This version: 03/2022

Methane Single Cell Protein: securing global protein supply against global catastrophic food shocks

Juan B. García Martínez[A*], *Joshua M. Pearce*[A,B], *James Throup, Jacob Cates, Maximilian Lackner*[C,D], *David C. Denkenberger*[A,E]

Affiliations:

[A] *Alliance to Feed the Earth in Disasters (ALLFED), Fairbanks, AK, USA.*

[B] *Department of Electrical & Computer Engineering, Western University, London, ON, Canada*

[C] *FH Technikum Wien, Höchstädtplatz 6, 1200 Wien, Austria*

[D] *Circe Biotechnologie GmbH, Brandstätte 1/27, 1010 Wien, Austria*

[E] *University of Alaska Fairbanks (Mechanical Engineering and Alaska Center for Energy and Power), Fairbanks, AK, USA 99775*

* Corresponding Author. Contact at: juan@allfed.info.

Abstract

Global catastrophes such as a supervolcanic eruption, asteroid impact or nuclear winter could cause global agricultural collapse due to reduced sunlight reaching Earth's surface. Human civilization's food production system is unprepared to respond to such events, but methane single cell protein (SCP) could be a key part of the solution. Current preparedness centers around food stockpiling, an excessively expensive solution given that an abrupt sunlight reduction scenario (ASRS) could hamper conventional agriculture for 5 to 10 years. Instead, it is more cost-effective to consider resilient food production techniques requiring little to no sunlight.

This study analyses the potential of SCP produced from methane (natural gas and biogas) as a resilient food source for global catastrophic food shocks from ASRS. The following are quantified: global production potential of methane SCP, capital costs, material and energy requirements, ramp-up rates and retail prices. In addition, potential bottlenecks to fast deployment are considered.

While providing a more valuable, protein-rich product than alternatives, the production capacity could be slower to ramp up. Based on 24/7 construction of facilities, 7-11% of global protein requirements could be fulfilled at the end of the first year. Despite significant remaining uncertainties, methane SCP shows significant potential to prevent global protein starvation during an ASRS at an affordable price — US$3-5/kg dry.

Keywords

Global Catastrophic Risk; Existential Risk; Single Cell Protein; Methanotrophic bacteria; Resilient food; Food Security; Global Catastrophic Food Shock; Nuclear Winter.

Highlights

- Methane single cell protein has significant potential as resilient food for catastrophes.
- Protein requirements for the entire global population could be fulfilled in 2.5 to 4.5 years.
- Stranded natural gas (vented, flared or reinjected) could cover most of the requirements.
- The product would be affordable at an expected retail cost between US$3-5/kg dry.
- Several recommendations and interventions were highlighted to expedite crisis response.

Abbreviations

Abrupt sunlight reduction scenario (ASRS)

Capital expenditure (CAPEX)

Carbon dioxide (CO_2)

Global catastrophic food shock (GCFS)

Natural gas (NG)

Net present value (NPV)

Single cell protein (SCP)

1 Introduction

1.1 Global catastrophic food shocks

Food security research is typically focused on adapting to gradual changes in aspects like population, resource scarcity, resource depletion, and slowly progressing climate change (Henchion et al., 2017) i.e. adaptation over long periods of time; there has been significantly less research on preparedness for more abrupt, extreme shocks. It is estimated, however, that within this century there is approximately an 80% chance that a food shock will reduce global food production by about 10% (Bailey et al., 2015), and up to 10% chance of near-total food production loss (Denkenberger and Pearce, 2014, 2015). As the COVID-19 pandemic has shown, even disasters not directly related to the food system can substantially increase the population at risk of starvation (Laborde et al., 2020; Ahn and Norwood, 2020), and affect other major systems like energy (Brosemer et al., 2020), which are integral to the food system. Such events are most dire for countries critically dependent on food imports (Manero et al., 2020; Shokrani et al., 2020; Manheim and Denkenberger, 2020). A scenario on the order of magnitude of 10% food production loss, such as severe pollinator loss or abrupt climate change, could still result in mass starvation (Beasley, 2020). While "incremental" climate change from global warming over many decades is often considered in the food security literature, there has been much less discussion of more abrupt or extreme climate changes, which have the potential to create severe, sudden food shocks (Denkenberger and Pearce, 2015) with very short windows for adaptation.

