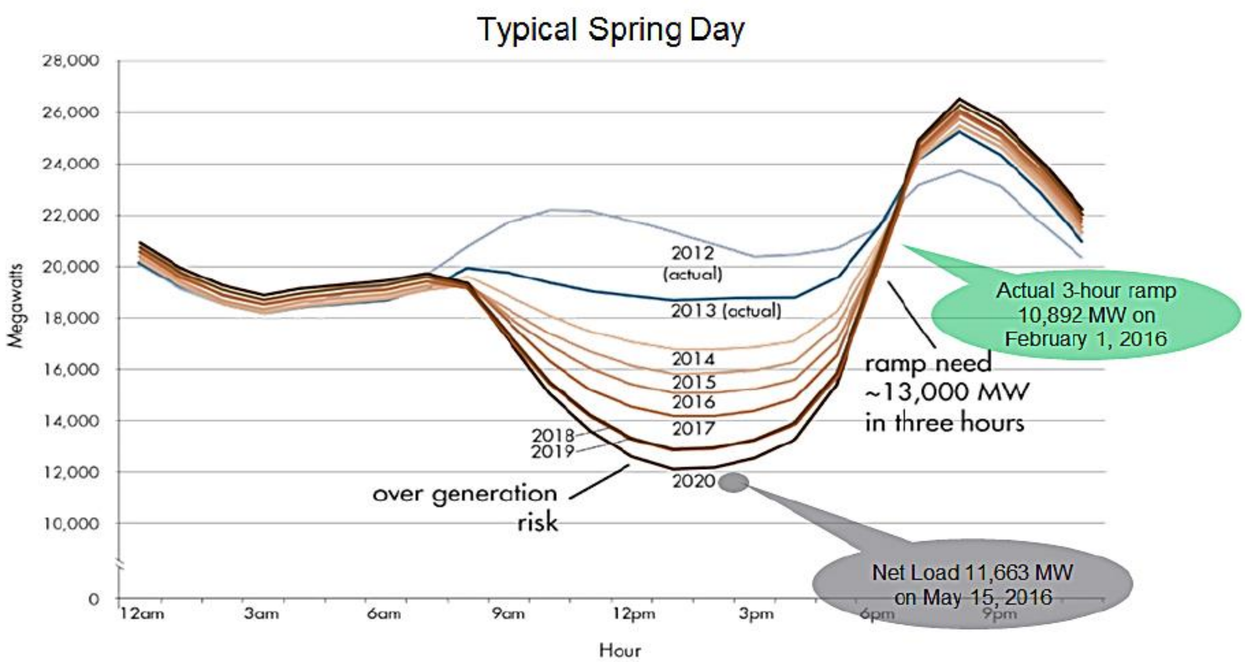

Figure 8. The CAISO duck curve shows the ramping need and overgeneration risk in the electric grid [33]

The actual generation can often exceed the real-time demand, to the point where the grid is unable to accept the excess power [33]. Without a viable energy storage option, this leads to power curtailment and with increased renewables penetration, curtailment is expected to become an important issue.

A study by Schoenung et al., analyzed the potential of excess renewable power based hydrogen to fulfill the hydrogen fuel demand for fuel cell electric vehicles (FCEV) in California [34]. The study predicts 12,000 GWh of excess electricity by 2030 which can potentially produce 243 million kg of hydrogen [34]. The price of excess electricity is assumed to be near zero or even negative during oversupply [33,34].

Although power curtailment has been a part of grid management in the past, it is becoming an increasingly important aspect with consequences on both the both infrastructure and the economy [35]. A study by Golden et al., discusses anticipated curtailment based on different sources and predicts significant increase in curtailment depending on specific scenarios such as 40% or 50% RPS [36]. A report by Denholm et al., addresses the power curtailment issue and the impact on system flexibility due to overgeneration from solar and wind [37]. The authors emphasize the critical need for flexible mechanisms to enable grid management.

Generation and Curtailment

The gross amount of curtailed power is considered to be excess electricity that is potentially available for other purposes. This assumption is useful in estimating the preliminary total availability. The curtailment data from CAISO is available on an hourly basis for both solar and wind generation in both MW and MWh [38]. Quantities less than 1 MW are filtered out for simplicity. Typical curtailment data during the month of February is shown in Table 5.

Table 5. Renewable energy curtailment data during a typical February 2017 day [39]

Hour	Fuel type	Curtailed MWh	Curtailed MW
8	Solar	57	147
8	Wind	4	
9	Solar	120	301
9	Wind	16	30
10	Solar	179	204
11	Solar	196	227
12	Solar	243	1000
12	Wind	9	106
12	Solar	14	43
12	Wind	2	27
12	Solar	73	880
12	Wind	46	557
12	Solar	16	189
12	Wind	20	235
13	Solar	188	232
13	Solar	1	2
14	Solar	175	193
14	Solar	1	1
15	Solar	173	197
16	Solar	22	100
16	Solar	0	
17	Solar	0	
17	Wind	0	3
Total		1555	

A total of 615 solar power plants and 128 wind power plants are currently under operation in in the state [40,41]. Figure 9 shows the electricity generation by different fuel type during a random spring day. Figure 10 shows the fluctuating solar and wind-based electricity generation that leads to curtailment. Generation from geothermal, biomass, biogas and small hydro can provide baseload power but is significantly less than solar and wind generation during the 24-hour day period.

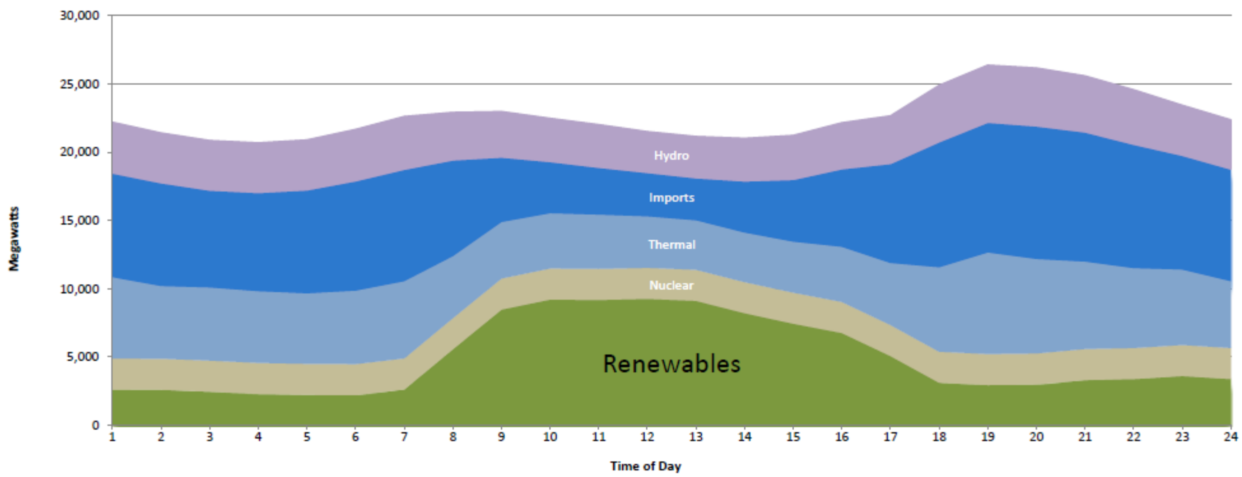

Figure 9. Hourly average breakdown of total electricity generation by resource type on a typical spring day [38]

