Stranded methane to food: techno-economic analysis of methanotrophic protein production

Sahar H. El Abbadi[1*], Evan D. Sherwin[2], Adam R. Brandt[2], Stephen P. Luby[3], and Craig S. Criddle[1]

[1]Stanford University, Department of Civil & Environmental Engineering, Stanford, 94305, USA
[2]Stanford University, Department of Energy Resources Engineering, Stanford, 94305, USA
[3]Stanford University, Division of Infectious Diseases and Geographic Medicine, Stanford, 94305, USA
[*]elabbadi@stanford.edu

ABSTRACT

Methane is emitted and flared from industrial sources across the United States, contributing to global climate change. This need not be the case. Methanotrophic (methane-oxidizing) bacteria can transform methane into useful protein-rich biomass (e.g., to replace fishmeal in animal feeds). Here, we analyze the economic potential of producing methanotrophic microbial protein from methane emitted and flared from wastewater treatment plants, landfills, and oil and gas facilities. Our results show that current technology can enable production equivalent to nearly 15% of the global fishmeal market at prices at or below the current cost of fishmeal of roughly $1,600 per metric ton. We find that methanotroph production is most sensitive to electricity costs, which can be reduced through lower prices or reducing electricity demand. Bioreactor cooling and biomass drying are the most energy intensive processes, and additional price savings can be achieved by reducing labor requirements.

Introduction

Humanity must address the challenge of meeting growing food demand in the face of global climate change. Current food systems directly emit greenhouse gases, but also emit them indirectly, e.g., land use change.[1] Yet meeting nutritional needs and ensuring food security will require increased consumption of protein-rich foods.[2] One important global source of protein and micronutrients is seafood, with per capita supply more than doubling between 1961 and 2015 from 9.0 kg to 20.2 kg per person[3] and absolute production increasing from 40 million metric tons/year (t/y) to nearly 180 million t/y over the same period.[4] Farming of fish and other aquatic animals through aquaculture now accounts for the production of almost half of all edible, animal-source seafood,[5] with 90% of the world's marine fisheries fully fished or overfished.[2] At present, however, production of aquaculture feed relies upon fishmeal for protein, consuming 70% of global fishmeal production,[6] and increasing pressures on overharvested marine resources.[7] While many plant proteins are a nutritionally promising substitute for fishmeal, they require additional inputs of land, freshwater and fertilizer.[8]

Methane is a potent greenhouse gas with at least 25 times the global warming potential of CO_2 over a 100-year time period.[9] Total annual methane emissions in the US for 2014-2018 exceeded 630 million metric tons of CO_2 equivalents (MMT CO_2 eq.) per year. In 2018, oil and gas systems accounted for nearly 30% of total methane emissions, with landfills and wastewater treatment accounting for another 17% and 2%, respectively.[10] Unlike other major methane emitters (enteric fermentation - 28%, rice cultivation - 2%), these sources often flare methane, releasing large amounts of CO_2 to the atmosphere.[10] Taken together, methane emissions and flaring release nearly 14 billion cubic meters (490 billion cubic feet) of greenhouse gases per year.[11] This is equivalent to over 420,000 TJ / year, exceeding the entire annual energy consumption of the Netherlands (403,000 TJ / year) in 2018.[12] Yet because these sources are geographically dispersed and small-scale in the context of current industrial chemical manufacturing, methane is emitted or flared rather than captured, cleaned and used.[11]

Methanotrophic bacteria are capable of transforming methane into microbial protein, which can be used as an animal feed for agriculture or aquaculture.[13] In fact, methantrophs have a similar amino acid profile to fishmeal, and have been approved for inclusion in salmon feed in the European Union (EU) at rates of up to 33%.[13] General interest in using microorganisms as a feed source, also referred to as single cell protein (SCP), has increased in recent years.[14–16] Because methanotrophs do not require light, dense cultures can be grown in bioreactors with low spatial footprints, and with additional opportunities for resource recovery and reuse that are not feasible with terrestrial agriculture.[14] Not surprisingly, some companies in the US and EU are commercializing production of methanotrophic SCP from natural gas.[16]

Using methane currently emitted or flared to produce methanotrophic SCP can incentivize capture of stranded resources with the dual benefit of reducing greenhouse gas emissions and generating a sustainable protein substitute for fishmeal. Stranded methane has also been proposed as a feedstock for future biomanufacturing, potentially enabling or enabled by a paradigm shift from large-scale megafacilities to smaller-scale, widespread, mobile production.[11] Methanotrophs are also the subject of multiple techno-economic analyses because of their potential to sequester carbon in bioplastic through accumulation of intracellular polyhydroxyalkanoate (PHA) granules. To date, however, these studies have focused on prospects for PHA production using methane from the natural gas grid as a low-cost carbon feedstock.[17–19] Moreover, PHA production is more chemically and labor intensive than SCP, requiring extraction of PHA granules from methanotroph cells and their subsequent purification.[20]

Pikaar et al. (2018) evaluate the economic potential and environmental impacts of SCP production using a variety of substrates as feedstock for hydrogenotrophic (renewable H_2 + CO_2), heterotrophic (organic carbon from farmed sugarcane) and methanotrophic microorganisms.[15] This study focused on methane sourced from the natural gas grid, or produced by growing crops for biogas production via anaerobic digestion.[15] Use of methane feedstocks from such supplies increases both the cost and environmental impact of methanotrophic SCP. To the best of our knowledge, our analysis is the first to evaluate the potential for capture and cleaning of stranded methane and its subsequent use for production of methanotrophic SCP. While we focus on the United States, the same approach can be applied to methane emitted and flared from industrial facilities worldwide.

In this work, we investigate the capacity of landfills, wastewater treatment plants, and oil and natural gas facilities to produce protein that is cost competitive with fishmeal using current technology. Using a techno-economic analysis, we investigate the market potential of methanotrophic SCP and key cost sensitivities. Our analysis assumes mature methanotrophic protein production facilities using current technology; we anticipate that costs will decrease substantially in the future. We conclude that stranded methane could supply 14% of the global fishmeal market by producing biomass at or lower than the current market price of fishmeal.

Results

Stranded Methane in the United States

In this study, we analyze methane emitted and flared from landfills, and oil and gas facilities, as well as methane generated at wastewater treatment plants but not currently utilized. We use publicly available data through the US Environmental Protection Agency (EPA)'s Greenhouse Gas Reporting Program (GHGRP),[21] Landfill Methane Outreach Program (LMOP),[22] and Clean Watershed Needs Survey (CWNS).[24–26] For oil and gas flaring, we use VIIRS Nightfire data, also publicly available.[23] Geographic distribution of methane sources and their respective sizes are depicted in Figure 1a for the contiguous US. Methane sources are geographically distributed across the country, with landfills and wastewater treatment plants concentrated near population centers.

We use fishmeal as a point of comparison for methanotrophic SCP. High quality fishmeal is 60-72% crude protein,[28] and methanotrophic biomass is 67%-81% crude protein.[13] Thus, for the purposes of this analysis, we define the SCP product as the organic biomass of the dried cell (commonly referred to as volatile suspended solids). Figures 1b, 1c and 1d depict cumulative distribution functions of methane source size (left y-axis) for the same data sets used in Figure 1a, and the corresponding cumulative SCP production (right y-axis), calculated using a representative methanotrophic microbial yield of 0.7 tons of SCP per ton of CH_4.[14] Horizontal lines in Figures 1b, 1c, and 1d depict the total production rate of the 2018 global fishmeal market of 15,900 tons/day.[4] The vertical lines depict the source size corresponding to a typically large industrial bioreactor volume (500 m^3), assuming a yield of 0.7 tons SCP/ton CH_4,[14] a cell growth rate of 4 d^{-1},[14] and a cell density of 30 g SCP/L.[17]

Mean methane production is lowest for wastewater treatment plants (less than 1 ton CH_4 / day) and highest for landfill flaring (31 tons CH_4 / day) and oil and gas flaring (10 tons CH_4 / day). Maximum reported values range from 148 tons CH_4 / day for wastewater treatment plants to 420 tons CH_4 / day directly emitted from oil and gas facilities. Low mean and median values compared with maximum reported sources sizes (see SI Table 6) as well as the heavy tail distribution are indicative of the high number of smaller methane sources and a small number of high emission point sources, evident in Figures 1b-d. Fully utilizing stranded methane resources and reducing their climate change impact will require harnessing sources smaller than conventional bioreactors. However, should these smaller sources become economically competitive and technologically viable, methanotrophic SCP production could readily exceed the current size of the global fishmeal market using US-based stranded methane alone.