The most extreme food shock threatening humanity in the near future would likely originate from an *abrupt sunlight reduction scenario* (ASRS), in which a catastrophe causes a significant reduction in the amount of sunlight reaching the Earth's surface. Potential causes include a "nuclear winter", in which the atmosphere is clouded by soot from a global nuclear war causing the burning of cities, with less likely triggers including a supervolcanic eruption or asteroid/comet impact (Cirkovic, 2008; Denkenberger and Pearce, 2014). In any of these cases, consequences such as subzero temperatures across the Northern Hemisphere summer (Robock et al., 2007; Coupe et al., 2019) would preclude conventional agriculture for many years (Denkenberger et al., 2017), leading to a *global catastrophic food shock* (GCFS) from near-total global agricultural production loss. Such events, which would affect human wellbeing globally and even imperil modern civilization, are categorized as *global catastrophic risks* (Bostrom and Cirkovic, 2011). In this work, an ASRS is addressed as a limiting case scenario, since a solution tailored to such extreme circumstances could be useful in the case of food shocks of any scale. For example, nuclear autumn is the more likely result of a limited-scale nuclear war scenario, which would be expected to create about a 10 to 20% food production reduction (Pearce and Denkenberger, 2018). In this study an ASRS is explored in which global industry is still largely functioning after the global catastrophic event. Other GCFS scenarios involve a loss of industrial capacity (Denkenberger et al., 2021), requiring different solutions (Denkenberger et al., 2017).

Such events would demand radical innovation in food production, and a variety of complementary solutions would be required to forestall mass starvation: we named these *resilient food solutions* (Pham et al., 2022). There appears to be no publicly available response plan to an ASRS as described here, neither from supranational organizations such as the United Nations nor any particular nation. Currently there are few organizations working on resilient food solutions for GCFS, such as the *Alliance to Feed the Earth in Disasters* (ALLFED, 2017), *Pennsylvania State University* in collaboration with *Open Philanthropy* (LaJeunesse, 2020), and the *Centre for the study of existential risk* at the *University of Cambridge* (Tzachor et al., 2021). Publicly available information on responding to a GCFS could be useful for expediting response in regions that lack the resources for planning and preparedness against extreme risks.

1.2 Resilient foods for global catastrophic food shocks (GCFS)

Given that an ASRS could last 5 to 10 years (i.e. nuclear winter), the cost of storing sufficient food for the global population is estimated to be extremely high in comparison to producing resilient foods that require less or no sunlight (Denkenberger and Pearce, 2015; Denkenberger et al., 2019). For example, in an ASRS cool-tolerant crops could be relocated to more adequate climates (Pham et al., 2022), simple greenhouses could be built on the tropics (Alvarado et al., 2020) and global seaweed production could be quickly ramped up (Mill et al., 2019), sugar could be produced from lignocellulosic biomass (Throup et al., 2022), synthetic fat could be produced from hydrocarbons (García Martínez et al., 2022), acetic acid could be produced from CO_2 via microbial electrosynthesis (García Martínez et al., 2021a), mushrooms could be grown on residue from logging, cellulose-digesting ruminants and insects could be used as a food source (Denkenberger and Pearce, 2015), and leaf protein concentrate could be obtained (Pearce et al., 2019). This work studies the use of microbial protein produced via methanotrophic bacteria as a potential component of a food-crisis response. These microbes are capable of metabolizing methane as both a carbon source and an energy source.

Resilient foods could be instrumental in avoiding starvation and sustaining society in the case of a severe food shock. Indeed, protein scarcity during wartime sparked initial interest in microbial protein (Ritala et al., 2017). Microbial protein also has applications outside of a disaster context, having been considered as a sustainable protein alternative (Claassens et al., 2016; Matassa et al., 2020; Leger et al., 2021; Khoshnevisan et al., 2022). This work addresses concerns about material constraints raised in previous studies of microbial protein as a resilient food in ASRS (Denkenberger and Pearce, 2014). The scope is akin to a FEL-1 stage (front-end loading) in which the concept is defined and preliminary budget estimates are produced, but the level of detail is not yet sufficient for construction (Warner, 2019).

The key aim of this work is contributing to global catastrophic risk response via preparedness, and more generally to resilience to existential risk via reduction of existential risk factors. Existential risks are defined as risks with the potential to eliminate humanity or its future potential (Bostrom, 2013). In contrast, risk factors do not directly cause extinction themselves but weaken our defenses to it (Cotton‑Barratt et al., 2020), such as social turmoil or bad global governance during a global catastrophe. In addition to prevention, response and resilience have been proposed as fundamental defense layers against existential risk (Cotton‑Barratt et al., 2020), which are the object of this work.