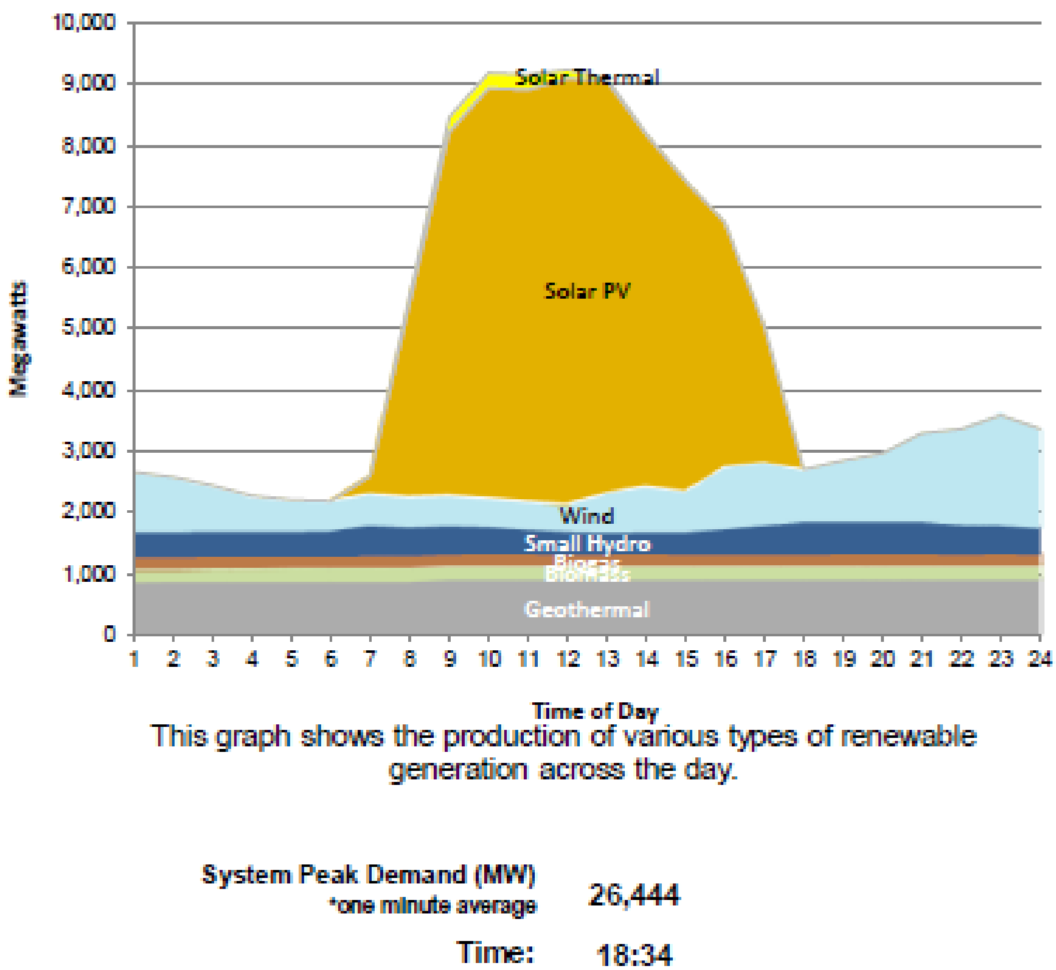

Figure 10. Hourly average breakdown of total electricity generation by renewable resource type in California [38]

Table 6 shows the amount of real-time power curtailment from January 2016 to March 2019. The data shows significant curtailment throughout the year ranging from 6.2 GWh to 122 GWh. During the entire thirty-month study period, about 1,388 GWh of power was curtailed in California. Power to gas and other forms of long-term storage integrated into the electric grid can mitigate these losses and also allow smooth integration of additional renewables into the grid.

Table 6. Solar and wind power curtailment from January 2016 to March 2019

	Total curtailment (MWh)
Jan-16	7,802
Feb-16	21,320
Mar-16	45,763
Apr-16	40,178
May-16	35,817
Jun-16	16,601
Jul-16	5,590
Aug-16	6,961
Sep-16	26,347
Oct-16	31,607
Nov-16	35,961
Dec-16	34,473
Jan-17	43,469
Feb-17	59,525
Mar-17	81,776
Apr-17	85,760
May-17	33,935
Jun-17	23,161
Jul-17	6,600
Aug-17	6,179
Sep-17	18,482
Oct-17	15,362
Nov-17	11,407
Dec-17	15,837
Jan-18	11,890
Feb-18	36,763
Mar-18	94,778
Apr-18	71,562
May-18	72,064
Jun-18	19,683
Jul-18	8,713
Aug-18	14,321
Sep-18	14,297

Oct-18	83,413
Nov-18	25,020
Dec-18	8,550
Jan-19	12,763
Feb-19	82,611
Mar-19	122,225
Total	1,388,566

Thermochemical Conversion Technologies

The types of waste biomass available in the state for thermochemical conversion include: MSW, agricultural residue and forest residue. Feedstock harvesting, transportation and pretreatment play key roles in the viability of biomass conversion. Biomass feedstocks often contain significant quantities of moisture that determines the role of pretreatment in the overall conversion process. Thermochemical conversion technologies can be classified in a number of ways, including feedstock moisture content requirements. Table 7, adapted from Kumar et al [42], shows major biomass conversion pathways, including thermochemical and biological approaches. Of the technologies listed, all except those listed under 'biological' technology options are classified as thermochemical. The technologies are classified as wet or dry biomass processes based on the role of moisture in the main reaction either as a major reactant, or as physical media to maintain the reaction environment. Wet biomass processes often do not benefit from drying the feedstock, and may require the feedstock to contain a certain quantity of moisture. Biomass can also be converted into RNG or hydrogen through aqueous phase reforming where the aqueous sugars from biological (fermentation) processes or liquids from flash pyrolysis are reformed under high temperatures and pressures to produce a gas. The net energy consumption, GHG and criteria pollutant and air toxic emissions from thermochemical biomass conversion are influenced by the conversion technology type, feedstock properties including moisture content, and the desired fuel. Advanced conversion technologies such as gasification and pyrolysis with modern emission control techniques result in significantly criteria pollutant and toxic emission reductions compared to traditional biomass use approaches. Experimental and modeling analysis has shown that integrated gasification systems can reduce criteria pollutants including NOx and SOx emissions by approximately an order of magnitude or more compared to direct fired boilers [73-76]. Gasification based conversion facilities for RNG or other renewable fuels and biopower production can meet the most stringent criteria pollutant and toxic emission requirements.

Of the technologies discussed above, the key options for RNG production are gasification and pyrolysis. The technologies, including catalytic and non-catalytic processes, can be broadly classified into three groups:

a. Oxygen/air blown gasification technologies
b. Hydrogasification (steam/H_2 driven) technologies
c. Pyrolysis processes

Table 7. Types of biomass conversion processes [42]

Feedstock	Technology	Features
Wet biomass	Biological	Anaerobic digestion, or alcohol production from sugars by biomass hydrolysis and fermentation
	Hydrothermal conversion	High pressure conversion to a hydrophobic oil. Often involves further catalytic conversion to methane, liquid fuels or chemicals
	Supercritical gasification	Conversion occurs under supercritical conditions
	Steam hydrogasification	Uses hydrogen and steam as the gasifying agents
Dry biomass	Slow pyrolysis	Heating up the biomass in the absence of air (or oxygen) with slow heating rates to produce biochar and gaseous products
	Fast pyrolysis	Extremely fast pyrolysis of biomass with very high heating rates resulting in crude oil like bio-oil and gaseous products
	Gasification	Biomass is converted into syngas using air or oxygen or hydrogen as the gasifying agent

Oxygen/Air Blown Processes

Oxygen or air blown processes are the primary focus of current gasification development, especially in commercial and large-scale demonstration projects. These processes are commonly known as partial oxidation (POX) technologies and the name reflects the sub-stoichiometric nature of the conversion process. Generally, a small amount of steam is added along with oxygen in these processes. The primary purpose of commercial partial oxidation gasifiers developed over the past few decades has been synthesis gas production. Modern POX gasifiers are aimed at maximizing syngas production and reducing the amount of methane in the product gas. However, there are several technologies that use oxygen, air or enriched air to produce RNG. The technologies available that use oxygen/air blown gasifier are:

a. Carbona, Bubbling/Circulating Fluidized Bed
b. Sierra Energy, Blast furnace-based gasifier
c. Synthesis Energy Systems, Bubbling Fluidized Bed
d. Taylor Energy, Jet Spouted Bed gasifier with pulse detonation

Hydrogasification

Hydrogasification processes do not use an oxidizing agent and the basic reaction is the direct methanation of carbon, thus making these attractive for methane production. Although this reaction is mildly exothermic, significant amount of energy must be spent in bringing the reactants up to temperature and also to sustain the process. Methane production is favored at high pressures and the process is generally operated at temperatures ranging from 750 °C to 1000 °C. A number of processes have been developed including the Hydrane gasifier by the U.S.

