Title

Waste to Hydrogren: Analysis of viable pathways, costs, and benefits of producing hydrogen from waste in California

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WASTE TO HYDROGEN

Analysis of viable pathways, costs, and benefits of producing hydrogen from waste in California

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Abstract

Producing hydrogen from waste provides an opportunity to divert waste from landfills while simultaneously transforming the hydrogen market away from fossil fuel production pathways, reducing market uncertainty for hydrogen as a clean energy carrier. This report aims to provide a deeper understanding of waste-to-hydrogen pathways by outlining existing and emerging waste management methods in California, explaining which pathways can produce hydrogen from different waste streams, and analyzing the costs and benefits of municipal solid waste gasification in Los Angeles County. The results of this analysis reiterate the profound differences between emerging thermochemical conversion technologies and the outdated transformation pathway of incineration. The lack of recognition of these differences in the policy landscape calls for two key recommendations. First, using novel satellite technology to more accurately measure and track landfill methane emissions to better quantify the social cost of landfilling and allow more informed comparisons of alternative technologies to this default disposal method. The second recommendation is to change the definition of gasification under state legislature to recognize hydrogen production as a viable output from the gasification process. Alternative technologies like gasification of waste to generate hydrogen have the potential to complement current waste management methods while leveraging a renewable hydrogen market, and this should be reflected more heavily in California state policy.

Introduction

Every year, over two billion tons of waste are sent to landfills across the globe and 8 million tons of plastic end up in the ocean. Californians alone generate over 77 million tons of solid waste, 44 million tons of which are sent to landfills[1]. As the waste crisis continues to grow, the world also faces unprecedented climate changes as warming greenhouse gases are emitted into the atmosphere, creating the need for transformation of the global energy system away from carbon-intensive fossil fuels. As technology and policy persist towards decarbonization, more innovative options to generate useful products from waste sources are emerging, to divert waste from oceans, land, and landfills, and attempt to create value from a source that is currently polluting the planet.

All waste management techniques, from landfilling, recycling, and composting, to incineration and anaerobic digestion, have diverse sets of byproducts, emissions characteristics, and potentially useful outputs. One waste management method that is beginning to gain attention for further research is thermochemical conversion of waste to produce hydrogen. The current hydrogen market is dependent on fossil-fuels for production, emitting over 680 million metric tons of carbon dioxide emissions every year.[2] Despite the carbon intensity of this industry, the actual consumption of hydrogen does not produce harmful greenhouse gas emissions, so reforming the production method is the most significant contributor to lowering the carbon intensity of the industry. Because of this zero-emissions end-use characteristic of hydrogen, combined with its ability to carry and store energy, the demand for hydrogen in California and globally is projected to continue increasing as the world works towards decarbonization goals.[3] However, zero-carbon production

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[1] CalRecycle, "California's 2019 Per Capita Disposal Rate Estimate," CalRecycle (State of California, February 17, 2021), https://www.calrecycle.ca.gov/lgcentral/goalmeasure/disposalrate/mostrecent.

[2] Laura Nelson et al., "Green Hydrogen Guidebook" (Green Hydrogen Coalition, August 2020), https://www.ghcoalition.org/guidebook.

[3] Jeffrey Reed et al., "Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California" (California Energy Commission, 2020).

methods are not currently competitive with fossil fuel alternatives, requiring innovative market solutions such as waste-to-hydrogen.

Exploring waste-to-hydrogen pathways is important for waste reduction strategies and decarbonizing the current and future hydrogen markets. Presently, conventional waste-to-energy methods are outdated and have greenhouse gas, toxic pollutant, and carcinogen emissions consequences that contribute to climate change, poor local air quality, water pollution, and create public health concerns. It is important to understand the advantages and consequences of new technologies that can generate hydrogen while subsequently reducing waste to ensure that these processes create a net benefit to the climate without harming the communities where waste-to-energy facilities are located. This understanding can also help make more informed policy decisions on the topic.

California's policy landscape is heavily focused on landfill diversion of recyclable materials and biomass waste. Procurement of these programs for the purpose of landfill diversion and generation of valuable goods or biofuels from these processes is extremely important towards reaching landfill diversion and greenhouse gas emissions goals. However, through strict definitions, contradictions and inconsistencies between different policies, there is currently a barrier for technologies that may have the potential to divert other waste streams, such as municipal solid waste and non-recyclable plastics, from landfills to generate valuable outputs.

This paper will begin by providing an overview of the main waste management methods in California, including the feasible waste stream inputs, potentially valuable outputs, benefits, and byproducts or other costs associated with conventional and emerging waste management methods. It will then explain how processes to generate hydrogen from waste can provide benefits and can fit into the clean energy transition by explaining the current market and future vision for hydrogen as an energy source. Next, waste-to-hydrogen is examined in greater detail, with an outline of the pathways to generate hydrogen from waste and the opportunities and challenges with each pathway. This will also include a case study focusing on Los Angeles County, with an analysis on the costs and benefits for gasification of municipal solid waste as compared to incineration. Finally, a policy analysis will lay out the current policy background as it relates to waste-to-hydrogen and recommendations to move forward.

Table 1: Overview of existing and emerging waste management methods in California

Destination	% of waste to destination in CA[4]	Feasible Inputs	Useful outputs	Pros	Byproducts & costs
Landfill	55%	-MSW -contaminated recyclables -biomass	Captured methane for fuel	-diversity of inputs -biogas produced by methane is cheap fuel source	-land use -methane emissions -local emissions, odors -capacity limits -high tipping fees
Mechanical recycling	37%	-recyclable plastics (1&2) -cardboard -paper	Consumer goods	-reduces raw material use for consumer goods	-reduced value in recent years -sorting requirements leading to human error

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[4] California Department of Resources Recycling and Recovery (CalRecycle), ed., "State of Disposal and Recycling for Calendar Year 2019" (CalRecycle, February 12, 2021), www.calrecycle.ca.gov/Publications/.

				-diversion from landfill	-large water and energy requirements
Composting	Included in recycling	-biomass	Nutrient-rich fertilizer	-small to large scale -increases carbon sequestration in soil	-limited inputs and outputs -local odors -NOx and PM2.5 formation[5]
Biochemical conversion – anaerobic digestion	12%	-organic waste or biomass	-Biogas (heating, transportation, electricity, renewable natural gas) **-hydrogen**	-diversion from landfill -LCFS credits -limited emissions if sorted properly -negative emission potential in future	-limited feedstocks and useful outputs -biogas cleanup requirements
Transformation (ie. incineration or mass burn facilities)	1%	-municipal solid waste -sewage sludge -ash byproduct combined with cement to make roads	-Electric power	-diverts waste from landfills -powers homes -diversity of possible inputs	-GHG emissions -toxins and carcinogens -only one useful output (electricity), for which we can produce cheaper and cleaner -ash byproduct
Thermochemical conversion - gasification	0%	-biomass -MSW -medical waste and toxic waste -sewage sludge -ash byproduct mixed with cement to make roads	-Syngas → -electricity, heat -**hydrogen** -chemicals -liquid fuels	-diversity of feedstocks and high-quality outputs -demonstrated at commercial scale (with different feedstocks) -easier to clean downstream before air emissions occur -negative emission potential in future	-not demonstrated at commercial scale with waste as a feedstock -GHG emissions -Ash and tar by-products -requires extremely high temperatures -local pollutants (meet EPA standards but still emitted)
Thermochemical conversion – pyrolysis	0%	-biomass -MSW -plastics	-bio-oil→**hydrogen,** transport fuel, electricity	-lack of oxygen input restricts gaseous emissions -biochar has useful applications	-not demonstrated at commercial scale for h2 production -Tars and char byproducts

Table 1 summarizes the major destinations for waste in California, all of which differ in the type of waste inputs, useful outputs, beneficial features, inherent issues, and byproducts.

Part 1: Existing and emerging waste management practices

The purpose of this section is to give an overview of the possible destinations for different waste streams, useful outputs that can create value from the waste, and inherent issues with these different applications. Each section will also highlight potential pathways to generate hydrogen in relevance to each waste management method. The main takeaways from this section are highlighted in Table 1.

1.1 Landfills

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[5] CalRecycle Organic Materials, "Composting Emissions and Air Permits," Composting Emissions and Air Permits (CalRecycle, June 2, 2021), https://www.calrecycle.ca.gov/organics/air.

Landfills are the conventional disposal method of waste, particularly municipal solid waste, in the United States. As of 2019, California had 298 landfill sites within the state.[6] As of 2015, 98 of these landfills were actively operating.[7]

Issues

The greatest climate impact from landfills come from methane emissions. When organic waste, such as food, yard waste, agricultural residue, and other waste that is sourced from living organisms is disposed of in landfills, anaerobic microbes digest them and release methane and carbon dioxide. At least 20% of methane emissions in California are from landfill point sources.[8] Since methane is 56 times more potent in terms of warming potential than carbon dioxide over a 20-year period, reducing organic waste in landfills is a priority for global warming mitigation.[9]

Landfills also emit toxins and carcinogens that are hazardous to the air quality and human health within local communities, such as vinyl chloride, ethyl benzene, toluene, and benzene.[10] Another environmental issue with landfills are the long-term land-use requirements. Since the waste that is disposed of in landfills is heterogeneous and combines a mixture of materials that do not naturally decompose, the land-use requirements for landfill disposal is large and long-term.

