Displacing fishmeal with protein derived from stranded methane

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ABSTRACT

Methane emitted and flared from industrial sources across the United States is a major contributor to global climate change. Methanotrophic bacteria can transform this methane into useful protein-rich biomass for animal feed. In the rapidly growing aquaculture industry, this can replace ocean-caught fishmeal, reducing demands on over-harvested fisheries. Here, we analyze the economic potential of producing methanotrophic microbial protein from stranded methane produced at wastewater treatment plants, landfills, and oil and gas facilities. Our results show that current technology can enable production equivalent to 14% of the global fishmeal market at prices at or below the current cost of fishmeal of roughly $1,600 per metric ton. Achievable cost reductions, e.g. reduced cooling or labor requirements, could allow stranded methane from the US alone to displace the entire global fishmeal market.

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 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]. Over-fishing marine environments leads to long-term loss in biodiversity and irreversible damage to marine ecosystems[8]. While many plant proteins are a nutritionally promising substitute for fishmeal, they require additional inputs of land, freshwater and fertilizer[9].

Methane is a potent greenhouse gas with at least 25 times the global warming potential of CO_2 over a 100-year time period[10]. Total annual methane emissions in the US for 2014-2018 exceeded 630 million metric tons of CO_2 equivalents 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[11]. 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[11]. Taken together, methane emissions and flaring in the US release nearly 14 billion cubic meters (490 billion cubic feet) of greenhouse gases per year[12]. This is equivalent to over 420,000 TJ / year, nearly the entire annual energy consumption of Pakistan (436,000 TJ / year) in 2018[13]. 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[12].

Methanotrophic bacteria are capable of transforming methane into microbial protein, which can be used as an animal feed for agriculture or aquaculture[14]. 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%[14]. General interest in using microorganisms as a feed source, also referred to as single cell protein (SCP), has increased in recent years[15–17]. 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[15]. Not surprisingly, some companies in the US and EU are commercializing production of methanotrophic SCP from natural gas[17].

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[12]. Methanotrophs are the subject of multiple techno-economic analyses because of their potential to sequester carbon in bioplastics through accumulation of intracellular polyhydroxyalkanoate (PHA) granules, an industrial process more complex than that needed for protein production[18–20]. Recent studies have also evaluated the numerous potential environmental benefits of methantrophic SCP, and indicate promising economics[16,21,22]. To the best of our knowledge, our analysis is the first to evaluate the market potential of methanotrophic SCP across the full range of existing sources of stranded methane. 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 below 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)[23], Landfill Methane Outreach Program (LMOP)[24], and Clean Watershed Needs Survey (CWNS)[26–28]. For oil and gas flaring, we use VIIRS Nightfire data, also publicly available[25]. Details on data access and processing are included in Methods and Supplementary Methods. The geographic distribution of included 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[30], and methanotrophic biomass is 67%-81% crude protein (see Supplementary Table S10 for composition comparison)[14]. 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). Supplementary Note 1 provides a more detailed nutritional comparison of fishmeal and methanotrophic SCP. 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[15]. 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[15], a cell growth rate of 4 d^{-1}[15], and a cell density of 30 g SCP/L[18].

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 S7) 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, phosphorus and trace metal micronutrients. Maintaining the bioreactor at a biologically viable temperatures requires cooling to remove the considerable quantities of metabolic heat produced during methanotrophic growth[15,18]. 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[18], and the cells produced are dewatered in biomass centrifuges and then dried in biomass 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, nitrogen (as ammonia), phosphorus, water, 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