Bureau of Mines (Department of Energy), HKV process (Hydrierende Kohlevergasung) by Rheinbraun in Germany, the Hygas gasifier by the Institute of Gas Technology (IGT), and the bluegas process by GreatPoint energy. A major issue with hydrogasification processes is the source of hydrogen supply since hydrogen production can be expensive. In addition to the hydrogen supply issue, hydrogasification was not very attractive due to the much slower reactivity of carbon with hydrogen compared to other gasifying agents. The reactivity of carbon with different species at 1073 K and 0.1 atmospheres are shown below.

$$\begin{array}{ccccccc} r_{O_2} & >> & r_{H_2O} & > & r_{CO_2} & > & r_{H_2} \\ 10^5 & & 3 & & 1 & & 3.1^{-3} \end{array}$$

Catalytic hydrogasification processes have been explored in order to overcome the slow reactivity of hydrogen with carbon.

The hydrogasification technologies available are:

a. CE-CERT process, Steam hydrogasification (UC Riverside)
b. Cortus Energy WoodRoll technology
c. Genifuel Corporation, Hydrothermal Liquefaction (HTL), Catalytic Hydrothermal Gasification (CHG)
d. GreatPoint Energy, bluegas process
e. Milena gasification process, ECN, Netherlands
f. Rentech Silvagas Process
g. West Biofuels, Fast Internally Circulating Fluidized Bed (FICFB) gasification process

Pyrolysis Based Processes

Pyrolysis is the thermal decomposition of the feedstock in the absence of oxygen. The products of biomass pyrolysis are char, bio-oil (also referred to as bio-crude) and gases including methane, hydrogen, carbon monoxide, and carbon dioxide. Pyrolysis can be further classified into slow and fast pyrolysis based on the residence time of the solid biomass in the reactor. Fast pyrolysis, also known as flash pyrolysis, is normally conducted under medium to high temperatures (usually 450°C to 550°C) at very high heating rates and a short residence time (e.g., milliseconds to a few seconds). Technologies include:

a. G4 Insights Inc., PyroCatalytic hydrogenation (fast pyrolysis)
b. Kore Infrastructure, traditional pyrolysis

A comparison of the technologies and current scale, if reported in the literature, are presented in Table 8. A brief summary of the technologies is provided in the following section.

Table 8. Thermochemical conversion technologies

Company	Technology	Current scale
	O_2/air blown	
Carbona U.S., Finland	Bubbling/Circulating Fluidized Bed, O_2 blown gasification	Feed = 21 TPD wood pellets; TIGAS Gasoline output = 23 bbl/day
Sierra Energy; Davis, CA	Blast furnace, O_2 blown gasification	10 TPD
Synthesis Energy Systems; Houston, TX,	Bubbling/Circulating Fluidized Bed, O_2 blown gasification	
Taylor Energy; CA	Jet-Spouted Bed (JSB) gasification with pulse detonation, O_2 blown gasification	2 Dry TPD biomass to syngas
	Steam/H_2 based	
CE-CERT Process; University of California Riverside	Circulating Fluidized Bed (CFB) steam hydrogasification	0.1 TPD
Cortus Energy, Sweden	WoodRoll technology	Modular 6 MW plant
Genifuel; USA	Hydrothermal Liquefaction (HTL), Catalytic Hydrothermal Gasification (CHG), Hot water	1 TPD 30% solid; Crude oil output = 1 bbl/day
GreatPoint Energy; Cambridge, MA	Catalytic hydromethanation Oxygen and steam	Pilot, 1 TPD of coal
Milena Gasification Process; Netherlands	CFB gasification technology; Steam or oxygen blown	0.52 million m^3/year RNG
Rentech Silvagas Process; Denver, Colorado	Hydrothermal Reforming	
West Biofuels; Woodland, CA	Fast Internally Circulating Fluidized Bed (FICFB) gasification: Pulse-Detonation-Combustor based feeding Steam and oxygen blown	3-20 MW RNG
	Pyrolysis based	
G4 Insights Inc.; Canada	PyroCatalytic Hydrogenation (fast pyrolysis)	
Kore Infrastructure, Paramount, CA	Slow pyrolysis	Pilot, 3 TPD

Note: RNG denotes methane from renewable feedstocks and SNG denotes methane from coal

Carbona Technology

Carbona technology is a Sweden based company owned by Andritz Oy that offers Bubbling Fluidized Bed (BFB) and Circulating Fluidized Bed (CFB) gasifiers [43,44]. The CFB gasifiers are intended for use with boilers and kilns while the BFB gasifiers are designed for Integrated Gasification Combined Cycle (IGCC) power plants and for fuel production, including liquid fuels and RNG. The gasification technologies are oxygen or air blown depending on process requirements. Thermal efficiency of the technology is in the range of 36-40% (Btu fuels/Btu biomass) [45]. Carbona claims that deployment of the technology has the potential to produce about 1.0 MMbbl crude oil per year and can reduce about 73.7% greenhouse gas compared to the conventional fossil gasoline. With current technology the process can convert 21 TPD biomass to 23 bbl/day TIGAS gasoline. The high pressure oxygen blown BFB gasifier can produce biofuels or RNG at a capacity of 100-200 MWth per unit [46]. The production cost is estimated to be 5-7¢/kWh depending on the type of fuel with capital investment of: $3.88 million (1MW), $5.88 million (3MW) $8.52 million (5MW).

Sierra Energy

Sierra Energy, a Davis, California based company, uses an oxygen blown gasifier based on a blast furnace to convert renewable feedstock into syngas [47,48]. The technology, referred to as 'FastOx' gasification, operates at slagging temperatures (~4000 °F) and can accept a wide range of feedstock types from petcoke, tires, MSW and biomass with minimum amount of toxic by-products [47]. The technology has been proven in a 10 TPD pilot plant and the company anticipates that commercial facilities can have feed throughputs as high as 10,000 TPD [47]. Sierra recently received funding to build a 20 TPD plant at Fort Hunter Liggett in Monterey County. The process has an electrical efficiency of 35% with gensets and 45% in a combined cycle power plant. The cost of hydrogen is estimated to be from $1-5/kg H_2 using 12.5-100 TPD systems respectively.

Synthesis Energy Systems

Synthesis Energy Systems (SES) is a Houston, Texas based company focusing on coal and biomass gasification in China. The SES Gasification Technology (SGT) uses a steam and oxygen blown bubbling fluidized-bed gasification system to convert coal, coal waste, biomass and municipal solid waste (MSW) to syngas [49]. The SGT process is based on the U-GAS gasification technology, originally developed by the US DOE and the Gas technology Institute (GTI). The company claims cold gas efficiencies of over 80% and greater than 99% carbon conversion efficiencies. SGT is used in commercial plants in China that convert bituminous coal to syngas. The plant capacities range from 28,000 Nm^3/hr (1 SES gasifier) to 120,000 Nm^3/hr (4 SES gasifiers) of syngas output using coal as the feedstock [49].