Useful outputs

The methane and carbon dioxide by-products of organic waste disposal, also referred to as biogas, can be collected from landfills and used as an energy resource. This is a simple and low-cost installation process since installing pipelines in landfills allows the biogas to spontaneously flow to a central location. In 2016, SoCalGas averaged a price for the renewable natural gas sold from landfills at $3.00 per MMBtu.[11] As of 2019, 143 of the 298 active and inactive landfills in California were listed as having systems to collect biogas.[12] It is important to note that landfills equipped with methane collection equipment still emit some methane into the atmosphere.[13]

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[6] Sarah E Baker et al., “Getting to Neutral: Options for Negative Carbon Emissions in California” (Livermore, CA: Lawrence Livermore National Laboratory, 2020), 35.

[7] CalRecycle Staff, “Landfill Tipping Fees in California” Sacramento, CA: California Department of Resources Recycling and Recovery, 2015), 3.

[8] Sarah E Baker et al., “Getting to Neutral: Options for Negative Carbon Emissions in California” p. 34. (Livermore, CA: Lawrence Livermore National Laboratory, 2020).

[9] Intergovernmental Panel on Climate Chance, “Global Warming Potentials ,” United Nations Climate Change (United Nations, 2021), https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials.

[10] EPA, “Municipal Solid Waste Landfills: National Emission Standards for Hazardous Air Pollutants (NESHAP),” EPA (Environmental Protection Agency, May 12, 2021), https://www.epa.gov/stationary-sources-air-pollution/municipal-solid-waste-landfills-national-emission-standards.

[11] SoCal Gas, “Biogas and Renewable Natural Gas ,” SoCalGas, A Sempra Energy utility, accessed June 2021, https://www.socalgas.com/clean-energy/renewable-gas/biogas-and-renewable-natural-gas.

[12] Sarah E Baker et al., “Getting to Neutral: Options for Negative Carbon Emissions in California” (Livermore, CA: Lawrence Livermore National Laboratory, 2020), 35.

[13] Thomas Kirchstetter and Corinne Scown et al., “Enabling Anaerobic Digestion Deployment to Convert Municipal Solid Waste to Energy ”(Berkeley, CA: California Energy Commission, 2020).

The resulting biogas is most commonly used as fuel in transportation, or processed and upgraded to renewable natural gas for uses like heating, cooking, and electricity production through the electric power grid.[14] Despite the fact that biogas products do emit greenhouse gases when consumed, they are considered renewable since the fuel originates from sources that would otherwise break down and emit greenhouse gases over time, and is therefore eligible for credits under California's low carbon fuel standard (LCFS).

Landfills that have reached capacity and are closed for future disposal still release biogas at a decreasing rate of 2-5% per year and are good contenders for production of low-cost renewable natural gas or electricity production.[15] Additionally, hydrogen can be produced from the biomethane that is collected from landfills through steam methane reformation. This is the same as the conventional process of steam methane reformation using natural gas, however since this is renewable methane from landfills, the hydrogen output is also renewable.

Tipping fees

In addition to the social costs of landfills contributing to warming through methane emissions, adverse health effects from local pollution, and high land-use, there are also direct financial costs to dispose of waste in landfills in the form of tipping fees. These fees are charged by both public and private landfills and fall on either waste management and collection companies or municipalities and taxpayers. The median tipping fee in Southern California, where 61% of the state's waste is disposed, is $56 per ton, $11 higher than the state median at $45 per ton. With a statewide range of $0-125, this is highly variable throughout California. In general, private landfill tipping fees are higher than public landfills since they do not also rely on tax revenue to operate. [16] There are 71 public and 27 private active landfills in the state as of 2015. [17] Overall, there is a general lack of transparency with landfill tipping fees in California, but there is consensus that tipping fees will continue to increase as landfills begin to reach capacity.

1.2 Mechanical Recycling

While 28.9 million tons of waste were recycled in 2019, making up 37% of the waste generated, this represents a low point in the continuously decreasing recycling rate in the state from its peak of 50% in 2014.[18] This 2019 value falls short of state's goal to recycle 75% of waste in 2020 by 29.2 million tons of waste.[19]

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[14] National Grid, "What Is Biogas?," What is biogas? | National Grid Group (National Grid, 2021), https://www.nationalgrid.com/stories/energy-explained/what-is-biogas.

[15] "21st Century Complete Guide to Biogas and Methane," U.S. Government Department of Agriculture and Environmental Protection Agency (Progressive Management Publications, 2015).

[16] CalRecycle Staff, "Landfill Tipping Fees in California" Sacramento, CA: California Department of Resources Recycling and Recovery, 2015), 22-24

[17] CalRecycle Staff, "Landfill Tipping Fees in California" Sacramento, CA: California Department of Resources Recycling and Recovery, 2015), 24

[18] California Department of Resources Recycling and Recovery (CalRecycle), ed., "State of Disposal and Recycling for Calendar Year 2019" (CalRecycle, February 12, 2021), www.calrecycle.ca.gov/Publications/.

[19] California Department of Resources Recycling and Recovery (CalRecycle), ed., "State of Disposal and Recycling for Calendar Year 2019" (CalRecycle, February 12, 2021), www.calrecycle.ca.gov/Publications/.

Although recycling requires high energy and water input, the process is still incredibly beneficial from environmental, economic, and waste reduction standpoints as it reduces the amount of raw material needed to make consumer goods. The greatest roadblock to increasing California's recycling rate is low quality bales from contamination and sorting discrepancies, primarily due to human error. In California, if 10% or more of a facilities haul is residual material, either being non-recyclable or contaminated, it must be sent to landfill.[20]

The value for recyclables has also decreased significantly in recent years as recycling facilities overseas tighten standards. In 2017, 55% of California's recyclable material was shipped overseas to China. However, China's National Sword Policies restrict 24 types of waste materials and limit contamination to 0.5% as of 2018. Meanwhile, estimated 20-35% of what Californians recycle is not actually recyclable, such as containers with food or oil residues, or soft plastic bags that cannot go through the same machinery as other forms of plastic waste. With this, California and the rest of the United States face obstacles with insufficient infrastructure and reduced commodity price to build on the recyclable market.

The prominent solution to create higher quality materials from recyclables is ultimately a higher quality feedstock, meaning addressing the issues with sorting and contamination of recyclables. Programs are underway to find solutions, like robotic sorting techniques and education to communities on which products are recyclable to reduce contamination and residual material.

Since plastics are essentially made up of carbon and hydrogen, or hydrocarbons, and other recyclables such as paper and cardboard are organic materials, these are all potential feedstocks for hydrogen extraction from thermochemical conversion, discussed in more detail in section 1.4. Alternative technologies should not compete with conventional mechanical recycling efforts and development of new programs to meet recycling goals, however with the recent reduction in recycling rates it is also important to consider options for the contaminated and low value bales that will otherwise be sent to landfills, or worse, the ocean.

1.3 Composting

Composting is the aerobic decomposition of organic waste feedstocks into compost, a nutrient-rich substance that can improve soil health that is primarily used in organic farming methods.[21] One of the main benefits of composting is that it can be processed at a wide range of scales, from single households to commercial facilities. Additionally, there are carbon sequestration benefits to soils containing compost.[22] While there are few adverse impacts from composting organic

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[20] Heather Jones, "What's That in Your Curbside Bin?," What's That in Your Curbside Bin? (CalRecycle, February 23, 2017), https://www.calrecycle.ca.gov/blogs/in-the-loop/in-the-loop/2017/02/23/what-s-that-in-your-curbside-bin.

[21] Alan Abbs and Crystal Real-Chen, "Composting in California: Addressing Air Quality Permitting and Regulatory Issues for Expanding Infrastructure" (California Air Pollution Control Officers Association, California Air Resources Board, and CalRecycle, August 2018), http://californiacompostcoalition.org/wp-content/uploads/2018/11/FINALC1-1.pdf, 9.

[22] Alan Abbs and Crystal Real-Chen, "Composting in California: Addressing Air Quality Permitting and Regulatory Issues for Expanding Infrastructure" (California Air Pollution Control Officers Association, California Air Resources Board, and CalRecycle, August 2018), http://californiacompostcoalition.org/wp-content/uploads/2018/11/FINALC1-1.pdf, 12.

material, there are concerns with potential contamination, particularly when the biogenic portion of municipal solid waste is used to generate compost.[23]

Procurement of composting programs in California is underway as SB-1383 sets goals for 75% diversion of organic waste from landfills. Under California policy, composting is considered a recycling activity, and it is therefore not subject to the same restrictions as other diversion processes, which will be discussed further in Part 4.

1.4 Waste-to-energy: Incineration, biochemical conversion, and thermochemical conversion

In addition to conventional waste disposal and recycling options, recovering useful energy from waste is another common practice in California. The two primary existing waste-to-energy methods include incineration and biochemical conversion. While incineration is an outdated approach to recover energy from waste, also known as transformation and is subject to restrictions, anaerobic digestion is more heavily incentivized through policy. Thermochemical conversion of waste is an emerging process, but modernization of these technologies can differentiate from incineration providing a potentially cleaner opportunity to generate a useful fuel, including hydrogen production. This section will clarify in more detail the notable differences between waste-to-energy technologies and their status in California.

1.4.1 Incineration

Incineration is the historically conventional method of transforming waste into electricity. Most commonly this is performed at mass burn facilities, where a large volume of waste is used as a fuel and burned in the presence of air to release carbon dioxide and heat. This generates steam and drives a turbine to produce electricity that can be sent to the grid to power homes.