Protein Production Economics

Methanotrophic growth requires inputs of methane, oxygen, nitrogen and phosphorus. Maintaining the bioreactor at a biologically viable temperatures requires cooling to remove the considerable quantities of metabolic heat produced during methanotrophic growth.[14,17] Biomass produced in the bioreactor must then be processed for storage and shipping. Our model includes the components illustrated in Figure 2. Gas compressors separately deliver pressurized methane and oxygen to the bioreactor; pressurized gases also provide mixing within the bioreactor. Growth occurs in pressurized, top-fed airlift bioreactors equipped with cooling jacket and coils,[17] and the cells produced are dewatered in biomass centrifuges and then dried in biomass

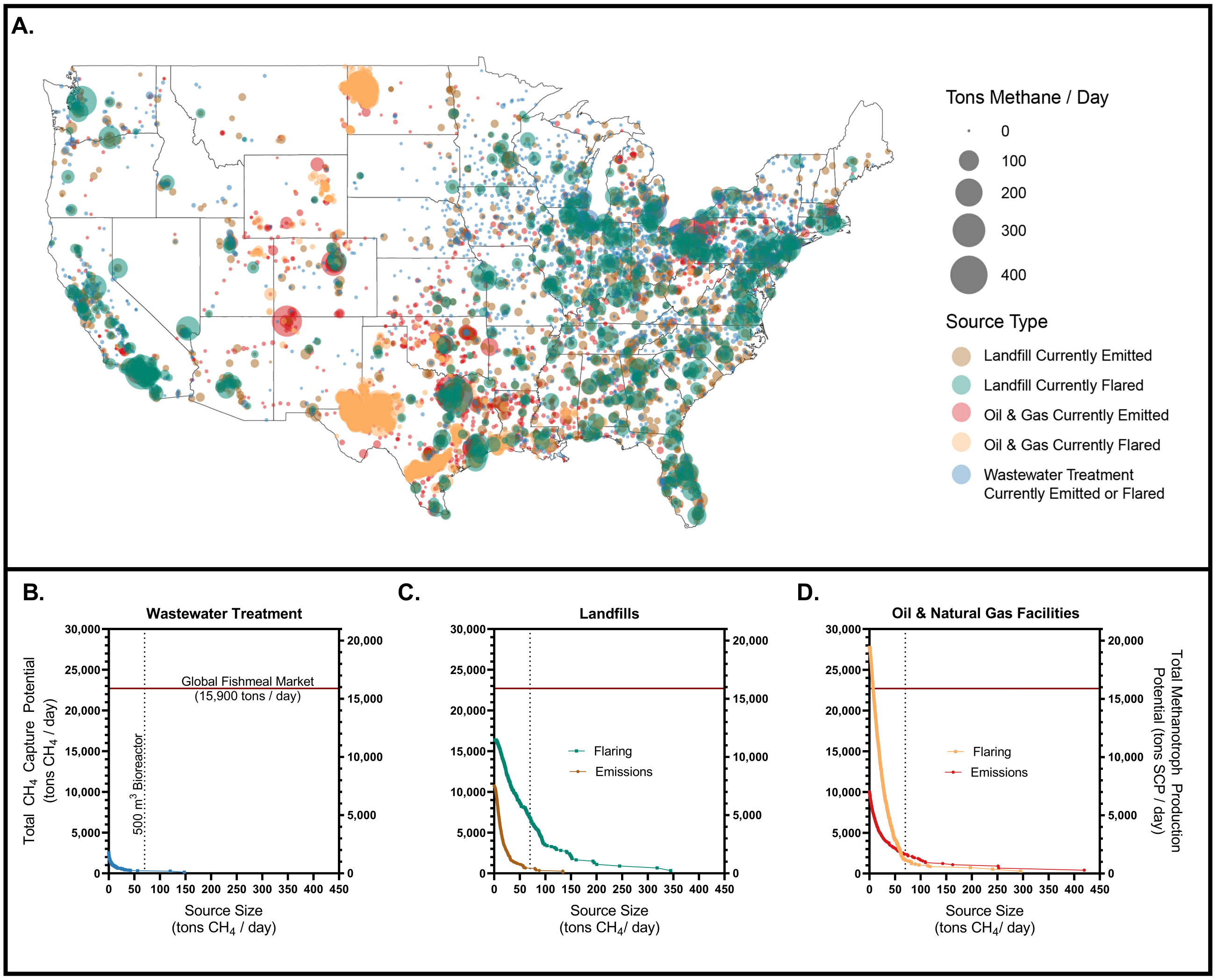

Figure 1. A. Unused methane generation in the United States. Point sources for methane currently emitted and flared from landfills,[21,22], oil & gas facilities,[21,23] and methane production from wastewater treatment plants currently not utilized.[24–26] Mapping in R. B-D. Cumulative methane capture potential (left y-axis, tons CH_4/day) for different source types. The right y-axis depicts the corresponding total methanotrophic production potential in tons of single cell protein (SCP) per day, assuming a yield of 0.7 tons SCP/ton CH_4. Horizontal line indicates production equivalent to the total global fishmeal market, 15,900 tons/day. Vertical line at source size of 86 tons CH_4/day corresponds to a 500 m^3 bioreactor, size typical for an industrial-scale reactor.[27]

dryers. We determine annualized capital cost, annualized operations and maintenance (O&M) and electricity demand for all equipment and processes (Table 1). We also include methane cleanup, ammonia, phosphorus and labor costs in our final calculation of total levelized cost of methanotrophic SCP production (Table 2). While additional micronutrients are required for microbial growth (e.g. trace metals), we consider these to be minor costs and are not included in the scope of the current analysis. Where we considered connecting methanotrophic SCP production to the natural gas grid, we also included the cost of natural gas.

We find the production costs for methanotrophic SCP are lower than the market price of fishmeal ($1,600 / ton) in our baseline scenario for landfills, oil and gas facilities, and natural gas grid (Figure 3). Our baseline production capacity for each scenario, summarized in Table 3, is based on the largest point source of methane from each type of facility, as these are likely to be the most cost-effective locations due to their large size and potential to benefit from economies of scale. For the grid scenario, we used the same production rate as the largest landfills, which are located near population centers where labor and electricity are readily available and therefore more representative of early production locations. All scenarios except for