Taylor Energy

Taylor Energy is a California based company commercializing an oxygen blown, pulse detonation enhanced gasification technology that converts renewable feedstock into syngas [50]. The Taylor Energy Syngas Process employs a robust Jet Spouted Bed (JSB) primary receiver. The JSB is powered by hot exhaust-gases discharged at supersonic velocity from a Pulse-Detonation-Combustor. Supersonic compression waves enhance comminution of the feed at the macro level and increase the rate of chemical reactivity at the molecular level. The thermal efficiency is 47% for biomass to FT-liquid. Currently, the technology is in a demonstration/pilot plant scale (3 TPD of feed throughput).

CE-CERT Process

CE-CERT process, a high efficiency gasification technology known as 'steam hydrogasification' is developed by the University of California, Riverside. The technology is undergoing demonstration in a 0.1 TPD feed throughput Process Development Unit (PDU) scale system [51]. This advanced conversion technology uses a proprietary hydrothermal treatment process to convert the feed into a slurry and is especially suited for the conversion of renewable feedstocks such as biomass and waste matter. The SHR (steam hydrogasification reaction) gasifier generates a high methane content product gas that is subjected to warm gas cleanup and sent to a shift reactor to increase the quantity of hydrogen. The product gas is then cooled down and H_2 is separated for recycle to the SHR as feed. The recycle hydrogen stream eliminates the hydrogen supply problem. The energy efficiency of the process is 50-60% under specific assumptions.

Cortus Energy

Cortus Energy is a Sweden based company that offers modular gasification systems to convert forest residue and energy crops to syngas [52–54]**.** The 'WoodRoll' technology combines drying, pyrolysis and gasification which offers flexibility with process configuration and enables the use of low grade and non-pre-treated feedstocks. The pyrolysis step converts the biomass into pyrolysis gas and carbon char. The process uses an indirectly heated char-steam gasifier heated by the pyrolysis gas. The tars resulted during pyrolysis are heat cracked into small components. The process is energetically self-sustaining and claims up to 80% energy efficiency from wet biomass (moisture up to 45%) when heat recovery is taken into account [52]. Cortus Energy received a $5 M grant by California Energy Commission for the Mariposa biomass power project in March 2017 [55]. The 2.4 MW heat and power project will be located in Mariposa County and will use a modular WoodRoll system with double gas engines and heat recovery. Cortus Energy currently offers modular 6 MW systems for power generation and RNG production and plans to scale up in the near future. The 6 MW system can produce 4.8 MW equivalent of RNG or 5.4 MW equivalent hydrogen.

Genifuel

Genifuel is a U.S. based company commercializing a Hydrothermal Liquefaction (HTL) process that converts biomass into bio-crude. The technology was licensed from Pacific Northwest National Laboratory (PNNL). The process can be used in conjunction with a Catalytic Hydrothermal Gasification (CHG) process to produce RNG [56–60]. The carbon conversion efficiency to fuel is estimated to be 85%. The bio-crude yield ranges from 35-45% of the input solids mass. The current process operates for 20% dry solids in 0% water at 350 °C and 21 MPa. The technology is demonstrated in a 1 TPD feed throughput system using wet algae slurry at 30% solids to produce about 1 bbl of crude-oil per day.

GreatPoint Energy

GreatPoint Energy is a Cambridge, Massachusetts based company commercializing a catalytic hydromethanation technology for converting coal, petcoke, and biomass to methane. The process thermal efficiency is estimated to be 60-70% [61].The process can convert about 85-90% of the carbon in the feedstock [61]. The technology is demonstrated in pilot scale (1 TPD of coal throughput) and has been licensed for commercial scale plants in China [62]. The technology is aimed for 1500-14,000 TPD of coal or coal-biomass comingled plants.

Milena Gasification Process

The Milena technology converts woody biomass into syngas or RNG and has been demonstrated in an 800 kW pilot plant. The process was developed by the Energy research Centre, Netherlands and uses a circulating fluidized bed that is air blown. The gasifier is surrounded by a Bubbling Fluidized Bed (BFB) combustor that supplies the heat and avoids nitrogen dilution of the syngas. The process is similar to the Battelle process but uses a settling chamber instead of a cyclone to separate the char and bed material from the product gas. Full carbon conversion and very high cold gas efficiencies (>80%) are claimed. There are plans to build a 4 MW production plant that is expected to produce 2.6 million m^3/year of RNG. The next step will be to build a 50 MWth plant (0.04 bcm/year). The anticipated scales of commercial RNG plants are between 50 and 500 MWth (0.04 – 0.4 bcm/year) [63]. The technology is commercially supplied by Royal Dahlman.

Rentech-SilvaGas Process

Rentech is a Denver, Colorado based company. Rentech-SilvaGas biomass gasification process uses the Battelle-Ferco dual reactor gasification system to convert biomass and waste into syngas. A reformer combusts the gasification char to indirectly supply the heat needed for the steam and hydrogen driven gasification process. The gasifier was operated in Burlington, VT for over 2 years in partnership with the US DOE as part of a biomass power project [64]. The Rentech-ClearFuels biomass gasification process converts biomass to hydrogen or syngas in a High Efficiency Hydrothermal Reformer (HEHTR). The technology has been piloted for more than 10,000 hours in an FT liquids production configuration [64]. Rentech is not currently active in the gasification arena.

West Biofuels

West Biofuels is a Woodland, California based company offering gasification processes for power generation and fuel production, including RNG. Their Fast Internally Circulating Fluidized Bed (FICFB) gasifier technology converts cellulosic biomass into a syngas that can be upgraded to RNG or to ethanol [65]. The FICFB process is similar to the Milena technology except the gasifier is a BFG system instead of the riser used by Milena. The technology has been proven in commercial scales for power generation including at Gussing, Austria and is intended to be scaled at 3-20 MW in commercial RNG plants. There are four plants in operation for electricity generation with a 25~30% energy efficiency [66]. An RNG production facility, intended to be at 100 MWgas, is under commissioning in Sweden.

G4 Insights Inc.

G4 Insight's is a Canada based company commercializing a catalytic hydropyrolysis technology that uses fast pyrolysis instead of gasification to convert biomass into a high methane content syngas. The pyrolyser vaporizes the volatiles in the feedstock in a hydrogen atmosphere. The pyrolysis vapors are catalytically converted to methane and steam in the presence of hydrogen at temperatures below 650 °C. The methane is separated and upgraded and a portion of the product methane is reformed to supply the hydrogen back to the process. The conversion efficiency from biomass to methane is greater than 70% on a HHV basis. G4 received a $2.5 million mobile demonstration project grant from the California Energy Commission. The project successfully demonstrated the production of transportation grade RNG from local forestry residue and subsequent use in an unmodified CNG vehicle in Placer County, California [67]. G4 intends to pursue two commercial scale outputs: 400 GJ/day from 30 TPD of bone dry woody biomass; and 10,000 GJ/day from 750 TPD of bone dry woody biomass.

Kore Infrastructure

Kore Infrastructure is a Southern California based company commercializing a pyrolysis technology for biosolids and biomass conversion to RNG and FT-liquids. The dried biosolids are sent to the pyrolyser where pyrolysis gas is produced at 650 °C and biochar is separated from the vapor product [68]. The syngas is upgraded and sent to the methanation reactor for RNG production [69]. KORE's pilot facility in Carson, California has operated for over five years [70]. This plant can convert 3 TPD of biosolids (~1000 ton per year) into an estimated 125,000 liters of liquid fuels per year [71]. The company expects to build a commercial plant by 2019 capable of handling 300 TPD with RNG production rate of 1000-1200 gge/day [69].

Design Basis Calculations

Two project proposals were developed as part of this project to demonstrate state of the art thermochemical conversion and power to gas technologies. Summary of the proposed projects in given below.

Pipeline Quality RNG Production via Gasification

Process Description

Taylor Energy, a California company, is developing Biomass-to-RNG technology designed for pipeline applications at community scale, using locally sourced renewable energy resources. Taylor Energy is developing novel gasification technology, integrated with a catalytic synthesis module being developed by Ceramatec Inc., for production of fuel grade RNG. Technology development will include a cryogenic syngas cleaning system that employs liquid-CO_2 as the scrubbing fluid.