Issues

In addition to emitting carbon dioxide and methane into the atmosphere through this process, burning waste also emits dioxins and furans, both of which are carcinogens and have long term health consequences on surrounding communities.[24] Nitrous oxides and sulfur oxides are also emitted from these facilities, contributing to air pollution, ozone formation, and smog.[25] Despite the implementation of pollution control systems such as scrubbers and filters, there is a limit to how much these harmful compounds can be cleaned. Since the combustion process emits them in gaseous form, clean-up must occur downstream making it logistically impossible to remove all the harmful substances before being emitted into the atmosphere.[26]

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[23] Alan Abbs and Crystal Real-Chen, "Composting in California: Addressing Air Quality Permitting and Regulatory Issues for Expanding Infrastructure" (California Air Pollution Control Officers Association, California Air Resources Board, and CalRecycle, August 2018), http://californiacompostcoalition.org/wp-content/uploads/2018/11/FINALC1-1.pdf, 14.

[24] GSTC, "Waste to Energy Gasification," Global Syngas Technologies Council, April 27, 2021, https://globalsyngas.org/syngas-technology/syngas-production/waste-to-energy-gasification/.

[25] National Research Council (US) Committee on Health Effects of Waste Incineration, "3. Incineration Processes and Environmental Releases," in *Waste Incineration and Public Health* (Washington, DC: National Academies Press, 2000).

[26] GSTC, "Waste to Energy Gasification," Global Syngas Technologies Council, April 27, 2021, https://globalsyngas.org/syngas-technology/syngas-production/waste-to-energy-gasification/.

Incineration plants are reliant on constant flow of incoming waste in order to remain economical and provide a steady flow of electricity output, creating logistical issues with transportation of waste to the facilities, where there is often congestion, pollution, and destruction to roads from the constant inflow of waste material.[27] Additionally, about 10% volume and 30% weight of the total MSW feedstock that is combusted generates ash byproduct, which contains toxic elements and must be sent to landfill.[28] There are also instances of ash in the road near incineration plants, and clogging sewage drains near the Long Beach facility.

Useful output

There is diversity in the waste streams that can be used as fuel for incineration, including municipal solid waste with non-combustibles removed, biomass, hazardous and medical waste. However, the useful output of incineration is limited to electricity production.

Status in California

There are currently two incinerators in operation in California. The Southeast Resource Recovery Facility (SERRF) is in Long Beach of Los Angeles County and transforms 1438 tons of municipal solid waste per day, with a generating capacity of 36 MW, powering 25,000 homes. This incinerator recently underwent $8 million in operational repairs to keep it operating until 2024 but is expected to phase out within the next decade due to old age. The second facility is in Stanislaus county, and powers 18,000 homes with 22.5 MW of electricity.[29]

It is highly unlikely that incineration will continue to be a form of electricity production after these two facilities stop operating. Aside from state policies, the public perspective towards incineration is the main factor in preventing this outdated energy source from continuing to operate as the consequences on local communities make it an unviable source of production. A 2019 study also shows that 80% of the country’s incinerators are in low-income neighborhoods, creating environmental justice issues with this source of waste management and electricity production.[30] With emissions reduction goals and availability of zero-emission electricity production sources, this an outdated form of waste management and energy production in the state of California.

1.4.2 Biochemical conversion: Anaerobic digestion

In anaerobic digestion, bacteria break down organic matter in the absence of oxygen. The feedstocks are limited to biomass, including manure, wastewater, food waste, agricultural residue, and the organic portion of municipal solid waste such as cardboard and paper.

There are two primary useful outputs from anaerobic digestion, including biogas and digestate. Biogas from anaerobic digestion reactors have same functions as landfill biogas, including electricity, transportation fuel, and purification to generate renewable natural gas. Digestate is the

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[27] Ways2H. Interview with MSW Gasifiation Developer. Personal, May 18, 2021.

[28] National Research Council (US) Committee on Health Effects of Waste Incineration, “3. Incineration Processes and Environmental Releases,” in *Waste Incineration and Public Health* (Washington, DC: National Academies Press, 2000).

[29] Kelly Puente, “Long Beach Is One of 2 Cities in California That Still Burns Trash. Will the Future Be Greener? ,” Long Beach Post News (Long Beach Post , June 11, 2019), https://lbpost.com/news/long-beach-is-one-of-2-cities-in-california-that-still-burns-trash-will-the-future-be-greener.

[30] Ana Isabel Baptista and Adrienne Perovich, “U.S. Municipal Solid Waste Incinerators: An Industry in Decline” (New York, NY: Tishman Environment and Design Center , 2019).

byproduct of the digestion process which can be separated and used for organic fertilizer, animal bedding, crop irrigation, and other agricultural applications. [31]

Hydrogen can also be generated by anaerobic digestion of organic waste by modifying the process, either through inhibiting methanation before the hydrogen and carbon combine to generate methane for renewable natural gas, or reformation of the methane produced.[32] Both of these processes are still being developed and are not commercially realized; however, it is an option for future renewable hydrogen supply from organic waste sources.

Issues

Even though biogas is a renewable fuel source, it is still a fuel composed of methane and carbon dioxide that are emitted when combusted, either as renewable natural gas, transportation fuel, or electricity production. One potentially adverse effect of making a larger market for biogas and renewable natural gas is the possibility of generating organic material specifically for this purpose, rather than solely using the waste sources, however this is not currently an issue in California.

Status in California

The availability of organic waste feedstock is projected to increase in California, with an estimated 54 million tons of biomass will be available in 2025 and 56 million tons in 2045. This is caused by a combination of 11% forecasted population growth of, which will require an increase in food availability and agriculture, and a lengthened farming season with climate change, lowering crop yield, and leading to more agricultural residue that must be managed.[33]

There are currently 15 anaerobic digestion reactors operating in California with 16 projects pending throughout the state.[34] This is primarily in response to policies that incentivize diversion of organic waste from landfills, such as SB 1383, and credits for renewable fuels by the low carbon fuel standard. [35]

1.4.3 Thermochemical conversion: gasification

Gasification converts feedstocks into a mixture of gases called synthesis gas, or syngas, composed primarily of carbon monoxide and hydrogen, and typically also contains nitrogen and carbon dioxide. While there are multiple different types of gasifiers that can differ in feedstocks, emissions, and syngas properties, they are all essentially vessels that provide a high temperature, high pressure environment with a small amount of oxygen and steam to create a chemical reaction to convert the feedstock into syngas and ash. Figure 1 shows the diverse set of outputs that are viable from syngas, including power, heat, chemicals, fuel, and hydrogen.

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[31] U.S. Environmental Protection Agency, "How Does Anaerobic Digestion Work?," EPA (Environmental Protection Agency, January 22, 2021), https://www.epa.gov/agstar/how-does-anaerobic-digestion-work.

[32] A. Zappi, R. Hernandez, and W. E. Holmes, "A Review of Hydrogen Production from Anaerobic Digestion," *International Journal of Environmental Science and Technology*, December 2021, https://doi.org/10.1007/s13762-020-03117-w.

[33] Sarah E Baker et al., "Getting to Neutral: Options for Negative Carbon Emissions in California" (Livermore, CA: Lawrence Livermore National Laboratory, 2020).

[34] CalRecycle, "California Anaerobic Digestion Projects Accepting Organics from the Municipal Solid Waste Stream (May 2021)" (Sacramento, May 2021).

[35] CalRecycle, "Anaerobic Digestion," CA.gov (CalRecycle, June 18, 2020), https://www.calrecycle.ca.gov/swfacilities/compostables/anaerobicdig.

Gasification differs from incineration in two ways. First, there is no combustion of raw material involved in the gasification process, meaning the syngas can be cleaned and treated upstream, prior to the point when gaseous substances are released into the atmosphere. This allows for greater control over emissions of both greenhouse gases, toxic substances, and higher quality products. Second, there is more diversity the potential useful outputs generated from the syngas. Figure 3 shows all the reactions that syngas can undergo to create various products, from power and heat if combusted, to hydrogen and other fuels if the syngas is purified. This diversity of both inputs and outputs from the gasification process and the ability to clean syngas before emissions occur are the most significant distinctions compared to other waste-to-energy options.[36]

Development status and efficiency for hydrogen production

Gasification is proven and currently utilized at a commercial scale using coal as a feedstock. Gasifiers can generate syngas with any carbon-based material, such as biomass, plastics, and municipal solid waste, with few technical modifications. This makes it an extremely flexible technology in terms of waste reduction, however the use of waste as a feedstock for gasification is not yet used at a commercial scale in the United States. Therefore, while gasification itself is widely used, the application to waste management is not yet fully realized.

Despite the similarities between types of gasification, there are significant differences between feedstocks in gasification. In terms of hydrogen, biomass gasification provides the highest efficiency compared to other hydrogen production methods, including coal gasification, electrolysis, and natural gas steam methane reforming.[37] The exergy efficiency of biomass gasification is 60%, compared to fossil fuel reforming which ranges from 45-50%. Annex 1 provides a more comprehensive comparison of the variation between different feedstock for gasification.

Negative emission potential

One prospective benefit of biomass gasification that is gaining recognition is its potential for a negative emissions pathway. Since the water gas shift reaction generates pure hydrogen that is separate from carbon molecules present in the syngas, this provides an opportunity to capture and sequester more carbon than any other waste-to-energy pathway.[38] When biomass that would otherwise emit greenhouse gases into the atmosphere regardless of the disposal method is used as a feedstock, this is effectively removing emissions from the carbon cycle, making it a negative emissions pathway. While this is an important consideration for hydrogen production through gasification, it is important to note that CCS technologies are not yet commercially available, and this potential application is dependent on the scaling of this technology.