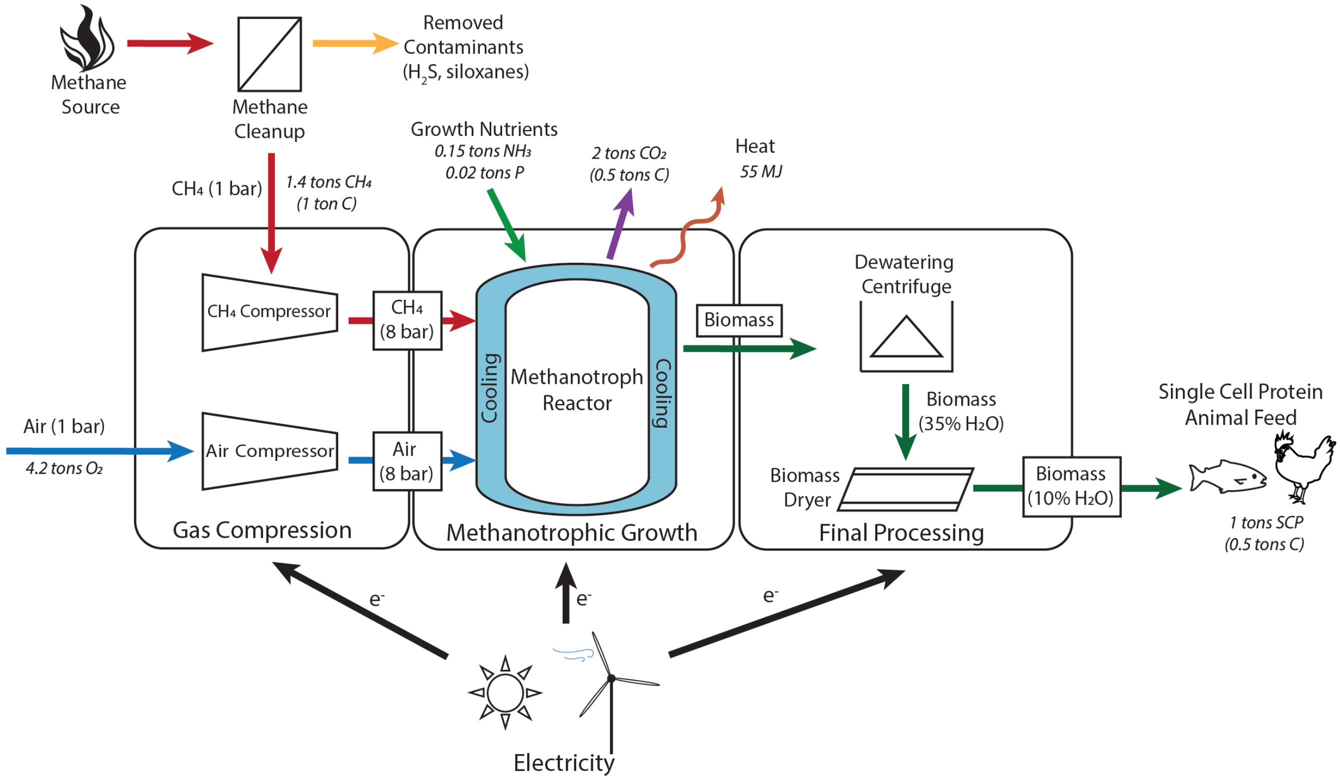

Figure 2. Process modeled for methanotrophic biomass production. Methane is cleaned to remove contaminants, then compressed and delivered to the growth bioreactor along with compressed air. Methanotrophic growth occurs in pressurized bioreactors equipped with cooling jackets and coils for removal of metabolic heat produced. Exhaust CO_2 is released from growth bioreactors, and biomass is processed in dewatering centrifuges and dryers, after which it can serve as single cell protein (SCP) feed for agriculture or aquaculture. The numbers in italics represent the mass or energy flow associated with the production of 1 ton of methanotrophic SCP.

wastewater treatment are capable individually of producing over 159 tons SCP / day, which represents 1% of the global fishmeal market (15,900 tons SCP / day)[4] and a meaningful market share for emerging technologies.

Electricity costs make up over 50% of total levelized cost in all baseline scenarios. Over 60% of this is the power needed for removing metabolic heat from the methanotrophic bioreactor (see Table 2). We thus depict cooling costs separately from electricity costs associated with powering other methanotroph production equipment in Figure 3. Cooling requires $509 / ton SCP, dewatering and drying combined require $177 / ton SCP and air compression requires $136/ton SCP (see Tables 1 and 2). Capital cost makes up just over 10% of total levelized cost, making it the second largest cost component after electricity for all baseline scenarios except wastewater treatment, where labor makes up 13% of costs compared to 12% for capital costs. Methane cleanup (where required), ammonia and phosphorous, and operations and maintenance each make up 5-10% of total levelized cost across all scenarios.

Despite the having a production rate over 50% lower than the other baseline scenarios, production at wastewater treatment plants is only 3-6% more costly compared to other baseline scenarios. This is because our model implements a conservative approach to capital cost scaling whereby large bioreactors do not benefit from economies of scale. Specifically, we assume industrial bioreactors will not exceed 500 m^3 in volume,[27] so for methane sources requiring total reactor volumes exceeding this cut-off, we maintain constant unit capital cost. This is representative of multiple reactors operating in parallel, as opposed to an increasingly large single bioreactor (see Methods below for more details). As all our baseline scenarios have a total bioreactor volume greater than 500 m^3, they do not gain additional benefit from economies of scale and all have the same capital cost contribution to total levelized cost. Labor costs do increase with decreasing production rate, resulting in the increased cost at wastewater treatment plants. For the grid scenario, the additional cost of natural gas ($127 / ton SCP) increases the total levelized cost, although this is partly offset by removing the requirement for methane cleanup ($89 / ton SCP).

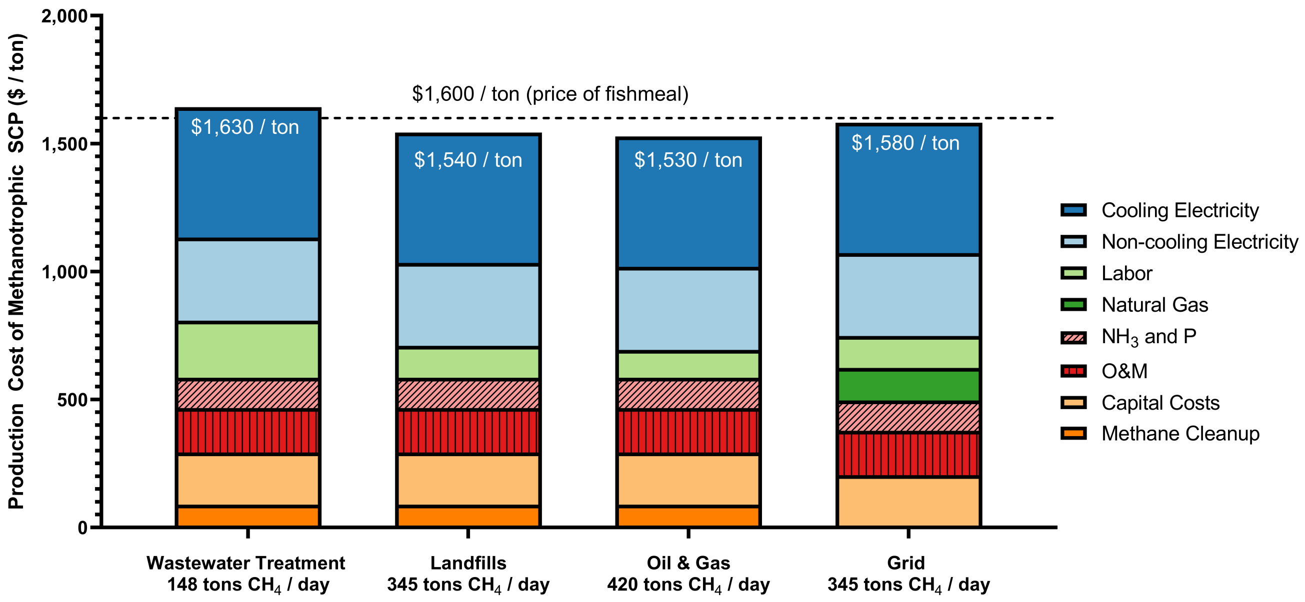

Figure 3. Levelized cost of methanotrophic microbial protein across baseline scenarios in which methane comes from wastewater treatment, landfills, oil and gas facilities, the natural gas grid. Baseline scenarios represent the largest feasible sources of stranded methane by source type. The grid baseline is sized to match the landfill baseline. In all cases, the largest cost is electricity. The power needed for heat removal is separated from other cooling costs to illustrate its impact. Wastewater treatment plants see a slight cost savings due to reduced requirements for NH_3 and phosphorus, which we assume are locally sourced from effluent. Grid scenario sees an increase in cost due to purchase of natural gas, which is slightly offset by the removal of the methane cleanup requirement.

Equipment	Unit Capital Cost ($ / ton SCP / day)	Annualized Capital Cost ($/ ton SCP)	Electricity Cost ($/ ton SCP)	Annualized O&M ($ / ton SCP)
Air Compressor	141,400	46	136	18
Methane Compressor	66,450	21	11	23
Bioreactor	196,700	60	509	67
Dewatering	5,695	2	11	2
Drying	96,850	31	166	33

Table 1. Equipment associated costs for baseline scenario. Electricity cost associated with the bioreactor is the electricity required for removal of metabolic heat produced during methanotroph growth. We sized equipment based on methane source size and then applied a utilization factor of 80% to account for time spent offline for maintenance and repair.

Figure 4 depicts a supply curve for production of methanotrophs from stranded sources of methane in Figure 1. Keeping prices below $1,600 / ton, the 2010-2020 average global price of fishmeal, these sources are able to produce nearly 2,200 tons SCP / day under baseline assumptions described in Methods and Table 5, or 14% of the global fishmeal market. Including sources that produce methane at costs of up to $2,050 could fully offset the global fishmeal market. Labor and electricity costs may be reduced at larger landfills and wastewater treatment plants, and are expected to increase for remote oil and gas facilities. Wastewater treatment plants may also be able to further reduce prices by locally sourcing nitrogen and phosphorus, or by using reactor configurations that enable use of treated wastewater effluent as cooling water instead of refrigerant.[17] In this analysis, we only consider methane that is not currently being used elsewhere. Thus, the full market potential for SCP production from methane will increase as we consider displacing other applications.

Figure 5 depicts a sensitivity analysis that begins with the cost of producing methanotrophic protein using the landfill base case size of 345 tons CH_4 / day, where levelized cost of methanotrophic SCP is $1,540 /ton (see SI for sensitivity analysis

	WWTP	**Landfills**	**Oil & Gas**	**Grid**
Methane Cleanup	89	89	89	0
Capital Costs	204	204	204	204
O&M	174	174	174	174
Nitrogen & Phosphorus	118	118	118	118
Natural Gas	0	0	0	127
Cooling Electricity	509	509	509	509
Non-cooling Electricity	324	324	324	324
Labor	223	124	109	124
Total ($ / ton SCP)	1,630	1,543	1,527	1,581

Table 2. Levelized cost breakdown for methanotroph production across three different substrate scenarios for current technologies in the four baseline scenarios.