Gasification Technology

Taylor Energy's thermal gasification process employs a robust Jet Spouted Bed for 1^{st}-stage gasification and a novel 2^{nd}-stage Venturi-Reformer; both stages are powered using a proprietary Pulse-Detonation method. Unique to this embodiment, hot exhaust-gases discharged at supersonic velocity provide low-cost process intensification. This is significant because supersonic compression waves enhance the rate of chemical reactivity due to the repetitive shockwaves that course through the process at 4-cycles per second, pushing the molecules together and intensifying thermal chemical reactions at the molecular level.

The Taylor Energy gasification process operates up to 1150 °C; below the ash-fusion temperature, but well above the 920 °C limit for typical circulating fluidized bed (CFB) gasifiers. Many process benefits are obtained by operating near – but below – the ash-fusion temperature. For example, a process goal is to reduce oxygen and steam consumption to minimize operating costs. The target feed rate for the test program is 3-tonne/day of biomass, possibly including municipal waste, and/or agricultural residues.

Methanation

The gasification / reforming technology will integrate with a new modular synthesis process being developed by Ceramatec, Inc. The catalytic synthesis module can be used for FT-liquids production with 2-bbl design capacity, or used for methanation of syngas to form CH4 at 10-scfm scale. Methanation is the reaction of carbon oxides and hydrogen, making methane and water. The successful integration of these key systems will advance the state-of-the-art leading to lower cost RNG, enabling a new embodiment that promises low capital and operating costs for community scale deployment of combined power and ultra-clean RNG production. Both the gasifier/reformer and the methanation module are designed for ease of fabrication, using mostly off-the-shelf components to minimize first-cost, and process intensification methods are employed to reduce operating costs.

Ceramatec's 10-scfm test module will be shipped to UC Riverside's test-site in 2018, after completing tests at the Energy and Environmental Research Center, in North Dakota, using biomass and coal. We propose to use this module to test RNG production methods using nickel catalysts.

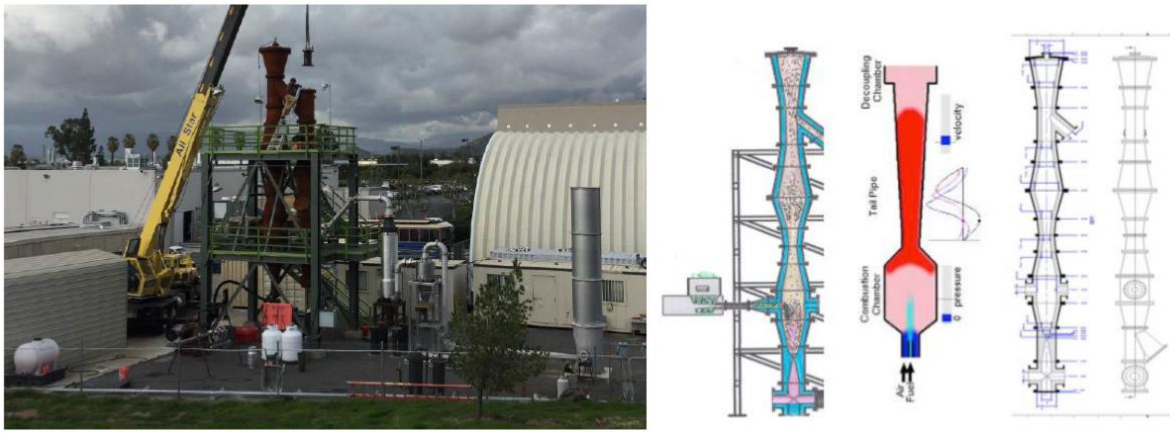

Figure 11. Taylor Energy's Modular Gasification / Reforming System Located at UCR

Syngas Cleaning

Fuels synthesis includes the use of a cryogenic syngas-cleaning module, including syngas compression. Essentially all trace contaminants can be removed (<0.1 ppm for each contaminant) from the low molecular weight gases (H_2, CO, CH_4, N_2) using cryogenic deep-cleaning methods that employ liquid-CO_2 as the scrubbing solvent. The research team proposes to develop and test a modular cryogenic syngas cleaning method that is being employed by KBR and others for ammonia synthesis at refinery scale.

A goal of the proposed research is to develop a gasifier/reformer embodiment that is low-cost compared to existing technologies. The Taylor Energy syngas process operates like an Entrained-Flow gasifier in many regards, but with improvements. The primary receiver is a Jet Spouted Bed (JSB) that retains oversized feed materials while fines are quickly elutriated by entrainment with process gases; the JSB serves to rapidly reduce the size of the feed in a high-temperature environment, which causes carbonaceous materials to become friable (more easily crumbled.) The intent of the 1st-stage JSB is to generate entrained-flow containing water vapor, volatiles, carbon-char, and particulate matter. A Spouted Bed is also created directly above the 1^{st}-stage by using a reactor section composed of converging and diverging nozzles, which serve to hold-up larger carbon-char particles for further reaction. This JSB accomplishes a type of internal circulation, without the cost and complexity of an external circulation loop.

This two-stage design has been demonstrated at bench-scale by Tsuji, T., and Uemaki, O., who showed that coal could be gasified with greater efficiency by operating just below the ash fusion temperature, at significantly lower temperature compared to entrained-flow slagging type gasifiers. The proposed modular gasification process is a very flexible and enables converting diverse energy feeds into a syngas intermediate suitable for a variety of modular synthesis applications. The resulting synfuels can include jet fuel and renewable natural gas, and co-production electric power. The techno-economic objectives will be accomplished using process intensification methods; for example, higher carbon conversion at lower temperature compared to slagging-type gasification methods.

Phase 1 Description

During phase 1, the team will develop the design basis for the proposed facility, and do the Front End Engineering Design (FEED), followed by detailed design. A detailed Techno-economic Analysis and Life Cycle Analysis will be conducted as well. The specific items to be evaluated during the design phase are listed below.

Project Design Basis

- *Basic Site Characteristics*
- *Basic Fuel Feedstock Characteristics*
  - Identify biomass ratio, type of biomass, basic computational analysis of feed
- *Environmental Requirements*

Basic Engineering Design Elements

- *Process Engineering*
  - Process area descriptions
  - Block Flow Diagram (BFD)
  - Process Flow Diagram (PFD), and
  - Process and Instrumentation Diagram (P&ID)
  - Process simulation output and heat and material balances (H&MB)
  - Major Process Equipment specifications
  - Basic Equipment and instrumentation lists
- *Project Cost Estimate*
  - Construction Cost Estimate
  - Operations Cost Estimate
- *Estimated Construction, Startup and Testing Schedule*

Other Items

- *Project execution and project management guidelines and procedures*
- *Logistics*
- *Material selection specifications and lists*
- *Balance of Plant (including roads, buildings, site prep, and layout)*
- *Construction Planning*

Phase 1 Budget

The proposed performance period for Phase 1 is eight months.
The budget for Phase 1 is $651,000

Future work

Phase 2 **-** Construction and Start-up Testing

- Phase 2 will involve construction, fabrication, and installation of the technology components and a successful evaluation of the Biomass-to-RNG system
- The estimated budget for Phase 2 is $1.2 million

Phase 3 **-** Testing Campaign and Evaluations

Power to Gas-Based Hydrogen Production

Project Description

StratosFuel is currently constructing a three-phase, renewable hydrogen production plant in the desert that will use wind power to electrolyze water. The electrolyzers will receive their renewable electricity supply from StratosFuel's established 30-year power purchase agreement with a renewable power plant in Southern California. StratosFuel has also established a partnership with Hydrogenics to build North America's largest 100% renewable hydrogen production facility. The facility is expected to be operational by 2019. The facility will be built in three stages:

- Stage 1 - 5 megawatt electrolyzer = 3,000 kilograms per day
- Stage 2 - 10 megawatt electrolyzer = 6,000 kilograms per day
- Stage 3 - 15 megawatt electrolyzer = 11,000 kilograms per day

The current project will blend hydrogen from biogas reforming and electrolysis. The proposed project will add the low carbon intensity hydrogen and methane production routes to the Stage 1 electrolysis facility. StratosFuel and team are currently working on obtaining a low carbon fuel standard pathway approval from the California Air Resources Board for the blending method.