Despite its proven competitiveness with incineration environmentally, some of the most significant issues with gasification of waste include byproducts such as tar, ash, and flue gas. Additionally, without commercial scale data on air emissions and costs, this form of energy or fuel production has not been proven economically, particularly with systems that can accept municipal solid waste

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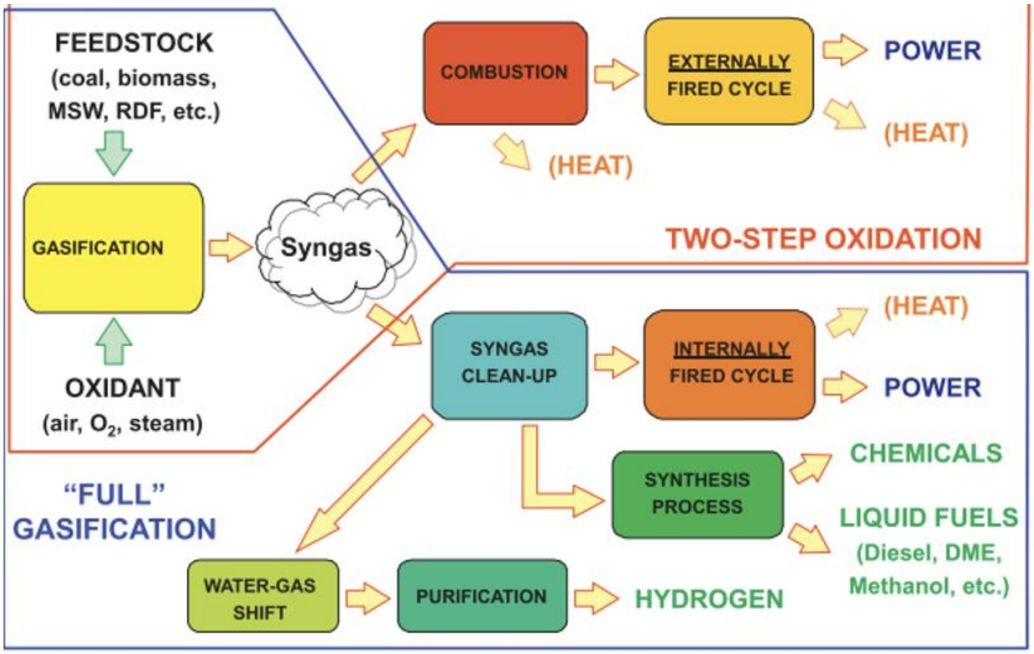
[36] Deborah Panepinto et al., "Environmental Performances and Energy Efficiency for MSW Gasification Treatment," *Waste and Biomass Valorization* 6, no. 1 (2014): pp. 123-135, https://doi.org/10.1007/s12649-014-9322-7.

[37] Ibrahim Dincer and Canan Acar, "Review and Evaluation of Hydrogen Production Methods for Better Sustainability," *International Journal of Hydrogen Energy* 40, no. 34 (2015): pp. 11094-11111, https://doi.org/10.1016/j.ijhydene.2014.12.035.

[38] Sarah E Baker et al., "Getting to Neutral: Options for Negative Carbon Emissions in California" (Livermore, CA: Lawrence Livermore National Laboratory, 2020), 53.

feedstocks.[39] It is estimated that about $100 million of investment will be required to make waste gasification technology commercially financeable for hydrogen fuel production in California.[40]

Figure 1: Gasification Overview[41]



4.4 Thermochemical conversion: pyrolysis

Pyrolysis is another kind of thermochemical conversion that decomposes feedstocks into bio-oil, like gasification, but in the absence of oxygen. The temperature and pressure required for this process are also lower than gasification. The bio-oil can be used as transportation fuel, combusted for electricity production, or go through the water-gas shift reaction to generate hydrogen.[42] The greatest opportunity for pyrolysis is, since it is operating in the absence of oxygen, flue gas is not released and all carbon content is solidified into char that can be landfilled without releasing emissions, added to soil, or used for concrete production.[43]

There are obstacles to the technological readiness of pyrolysis because of the tar by-products and other bottom residues that can create damage to the system and low yield of useful energy products

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[39] Sandra Teixeira et al., "Prospective Application of Municipal Solid Wastes for Energy Production in Portugal," *Energy Policy* 71 (2014): pp. 159-168, https://doi.org/10.1016/j.enpol.2014.04.002.

[40] Jeffrey Reed et al., "Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California" (California Energy Commission , 2020), 71.

[41] Consonni, S; Viganò, F. Waste gasification vs. conventional Waste-To-Energy: A comparative evaluation of two commercial technologies, *Waste Management*, Vol 32, Iss 4, 653-666 (2012)

[42] Sarah E Baker et al., "Getting to Neutral: Options for Negative Carbon Emissions in California" (Livermore, CA: Lawrence Livermore National Laboratory, 2020), 57.

[43] Sarah E Baker et al., "Getting to Neutral: Options for Negative Carbon Emissions in California" (Livermore, CA: Lawrence Livermore National Laboratory, 2020), 59.

compared to other waste-to-energy options.[44] Because the research on how to increase efficiency of the system and correctly handle byproducts is still underway, this technology has great potential but is still far enough behind in its development that it cannot yet be considered for near-term solutions for waste management or hydrogen production in California. The remainder of this paper will discuss pyrolysis as a potential waste-to-hydrogen pathway when applicable but focus more heavily on gasification as a thermochemical conversion process that is further along its developmental learning curve.

The purpose of this section is to provide a detailed overview of the most common existing and emerging waste management options in California to give a sense of the major disposal methods for later discussion on how these may impact procurement of waste-to-hydrogen policies. Part 2 will explain the significance of hydrogen as a commodity and energy carrier, why waste-to-hydrogen should be considered, and potential pathways to produce hydrogen from waste.

Part 2: Waste-to-hydrogen

As discussed in Part 1, there are many existing and potential methods to create valuable outputs from waste in California. One option that is not being utilized is producing hydrogen from waste streams. There are two central reasons why waste feedstocks should be considered for hydrogen production. First, the global hydrogen market must begin to reduce the fossil-fuel dependence to lower the carbon intensity of hydrogen production. Second, there is a growing demand for hydrogen because of its characteristics as an energy carrier that only emits water vapor when consumed. This leads to many applications in decarbonizing energy systems. However, if hydrogen supply is reliant on fossil fuel feedstocks, the carbon footprint of the industry will continue to rise in meeting this growing demand. Technologically, there are methods to produce hydrogen with zero associated lifecycle CO_2-eq emissions, but these are not currently cost competitive, and growing a carbon-free hydrogen economy requires innovative market and technological solutions to leverage a future for renewable hydrogen.

There are three main companies in the early stages of waste-to-hydrogen planning projects in California, including Ways2H, SGH2, and Standard Hydrogen. All of these companies have slightly different designs and face obstacles in the California policy landscape but are continuing to move forward with plans to commercialize the products because of the potential to reduce the waste problem while generating a high value but cheap supply of hydrogen.[45]

This section will provide more detail on the current and future hydrogen markets, the role that waste-to-hydrogen can play in meeting these two central goals for reducing the carbon intensity of the current hydrogen market and meeting the growing demand of hydrogen without increasing the carbon footprint of the market. Finally, an overview of projected supply and demand growth will lead into discussion on how supplying hydrogen from waste sources has an economic advantage over other hydrogen production methods and can therefore contribute to growing supply and

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[44] Deborah Panepinto et al., “Environmental Performances and Energy Efficiency for MSW Gasification Treatment,” *Waste and Biomass Valorization* 6, no. 1 (2014): pp. 123-135, https://doi.org/10.1007/s12649-014-9322-7.

[45] Arlene Karidis, “Could Trash-to-Energy Technology Feed Hydrogen Demand?,” Greenbiz (Greenbiz Group Inc., July 15, 2020), https://www.greenbiz.com/article/could-trash-energy-technology-feed-hydrogen-demand.

demand for reducing market uncertainty in order to help scale technology required to produce hydrogen with zero emissions.

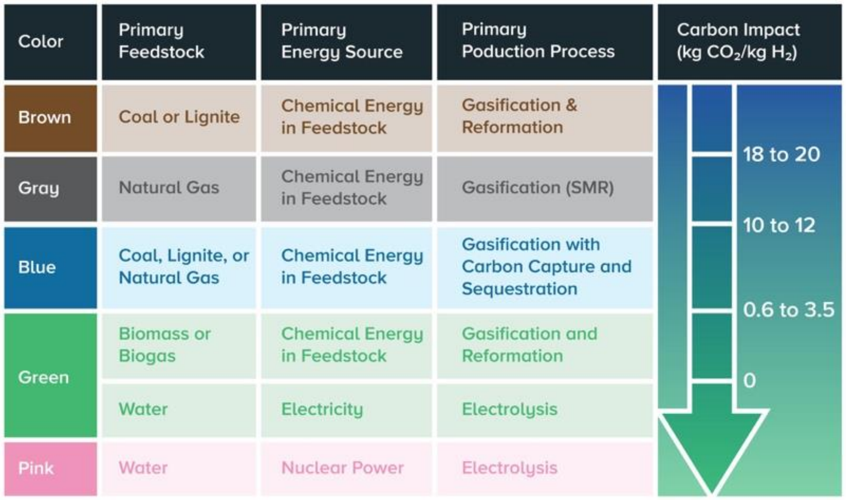
2.1 Current and Future Hydrogen Markets

Today's global hydrogen demand is about 70 million metric tons, used primarily for industrial processes such as oil refining, methanol production, and ammonia for fertilizer.[46] Figure 2 shows the different feedstocks, energy sources, and carbon intensities that can be used to produce hydrogen. Currently, over 95% of the hydrogen market today is gray or brown hydrogen, produced using raw inputs of coal or natural gas feedstocks with 10-20 kg of CO2 emitted for every kilogram of hydrogen produced. It is through these production processes that the hydrogen market contributes to 630 million metric tons of carbon dioxide emissions, more than the annual emissions from the entire country of Germany.[47]

Despite this large contribution to warming through greenhouse gas emissions and reliance on fossil fuels in today's hydrogen market, the consumption of hydrogen gas or fuel itself does not emit greenhouse gases. Decarbonizing the hydrogen market requires changing the production method away from fossil fuels, most notably the coal and natural gas feedstocks that hydrogen is extracted from.