1.3 Background on Single Cell Protein (SCP)

Microbial protein, referred to as single-cell protein (SCP), has been proposed as an alternative to animal products in meeting the growing global protein demand (Ritala et al., 2017). A variety of microorganisms, including bacteria, fungi and microalgae, can be cultivated for SCP production (Ritala et al., 2017). Fungal SCP is already sold for human consumption under the brand name

Quorn; however, the current production process relies on sugar (Ritala et al., 2017), a human-edible feedstock, making this product less useful in a GFCS. Conversely, during an extreme food supply crisis it could be desirable to produce SCPs for human consumption from non human edible feedstocks such as hydrocarbons, carbon dioxide (CO_2) or available biowastes (Matassa et al., 2020), rather than using feedstocks such as sugars which could be more efficiently used directly for human consumption in such a dire situation. This would effectively increase food availability by virtue of obtaining a nutritionally rich product from inedible sources. Additionally, SCPs obtained from these resilient feedstocks would not compete on the input side with traditional protein sources. Methanol can also be used as an ASRS-resilient feedstock for SCP production, as was used for the first commercially available microbial protein product: Pruteen, from Imperial Chemical Industries. However, methanol is more localized and produced in smaller quantities than methane. Hydrocarbons can also serve as an ASRS-resilient feedstock for SCP production (Jenkins, 1988), specifically the paraffin components of petroleum which can also be used to produce synthetic fat (García Martínez et al., 2022).

Much research has focussed on SCPs on the grounds of sustainability due to their low water and land use (Matassa et al., 2015, 2016, 2020; Pikaar et al., 2018; Sillman et al., 2019). Methane-based bacterial SCP can use orders of magnitude less water and land than traditional protein sources such as meat and plant-based proteins. For example, *Feedkind™* approximately uses 100 times less water and 1000 times less land per ton compared to soybeans (Cumberlege et al., 2016). Compared to other sunlight-independent food sources such as crops grown under artificial light or microalgae grown in photobioreactors, SCP has a very high energy efficiency (Alvarado et al., 2021). Due to its CO_2 emissions, SCP from natural gas is less sustainable than renewable hydrogen-based bacterial SCP, a similar type of SCP that could also be used as resilient food for GCFS (García Martínez et al., 2021b). However, methane SCP's lower requirements in terms of equipment imply a faster ramp-up and lower cost, which are fundamental characteristics for the potential of methane SCP as resilient food for GCFS (García Martínez et al., 2021b). This is because H_2 SCP requires construction of costly hydrogen production facilities while methane SCP can leverage existing natural gas extraction facilities. Most significantly for the purposes of crisis response, these types of SCP can produce high-quality, protein-rich food independently of traditional agriculture, specifically avoiding the need for sunlight and human edible inputs. For this type of closed-environment food production systems, exposure to several risk factors that affect conventional agriculture is greatly reduced or completely nullified, such as: institutional factors (i.e. trade restrictions), abiotic factors (i.e. environmental degradation, extreme weather events, or climate variability), and biotic factors (i.e. pathogens or pests) (Tzachor et al., 2021).

Methanotrophic bacteria can be found in nature where methane naturally occurs, e.g. in swamps or tundra regions, and have been studied as a food source since the 1970s. Interest in them declined, but has been recovering thanks to their ability to produce high-quality protein with minimal land and water use. Methane SCP is one of the most advanced and accessible SCP production technologies, and is currently on the verge of large-scale commercialization (Flanagan, 2022). Methane is a relatively ubiquitous resource, and gas fermenters can be built at different scales, with a typical commercial plant size being 10,000 to 20,000 tons of protein per year. With several reactors being built on one site with joint use of utilities, economies of scale allow for production capacities on the order of 100,000 to 200,000 tons of SCP per year.