Phase 1 Description

During phase 1, the team will develop the design basis for the proposed facility, and do the Front End Engineering Design (FEED), followed by detailed design. A detailed Techno-economic Analysis and Life Cycle Analysis will be conducted as well. The specific items to be evaluated during the design phase are listed below.

- Preliminary design and review (kick-off meeting) 1.0 months
- Completion of the detail design 2.0 months
- Construction of the civil work (workshop buildings and foundations of the equipment, etc.) 2.0 months
- Manufacture of non-standard equipment and valves, purchase of standard equipment and auxiliary material 3.0 months
- (It can be done with the construction of civil work simultaneously)
- Shipment 1.5 months
- Erection and Installation 2.0 months

- Blowing-off, leakage-test, pressure-test, adjustment and start-up month
- Commissioning 0.5 month

Project performance period: It will approximately take 11 months to solidify the design phase of producing renewable hydrogen by blending methane and electrolysis hydrogen.

Phase 1 Budget

The proposed performance period for Phase 1 is three months.

The budget for Phase 1 is $200,000. The $200,000 will include design and engineering on the project, and some permits, such as Title V, and land use permits. A breakdown is listed below:

- $150,000 for design and engineering.
- $50,000 permits.

Future work

Phase 2 **-** Construction and Start-up Testing

- Phase 2 will involve construction, fabrication, and installation of the technology components and startup testing and evaluation.

Phase 3 **-** Testing Campaign and Evaluations

- The program-end goal is operation of the facility to produce low carbon intensity hydrogen and methane. During this phase we anticipate to produce 3 MT of hydrogen from methane, and 3 MT of hydrogen from electrolysis. The hydrogen will comply with SAE J2719 and will be supplied to hydrogen fueling stations and other fuel cell mobility applications.

Life Cycle and Techno-Economic Analysis

Life cycle and economic analysis were conducted for the biomass conversion and the electrolysis pathways using typical process parameters and pathway assumptions. The evaluation was performed for hydrogen production due to the lack of experimental or commercial deployment data on the methanation technology options. The results for RNG production analysis are expected to be similar in magnitude for the major parameters. Natural gas reforming pathway was also evaluated and used as the baseline to compare the performance of the renewable technology pathways. The WTW results of the gaseous hydrogen life cycle analysis, including the energy consumption per mile driven and the GHG emissions are presented below [78]. The results include the total (Well to Wheels) energy use per mile driven using the specified fuel and vehicle technology. Fossil energy use is also listed which is further split into petroleum, coal and natural gas. The results show that the renewable technology pathways result in significantly reduced GHG emissions, criteria pollutants, and air toxics. The renewable pathways also help reduce short lived climate pollutant emissions by reducing Particulate Matter. The economic analysis results show higher production costs for the renewable pathways, especially electrolysis. The assumptions, parameters and results, adapted from [78] are presented in the following sections.

Life Cycle Analysis:

The basic assumptions used in the CA-GREET Tier2 model for all the process pathways are listed below:

- Analysis year: 2015
- Centralized production pathways are assumed
- CAMX grid (California-Mexico grid) mix is considered as regional electricity mix for utility supply for all the cases except solar or wind
- CAMX grid electricity mix: 56.2% natural gas, 28% renewable, 11.5% hydro, 3.1% nuclear and 2.2% other sources (California ISO 2017)
- CA Crude is selected for regional crude oil use
- H2A model by NREL is selected for the Hydrogen production process
- Scenarios for H2A Model Cases: Future scenario. The assessment is performed for the future (2025-2030) technologies.
- Natural gas (NG) feedstock is considered as North American (NA) NG
- Final product hydrogen use: passenger car with 24.81 MPGGE
- NG transmission distance: Interstate pipeline: 1000 miles; Instate mile: 0 miles
- Electric Transmission and Distribution Loss: 6.5%
- Co-product credits: none
- Steam/electricity export credits: none

Fossil natural gas reforming pathway was assessed as the baseline value to evaluate the renewable hydrogen pathways. Natural gas reforming accounts for more than 95% of current production. The technology involves the steam methane reforming (SMR) and water gas shift (WGS) reactions. Pressure swing adsorption is used to separate hydrogen from the other species. The hydrogen produced at a central facility is compressed and injected into a pipeline, through which it is transported to the refueling station. There the hydrogen is further compressed and dispensed as a gaseous fuel to the vehicle fuel tank. The feedstock is North American Natural gas (NA NG) consisting of a high methane percentage (94.9%) and varying ethane, propane, butane and inert gas composition. The approximate gross heating value of the natural gas is 1014.5 Btu/ft^3. Thermal efficiency of natural gas reforming to produce hydrogen (LHV of H_2 to the total energy input of the system including NG) is assumed to be 72% for gaseous hydrogen production.

Natural gas is fed to the plant from the pipeline and is generally sulfur-free, but odorizers with mercaptans must be cleaned from the gas to prevent contamination in the reformer. The desulfurized natural gas feedstock is mixed with process steam and is reacted inside the reformer to produce syngas. The reforming process is performed at high-temperatures (800°C–1,000°C) in the presence of a catalyst, for ex. nickel. The syngas is further processed in a shift reactor to increase the hydrogen concentration. The H_2 is purified and then compressed and/or liquefied as required.

The centralized hydrogen production pathway via electrolysis assumes that renewable power from a solar PV power plant is used to electrolyze water whereas the distributed pathway assumes the use of grid power. The centrally produced hydrogen is compressed and injected into a pipeline, through which it is transported to the refueling station (Ruth 2009). The electrolyzer produces hydrogen and oxygen from feed water. The hydrogen and oxygen are separated using gas/lye (KOH) separators. The oxygen is released to the atmosphere, and the hydrogen is fed to the gas scrubber subsystem, which purifies the hydrogen.

- Hydrogen purity: 99.9 % (Ruth 2009)
- Process thermal efficiency (ratio of H2 LHV to total energy input to system): 66.8%

The centralized biomass gasification pathway assumes that woody biomass feedstock within a 50-mile radius is collected and transported via truck to the hydrogen production facility. A biomass gasifier converts the biomass to syngas, which is then upgraded to hydrogen. PSA is used to obtain the required hydrogen purity (Ruth 2005). During the upgrading step, the syngas generated from the gasification process is cleaned up and subjected to the water gas shift reaction. The product gas is sent to a gas cleanup unit and a hydrogen separator to achieve the required hydrogen purity. The hydrogen is then subject to compression and/or liquefaction for storage. The biomass source for this study is assumed to be switchgrass and the overall thermal efficiency of biomass gasification to gaseous hydrogen is assumed to be 57%.