The cleanest production method uses electrolysis, a technique to split water (H_2O) into hydrogen and oxygen components, with wind or solar as the power source to drive the reaction. With zero-emission power source and oxygen as the only by-product, this process does not emit any harmful greenhouse gases into the atmosphere throughout the entire lifecycle, generating zero-emission green hydrogen. However, right now green hydrogen is not cost competitive with gray or brown hydrogen, primarily because of high cost of electrolyzer equipment and the costs associated with 100% renewable energy powering an electrolysis plant.

Figure 2: The Colors of Hydrogen [48]



Color	Primary Feedstock	Primary Energy Source	Primary Poduction Process	Carbon Impact (kg CO_2/kg H_2)
Brown	Coal or Lignite	Chemical Energy in Feedstock	Gasification & Reformation	18 to 20
Gray	Natural Gas	Chemical Energy in Feedstock	Gasification (SMR)	10 to 12
Blue	Coal, Lignite, or Natural Gas	Chemical Energy in Feedstock	Gasification with Carbon Capture and Sequestration	0.6 to 3.5
Green	Biomass or Biogas	Chemical Energy in Feedstock	Gasification and Reformation	0
	Water	Electricity	Electrolysis	
Pink	Water	Nuclear Power	Electrolysis	

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[46] Laura Nelson et al., "Green Hydrogen Guidebook" (Green Hydrogen Coalition, August 2020), https://www.ghcoalition.org/guidebook.

[47] Laura Nelson et al., "Green Hydrogen Guidebook" (Green Hydrogen Coalition, August 2020), https://www.ghcoalition.org/guidebook.

[48] https://www.linkedin.com/company/green-hydrogen-coalition/posts/?feedView=all

In addition to the current hydrogen production processes, the second reason to consider waste-to-hydrogen solutions is the potential future applications for decarbonizing the energy system as a zero-emission fuel and feedstock. Hydrogen is being considered as a fuel source for many difficult to decarbonize sectors, including heavy-duty, long-haul transportation, where electric vehicles that require long charging times are not economical options. Industrial processes that require extremely high temperatures that cannot be achieved from electrification, such as steelmaking, may also rely on hydrogen in future efforts to decarbonize.

Finally, hydrogen can store energy on seasonal time scales, allowing for a clean electricity or fuel source that can be dispatched on longer time scales than mineral batteries which can store energy on a time scale of hours. Because of this long-term storage potential that mineral batteries do not currently offer, hydrogen can also fill a gap in the future vision of a high-renewables electric grid, reducing curtailment by diverting oversupply of wind and solar to electrolysis plants to produce hydrogen for dispatch later in the day, week, or season. All these potential applications, and many more, increase the importance of making cleaner hydrogen production economical as one of the only contenders to compete with natural gas and other fossil fuels for the same uses.

2.2 Waste-to-hydrogen market, supply, and demand

Estimates show that hydrogen demand in California alone will range from 1.4-4.0 million tons by 2045.[49] Growing the hydrogen market to meet this demand increase without changing the production method will draw upon increasing volumes of natural gas and coal feedstocks, contributing even more to methane and carbon dioxide emissions than the 630 million metric tons emitted annually from hydrogen production.

Despite the diverse variety of applications and options for hydrogen in the clean energy transition and the need to decarbonize the current market, green hydrogen production is not currently economical at $5 per kg.[50] Scaling green hydrogen to achieve cost parity with the lowest-cost low-carbon alternatives requires driving the costs down to an average of $2.50 per kilogram. Reduced cost of renewable supply combined with scaling of electrolysis equipment and infrastructure build-out will be the greatest contributors to lowering costs. At present, cost projections for green hydrogen are promising, with a price drop of 80% for wind and solar between 2010-2020 and an estimated 14x more solar capacity to be available by 2030.[51]

Using waste as a feedstock for hydrogen production provides a unique opportunity to not only create value from waste and shifting the current hydrogen market away from fossil fuel feedstocks, but also facilitates for the future of hydrogen for applications in energy system decarbonization. Reducing market uncertainty is among the top requirements to establish a low-carbon hydrogen market,[52] and one way to do this is by increasing the supply and demand for hydrogen through

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[49] Sarah E Baker et al., "Getting to Neutral: Options for Negative Carbon Emissions in California" (Livermore, CA: Lawrence Livermore National Laboratory, 2020), 53.

[50] Department of Energy, "Secretary Granholm Launches Hydrogen Energy Earthshot to Accelerate Breakthroughs Toward a Net-Zero Economy," Energy.gov (Department of Energy, June 7, 2021), https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net.

[51] Hydrogen Council, "Path to Hydrogen Competitiveness: A Cost Perspective" (Hydrogen Council, 2020), 3.

[52] Hydrogen Council, "Path to Hydrogen Competitiveness: A Cost Perspective" (Hydrogen Council, 2020), vii.

waste-to-hydrogen solutions. This is economically superior to alternative hydrogen production options in the short term because waste-to-hydrogen plants can collect upstream and downstream revenue. As a waste management technique, municipalities and other entities sending waste to a plant will pay tipping fees to generate upstream revenue, while the plant will also sell pure hydrogen that is produced. This differs from other production methods that only collect downstream revenue, providing leverage to increase the supply and demand, reduce market uncertainty for green hydrogen, and add more diversity to local landfill diversion efforts.

2.3 Waste-to-hydrogen pathways

Hydrogen can be extracted from waste sources by two broad methods: biomethane reformation and thermochemical conversion. These specific processes are described in greater detail in Part 1, but the relevant methods as they relate to hydrogen production are outlined below followed by a discussion on the contribution that each is projected to play in the supply mix through 2050.

- **Biomethane reformation:** this pathway uses the same process as hydrogen produced from natural gas, however the feedstock comes from biogenic waste sources that contain carbon that is already in the carbon cycle, making it a renewable feedstock. The two main sources of biomethane, or renewable natural gas, are:
  - Processed biogas from anaerobic digestion of biomass or sewage sludge
  - Biomethane captured from landfills
- **Thermochemical conversion:** This pathway also uses similar technology to hydrogen production from coal, however technological modifications must be made in order to process biomass, municipal solid waste, plastic, and other heterogenous feedstocks. The two types of thermochemical conversion that can extract hydrogen from waste are:
  - Gasification
  - Pyrolysis

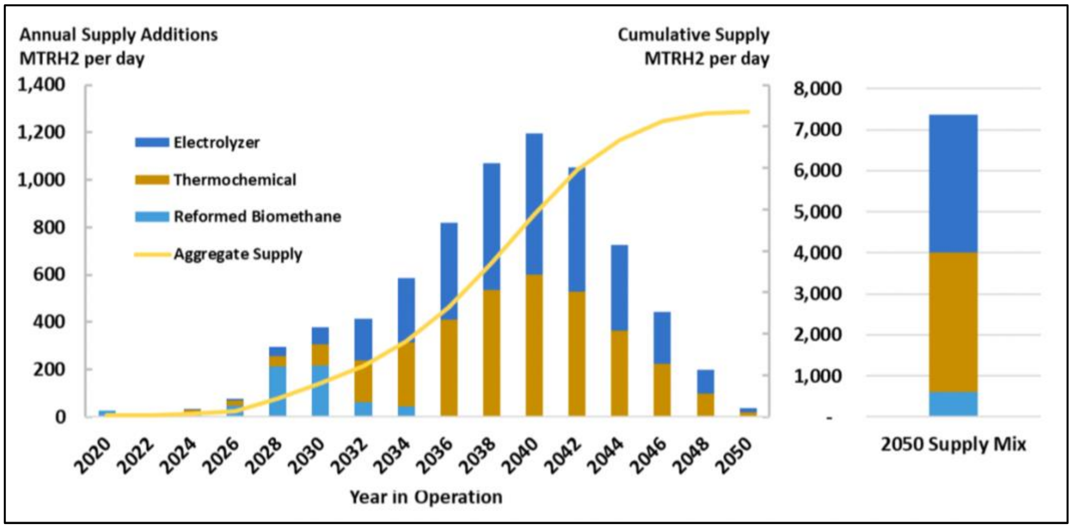
Biomethane reformation is advantageous to the conventional natural gas reformation that makes up over 75% of the hydrogen production today because the carbon in the biogenic waste feedstock is already part of the carbon cycle. However, there are two reasons why biomethane reformation has a limited impact on transforming hydrogen supply. First, biogas and biomethane can be used for similar end-use applications as hydrogen, without the added step of hydrogen production. This adds a cost that is difficult to justify long-term for a renewable fuel that is in high demand for heavy duty transportation, aviation, and more. It also does not provide the same economic benefits as using raw waste as a feedstock, as this method would not include the upstream revenue from tipping fees discussed in the previous section. Second, while this solution does help to replace fossil fuel feedstocks, it also has the potential to prolong reliance on natural gas in the industry, instead of shifting production and infrastructure away from conventional fossil fuel sources.

The limitation of biomethane use in hydrogen production is demonstrated in Figure 3, as annual supply additions of reformed biomethane increase until 2030 and are quickly replaced by growth in thermochemical and electrolysis methods through 2040. By 2050, the projected supply mix is less than 10% of the hydrogen supply mix, with thermochemical conversion representing half of renewable hydrogen production as a complement to electrolysis.