Scenario	**Source Size (tons CH_4/day)**	**Total Reactor Volume (m^3)**	**Methanotroph Production (tons SCP/day)**
Wastewater Treatment	148	860	83
Landfills	345	2010	193
Oil & Gas	420	2450	235
Grid	345	2010	193

Table 3. Baseline size across four location scenarios. Source sizes represent the largest point sources from emissions or flaring in each location. Total reactor volume and methanotroph production rate are calculated based on a methane utilization rate of 0.14 tons CH_4 / m^3 - day and a microbial yield of 0.7 tons volatile suspended solids (SCP) / ton CH_4. Methanotroph production potential assumes the same microbial yield, and also applies a utilization factor of 80% to allow for time needed for maintenance and repairs.

of wastewater treatment, oil and gas base cases and grid scenarios). We choose landfills as a base case as they are typically located in close proximity to population centers, meaning labor and electricity are likely readily available. The high cost of cooling is reflected in the sensitivity to coefficient of performance (COP) for the assumed refrigeration system;[17] doubling COP reduces levelized cost by nearly 20%, whereas decreasing COP from 3 to 2 increases cost by nearly 20%. The high sensitivity to electricity also reflects the overall importance of cooling costs to the model, as well as the high costs associated with compressing gases and drying biomass. Decreasing cost of electricity to $0.06 / kWh, in line with industrial rates in the lowest-cost parts of the US, reduces levelized cost by 22% to $1,185/ton SCP, whereas increasing the price to the high end of those available to residential consumers, $0.14 / kWh, increases levelized cost by 22% to $1,852 / ton.

The model is also sensitive to labor, unit capital cost and microbial yield. We increase labor by 350% to 4.5 worker-hrs / ton SCP, reflecting a 90% smaller facility at a size our model suggests would be necessary to fully offset the fishmeal market using the current supply of stranded methane from the sources analyzed. This increase in labor required introduces 23% increase in cost to nearly $1,870 / ton. Increasing unit capital cost by 156% to the high value reported in literature, $1.3M / ton,[15] increases total levelized cost by 20%. Increasing microbial yield by 29% to the high value reported in the literature decreases price by 1.8% to $1,490, indicative of the potential of selecting for higher yield organisms to introduce additional marginal cost savings.

The costs of non-methane substrates (NH_3 and phosphorus) have minimal impact on levelized cost within the price ranges observed for these compounds over the past 10 years. Increasing cost of NH_3 by 47% increases levelized cost by just under 3%, and increasing phosphorus by 30% increases levelized cost by less than 1%.

Discussion

We find that methantrophic biomass is cost competitive with fishmeal when produced with current technology. Stranded methane in the United States can serve as a growth substrate capable of offsetting 14% of the global fishmeal market. Companies are already commercializing production of methanotrophic protein using natural gas, which we find to be economically competitive with fishmeal. We find that replacing natural gas with stranded methane could prove to be even more profitable at large scale. The largest sources of stranded methane can serve as a starting point for industrial production, enabling technological advances and cost reductions that can further expand production to include smaller sources of methane at more remote locations. Production at smaller sources of methane will enable enough protein production to fully offset demand for fishmeal. Reaching such production levels will require meaningful cost reductions for smaller scale facilities, potentially through increased electrical

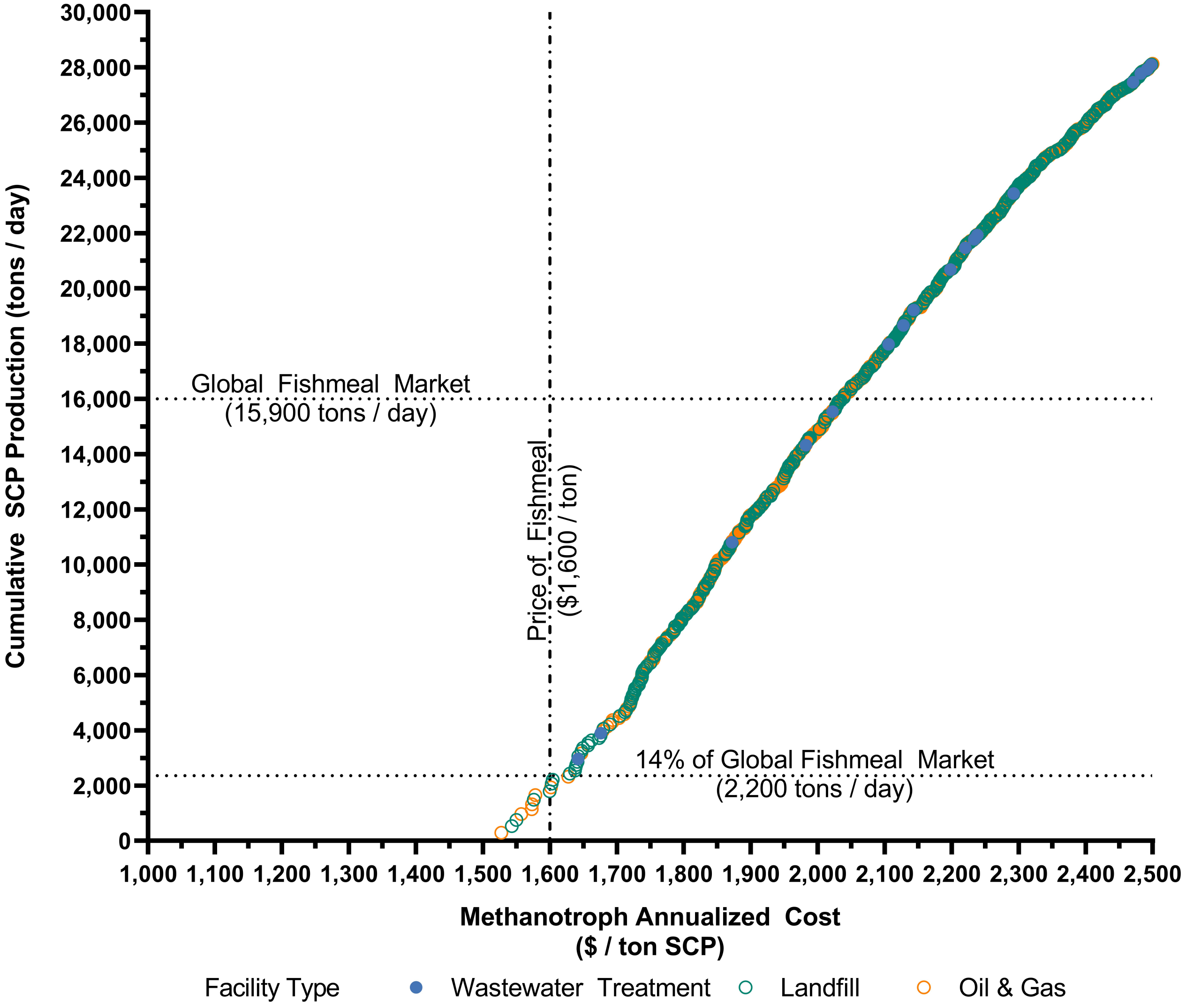

Figure 4. Supply curve for methanotrophic production using stranded methane. Each point represents a point source of methane, and the x-axis indicates the corresponding levelized cost of protein that can be produced from that facility. The y-axis indicates the cumulative amount of protein that can be produced with each additional facility. Maintaining the cost of methanotrophic protein at below that of fishmeal can potentially produce over 15% of the global fishmeal market. Allowing costs to reach $2,050 could enable fully offsetting the global fishmeal market. We only include methane from facilities that are not currently being used elsewhere: the full market potential for SCP production from methane is even higher if we consider displacing other applications.

efficiency and reduced labor requirement.

We identify a number of priority areas for cost reduction to enable commercialization and expansion of methanotroph protein production. Across all production baseline scenarios, cooling costs are dominant. Reactors may be designed to facilitate surface area for heat transfer,[29] while cultures of thermophilic methanotrophs can reduce the total amount of heat that needs to be removed by operating at higher temperatures.[17] Electricity costs may be further by reduced by switching electric-powered applications to gas, which can also reduce reliance on grid electricity for remote locations.