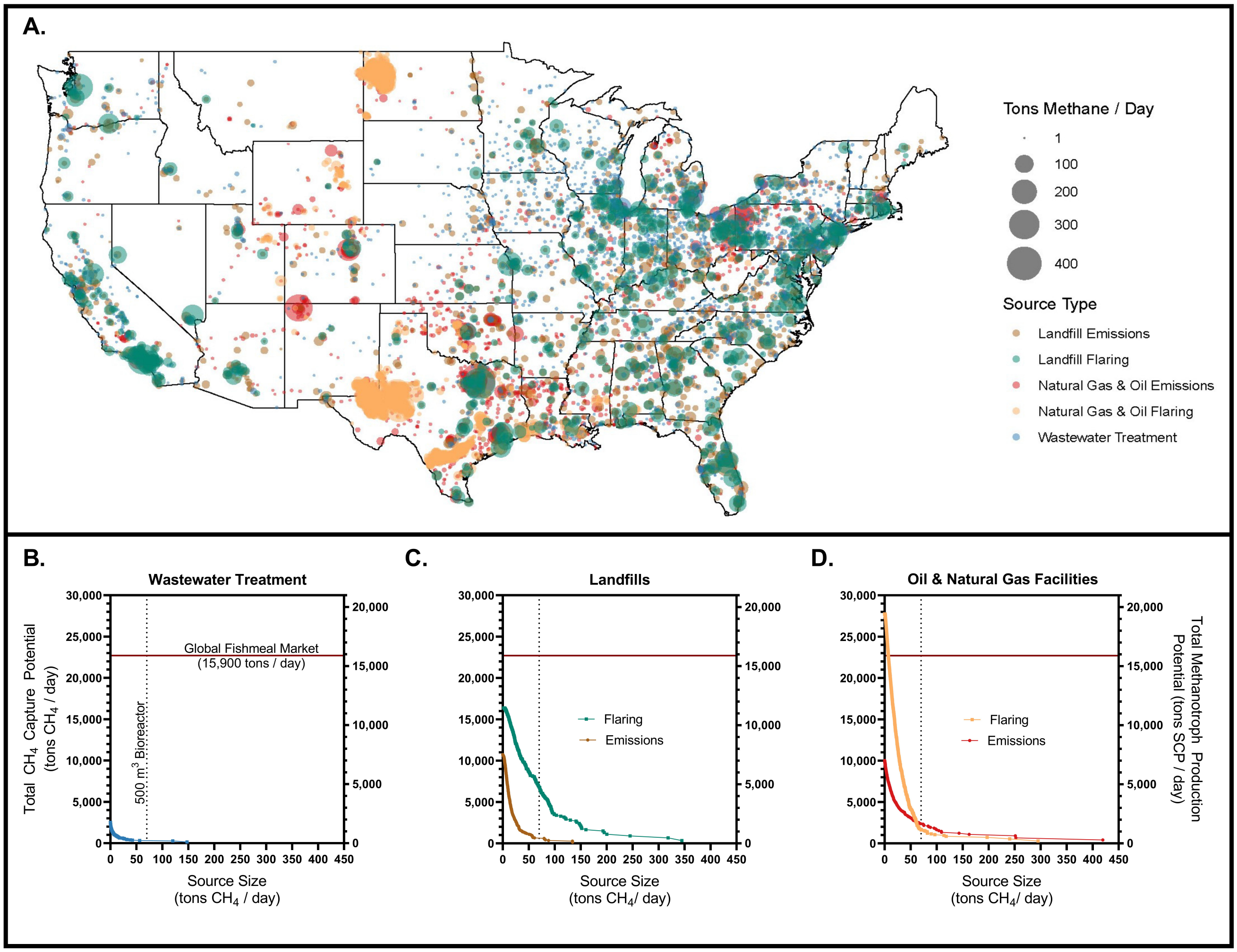

Figure 1. A. Unused methane generation in the United States. Point sources for methane currently emitted and flared from landfills[23,24], oil & gas facilities[23,25], and methane production from wastewater treatment plants currently not utilized[26–28]. Mapping in R. B-D. Cumulative methane capture 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, a typical size for an industrial-scale reactor[29].

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 for fishmeal in our baseline scenarios for facilities sourcing methane from landfills, oil and gas facilities, and the natural gas grid. We use the 10-year average market price of fishmeal, $1,600/ton for comparison, and include historical fishmeal prices for the last three decades in Supplementary Figure S7. 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 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), an amount inline with previous studies of