Table 9. Well-to-Tank Energy Consumption and Emissions for the electrolysis and gasification pathways

	FCV: G.H2, Central Plants, NANG	FCV: G.H2, Central Plants, Solar	FCV: G.H2, Central Plants, Biomass
	Btu/MJ or g/MJ	Btu/MJ or g/MJ	Btu/MJ or g/MJ
Total Energy	893	686	1,995
WTP Efficiency	84.3%	0.00	0.00
Fossil Fuels	872	-637	503
Coal	139	-829	35
Natural Gas	703	1,118	404
Petroleum	30	0	65
CO2 (w/ C in VOC & CO)	113	24	34
CH4	0	0	0
N2O	0	0	0
GHGs	123	25.20	45.00
VOC: Total	11.10	0.00	0.01
CO: Total	35.67	0.02	0.05
NOx: Total	48.00	0.04	0.09
PM10: Total	1.61	0.01	0.01
PM2.5: Total	1.13	0.00	0.00
SOx: Total	21.75	0.05	0.06
VOC: Urban	0.67	0.00	0.00
CO: Urban	3.51	0.00	0.01
NOx: Urban	4.97	0.01	0.01
PM10: Urban	0.32	0.00	0.00
PM2.5: Urban	0.23	0.00	0.00
SOx: Urban	3.07	0.01	0.00

Table 10. Well to Wheel energy consumption and emissions for gaseous hydrogen production via centralized natural gas reforming pathway

FCV: G.H2, Central Plants, NA NG								
	Btu/mile or g/mile				Btu/MJ or g/MJ			
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	280.831	1747.340	2153.472	4181.643	123.603	769.065	947.818	1840.487
Fossil Fuels	279.989	1701.283	2153.472	4134.743	123.233	748.794	947.818	1819.844
Coal	5.671	309.745	0.000	315.416	2.496	136.330	0.000	138.826
Natural Gas	264.247	1333.005	2153.472	3750.724	116.304	586.702	947.818	1650.824
Petroleum	10.070	58.532	0.000	68.603	4.432	25.762	0.000	30.194
CO2 (w/ C in VOC & CO)	15.522	242.327	0.000	257.849	6.832	106.656	0.000	113.488
CH4	0.466	0.306	0.000	0.772	0.205	0.135	0.000	0.340
N2O	0.003	0.003	0.000	0.006	0.001	0.001	0.000	0.003
GHGs	28.175	250.862	0.000	279.037	12.401	110.413	0.000	122.814
VOC: Total	0.023	0.022	0.000	0.046	0.010	0.010	0.000	0.020
CO: Total	0.075	0.099	0.000	0.174	0.033	0.043	0.000	0.077
NOx: Total	0.095	0.180	0.000	0.275	0.042	0.079	0.000	0.121
PM10: Total	0.001	0.042	0.018	0.061	0.001	0.019	0.008	0.027
PM2.5: Total	0.001	0.036	0.005	0.042	0.000	0.016	0.002	0.018
SOx: Total	0.027	0.145	0.000	0.172	0.012	0.064	0.000	0.076
VOC: Urban	0.001	0.003	0.000	0.004	0.001	0.001	0.000	0.002
CO: Urban	0.007	0.018	0.000	0.025	0.003	0.008	0.000	0.011
NOx: Urban	0.008	0.036	0.000	0.044	0.004	0.016	0.000	0.019
PM10: Urban	0.000	0.011	0.013	0.023	0.000	0.005	0.006	0.010
PM2.5: Urban	0.000	0.010	0.003	0.013	0.000	0.004	0.001	0.006
SOx: Urban	0.001	0.039	0.000	0.040	0.000	0.017	0.000	0.018

Table 11. Well to Wheel energy consumption and emissions for gaseous hydrogen production via centralized electrolysis pathway

FCV: G.H2, Central Plants, Solar								
	Btu/mile or g/mile				Btu/MJ or g/MJ			
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	812.743	745.846	2153.472	3712.060	357.716	328.273	947.818	1633.807
Fossil Fuels	0.000	705.651	0.000	705.651	0.000	310.582	0.000	310.582
Coal	0.000	270.312	0.000	270.312	0.000	118.974	0.000	118.974
Natural Gas	0.000	387.177	0.000	387.177	0.000	170.410	0.000	170.410
Petroleum	0.000	48.163	0.000	48.163	0.000	21.198	0.000	21.198
CO2 (w/ C in VOC & CO)	0.000	53.977	0.000	53.977	0.000	23.757	0.000	23.757
CH4	0.000	0.117	0.000	0.117	0.000	0.052	0.000	0.052
N2O	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.001
GHGs	0.000	57.263	0.000	57.263	0.000	25.204	0.000	25.204
VOC: Total	0.000	0.007	0.000	0.007	0.000	0.003	0.000	0.003
CO: Total	0.000	0.035	0.000	0.035	0.000	0.015	0.000	0.015
NOx: Total	0.000	0.084	0.000	0.084	0.000	0.037	0.000	0.037
PM10: Total	0.000	0.013	0.018	0.031	0.000	0.006	0.008	0.014
PM2.5: Total	0.000	0.008	0.005	0.013	0.000	0.004	0.002	0.006
SOx: Total	0.000	0.119	0.000	0.119	0.000	0.052	0.000	0.052
VOC: Urban	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000
CO: Urban	0.000	0.007	0.000	0.007	0.000	0.003	0.000	0.003
NOx: Urban	0.000	0.018	0.000	0.018	0.000	0.008	0.000	0.008
PM10: Urban	0.000	0.004	0.013	0.016	0.000	0.002	0.006	0.007
PM2.5: Urban	0.000	0.002	0.003	0.006	0.000	0.001	0.001	0.003
SOx: Urban	0.000	0.034	0.000	0.034	0.000	0.015	0.000	0.015

Table 12. Well to Wheel energy consumption and emissions for gaseous hydrogen production via centralized biomass gasification pathway

FCV: G.H2, Central Plants, Biomass								
	Btu/mile or g/mile				Btu/MJ or g/MJ			
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	705.949	3825.878	2153.472	6685.299	310.713	1683.902	947.818	2942.433
Fossil Fuels	147.484	996.480	0.000	1143.964	64.913	438.585	0.000	503.498
Coal	1.758	77.467	0.000	79.225	0.774	34.096	0.000	34.870
Natural Gas	82.895	834.104	0.000	916.999	36.485	367.118	0.000	403.603
Petroleum	62.831	84.909	0.000	147.740	27.654	37.371	0.000	65.025
CO2 (w/ C in VOC & CO)	11.508	65.205	0.000	76.713	5.065	28.699	0.000	33.764
CH4	0.022	0.178	0.000	0.200	0.010	0.078	0.000	0.088
N2O	0.033	0.035	0.000	0.069	0.015	0.016	0.000	0.030
GHGs	22.014	80.222	0.000	102.236	9.689	35.308	0.000	44.998
VOC: Total	0.010	0.020	0.000	0.031	0.005	0.009	0.000	0.013
CO: Total	0.024	0.080	0.000	0.104	0.011	0.035	0.000	0.046
NOx: Total	0.062	0.144	0.000	0.206	0.027	0.063	0.000	0.091
PM10: Total	0.004	0.010	0.018	0.031	0.002	0.004	0.008	0.014
PM2.5: Total	0.003	0.008	0.005	0.015	0.001	0.003	0.002	0.007
SOx: Total	0.030	0.108	0.000	0.138	0.013	0.048	0.000	0.061
VOC: Urban	0.000	0.002	0.000	0.002	0.000	0.001	0.000	0.001
CO: Urban	0.001	0.015	0.000	0.016	0.000	0.007	0.000	0.007
NOx: Urban	0.001	0.018	0.000	0.019	0.001	0.008	0.000	0.008
PM10: Urban	0.000	0.001	0.013	0.013	0.000	0.000	0.006	0.006
PM2.5: Urban	0.000	0.001	0.003	0.004	0.000	0.000	0.001	0.002
SOx: Urban	0.001	0.002	0.000	0.003	0.000	0.001	0.000	0.001

Economic Analysis

The economic analysis was conducted using the H2A cost analysis model. Assumptions used in the economic analysis and the results are discussed below. The pathways analyzed are:

- Electrolysis using renewable power
- Biomass gasification

The assumptions are listed below.