As methanotrophic production scales down to capture smaller sources of methane, labor cost per ton of protein increases.[20]

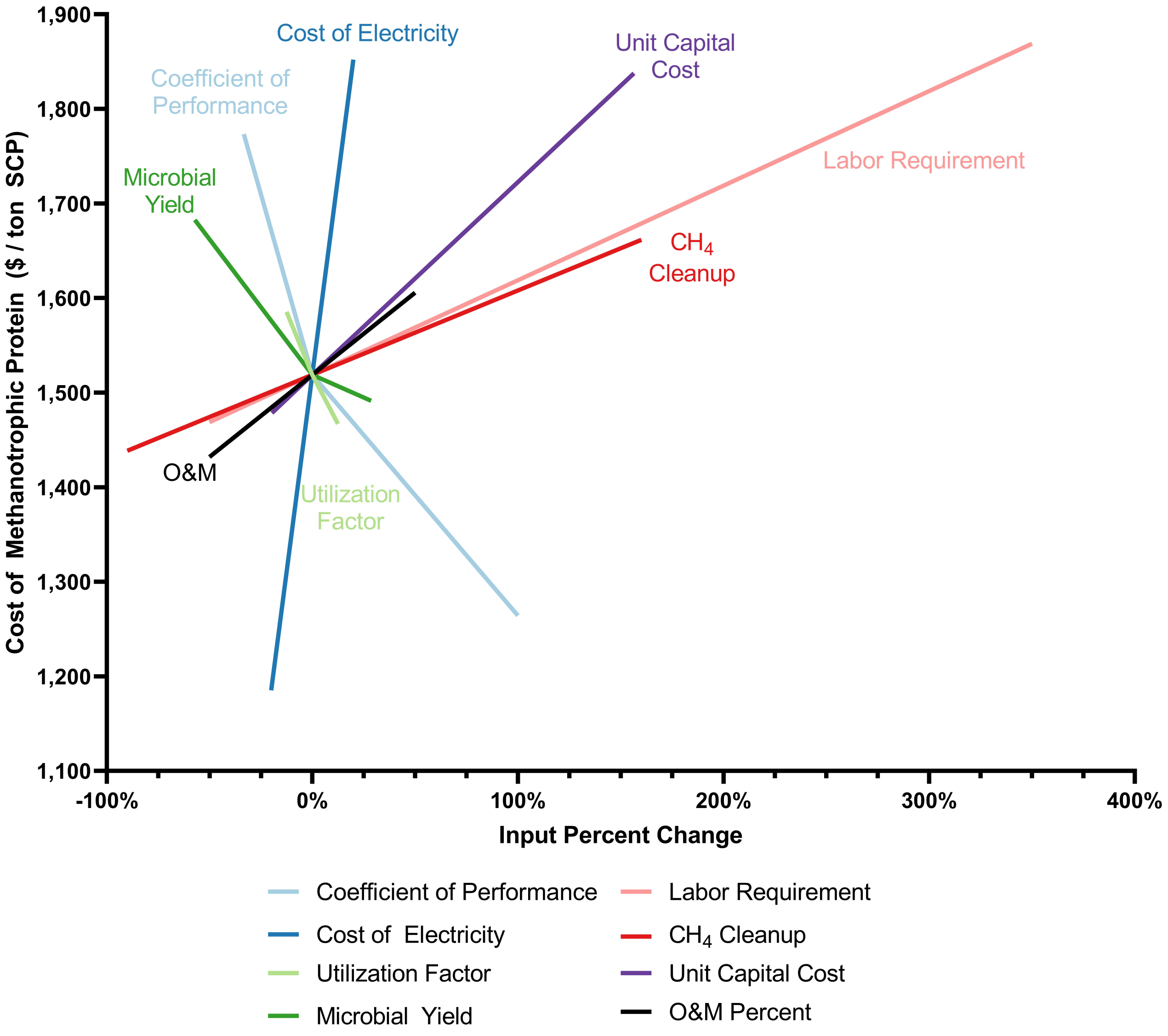

Figure 5. Sensitivity analysis for baseline methanotroph production at landfills, individually varying parameters to low and high values. The x-axis represents the resulting percent change of each parameter input, and the y-axis represents the corresponding levelized cost of production ($/ton SCP). Production is highly sensitive to cost of electricity, cooling coefficient of performance (COP) and labor. Levelized cost is also sensitive to unit capital cost and microbial yield.

Thus, research and development priorities would benefit from focusing on automating processes to reduce labor requirements at small-scale facilities. Automation will also enable utilizing stranded methane from remote oil and gas facilities not readily accessible by population centers, where labor is at a premium. As technology advances, smaller methane point sources are also likely to benefit from economies of unit number, whereby production of many smaller units enables greater capital cost savings than production of larger-scale facilities.[11]

In our analysis we make the generous assumption that currently vented methane emissions can be captured and concentrated at minimal additional capital cost. While this is the case for methane flares, vented sources of methane may be more diffuse and require greater capital investment for capture. We also consider methane emissions and flaring as separate sources of methane. However, for landfills and oil and gas facilities, point sources for flaring and emissions may occur in close proximity or even at the same facility. Thus, further opportunities for large scale production may be available by collecting methane from physically proximate sources and using pooled gas to feed a larger bioreactor than would be feasible from any of the individual sources on their own. Additionally, our analysis is focused on the United States due to the availability of high quality data; however, stranded methane around the world could be used with similar systems.

While our analysis finds that large wastewater treatment plants are currently not cost competitive with fishmeal, these facilities present a number of opportunities for future cost reductions. Nitrogen and phosphorus may be locally sourced from partially treated effluent, potentially offsetting nutrient costs. Located near population centers, labor and electricity are also readily available at wastewater treatment plants. Wastewater treatment plants also have effluent water readily available onsite, which can replace refrigerant for cooling should thermophilic production be adopted.[17] Future research should further investigate the cost saving opportunities presented by co-located at wastewater treatment plants through different cooling and nutrient recovery technology configurations.

Overall, our analysis demonstrates the market potential for methanotrophic SCP grown on stranded methane to serve as a replacement for fishmeal in animal feed. While we do not include a life-cycle assessment, incentivizing capture of methane provides a beneficial end-use for gas that is currently emitted or flared. Further environmental benefits can be derived by offsetting the need for fishmeal, reducing pressure on over-harvested marine ecosystems. Fishmeal prices show an increasing trend over the last 30 years (see Supplemental Figure 2),[30] while total production has decreased over the same period.[31] Our analysis indicates that, when compared with the 2010-2020 average price of fishmeal, a 20% decrease in the cost of methanotrophic SCP production from stranded methane could enable fully offsetting the global fishmeal market.

Methods

Data

Wastewater Treatment Data We use data from the US Environmental Protection Agency (EPA)'s publicly available Clean Watershed Needs Survey (CWNS) to identify wastewater treatment facilities with anaerobic digestion, and their corresponding geographic location (latitude and longitude), average daily treatment rate and presence of biogas utilization unit processes. Using methods described by Gingerich & Mauter,[32] we merged the 2004, 2008 and 2012 data to generate a dataset for all wastewater treatment facilities with anaerobic digestion that did not have on-site biogas utilization facilities, their reported wastewater flow rates and geographic coordinates. Biogas produced from the flow was calculated by using the conversion 1.5 sfc of biogas produced per 100 gallons of wastewater processed[33] and 60% methane content in biogas, a conservative estimate for anaerobic digestors[34]. see SI Methods for further detail.

Landfill Data For landfill direct emissions data, we use EPA's publicly available Facilities Level Information on GreenHouse gases Tool (FLIGHT)[21] for 2019 methane emissions from the following sectors: municipal landfills, industrial landfills and solid waste combustion. For flaring data, we used EPA's Landfill Methane Outreach Program (LMOP) from August 2020.[22] See SI Methods for further detail.

Natural Gas and Petroleum Data For natural gas and petroleum direct emissions data we also used the EPA FLIGHT database,[21] downloading all 2019 methane emissions for the Petroleum and Natural Gas Systems sector, including all sub-headings. For flaring data, we used Visible Infrared Imaging Radiometer Suite (VIIRS) data from 2019.[23] See SI Methods for further detail.

Techno-economic Model

This analysis models a methanotroph production system consisting of the following costs components: capital costs, operations and maintenance, methanotroph nutrient requirements (ammonia, phosphorus), labor, and electricity. We include the cost of methane cleanup ($/ton CH4) as an additional input. We establish baseline values (approach detailed below) for each input to determine the levelized cost in four different scenarios: co-location with wastewater treatment plants, landfills, natural gas facilities, and a facility with a paid connection to the natural gas grid.