Thermochemical conversion by gasification is currently how 23% of hydrogen is produced using coal as a feedstock. However, any feedstock that contains carbon and hydrogen can undergo gasification to produce high value hydrogen. The biggest barrier to using waste is that it is a heterogeneous mixture of materials, however many emerging technologies, like plasma and FastOx gasifiers, are designed to overcome this by using very high temperatures to process feedstocks like biomass, municipal solid waste, hazardous waste, medical waste, and plastics.

Several studies show that gasification of waste is the most competitive waste management alternative to incineration in terms of emissions, efficiency, and economics, differentiating it from outdated and heavily polluting forms of waste-to-energy.[53] These favorable attributes combined with the potential that emerging gasification technologies have for processing waste streams that have no other management options than landfilling and incineration creates room for further analysis. The next section will analyze the costs, benefits, and unknowns associated with building a gasification plant in Los Angeles County, along with discussion about notable distinctions between gasification and other waste management methods.

Figure 3: Base-Case Buildout and 2030 Spatial Detail [54]



Part 3: Analysis of costs and benefits for a gasification in Los Angeles County

3.1 Background and Context

Los Angeles County provides a unique opportunity to analyze some of the social and financial impacts of building a gasification plant to generate hydrogen from waste. Long Beach, which is part of Los Angeles County, is home to the Southeast Resource Recovery Facility (SERRF), one the two remaining municipal solid waste incinerators in the state.

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[53] Deborah Panepinto et al., "Environmental Performances and Energy Efficiency for MSW Gasification Treatment," *Waste and Biomass Valorization* 6, no. 1 (2014): pp. 123-135, https://doi.org/10.1007/s12649-014-9322-7.

[54] Jeffrey Reed et al., "Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California" (California Energy Commission , 2020), p. 66 fig. 45.

SERRF transforms 1,014 tons of waste per day, or approximately 370,000 tons each year, with a generating capacity of 36MW.[55] This makes up about 1% of the total solid waste disposed in LA in 2017, and 3% diversion from landfills.[56] Incineration plants like SERRF are harmful to the local community and generate more air pollution than natural gas.[57] Lifecycle analyses of MSW facility impact on carbon dioxide emissions also show that they emit 1,016 pounds of CO_2 per MWh of electricity generated.[58] This value considers the avoided GHG emissions from landfill diversion. With a gross electricity generation of 219,081MWh in 2019,[59] it can therefore be estimated that the SERRF generates 22.3 million pounds of CO_2-eq emissions each year. SERRF recently underwent $8 million in updates to keep it operating through 2024, after which the future of the facility is unknown.[60]

While the phase out of this waste-to-energy facility is favorable for the Long Beach community and the climate, the growing landfill issue in the Los Angeles and surrounding areas creates concern. Although there are diversion policies in place, they are mostly relevant to organic waste and recyclables, creating no other immediate option for the municipal solid waste that is transformed at SERRF than disposal in landfills. In preparation for local landfills reaching capacity, there are plans in place to haul waste by train to two landfills that have already been built in the desert. This is termed "waste-by-rail" and includes Mesquite Regional Landfill, 210 miles from LA county, and H.M. Holloway Landfill, 156 miles away.[61] This option comes with a multitude of negative consequences, including greenhouse gas emissions from transportation, pollution from long-haul waste transport, and high operating costs from the entire operation.

The Los Angeles County 2019 Waste Management report highlights the need to develop and study and promote alternative technologies to prioritize over landfilling.[62] Los Angeles is also the first large city to make clean hydrogen commitments through HyDeal LA, signaling a potential openness to hydrogen production through these pathways.[63] The combination of SERRF phasing

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[55] Covanta, "Reducing Landfill Waste," Covanta Long Beach (Covanta), accessed June 2021, http://www.covanta.com/where-we-are/our-facilities/long-beach.

[56] Los Angeles Almanac, "Solid Waste Disposal Los Angeles County," Solid Waste Disposal for Los Angeles County, California (Given Place Media, 2017), http://www.laalmanac.com/environment/ev04.php.

[57] U.S. Environmental Protection Agency, "Air Emissions from MSW Combustion Facilities | Energy Recovery from Waste," EPA (Environmental Protection Agency, March 29, 2016), https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/airem.html#2.

[58] U.S. Environmental Protection Agency, "Air Emissions from MSW Combustion Facilities | Energy Recovery from Waste," EPA (Environmental Protection Agency, March 29, 2016), https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/airem.html#2.

[59] California Energy Commission, "California Biomass and Waste-To-Energy Statistics and Data," California Energy Commission (CA.gov, 2019), https://ww2.energy.ca.gov/almanac/renewables_data/biomass/index_cms.php.

[60] Kelly Puente, "Long Beach Is One of 2 Cities in California That Still Burns Trash. Will the Future Be Greener? ," Long Beach Post News (Long Beach Post , June 11, 2019), https://lbpost.com/news/long-beach-is-one-of-2-cities-in-california-that-still-burns-trash-will-the-future-be-greener.

[61] Public Works Los Angeles County, "Countywide Integrated Waste Management Plan: 2019 Annual Report" (Los Angeles, CA: County of Los Angeles, 2020), 81.

[62] Public Works Los Angeles County, "Countywide Integrated Waste Management Plan: 2019 Annual Report" (Los Angeles, CA: County of Los Angeles, 2020), 50.

[63] Elizabeth McCarthy, "Los Angeles Plans to Jump-Start a Green Hydrogen Market in the US," Canary Media (Canary Media, June 8, 2021), https://www.canarymedia.com/articles/los-angeles-seeks-to-jump-start-a-green-hydrogen-market-in-the-u-s/.

out in the near-term, landfills reaching capacity, and willingness by the county to explore alternative technologies for waste diversion and potentially hydrogen production, provides an opportunity to analyze the local impacts of emerging waste diversion technologies for hydrogen production. This section will explore the option of building a small, modular municipal solid waste gasifier in Los Angeles County to replace the Southeast Resource Recovery Facility by detailing opportunities and challenges from this process, along with missing data that is needed for a comprehensive cost-benefit analysis in the future.

A comprehensive cost benefit analysis on this issue, including all economic factors and externalities associated with gasification and the alternative of landfilling, would be an ideal option for analyzing gasification compared to landfilling alternative. However, due to lack of public data, particularly regarding GHG emissions from gasifying municipal solid waste, the range of estimations were too high to provide an accurate value. While not enough quantifiable data was available for a full cost-benefit analysis on gasification of municipal solid waste in Los Angeles County at the time of writing this report, the information may contribute to future studies attempting to determine net present value of a system like this. For this purpose, detailed data on the financial costs and benefits, greenhouse gas emissions, toxins, and missing data are outlined in Annex 2.

Despite the shortcomings in comparing landfilling to gasification of municipal solid waste, the central findings from this analysis further reiterates the major differences between incineration and gasification as landfill diversion options. This is significant to inform policy, which currently creates barriers to thermochemical conversion technologies like gasification and are further discussed in Part 4. The following sections will outline the assumptions used in the analysis, benefits, and costs associated with gasification compared to incineration, and a discussion.

3.2 Assumptions

This analysis is based on a gasifier designed to process 24 tons of municipal solid waste per day to yield 1.2-1.5 tons of 99.99% pure hydrogen.[64] With approximately 4 maintenance stops per year, 5 days each, the analysis assumes that the plant runs for 345 days of the year.[65] Under the assumption that the plant is running at full capacity on these days, this results in 8,208 tons of waste processed to approximately 466 tons of hydrogen.

3.3 Benefit: reduced land use and local impact

One significant factor in determining the societal value of a gasifier in terms of waste management is the size. A 24 ton/day gasifier is a modular design that requires 22m X 22m, requiring 484m^2 of space.[66] This compares to SERRF, which occupies approximately 24,000m^2 in Long Beach, almost 50 times more land use than a modular gasifier.[67] The gasifier is small enough to fit in convenient locations like waste transfer stations, creating major logistical benefits compared to incineration,

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[64] San Diego Energy District and Ways2H, “PowerPoint Presentation and Webinar” (San Diego , n.d.).

[65] Ways2H. Interview with MSW Gasification Developer. Personal, May 18, 2021.

[66] San Diego Energy District and Ways2H, “PowerPoint Presentation and Webinar” (San Diego , n.d.).

[67] h*Maps.google.com*, n.d., *Maps.google.com*, n.d., https://www.google.com/maps/place/Southeast+Resource+Recovery/@33.7590098,-118.2412784,18z/data=!4m5!3m4!1s0x80dd36ed7e0890b5:0xff787dc75184105c!8m2!3d33.7595405!4d-118.23983 .

which requires transportation of large volumes of waste to the plant resulting in local pollution of garbage, ash on roads, and traffic congestion to satisfy the constant waste supply needs.

In addition to land use and logistical opportunities, another benefit of small modular gasifiers comes from the reduced local air emissions impact compared to incineration. In addition to the potential to be cleaner than incineration due to pre-combustion cleanup of syngas, the absolute volume of waste being gasified is significantly smaller than required for an incinerator, greatly reducing the emission impact that any single modular gasifier would have on the local community simply because of the scale. However, this also creates a challenge when it comes to diversion efforts, outlined in the following section.