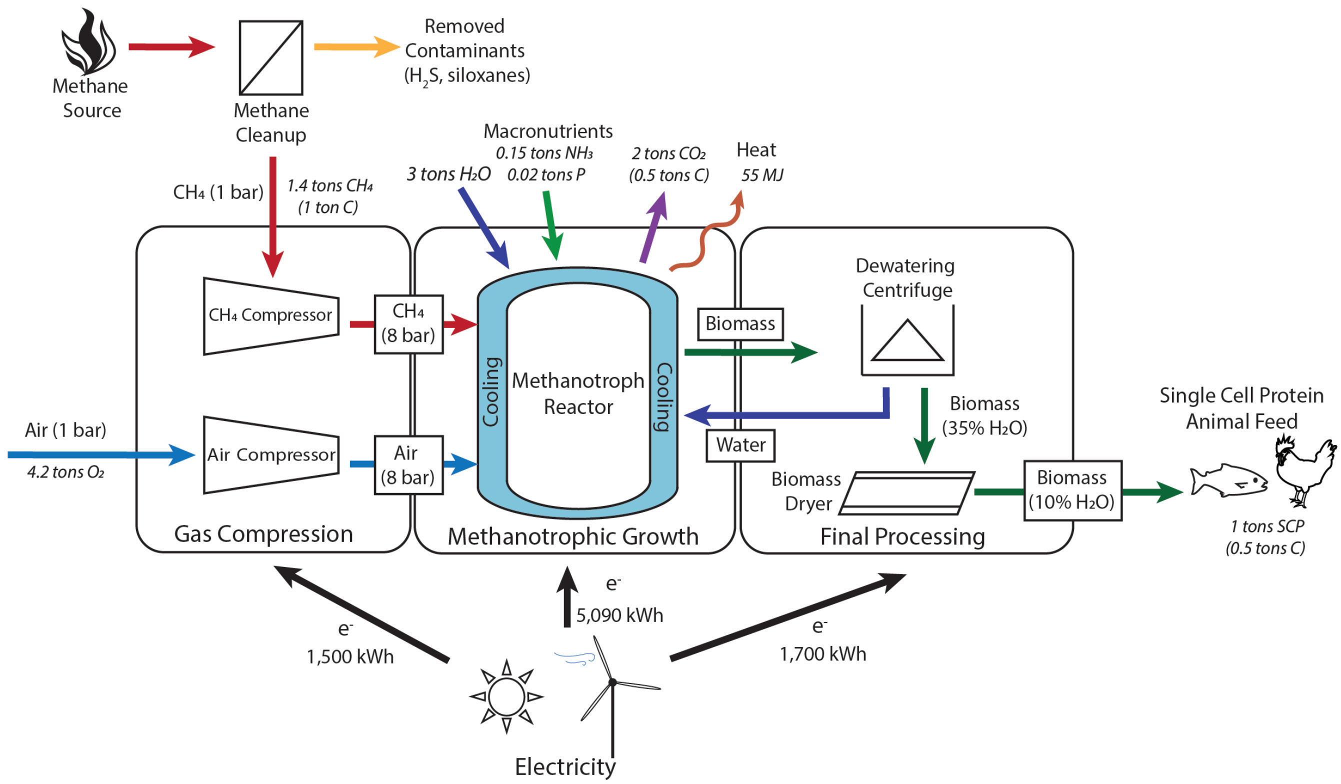

Figure 2. Process modeled for methanotrophic biomass production. Methane is cleaned to remove contaminants, then compressed and delivered to the growth bioreactor along with compressed air, which is the source of oxygen. Methanotrophic growth occurs in pressurized bioreactors equipped with cooling jackets 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.

methanotrophs[18]. We thus depict cooling costs separately from electricity costs associated with powering other methanotroph production equipment in Figure 3. Considering electricity alone, 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 below 15% of total levelized cost in all scenarios, making it the second largest cost component after electricity, except for in the wastewater treatment scenario, where labor costs increase (making up 13% of costs total cost compared to 12% for capital cost). Methane cleanup (where required), nutrient media (N, P, H_2O), and operations and maintenance each make up 5-10% of total levelized cost across all scenarios.

Despite 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[29], 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 4 depicts a supply curve for production of methanotrophs from stranded sources of methane in Figure 1. Keeping prices at or 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 \$2,040 could fully offset the global fishmeal market by producing over