Methanotrophic Properties

For the purposes of this analysis, we defined the final SCP product as the organic biomass of the dried cell (also referred to as volatile suspended solids). Microbial properties of yield (ton SCP produced / ton substrate consumed), cell density (grams SCP / L), and specific growth rate (day^{-1}) determine how much biomass can be produced in a reactor for a given period of time (see Equations 1 and 2 in SI). We use these parameters to determine methanotroph production rate for our baseline levelized cost calculations. Using the stoichiometry in Equation 1 to describe methanotrophic growth,[14] we calculate baseline microbial yields for each compound required for growth: methane, oxygen and ammonia. For phosphorus, we assume 2% of biomass by weight (Table 4).[34]

$$CH_4 + 1.5\,O_2 + 0.10\,NH_3 \rightarrow 0.10\,C_5H_7O_2N + 0.5\,CO_2 + 1.8\,H_2O + 643\,kJ\,Heat \tag{1}$$

For cell density in the bioreactor, microbial growth rate (g SCP / d) / g SCP and heat production (kJ / g SCP), we surveyed the literature to identify representative values for industrial methanotrhopic growth (Table 3). We used these inputs to determine methane utilization rate and the size of the bioreactor needed for a given source size. See SI Methods for further detail.

Parameter	Units	Baseline Value
Growth Rate	g SCP / g SCP - day	4[14]
Yield	g SCP / g CH_4	0.7[14]
Oxygen yield	g SCP / g O_2	0.2[14]
Ammonia yield	g SCP / g NH_3	6.6[14]
Phosphorus yield	g SCP/ g P	153[34]
Cell Density	g / L	30[17]
Methane Utilization Rate	tons CH4 / m3 - d	0.14
Heat Production	kJ / g SCP	55[14]

Table 4. Baseline methanotroph properties: growth rate, substrate yields, bioreactor cell density, calculated methane utilization rate and heat production. Yield is the amount of methanotrophic Single Cell Protein (SCP) produced per input of a given substrate, and here unless a different input is specifies, refers to the yield on methane. Oxygen and ammonia yields are derived from stoichiometry in Equation 1 and phosphate yield is based on an assumption of 2% phosphorus in cell biomass[34]. Yield and growth rate vary across different methanotrophic species.[35] Baseline values in this analysis are representative values from methanotrophic industrial production,[14,17] but species selection may further optimize production rates.

Capital Costs

We model a methanotroph production system with the following components: methane and air compression, growth bioreactor, dewatering centrifuge, and drying (see Figure 2). We first determine a literature baseline unit capital cost value based on reported capital costs and capacity. This literature baseline value was then scaled to the size required by the methane source baseline established in this analysis described in Table 3. We assume all equipment costs except the bioreactor have constant unit capital cost, to represent increasing unit number of the equipment operating in parallel. For the bioreactor, we used a 500 m^3 benchmark the largest bioreactor size, representative of the largest industrial aerated stirred tank reactors in operation.[27] For bioreactors smaller than 500 m^3, we applied a scaling relationship based on total bioreactor volume described in Equation 2. For bioreactors 500 m^3 or greater, we used the unit capital cost of a 500 m^3 reactor as a model for multiple reactor operating in parallel. For the scaling factor n, we use 0.7, a mid-value of reported and calculated scaling factors in the literature.[27,36]

$$Cost_2 = Cost_1 \left(\frac{Size_2}{Size_1} \right)^n \tag{2}$$

Gases are pressured from 1 bar to 8 bar before delivery to the methanotrophic bioreactor. For air and methane compression, we used continuous centrifugal air compressor described in Levett et al.[17] For air compression, we calculated unit capital cost using reported air flow rate, capital costs and electricity usage for a 52.8 MW compressor (Table 1. To establish the literature baseline unit capital cost for methane compression, we used the same compressor specifications but scaled capital cost for the reduced methane flow rate reported in Levett et al. using the size scaling exponent for air compression (n = 0.34).[37] We modeled power consumption of in Aspen Plus to determine the power rating of 3.6 MW for reported methane flow rate.

Pressurized gases and media enter the continuous airlift methanotrophic bioreactor. Heat is removed via cooling jacket and coils included in bioreactor capital cost. Biomass from the bioreactor is dewatered in a biomass centrifuge, reducing the water content to 35%.[17] Biomass is then dried in a continuous rotary drum dryer that further reduces moisture content to 10%.[17]

All costs were adjusted to 2020 US dollars using annual average Consumer Price Index for all urban consumers as reported by the US Bureau of Labor Statistics [REF].[38] We calculated total annualized capital cost using an equipment lifetime of 20 years[17] and a baseline weighted average cost of capital (WACC) of 10%, representative of a new technology (Calculations in SI).[39] Cost of operations and maintenance of equipment was set at 10% of total capital cost per year.[17]

Electricity Costs

To calculate electricity costs, we consider the power demand of individual equipment needed for each stage methanotrophic biomass production: gas compression (methane and air), growth reactor, dewatering and drying. We used reported power demand in Levett et al.[17] and equipment capacity for each unit process to determine electricity cost in $2020 per ton SCP. The electricity needed for cooling the growth reactor was determined using the heat production rate (Equation 3)[14] and divided by COP (heat energy removed per electricity input) to determine the electricity needed for heat removal. For price of electricity, we use $0.10 / kWh, representative of commercial prices[40]. This is a conservative assumption, as landfills and wastewater treatment plants may have access to industrial prices for electricity (averaging around $0.07 / kWh in the US[40]). However, these facilities may not be able to reach the same scale as large industrial customers and thus may pay closer to commercial rates. Note that remote oil and gas facilities may not have an electric grid connection, potentially increasing electricity costs at these locations.

$$Heat\,Production\,Rate = \Delta_c H_{MET} * \frac{1}{Y} * \mu * \rho * V \tag{3}$$

Where
$\Delta_c H_{met}$ is metabolic heat production (kJ / g CH_4)
Y is cell yield (g SCP / g CH_4)
μ is growth rate (day^{-1})
ρ is cell density g SCP / L
V is reactor size (liters)

Methane Cleanup

We assumed all stranded methane in this analysis requires cleaning to remove contaminants before use as a methanotroph feedstock. As methanotrophs metabolize and assimilate CO_2 into their biomass,[41] cleanup costs will be lower than those required for injected biomethane into the natural gas grid.[42] Because of the different levels of treatment required to clean and upgrade bio/landfill/natural gas, we calculated the cost of methane cleanup separately from the equipment costs associated with methanotrophic biomass production (bioreactor, gas compression systems, post-processing). We surveyed the literature to calculate the cost of methane cleanup per ton CH_4, and considered systems designed for desulfurization and siloxane removal.[43–45] We included the annualized capital cost, variable and/or electricity costs (see SI Methods for further detail). Depending on the extent of contaminant removal, cleanup costs reported in the literature ranged from \$5 / ton CH_4 to \$128 / ton CH_4. We use a mid value of \$50 / ton CH_4 as our baseline value, representative of the cost of upgrading a wastewater treatment facility to include an adsorption unit for biogas cleanup.[44] For the grid baseline scenario, we removed the cost of methane cleanup.

Substrate Costs

Microorganisms require substrates that serve as sources of macro- and micro- nutrients necessary for growth. Macronutrient requirements are provided in Equation 1. For methanotrophs, methane serves as the source of energy and carbon. For facilities located at wastewater treatment plants, landfills and oil and gas facilities, we assume methane is readily available at no additional capital cost. While this is a reasonable assumption for flared methane, we recognize that this is a generous assumption for methane currently directly emitted. For the grid scenario, we used World Bank Commodity Price Index price for US natural gas averaged over the last 10 years (\$170 / ton CH_4).[30]

We use urea and diammonium phosphate as sources for nitrogen and phosphorus. We calculate baseline substrate costs using yield values (mol SCP / mol substrate) and assume a phosphorus content in biomass of 2% (Table 4).[34] For baseline prices we use the 10 year average from 2010 to 2020 reported by the World Bank Commodity Price Index, converted to \$ 2020 for urea (CH_4N_2O) and diammonium phosphate ($(NH_4)_2HPO_4$), respectively.[30] This results in baseline costs of \$550 / ton NH_3 and \$1,790 / ton phosphorus, or \$83 / ton SCP for ammonia and \$36 / ton SCP for phosphorus, using yield assumptions in Table 4.

We compare three different approaches for sourcing oxygen: compressed air,[17] generating pure O_2 onsite using an air separation unit,[46] and purchasing commercial O_2.[15] All methods resulted in costs that ranged from \$36 - \$42 / ton O_2 (see SI Methods). As the cost ranges were comparable across each of these different approaches, our model uses compressed air to feed oxygen to the bioreactor. Thus, the cost of oxygen is accounted for in the capital cost of the air compressor and associated electricity cost (described above), rather than a direct input to our substrate cost calculation.