3.4 Cost: reduced waste diversion

The downside to a modular gasifier is that it also processes significantly less waste. A 24 ton/day gasifier running on full capacity 345 days/year will divert 0.075% of what is currently sent to landfills from Los Angeles County.[68] This is equal to 2.24% of the waste that is currently transformed at SERRF.[69] While this is still enough to supply 280 hydrogen-fueled cars per day[70], the reduced diversion from landfills is a challenge in justifying a single gasifier for the purpose of waste diversion. Therefore, about 44 gasifiers of this size would be required to satisfy the same landfill diversion as SERRF does today. One solution to this challenge is creating a network of gasifiers in waste transfer stations to increase the diversion impact.

3.5 Discussion

Despite the reduction in waste diversion from a small gasifier compared to incineration, this also inherently means that the plant will have less impact on the local community than both larger landfills or incinerators simply since they do not handle as much waste and will produce less absolute local pollution. Modeling studies also show that regardless of size, gasification of municipal solid waste is advantageous to landfilling in terms of both efficiency and environmental factors.[71] It is also the most competitive alternative to incineration for producing energy products, like hydrogen, from municipal solid waste.[72] Therefore, while implementation of a single modular gasifier may not be justifiable for the sole purpose of waste diversion, preliminary environmental and efficiency results suggest it should still be considered in complement to anaerobic digestion, composting, and recycling. Additionally, because of the size, a network of modular reactors located in transfer stations and waste management facilities could increase landfill diversion without having a large impact on any single local community, however this would naturally require much higher capital expenditure.

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[68] Los Angeles County, "LA Landfill Data - 2019 Countywide Destination Details (Spreadsheet)" (Los Angeles, 2020).

[69] Calculated derived using data from source: Los Angeles County, "LA Landfill Data - 2019 Countywide Destination Details (Spreadsheet)" (Los Angeles, 2020).

[70] San Diego Energy District and Ways2H, "PowerPoint Presentation and Webinar" (San Diego , n.d.).

[71] A Bjorklund, "Hydrogen as a Transportation Fuel Produced from Thermal Gasification of Municipal Solid Waste: an Examination of Two Integrated Technologies," *International Journal of Hydrogen Energy* 26, no. 11 (2001): pp. 1209-1221, https://doi.org/10.1016/s0360-3199(01)00074-x.

[72] Deborah Panepinto et al., "Environmental Performances and Energy Efficiency for MSW Gasification Treatment," *Waste and Biomass Valorization* 6, no. 1 (2014): pp. 123-135, https://doi.org/10.1007/s12649-014-9322-7.

The results of this analysis further reiterate the technological differences between gasification and incineration as waste-to-energy technologies. While the landfill diversion that a modular gasifier can offer is less than an incinerator, the local impact that a small gasification plant will have on any single community is also negligible compared to large incinerators. This distinction comes in the form of land use, local pollutant emissions, and greenhouse gas emissions based solely on the difference in scale of these two technologies. These differences must be represented in policy and in the public landscape, as incineration and gasification are often grouped into the same category. The next section will provide an overview of relevant policies that incentivize or discourage various waste management options, highlighting the barriers that California policy creates for gasification technologies.

Part 4: Policy background

4.1 Definitions by the state legislature and relevant statewide policies

The definitions for gasification, transformation, and biomass conversion are extremely important for understanding the policy framework as it impacts waste management and analyzing the viability of waste-to-hydrogen pathways. They are defined as follows:

"'Gasification' means a technology that uses a non-combustion thermal process to convert solid waste to a clean burning fuel for the purpose of generating electricity, and that, at minimum, meets all of the following criteria:"

- Does not use air or oxygen except for temperature control
- No discharge of toxins or GHG emissions
- No hazardous waste or discharge to surface
- Removes all recyclable materials [73]

"Under state legislature, effective January 1, 2014: 'Transformation' means incineration, pyrolysis, distillation, or biological conversion other than composting. "Transformation" does not include composting, gasification, EMSW conversion, or biomass conversion."[74]

"'Biomass conversion' means the production of heat, fuels, or electricity by the controlled combustion of, or use of other non-combustion thermal conversion technologies on, the following materials, when separated from solid wastes"[75] Therefore, this definition includes gasification and pyrolysis of biomass as a biomass conversion process.

AB 939: Solid waste management, waste reduction, recycling, composting, and market development

Assembly Bill 939 has been in place since 1989 and requires 50% diversion of solid waste from landfills, of which 10% can come from transformation or biomass conversion. This is on the

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[73] "Public Resources Code - PRC. Division 30. Waste Management. Definitions.," California Legislative Information (State of California, 2008), https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=PRC§ionNum=40117.&highlight=true&keyword=gasification.

[74] "Public Resources Code - PRC. Division 30. Waste Management. Definitions," California Legislative Information (State of California, 2013), https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=PRC§ionNum=40201.

[75] "SB-498 Solid Waste: Biomass Conversion.," California Legislative Information (State of California, September 28, 2014), https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB498.

jurisdiction level and there are penalties up to $10,000 per day for jurisdictions who do not meet diversion goals. Therefore, under California's definition of transformation, only 10% of a jurisdictions' waste can be considered diverted if it is converted to energy or fuel through incineration, and any more than this will be considered disposal and incur a fine. Mechanical recycling and composting do not have limits. [76]

Section 40201 of AB 939 lists a different definition of transformation than the state legislature above. The main difference is inclusion of gasification in this definition, as follows: "*Transformation means incineration, pyrolysis, distillation, gasification, or biological conversion other than composting. 'transformation' does not include composting."*[77] This is important because biomass conversion only includes biomass inputs, so it is important to clarify whether thermochemical conversion of non-biomass materials, like municipal solid waste or plastic, would be considered transformation under the 10% diversion credit. This creates confusion under the policy framework regarding thermochemical conversion of solid wastes other than biomass, and if this would be considered diversion or disposal under the 10% limit under AB 939.

AB 341: Solid Waste Diversion

Assembly Bill 341 requires that 75% of solid waste generated in California must be reduced, recycled, or composted by 2020.[78] This goal was not met, as the 2019 recycling rate was 37%, down from the 50% peak in 2014[79]. The failure to meet this goal contributed to the implementation of SB 1383, which takes more specific measures to reduce and recycle solid waste form landfills by creating markets for these materials.

SB 1383: Short-lived climate pollutant reduction strategy

Senate Bill 1383 was signed into law in September of 2016 to outline a strategy to reduce short-lived climate pollutants, most notably methane, emissions in California. The bill sets a statewide goal to reduce organic waste disposal in California landfills 50% below 2014 levels by 2020 and 75% below 2014 levels by 2025.[80] While it does not restrict any substance from being sent to landfill or create penalties for failing to meet the goal, it does give CalRecycle the authority to implement programs that will push the state towards the goal. Therefore, this bill creates a policy incentive for procurement of organics recycling programs, such as anaerobic digestion and composting, to drive forward a market for organic waste through these processes. [81]

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[76] Public Works Los Angeles County, "Countywide Integrated Waste Management Plan: 2019 Annual Report" (Los Angeles, CA: County of Los Angeles, 2020), 11.

[77] "Bill Text - AB-939 Solid Waste Management, Source Reduction, Recycling, Composting, and Market Development.," California Legislative Information (State of California, September 30, 1989), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=198919900AB939.

[78] "Bill Text - AB-341 Solid Waste: Diversion.," California Legislative Information (State of California, October 6, 2011), https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201120120AB341.

[79] California Ocean Protection Council, "Plastic Pollution," Ocean Protection Council (State of California, 2021), https://www.opc.ca.gov/programs-summary/marine-pollution/plastics/.

[80] "Bill Text - SB-1383 Short-Lived Climate Pollutants: Methane Emissions: Dairy and Livestock: Organic Waste: Landfills.," California Legislative Information (State of California, September 19, 2016), https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB1383.

[81] CalRecycle, Interview with Solid Waste Programs Expert. April 23, 2021.

SB 498: Solid Waste - Biomass Conversion [82]

Senate Bill 498 updated AB 939 in 2014, expanding the definition of "biomass conversion" to include non-combustion thermal conversion technologies, which include gasification and pyrolysis according to the EIA.[83] This allows for cleaner non-combustion conversion technologies to convert biomass into fuels and other valuable products.[84]

AB 1594[85]

Green material used for alternative daily cover in landfills will no longer count towards the 50% diversion goal in California. This is a significant update to the policy because it increases the supply of biomass for other uses, such as anaerobic digestion, composting, or gasification.

4.2 Policy Analysis

The most significant takeaways from waste policies in California as they relate to waste-to-hydrogen processes include the definition of gasification and the contradictory nature of SB-1383 and AB-939. The definition of gasification is extremely strict, restricting greenhouse gas emissions, discharge of toxins, or oxygen use except for temperature control. While it is important to place stringent air emission regulations for waste-to-energy processes, the lack of flexibility in this definition is harmful to the potential role that this technology can have in complementing other waste diversion activities for waste streams that do not have another option other than landfills. Under this definition, the development of a gasification plant would not be viable even if the greenhouse emissions were proven to be a certain percentage below other options, such as landfilling.

Even more importantly for hydrogen production, the definition of gasification limits the output to "a clean burning fuel for the purpose of generating electricity." This not only creates confusion as to whether gasification of waste to generate hydrogen would be considered under the definition of gasification, and therefore if a process like this can count towards a 10% diversion credit. It is also backwards in limiting this definition to electricity production, as California has cleaner and zero-carbon electricity supply options, but is currently still relying on fossil fuel hydrogen production.

AB 939 and SB 1383 are extremely important and influential policies for waste diversion efforts in California but fall short when it comes to waste streams other than biomass. Diversion of organic material is incredibly important as it makes up half of landfill contents and have the largest contribution to landfill methane emissions,[86] however the cap on transformation credits in AB 939 creates very little room for diversion of municipal solid waste and other non-recyclables in complement to the existing waste management systems.