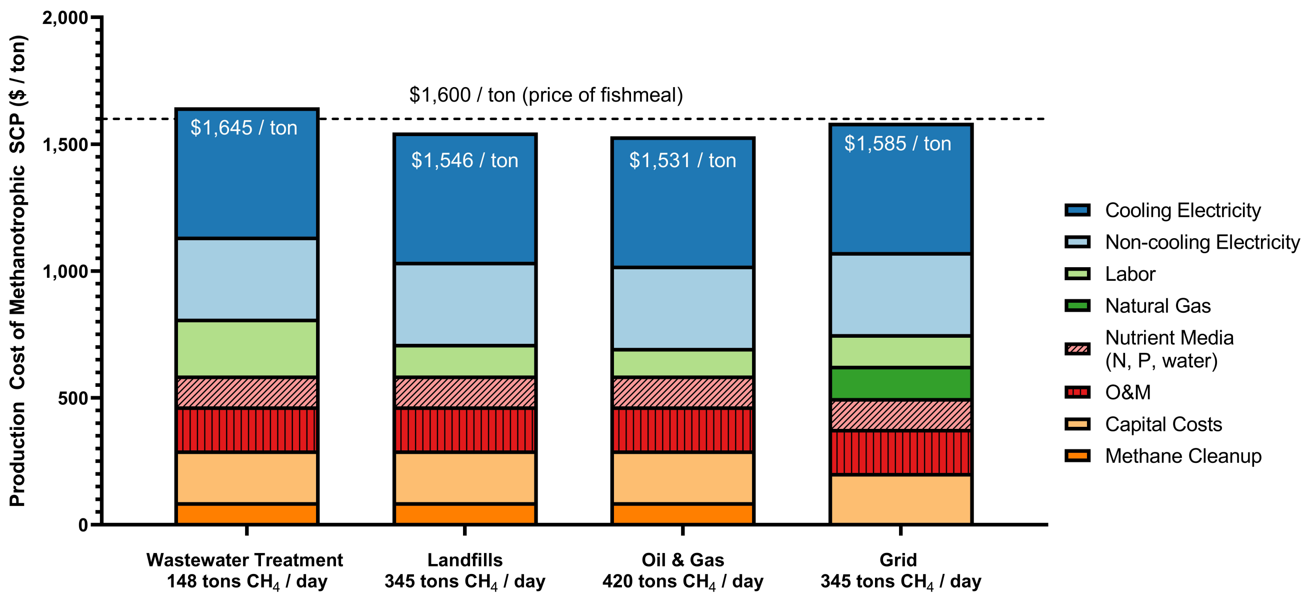

Figure 3. Levelized cost of methanotrophic microbial protein across baseline scenarios in which methane comes from wastewater treatment, landfills, oil and gas facilities, the natural gas grid. Baseline scenarios represent the largest feasible sources of stranded methane by source type. The grid baseline 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. 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. All baseline scenarios except wastewater treatment are lower than the average 10-year market cost of fishmeal, $1,600/ton. Wastewater treatment plants, however, have potential to reduce costs with locally sourced nutrients and cooling water.

15,900 tons SCP/day. The different location scenarios considered offer various opportunities and challenges for cost reduction. Landfills and wastewater treatment plants may have labor and electricity readily available, whereas we expect these costs 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[18]. Furthermore, 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.

We identify key cost sensitivities in Figure 5, which 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 $1,546 /ton (see SI for sensitivity analysis of wastewater treatment, oil and gas base cases and grid scenarios). Input variables included in this figure are those that result in a change of 5% or greater in calculated levelized cost. 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[18]; doubling COP reduces levelized cost by over 15%, whereas decreasing COP from 3 to 2 increases cost by over 15%. 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 $1,214/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 $1,881 / 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 28% increase in cost to nearly $1,985 / ton. Increasing unit capital cost by 156% to the high value reported in literature, $1.3M/ton/day[16], increases total levelized cost by 21%. Increasing microbial yield by 29% to the high value reported in the literature decreases price by 1.8% to $1,520, indicative of the potential of selecting for higher yield organisms to introduce additional marginal cost

Table 1. Equipment associated costs for baseline scenarios. Unit capital costs are the result of a scaling-based calculation described in Supplementary Methods. Details of annualized capital cost calculations are also available in Supplementary Methods. 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. Values for totals may differ slightly due to rounding.

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	57	137	48
Methane Compressor	66,450	27	11	23
Bioreactor	196,700	79	509	67
Dewatering	5,695	2	11	2
Drying	96,850	39	166	33
Total	507,100	204	834	174

Table 2. Levelized cost breakdown ($/ ton SCP) for methanotroph production across three different substrate scenarios for current technologies in the four baseline scenarios. Nutrient media includes the cost of purchasing nitrogen, phosphorus, and water. Values for totals may differ slightly due to rounding.