Labor Costs

To determine the labor demand in worker-hrs / ton SCP for a given plant size, we used values reported in the literature for bioplastic production of polyhydroxybutyrate (PHB). Criddle et al. (2014) report the number of personnel needed for the three stages of production (fermentation, extraction and packaging) for plant capacity ranging from 500 tons PHB / year to 100,000 tons PHB / year (summarized in SI). We used the number of personnel required for fermentation and packaging (PHB biopolymer extraction is not necessary for protein biomass production) and the total reported hours of operation per year to determine worker-hrs needed per ton of PHB produced in a given plant size. We directly used these values as the worker-hrs needed to produce an equivalent mass of methanotrophic biomass (see SI Methods for full details). This is a conservative assumption, as fermentation bioreactors that can support a fixed rate of PHB production can likely produce twice as much methanotrophic biomass: PHB makes up 50% of cell biomass and requires a multi-stage fermentation.[47]

Utilization Factor

We apply a utilization factor of 80% to our baseline scenario to account for plant downtime for maintenance and repair. The average utilization of oil refinery capacity over the last 10 years is 90%[48]. To account for potentially variable quantity and quality of gas production across our different scenarios, we chose 80%. When methane is sourced from wastewater treatment or the natural gas grid, we anticipate this value to be highly conservative.

We applied the utilization factor to all inputs that vary with the final single cell protein production rate: annualized capital cost, annualized operations and maintenance, worker hours needed, and total annualized methane cleanup. While total annualized methane cleanup includes variable costs which are fixed per ton of CH_4 treated, we assumed costs are dominated by capital.

Total Levelized Cost

We calculated the total levelized cost of producing methanotrophic protein including all techno-economic parameters described above (Equation 4).

$$Total\,Levelized\,Cost = Annualized\,Capital\,Cost + Annualized\,O\&M + Electricity\,Cost + Substrate\,Cost + Labor\,Cost \quad (4)$$

We calculated the baseline facility size (in tons of methane utilized per day) for each methane source scenario (wastewater treatment, landfills, oil and gas and grid) using the largest point sources in our database, with the grid case at the same scale as the landfill case. We compare methantroph production cost to the price of fishmeal, represented by the average price over the last ten years, \$1,612 / ton (10-year low and high are \$1,351 / ton and \$1,944 / ton, respectively).[30]

Sensitivity Analysis

The sensitivity analysis individually varies each input parameter from its baseline to low and high values, representing the feasible range of current values reflected in the existing literature, and calculates the resulting total annualized cost of methanotrophic biomass.

We surveyed the literature to determine low and high unit capital costs for methanotrophic biomass production. Our survey included techno-economic analyses where methanotrophic biomass itself was the final product as well as those where methanotrophs were being for polyhydroxyalkanoate (PHA) production. In the latter scenario, capital costs were adjusted to include only the processes necessary for methanotrophic biomass production (See SI Methods). For Weighted Average Cost of Capital (WACC), we used a low value of 8% and high value of 12%, representing modest variation in potential investor confidence in this emerging technology.[39] We varied COP from baseline of 3[17] to a low of 2 and a high value of 6.

For ammonia and phosphorus, we maintained the baseline described above, using the average 10 year price. We used the average price from the years with the highest and lowest average price over the same period as low and high values, respectively. For cost of electricity, we use a low value of \$0.06 / kWh, which is a low-end price for industrial consumers in the United States.[40] For the high value, we used \$0.14 / kWh, just above average residential prices in the US.[40] Our baseline value for labor requirement (1 worker-hr / ton) is based literature for polyhydroxybutyrate (PHB) production. Thus, for the low input value we reduce labor requirement by 50% compared to baseline, as fermentation to produce biomass will have increased output of final product as PHB will only reach 50% of total cell dry mass (thus bioreactors producing 500 tons / year of PHB can produce 1000 tons / year of protein).[47] For the high value input, we calculated the plant size needed in order to completely meet market demand for fishmeal based on the supply curve in Figure 4, applying the labor cost scaling relationship described in the SI Methods to determine the associated labor requirement. This high input value of 6 worker-hrs / ton SCP corresponds to a source size of 24 tons CH_4/ day, and produces methanotrophic biomass at \$1,972 / ton under baseline assumptions at a landfill or oil and gas facility.

Supply Curve

To make the supply curve depicted in Figure 5, we generated a master dataset with the total annualized cost of methanotroph production, under baseline assumptions, for each methane source included in Figure 2. We sorted methane sources in order of increasing production cost, and calculated the cumulative biomass production rate (tons / day) as higher cost locations are incrementally added to total production. We use the 10 year average price of fishmeal \$1,600.[30] and the 2018 reported production rate, 15,900 tons / day,[4] as points of reference.

Input Parameter	Units	Low	Baseline	High
Cost of Ammonia[30]	\$ / ton NH_3	400	550	810
Cost of Phosphorus[30]	\$ / ton P	1,315	1,790	2,300
COP	kW heat removed / kW(e)	2	3[17]	6
Unit Capital Cost	\$ / ton SCP / day	407,000[18]	507,000	1,300,000[15]
Cost of Electricity[40]	\$ / kWh	0.06	0.10	0.14
WACC	%	8%	10%	12%
Labor Requirement	worker-hrs / ton SCP	0.5	1[17,20]	4.5
CH_4 Cleanup	\$ / ton CH_4	5[43]	50[44]	130[45]
Microbial Yield	tons SCP / ton CH_4	0.3[35]	0.7[14,17]	0.9[35]
Scaling Factor (n)		0.6[36]	0.7	0.8[27]
O&M percent	%	5	10[17,18]	15[15]
Utilization Factor	%	0.7	0.8	0.9

Table 5. Baseline, low and high inputs for sensitivity analysis. Baseline scenario is used in the main analysis. Low and high values represent the range reported in the literature current technology or prices. Substrate cost baseline values reflect the 10-year price average. Low and high substrate costs are the annual average low and high values within the same time period.[30] Baseline electricity costs reflect typical commercial prices, low value and high value represent typical industrial and residential prices, respectively.[40] Unit capital cost, labor requirements, methane clean, microbial yield and scaling factor reflect mid, high and low values reported in the literature. Unit capital cost baseline value is the result of this analysis.

References

1. Mbow, C. *et al.* Food Security. In *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, 437–550 (Intergovernmental Panel on Climate Change, 2019).
2. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492, DOI: 10.1016/S0140-6736(18)31788-4 (2019). Publisher: Elsevier.
3. Gephart, J. A. *et al.* Scenarios for Global Aquaculture and Its Role in Human Nutrition. *Rev. Fish. Sci. & Aquac.* **29**, 122–138, DOI: 10.1080/23308249.2020.1782342 (2021). Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/23308249.2020.1782342.
4. FAO. *GLOBEFISH Highlights January 2020 ISSUE, with Jan. – Sep. 2019 Statistics* (FAO, 2020).
5. Edwards, P., Zhang, W., Belton, B. & Little, D. C. Misunderstandings, myths and mantras in aquaculture: Its contribution to world food supplies has been systematically over reported. *Mar. Policy* **106**, 103547, DOI: 10.1016/j.marpol.2019.103547 (2019).
6. Shah, M. R. *et al.* Microalgae in aquafeeds for a sustainable aquaculture industry. *J. Appl. Phycol.* **30**, 197–213, DOI: 10.1007/s10811-017-1234-z (2018).
7. Naylor, R. L. *et al.* Feeding aquaculture in an era of finite resources. *Proc. Natl. Acad. Sci.* **106**, 15103–15110, DOI: 10.1073/pnas.0905235106 (2009). Publisher: National Academy of Sciences Section: Perspective.
8. Malcorps, W. *et al.* The Sustainability Conundrum of Fishmeal Substitution by Plant Ingredients in Shrimp Feeds. *Sustainability* **11**, 1212, DOI: 10.3390/su11041212 (2019). Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.
9. Boucher, O., Friedlingstein, P., Collins, B. & Shine, K. P. The indirect global warming potential and global temperature change potential due to methane oxidation. *Environ. Res. Lett.* **4**, 044007, DOI: 10.1088/1748-9326/4/4/044007 (2009).
10. US Environmental Protection Agency. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018. Tech. Rep. 430-R-20-002, United States Environmental Protection Agency (2020).
11. Clomburg, J. M., Crumbley, A. M. & Gonzalez, R. Industrial biomanufacturing: The future of chemical production. *Science* **355**, DOI: 10.1126/science.aag0804 (2017). Publisher: American Association for the Advancement of Science Section: Review.
12. U.S. Energy Information Administration. International - Electricity net consumption (billion kWh) (2019).