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[82] "SB-498 Solid Waste: Biomass Conversion.," California Legislative Information (State of California, September 28, 2014), https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB498.

[83] "Biomass Explained ," U.S. Energy Information Administration (EIA) (EIA, June 8, 2021), https://www.eia.gov/energyexplained/biomass/.

[84] Public Works Los Angeles County, "Countywide Integrated Waste Management Plan: 2019 Annual Report" (Los Angeles, CA: County of Los Angeles, 2020), 11.

[85] CalRecycle, "Green Material Used as Alternative Daily Cover (ADC)," CalRecycle (State of California, June 14, 2021), https://www.calrecycle.ca.gov/lgcentral/basics/adcgreen/.

[86] CalRecycle, "California's Short-Lived Climate Pollutant Reduction Strategy," California's Short-Lived Climate Pollutant Reduction Strategy (State of California, June 7, 2021), https://www.calrecycle.ca.gov/organics/slcp.

The two policies are also contradictory regarding conversion technologies. While SB-1383 requires procurement of programs to divert organics from landfills, AB-939 restricts which activities can come from this by putting a 10% limit on biomass conversion and transformation for diversion credits. This leaves anaerobic digestion, composting, and recycling as the only options that are not limited to this 10% cap. Although municipalities may still choose to send more waste to transformation facilities, this would not count towards diversion credits, and they will still need to divert 40% of solid waste from landfills to avoid a $10,000 fine.

Overall, the policies in California fall short regarding landfill diversion of waste streams other than biomass and recyclables. This, combined with the restrictions set in the definition of gasification, creates a barrier to the development of technologies that can generate hydrogen from any waste streams, especially municipal solid waste, and non-recyclables. This policy landscape is a further disincentive for developers to prove the environmental efficacy and effectiveness of thermochemical conversion technologies in complement to other landfill diversion options.

Part 5: Recommendations

Landfill methane emission tracking and tipping fees

Mentioned in the previous section, California policy has a large focus on diversion of biomass from landfills. Although there may be enough biomass availability for hydrogen production due to a projected increase in biomass resources from agricultural residue and food waste from population growth, there is also a need to create more diverse solutions for municipal solid waste and non-recyclable materials aside from landfilling. The first step in this process is to obtain more accurate methane emissions information to better compare emerging technologies that can accommodate these waste streams, to the alternative of landfilling. This improved tracking can be done using methane tracking satellites that are currently being planned for deployment in 2022 to track methane leaks from natural gas pipelines.[87] Using the satellites to gain a better sense of landfill emissions should be another application of this novel technology.

In addition to enabling more accurate processes for comparing landfilling to other disposal and transformation options, this data should also contribute to ensuring that tipping fees include the full social cost of landfilling. While any changes should be slowly implemented to reduce the impact that this may have on taxpayers, it is also vital that alternative methods to dispose of waste can sufficiently complement each other by creating a fairer market, where ultimately the options with the lowest social cost, from local and GHG emissions to land use, become the most cost-effective. This can further contribute to ensuring that alternative technologies are complementary to recycling, anaerobic digestion, and composting, rather than competing with them.

Gasification definition

The definition of gasification in California should be reformed in a way that still places strict limits the air emissions and oxygen content to avoid combustion, but is consistent with its technological, physical, and chemical processes. In short, a requirement for zero greenhouse gas emissions would prohibit any waste diversion method, including anaerobic digestion or composting. This part of

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[87] Jeff St. John, "New Satellites Can Mitigate Methane's Outsize Impact on Climate Change," Canary Media (Canary Media, May 3, 2021), https://www.canarymedia.com/articles/how-new-satellites-can-drive-action-against-methanes-outsize-impact-on-climate-change/.

the definition should be modified to reflect this fact, and instead require that greenhouse gas emissions are proven to be less than or equal to the alternative disposal method for a particular waste stream.

The second modification to this definition, and most significant as it relates to hydrogen production, is the requirement that gasification produce a clean burning fuel *for the purpose of generating electricity.* This should be modified to reflect all possible clean products that can come from gasification, including hydrogen, for two reasons. First, there are cleaner, lower emission, economically competitive options for electricity production than gasifying solid waste. At present, other low-carbon hydrogen production methods are not economically competitive with brown and gray hydrogen produced with fossil fuels. Second, not only does hydrogen consumption avoid additional greenhouse gas emissions, but it is also the gasification pathway with the potential to capture the most carbon dioxide creating a negative emissions pathway when carbon capture and sequestration becomes a viable addition to these systems. While this is not yet commercially available and requires scaling up, it is still important to consider in the policy framework to better enable negative emissions options for the future.

Conclusion

The prospect of generating hydrogen from waste must be considered to meet existing and growing demand for hydrogen while simultaneously reducing dependence on fossil fuels for its production. Despite the progress that gasification technologies have made with enabling small-scale, potentially cleaner transformation of diverse waste streams into useful outputs like hydrogen, the policy landscape in California creates obstacles to the development and scaling of these options. Additionally, while California is successful in passing essential policies for organic, recyclable, and biomass diversion from landfills, there are less options for diversion municipal solid waste and other non-recyclable materials that don't have negative impact on local communities and the environment like incineration. The Los Angeles analysis shows that while there is reduced landfill diversion from a single modular gasifier than MSW incineration facility, the small-scale design minimizes the impact that this process will have on any local community and eliminates the logistical difficulties with large waste management centers. This process can also contribute to further development of a clean hydrogen market by increasing supply and demand, effectively reducing market uncertainty needed to scale green hydrogen technology.

While thermochemical conversion processes still need to prove environmental efficacy at a larger scale, this requires policy to remove barriers for the technology itself. The two recommendations from this analysis include using novel satellite technologies for more accurate point-source landfill emission tracking to enable better comparisons for waste streams that are routinely sent to landfills and changing the definition of gasification to include hydrogen and better reflect technological realities. These are the first steps in facilitating the development of gasification to contribute to waste diversion and build up a hydrogen economy while still ensuring these options are socially and environmentally responsible and complementary to existing clean landfill diversion methods.

Annex 1: Comparison of the opportunities and challenges for gasification of biomass, municipal solid waste, and non-recyclable plastics

	Biomass	MSW	Non-recyclable plastic
Best alternative	-Composting -Anaerobic digestion	-Landfill -Incineration	-Landfill -potential future recycling programs
Challenges	-Alternative options have lower CO_2 and SO_2 emissions -higher tar yield*	-heavy metals in ash -dioxin emissions*	-High chlorine content leads to dioxin formation (regulated carcinogen)** -low H2 yield
Opportunities	-Highest efficiency feedstock for h2 production -Negative emissions potential with carbon capture -advantageous to landfilling	-Diversion from landfill -Environmentally favorable to incineration	-Diversion from landfill and/or oceans

*Plasma gasification eliminates issue
**Plasma gasification dioxin content is 100x lower than incineration

Annex 2: Cost-Benefit Analysis Information

Financial Costs and Benefits of a 24 ton/day MSW gasifier[88]

Costs		Notes
Capital Costs	$25,000,000	
Operating costs per year	$1,200,000-1,500,000	Includes all operating costs including supplementary water and oxygen input.*
Energy input	N/A	Closed loop system – energy input is negligible**
Benefits		
Tipping fee per ton of waste	$80	Projection
LCFS Credit	$150	Projection
Job creation (full-time)	~10	

* 24 tons/day of water and 200kg/hour of oxygen required to operate the system [89]
** meaning all heat and electricity is supplied by the by-products of the syngas, so energy input is only required during the first 24 hours of operation. This is characteristic for most modern gasifiers.

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[88] Ways2H. Interview with MSW Gasification Industry Expert .Personal, May 18, 2021.

[89] Ways2H. Interview with MSW Gasification Industry Expert .Personal, May 18, 2021.

*Preliminary calculations based on levelized cost of hydrogen put the production cost of hydrogen at $1.6 per kg over 25 years, assuming $80 tipping fees and $150 credits from the low carbon fuel standard.

Emissions

GHG	**Data**	**Cost**	**Note**
CO2	4.6 mol % of flue gas[90]	Greenhouse gas contributes to warming	Missing flow rate for MSW → impossible to quantify
CH4	0	GHG	
Pollutant[91]			**U.S.EPA Standard**
SOx	4.2 mg/m^3	Acidification	31mg/m^3
NOx	48 mg/m^3	Ozone formation, smog	500 mg/m^3
HCl	7.08 mg/m^3	Acid, Public health	29 mg/m^3
Byproduct			
Ash	5-10% (contains heavy metals)	Landfill disposal or use for concrete filler	Incineration produces 20% ash byproduct
Tar	TBA		
Slag	TBA		

Missing data

Emissions: The most significant piece of missing data was a reliable estimate of the flow rate of municipal solid waste, which prohibited the calculation of emissions in the flue gas. While there was data available on the flow rate of wood chips for gasification, the nature of municipal solid waste makes this an insufficient assumption because of the mixed, heterogeneous characteristics of municipal solid waste. In the absence of commercial scale data on these emissions, obtaining this information is the next step in enabling an accurate estimate of emissions from this process.

Landfill comparison: To accurately evaluate the option of gasification for a certain amount of waste compared to landfilling, an estimate on the social cost of landfilling per ton of municipal solid waste in California would be ideal. In the absence of this, future researchers can obtain data on greenhouse gas emissions, local emissions, and land use from a given amount of MSW in replacement of a social cost of landfills.

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[90] Ways2H. Interview with MSW Gasification Industry Expert .Personal, May 18, 2021.

[91] San Diego Energy District and Ways2H, “Powerpoint Presentation and Webinar” (San Diego , n.d.).

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