	Levelized Cost Across Baseline Scenarios ($/ton SCP)			
	WWTP	Landfill	Oil and Gas	Grid
Methane Cleanup	89	89	89	0
Capital Costs	204	204	204	204
O&M	174	174	174	174
Nutrient media (N, P, H_2O)	122	122	122	122
Natural Gas	0	0	0	127
Cooling Electricity	509	509	509	509
Non-cooling Electricity	324	324	324	324
Labor	223	124	109	124
Total ($ / ton SCP)	1,645	1,546	1,531	1,585

savings.

Input parameters that introduce changes in levelized cost less than 5% are summarized in Supplementary Table S8. 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 under 3%, and increasing phosphorus by 30% increases levelized cost by less than 1%. Infrastructure lifetime, weighted average cost of capital (WACC), scaling factor (n), and ultization factor also introduce changes of less than 5%.

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 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

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.

Scenario	Source Size (tons CH_4/day)	Total Reactor Volume (m^3)	Methanotroph Production (tons SCP/day)
Wastewater Treatment	148	860	83
Landfills	345	2,010	193
Oil & Gas	420	2,450	235
Grid	345	2,010	193

surface area for heat transfer[31], while cultures of thermophilic methanotrophs can reduce the total amount of heat that needs to be removed by operating at higher temperatures[18]. 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[32]. 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[12].

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. We also do not consider in this analysis the potential for policies (such as carbon credits or tax) to further the economic favorability of methanotrophic SCP.

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 likely accessible from wastewater treatment plants. Wastewater treatment plants also have effluent water readily available onsite, which can replace refrigerant for cooling should thermophilic production be adopted[18]. 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.

Methantrophic SCP will also economically benefit from increasing cost and environmental limitations on fishmeal production. Since the year 2000, fishmeal prices have nearly tripled in real terms (see Supplemental Figure S7)[33], while total production has decreased[34]. And yet fishmeal currently accounts for nearly 20% of capture fishery production, despite decreasing inclusion rates of fishmeal in aquaculture feed (discussed fully in Supplementary Note 2)[4]. The ability of methanotrophs to confer health benefits to fish and shrimp may also increase their value (discussed in Supplementary Note 3)[15].

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. In fact, our analysis indicates that a 20% decrease in the cost of methanotrophic SCP production from stranded methane could enable fully offsetting the global fishmeal market. While beyond the scope of the current analysis, expanding methanotrophic production to secondary markets (terrestrial animal feed, bioplastic production) can serve as a means to incentivize methane capture beyond the current fishmeal market.