13. Øverland, M., Tauson, A.-H., Shearer, K. & Skrede, A. Evaluation of methane-utilising bacteria products as feed ingredients for monogastric animals. *Arch. Animal Nutr.* **64**, 171–189, DOI: 10.1080/17450391003691534 (2010).

14. El Abbadi, S. H. & Criddle, C. S. Engineering the Dark Food Chain. *Environ. Sci. & Technol.* **53**, 2273–2287, DOI: 10.1021/acs.est.8b04038 (2019).

15. Pikaar, I. *et al.* Decoupling Livestock from Land Use through Industrial Feed Production Pathways. *Environ. Sci. & Technol.* **52**, 7351–7359, DOI: 10.1021/acs.est.8b00216 (2018).

16. Ritala, A., Häkkinen, S. T., Toivari, M. & Wiebe, M. G. Single Cell Protein—State-of-the-Art, Industrial Landscape and Patents 2001–2016. *Front. Microbiol.* **8**, 2009, DOI: 10.3389/fmicb.2017.02009 (2017).

17. Levett, I. *et al.* Techno-economic assessment of poly-3-hydroxybutyrate (PHB) production from methane—The case for thermophilic bioprocessing. *J. Environ. Chem. Eng.* **4**, 3724–3733, DOI: 10.1016/j.jece.2016.07.033 (2016).

18. Listewnik, H.-F., Wendlandt, K.-D., Jechorek, M. & Mirschel, G. Process Design for the Microbial Synthesis of Poly-beta-hydroxybutyrate (PHB) from Natural Gas. *Eng. Life Sci.* **7**, 278–282, DOI: 10.1002/elsc.200620193 (2007).

19. Roland-Holst, D., Triolo, R., Heft-Neal, S. & Bijan, B. Bioplastics in California: Economic Assessment of Market Conditions for PHA/PHB Bioplastics Produced from Waste Methane. Tech. Rep. DRRR-2013-1469, California Department of Resources Recycling and Recovery, Sacramento, CA (2013).

20. Criddle, C. S., Billington, S. L. & Frank, C. W. Renewable Bioplastics and Biocomposites From Biogas Methane and Waste-Derived Feedstock: Development of Enabling Technology, Life Cycle Assessment, and Analysis of Costs. Tech. Rep. # DRRR-2014-1502, California Department of Resources Recycling and Recovery (2014).

21. Environmental Protection Agency. Facilities Level Information on GreenHouse gases Tool (2019).

22. Environmental Protection Agency. Landfill Gas Energy Project Data and Landfill Technical Dat (2020).

23. Earth Observation Group. Global Gas Flaring Observed From Space (2019).

24. Environmental Protection Agency. Clean Watershed Needs Survey (CWNS) 2004 Report and Data (2004).

25. Environmental Protection Agency. Clean Watershed Needs Survey (CWNS) 2008 Report and Data (2008).

26. Environmental Protection Agency. Clean Watershed Needs Survey (CWNS) 2012 Report and Data (2012).

27. Humbird, D., Davis, R. & McMillan, J. Aeration costs in stirred-tank and bubble column bioreactors. *Biochem. Eng. J.* **127**, 161–166, DOI: 10.1016/j.bej.2017.08.006 (2017).

28. Cho, J. H. & Kim, I. H. Fish meal – nutritive value. *J. Animal Physiol. Animal Nutr.* **95**, 685–692, DOI: https://doi.org/10.1111/j.1439-0396.2010.01109.x (2011). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1439-0396.2010.01109.x.

29. Petersen, L. A., Villadsen, J., Jørgensen, S. B. & Gernaey, K. V. Mixing and mass transfer in a pilot scale U-loop bioreactor: Mixing and Mass Transfer in a Pilot Scale U-Loop Bioreactor. *Biotechnol. Bioeng.* **114**, 344–354, DOI: 10.1002/bit.26084 (2017).

30. The World Bank. Commodity Prices - Annual prices. Tech. Rep., The World Bank (2021).

31. Jannathulla, R. *et al.* Fishmeal availability in the scenarios of climate change: Inevitability of fishmeal replacement in aquafeeds and approaches for the utilization of plant protein sources. *Aquac. Res.* **50**, 3493–3506, DOI: https://doi.org/10.1111/are.14324 (2019). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/are.14324.

32. Gingerich, D. B. & Mauter, M. S. Air Emission Reduction Benefits of Biogas Electricity Generation at Municipal Wastewater Treatment Plants. *Environ. Sci. & Technol.* **52**, 1633–1643, DOI: 10.1021/acs.est.7b04649 (2018). _eprint: https://doi.org/10.1021/acs.est.7b04649.

33. Parker, N., Williams, R., Dominguez-Faus, R. & Scheitrum, D. Renewable natural gas in California: An assessment of the technical and economic potential. *Energy Policy* **111**, 235–245, DOI: 10.1016/j.enpol.2017.09.034 (2017).

34. Rittmann, B. E. & McCarty, P. L. *Environmental Biotechnology: Principles and Applications* (McGraw-Hill Education, 2013).

35. Meraz, J. L., Dubrawski, K. L., El Abbadi, S. H., Choo, K.-H. & Criddle, C. S. Membrane and Fluid Contactors for Safe and Efficient Methane Delivery in Methanotrophic Bioreactors. *J. Environ. Eng.* **146**, 03120006, DOI: 10.1061/(ASCE)EE.1943-7870.0001703 (2020).

36. Vo, T. T. Q., Wall, D. M., Ring, D., Rajendran, K. & Murphy, J. D. Techno-economic analysis of biogas upgrading via amine scrubber, carbon capture and ex-situ methanation. *Appl. Energy* **212**, 1191–1202, DOI: 10.1016/j.apenergy.2017.12.099 (2018).

37. Garrett, D. E. *Chemical Engineering Economics* (Van Nostrand Reinhold, New York, 1989).

38. U.S. Bureau of Labor Statistics. CPI for All Urban Consumeres (CPI-U). Tech. Rep., U.S. Bureau of Labor Statistics (2020).

39. New Constructs. Weighted Average Cost of Capital (WACC): Explanation and Examples. Tech. Rep. (2016).

40. U.S. Energy Information Administration. Retail sales of electricity to ultimate customers (Annual). Tech. Rep., U.S. Energy Information Administration (2020).

41. Yang, S. *et al.* Global Molecular Analyses of Methane Metabolism in Methanotrophic Alphaproteobacterium, Methylosinus trichosporium OB3b. Part II. Metabolomics and 13C-Labeling Study. *Front. Microbiol.* **4**, DOI: 10.3389/fmicb.2013.00070 (2013).

42. Czyrnek-Delêtre, M. M., Ahern, E. P. & Murphy, J. D. Is small-scale upgrading of landfill gas to biomethane for use as a cellulosic transport biofuel economically viable? *Biofuels, Bioprod. Biorefining* **10**, 139–149, DOI: 10.1002/bbb.1627 (2016). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/bbb.1627.

43. Tansel, B. & Surita, S. C. Managing siloxanes in biogas-to-energy facilities: Economic comparison of pre- vs post-combustion practices. *Waste Manag.* **96**, 121–127, DOI: 10.1016/j.wasman.2019.07.019 (2019).

44. Aguilera, P. G. & Gutiérrez Ortiz, F. J. Techno-economic assessment of biogas plant upgrading by adsorption of hydrogen sulfide on treated sewage–sludge. *Energy Convers. Manag.* **126**, 411–420, DOI: 10.1016/j.enconman.2016.08.005 (2016).

45. Pipatmanomai, S., Kaewluan, S. & Vitidsant, T. Economic assessment of biogas-to-electricity generation system with H2S removal by activated carbon in small pig farm. *Appl. Energy* **86**, 669–674, DOI: 10.1016/j.apenergy.2008.07.007 (2009).

46. Clausen, L. R., Elmegaard, B. & Houbak, N. Technoeconomic analysis of a low CO2 emission dimethyl ether (DME) plant based on gasification of torrefied biomass. *Energy* **35**, 4831–4842, DOI: 10.1016/j.energy.2010.09.004 (2010).

47. Rostkowski, K. H., Pfluger, A. R. & Criddle, C. S. Stoichiometry and kinetics of the PHB-producing Type II methanotrophs Methylosinus trichosporium OB3b and Methylocystis parvus OBBP. *Bioresour. Technol.* **132**, 71–77, DOI: 10.1016/j.biortech.2012.12.129 (2013).

48. US Energy Information Administration. U.S. Refinery Utilization and Capacity (2019).