- Plant startup year: 2018
- Analysis Methodology — Discounted Cash Flow (DCF)
- Technology Development Stage — All Central and Forecourt cost estimates are based on mature, commercial facilities
- Equity financing: 20%
- Debt: 80%
- Interest rate on debt: 6%
- Depreciation schedule length: 20 years
- Depreciation type: MACRS
- Debt period: 20 years
- Plant life: 40 years
- Analysis period: 40 years
- 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
- Hydrogen Pressure at Gate – 1 bar
- Working capital: 15 % of yearly change in operating costs
- Length of construction period
    - 1 year (Electrolysis)
    - % of Capital Spent in 1^{st} year of Construction: 100%
    - Length of construction period: 3 year (Natural gas reforming and Biomass gasification)
    - % of Capital Spent in 1^{st} year of Construction: 8%
    - % of Capital Spent in 2^{nd} year of Construction: 60%
    - % of Capital Spent in 3^{rd} year of Construction: 32%
- Industrial electricity (U.S. 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)

- Cooling water
    - Price $(2012)/ Mgal: 86.28
- Process water
    - Price $(2012)/ Mgal: 1,807.67

The default assumptions from the H2A model are used except for the industrial natural gas price and equity value. The equity is assumed to be 20% and the industrial natural gas price is from the EIA's California natural gas prices database. The specific assumptions for each centralized pathway along with the hydrogen production costs are listed in Table 13[1].

Table 13. Specific assumptions and results for the centralized production pathways

Components	Solar electrolysis	Biomass gasification
Plant design basis (kg/day)	50,000	50,000
Operating capacity factor (%)	97	90
Reference year	2012	2012
Basis year	2012	2005
Primary feed	Electricity, Water	Woody biomass, Water
Operation type	PEM electrolyzer	Gasification
Primary feed usage	Electricity: 54.3 (kWh/kg H_2)	Biomass Feedstock: 12.8 kWh/kg H_2 Biomass feedstock price: 0.1 $(2012)/kg (Webb 2015) Process water: 1.321 gal/kg H_2
Utility usage	Cooling water: 290 gal/kg H_2	Commercial Natural gas: 0.2 Nm^3/kg H_2 Industrial electricity: 1 kWh/kg H_2 Cooling water: 79.26 gal/kg H_2

[1] Ramsden 2009, Ramsden, T., Steward, D., & Zuboy, J. (2009). Analyzing the levelized cost of centralized and distributed hydrogen production using the H2A production model, version 2 (No. NREL/TP-560-46267). National Renewable Energy Laboratory (NREL), Golden, CO.

Components	**Solar electrolysis**	**Biomass gasification**
Indirect Depreciable Capital Costs	Site preparation: $2,280,600 Engineering & design: $11,403,000 Process contingency: $ 8,008,000 Project contingency: $ 8,008,000 Up-Front Permitting Costs (legal and contractors fees included here): $ 17,104,500	Site preparation: $1,100,000 Engineering & design: $14,500,000 Project contingency: $ 16,800,000 Up-Front Permitting Costs (legal and contractors fees included here): $ 10,100,000
Non-Depreciable Capital Costs	Cost of land: $50,000/acre Land required: 5 acres	Cost of land: $50,000/acre Land required: 50 acres
Fixed Operating Costs	Total plant staff: 15 Burdened labor cost, including overhead ($/man-hr): 50 Production Maintenance and Repairs: $3,421,000/year	Total plant staff: 60 Burdened labor cost, including overhead ($/man-hr): 50 G&A rate: 20% of labor cost Property tax and Insurance rate: 2% of total capital investment Material costs for Maintenance and Repairs: $600,000/year
Other Variable Operating Costs (for the first year)	-	Other variable operating costs (e.g., environmental surcharges): $100,000/year Other Material Costs: $7,400,000/year Waste treatment costs: $1,300,000/year Solid waste disposal costs: $800,000/year
Unplanned Replacement Capital Cost Factor	0.5%	0.5%

Components	Solar electrolysis	Biomass gasification
Capital cost	Total: $101,812,500 Electrolyzer Stack: $47,852,000 Electrolyzer BoP: $53,961,000	Total: $ 111,900,000 Feed Handling & Drying: $20,100,000 Gasification, Tar Reforming, & Quench: $17,800,000 Compression & Sulfur Removal: $16,600,000 Steam Methane Reforming, Shift, and PSA: $32,100,000 Steam System and Power Generation: $15,300,000 Cooling Water and Other Utilities: $3,600,000 Buildings & Structures: $6,400,000
Installation cost factor	12% of the capital cost	Included in the capital cost
Replacement cost	15% of the capital cost Interval: 7 years	$5,900,000
Hydrogen production cost ($/kg H_2)	**6.16**	**2.49**

Outreach

As part of the outreach efforts, the UCR College of Engineering - Center for Environmental Research and Technology (CE-CERT) hosted a ribbon cutting ceremony for the Center for Renewable Natural Gas (CRNG) and a Renewable Natural Gas Symposium on May 17, 2017. The symposium included talks and in-depth discussions of RNG adoption from lab to market and was attended by more than 200 participants. Speakers at the event included Rob Oglesby, Executive Director, California Energy Commission, George Minter, Regional Vice President, Southern California Gas Company, Ryan McCarthy, Science & Technology Policy Advisor, California Air Resources Board, and Keith Wipke, Fuel Cell & Hydrogen Technologies Program Manager, National Renewable Energy Laboratory.

Panel discussion topics included Thermochemical RNG Production, Commercial Scale Power to Gas, RNG Policy in California, and Challenges to Expediting Commercial RNG Production.

Summary and Discussion

Renewable Natural Gas (RNG) is an important alternative fuel that can help the State of California meet several GHG and renewable energy targets. Despite considerable potential, current RNG use on national and state levels are not significant. As part of this grant, the University of California, Riverside (UCR) has established a research center dedicated to the development of technologies that will enable RNG production and use in substantial quantities in California and elsewhere. The new center, referred to as the Center for Renewable Natural Gas (CRNG), leverages on-going research and collaborations at the Bourns College of Engineering – Center for Environmental Research & Technology (CE-CERT) at UCR to maximize the impact.

RNG production potential in California through thermochemical conversion was evaluated by assessing technical biomass availability in the state. Biomass feedstocks are defined broadly and include most carbonaceous matter including waste. The types of waste biomass available in the state are classified into three categories: municipal solid waste (MSW), agricultural residue and forest residue. MSW is the largest biomass contributor in the state with approximately 18.0 MMBDT/year of technical production. The technical availability estimate for agricultural residues (including animal manure, food processing and fiber-based feedstocks) is about 8.6 MMBDT/year. The technical forest residue biomass availability in California is about 14.3 MMBDT/year. A total of 32.1 MMBDT per year of biomass is estimated to be technically available in the state. The energy content of this biomass is equivalent to approximately 602 million mmbtu/year.

The report also provides a survey of current renewable electricity generation and curtailment trends. A total of 615 solar power plants and 128 wind power plants are currently under operation in in the state. Real-time data from November 2016 to October 2017 show significant curtailment throughout the year ranging from 6.2 GWh to 85.2 GWh. During the entire twelve month study period, about 440 GWh of power was curtailed in California. Power to gas and other forms of long term storage integrated into the electric grid can mitigate these losses and also allow smooth integration of additional renewables into the grid.

Oxygen/air blown gasification, hydrogasification and pyrolysis are the three major technology options available for biomass conversion to gas. A literature survey of available thermochemical conversion technologies was conducted. Although there are no commercial thermochemical biomass to RNG conversion facilities in operation, a number of gasification and pyrolysis technologies are undergoing pilot scale demonstration and development. Design basis for two thermochemical and power to gas conversion projects were developed as part of this project. Life cycle and economic analysis were conducted for the recommended processes. The results show that the renewable technology pathways result in significantly reduced GHG emissions, criteria pollutants, and air toxics. The renewable pathways also help reduce short lived climate pollutant emissions by reducing Particulate Matter. The economic analysis results show higher production costs for the renewable pathways, especially electrolysis. Significant research, development, and deployment efforts are necessary to achieve successful commercialization of thermochemical RNG production.

Outreach and education activities including a ribbon cutting ceremony for the Center for Renewable Natural Gas and an RNG themed symposium were also conducted as part of the project.

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