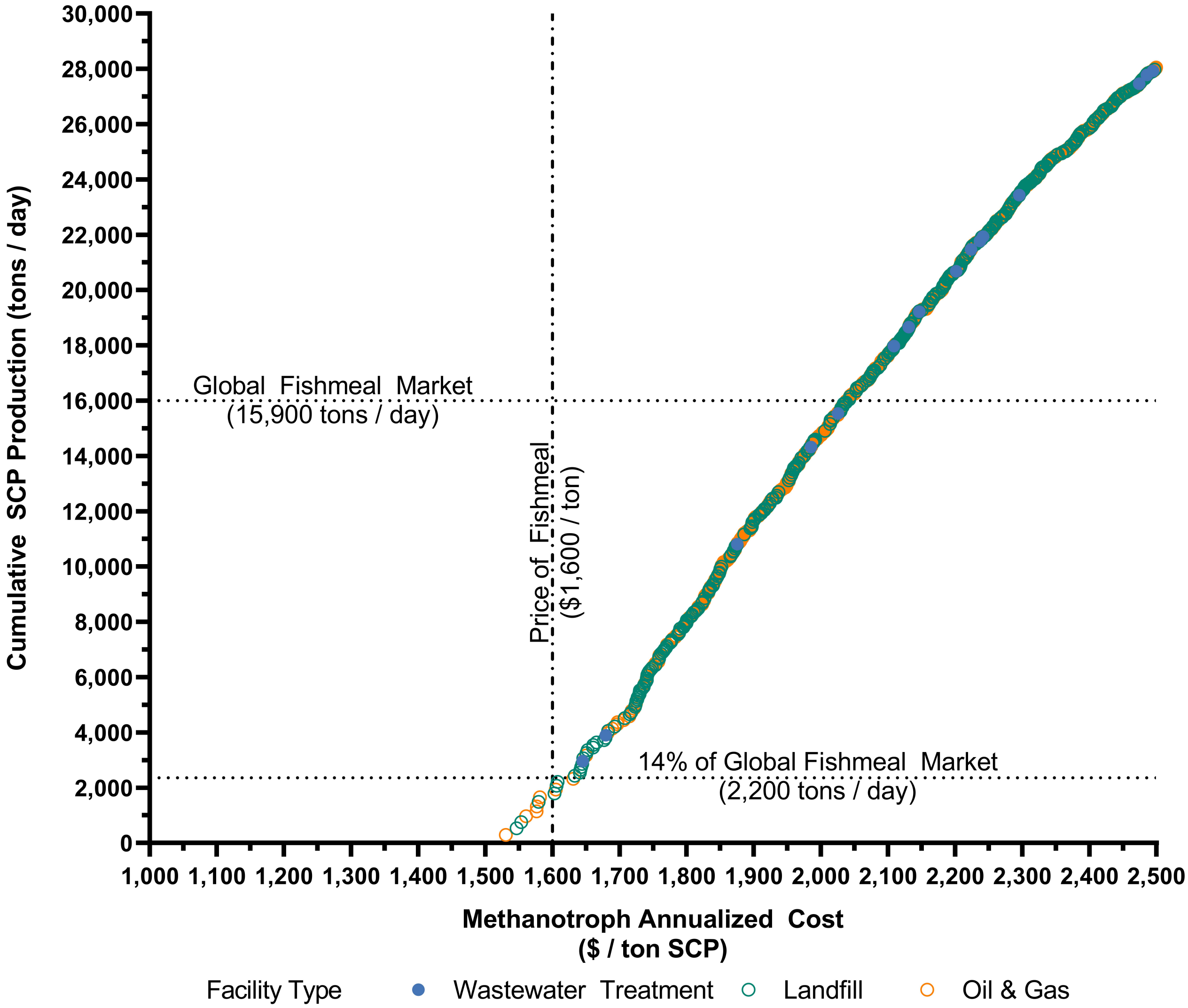

Figure 4. Supply curve for methanotrophic production using stranded methane. Each point represents a point source of methane, and the x-axis indicates the corresponding levelized cost of protein that can be produced from that facility. The y-axis indicates the cumulative amount of protein that can be produced with each additional facility. Maintaining the cost of methanotrophic protein at below that of fishmeal can potentially produce over 14% 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.

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[35], we merged the 2004, 2008 and 2012 data to generate a dataset for all

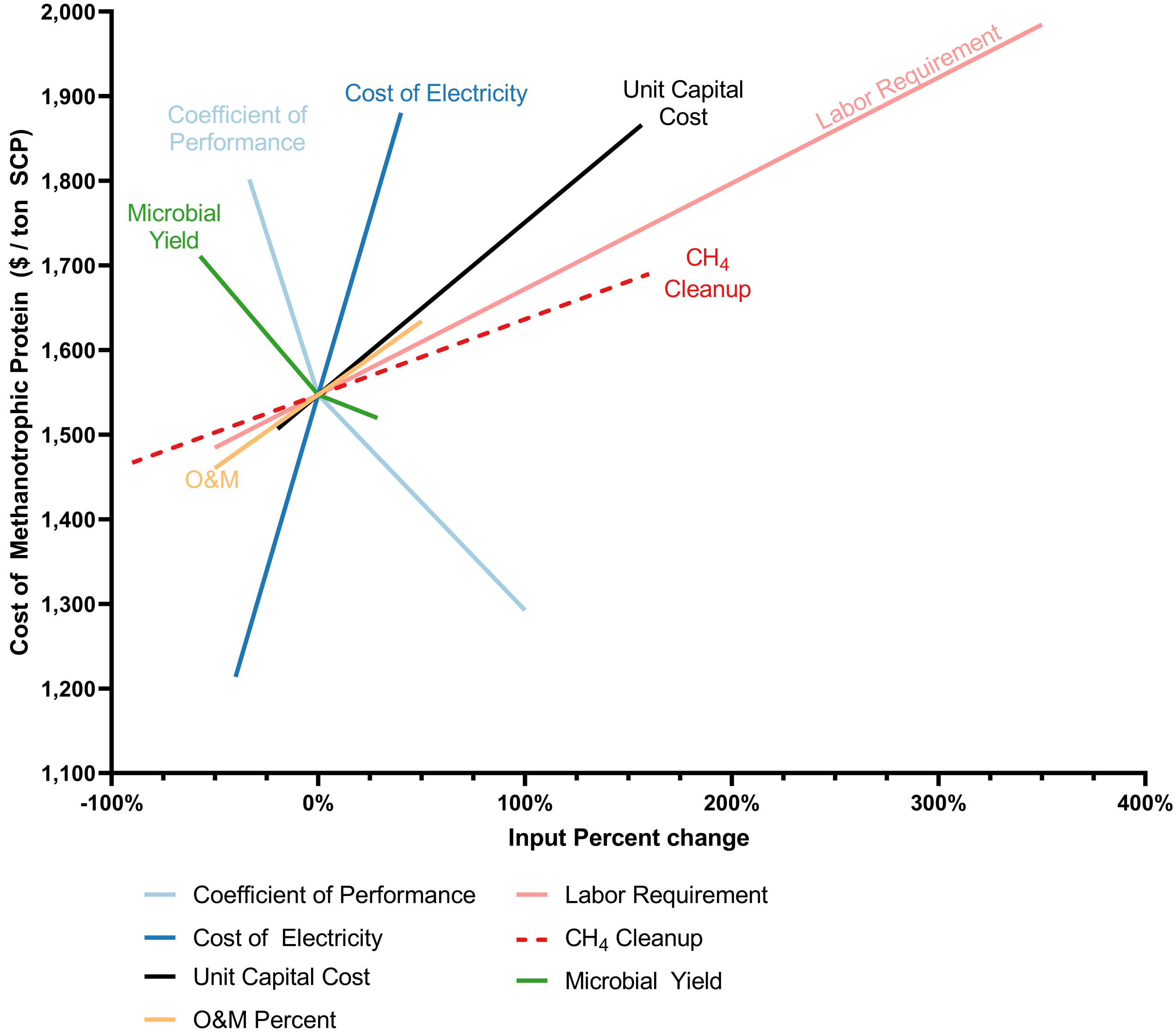

Figure 5. Sensitivity analysis for baseline methanotroph production at landfills, individually varying parameters to low and high values. The x-axis represents the resulting percent change of each parameter input, and the y-axis represents the corresponding levelized cost of production $/ton SCP (note: to show differences more clearly, the y-axis does not end at zero). We include all input parameters that result in a change of 5% or greater in calculated levelized cost of methanotrophic SCP ($/ton). 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. Changes in slope for microbial yield and coefficienct of performance are reflective of non-linearities in these inputs.

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[36] and 60% methane content in biogas, a conservative estimate for anaerobic digestors[37]. 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)[23] 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[24]. 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[23], 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[25]. See Supporting 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 Supplementary Equations (S1) and (S2)). 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[15], we calculate baseline microbial yields for each compound required for growth: methane, oxygen and nitrogen (in units of N as ammonia). For phosphorus, we assume 2% of biomass by weight (Table 4)[37].

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

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.

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 phosphorus yield is based on an assumption of 2% phosphorus in cell biomass[37]. Yield and growth rate vary across different methanotrophic species[38]. Baseline values in this analysis are representative values from methanotrophic industrial production[15,18], but species selection may further optimize production rates. Units for methane utilization rate are in terms of tons CH_4 per m^3 of reactor volume per day.

Parameter	Units	Baseline Value
Growth Rate	g SCP / g SCP - day	4[15]
Yield	g SCP / g CH_4	0.7[15]
Oxygen yield	g SCP / g O_2	0.2[15]
Ammonia yield	g SCP / g NH_3	6.6[15]
Phosphorus yield	g SCP/ g P	153[37]
Cell Density	g / L	30[18]
Methane Utilization Rate	tons CH_4 / m^3 - d	0.14
Heat Production	kJ / g SCP	55[15]

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. For the bioreactor, 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[29]. 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 (see Supplementary Methods for additional details). For the bioreactor scaling factor n, we use 0.7, a mid-value of reported and calculated scaling factors in the literature[29,39].

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

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[18]. 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)[40]. 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%[18]. Biomass is then dried in a continuous rotary drum dryer that further reduces moisture content to 10%[18].

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[41]. To calculate levelized capital cost, we use a weighted average cost of capital (WACC) of 10%, representative of a new technology[42]. We assume infrastructure lifetime of 20 years[18]. For calculations, see Supplementary Methods and Supplementary Equation (S9). Cost of operations and maintenance of equipment was set at 10% of total capital cost per year[18].

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[18] 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))[15] 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[43]. 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[43]). 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[44], cleanup costs will be lower than those required for injected biomethane into the natural gas grid[45]. 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[46–48]. 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[47]. For the grid baseline scenario, we remove the cost of methane cleanup.

Macro-nutrient 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 aside from cleanup. 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)[33].

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)[37]. 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[33]. 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[18], generating pure O_2 onsite using an air separation unit[49], and purchasing commercial O_2[16]. 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) using methanotrophs. Specific stains of methanotrophic bacteria can accumulate PHB when subjected to imbalanced growth conditions in a process that is similar to methanotrophic SCP production, albeit with additional processing steps[50] (Supplementary Note 1 discusses the differences between PHB and SCP cultivation). 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 more fully in Supplementary Methods)[32]. 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 can make up 50% of cell biomass when methanotrophs are subjected to the required multi-stage fermentation process described by Criddle and colleagues[32,51].

Water and Land Requirements

We determine a water requirement of 33.3 tons H_2O/ton SCP using the cell density of 30 g/L. For our system, we assume that 90% of the water requirement is met by capturing water from dewatering centrifuges and recycling it to the main growth reactor(s)[18]. The remaining water requirement is met through purchasing water at \$1/m^3, a relatively high value. This could be representative of the cost of desalinated water[52] or building a pipeline to transport water to a remote location. Due to the comparatively low cost of water in our results, we combine this cost with that of macro-nutrients nitrogen and phosphorus, referring to the cost of all three as "nutrient media."

In our analysis, we do not add additional costs for purchase of land. For scenarios under consideration, the methanotrophic SCP production equipment is being added to an existing facility, which we assume has sufficient vacant space.

Utilization Factor

We apply a utilization factor of 80% to our baseline scenario to account for plant downtime for maintenance and repair. This means the facility produces 80% as much SCP as it could over the whole year if it operated at full capacity all the time. The average utilization of oil refinery capacity over the last 10 years is 90%[53]. 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 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 using Equation (4). For additional details on full formulation, see Supplementary Method and Equation (S11).

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

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)[33].

Supply Curve

To make the supply curve depicted in Figure 4, 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) for comparison, although see Supplementary Figure S7 for historical fishmeal prices from the last four decades[33]. Fishmeal production rate of 15,900 tons/day is from 2018[4].

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, summarized in Table 5. 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), used in converting capital cost into levelized cost, we use a low value of 8% and high value of 12%, representing modest variation in potential investor confidence in this emerging technology[42]. We vary COP from baseline of 3[18] 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[43]. For the high value, we used \$0.14 / kWh, just above average residential prices in the US[43]. 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)[51]. 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.

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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[33]. Baseline electricity costs reflect typical commercial prices, low value and high value represent typical industrial and residential prices, respectively[43]. 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.

Input Parameter	Units	Low	Baseline	High
Ammonia price[33]	\$ / ton NH_3	400	550	810
Phosphorus price[33]	\$ / ton P	1,315	1,790	2,300
COP	kW / kW(e)	2	3[18]	6
Unit capital cost	\$ / ton SCP / day	407,000[19]	507,000	1,300,000[16]
Cost of electricity[43]	\$ / kWh	0.06	0.10	0.14
WACC (discount rate)	%	8%	10%	12%
Labor requirement	worker-hrs / ton SCP	0.5	1[18,32]	4.5
CH_4 cleanup	\$ / ton CH_4	5[46]	50[47]	130[48]
Microbial yield	tons SCP / ton CH_4	0.3[38]	0.7[15,18]	0.9[38]
Scaling Factor (n)		0.6[39]	0.7	0.8[29]
O&M percent	%	5	10[18,19]	15[16]
Utilization Factor	%	0.7	0.8	0.9

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