Bacterial SCP from methane could potentially become an ingredient in a variety of food products, including solid foods like bread, pasta, and plant-based meats, as well as in liquid foods and drinks, such as plant-based dairy products, protein shakes, or broths (Southey, 2019). Bacterial SCP from methane has high protein completeness because its essential amino acid content is similar to, or higher than, the FAO guidelines (Ritala et al., 2017). Its amino acid content is superior to that of soybean meal, and it boasts a higher protein content in general (Pikaar et al., 2018). To date, there are no publicly available studies of bacterial SCP bioavailability in humans, but recent studies in fish point to bacterial SCP having a high digestibility (Glencross et al., 2020; Rajesh et al., 2022). Because of the fat content of methane SCP, its reported caloric content is 22 MJ/kg (Unibio Group, 2020a), noticeably higher than the average 17 MJ/kg caloric content of carbohydrates (U.S. Department of Agriculture, 2016). Methane SCP also boasts a notable micro-nutritional profile, containing significant amounts of B-group vitamins (esp. B1, B2, B3, B7, B8, B12), minerals (e.g. iron and magnesium) and essential fatty acids (Silverman, 2020; Duchene, 2016).

However, bacterial SCP has a high content of nucleic acids (8-12%) (Volova and Barashkov, 2010). This could cause health problems, such as gout and kidney stones (Ritala et al., 2017), if bacterial SCP were to be used as a significant food source for animals with long lifespans. Significant SCP consumption is not recommended for humans, unless the nucleic acid content is reduced during processing prior to use. The maximum safe limit of nucleic acid consumption for an adult human is 4 g/day (Adjei et al., 1995), which is equivalent to the amount present in 234 kcal worth of unprocessed bacterial SCP. This amount of unprocessed bacterial SCP in turn amounts to up to 59% of a daily recommended protein intake for human adults of 60 g/day. Unibio A/S claims to have developed a method to reduce nucleic acids to below 1% (Jorgensen, 2011).

Conversely, fungal SCP has been considered a safe component of the human diet for several years (U.S. Food and Drug Administration, 2002). Fungal SCP has a particularly low nucleic acid content compared to other SCPs. It is sold after post-processing that further reduces the nucleic acid content (Ritala et al., 2017) to below 2% of dry weight (Marlow Foods Ltd., 2001). If human adult daily protein requirements were to be fulfilled solely using fungal SCP, the total nucleic acid intake would still remain below the daily safe limit. Research has established that there are little to no threats associated with human consumption of fungal SCP, and this protein source is associated with a low incidence of allergic reactions compared to other sources (Finnigan et al., 2019). Although fungal SCP sets a favorable precedent, bacterial SCP by comparison is considerably less studied as a food source for humans, and requires more studies to establish its safety for human consumption. However, according to Solar Foods, compositional data of their bacterial SCP product "raises no safety nor allergenicity concerns" (Solar Foods, 2021).

Key players currently pioneering mass production of methane SCP are Calysta Inc., Unibio A/S, Circe Biotechnologie GmbH, and String Bio Pvt Ltd. While these companies generally appear to be focusing on production of animal feed such as for the aquaculture sector, all four have explicitly shown interest in producing protein directly for human consumption (TEMASEK, 2020; Jensen, 2021; Lee, 2021; Circe Biotech, 2021). Separately, hydrogen-based SCP production companies such as Solar Foods and Air Protein are already developing the technology to produce human food-grade bacterial SCP and have applied for regulatory approval for human consumption (Solar Foods, 2021), which is a positive sign with regards both to the sustainability of the SCP for food concept but also for the possibility of consumer safety studies of bacterial SCP in the near future. This work assessed the viability of SCP as a direct human food source, rather than as an animal feedstock because the caloric conversion efficiency of animal products is low, at 3%-31% (Shepon et al., 2016), which is undesirable during a food-shortage scenario in which the intention is to maximize calories available for human consumption.

This study begins by examining the technical processes necessary to scale up methane SCP production to meet nutritional needs during a GCFS. Next, the viability of this resilient food is assessed by estimating the capital costs of quick deployment of the technology and the speed at which global production could be ramped up, quantifying the resources required, and estimating the associated production costs and retail prices. The results are presented and discussed in terms of the possibility of using methane SCP as a techno-economic insurance against GCFS.

2 Methods

Methane SCP production requires three main inputs: 1) methane, which acts as both an electron donor and a carbon source, 2) a nitrogen source and 3) an oxygen source. Additionally, some minerals are also needed in smaller quantities. Anaerobic methane fermentation (Switzenbaum et al., 1990) has significantly lower yields and is hence not considered.

Natural gas (NG) is the largest source of methane available to industry. One important alternative is biogas obtained from anaerobic digestion of organic matter. It can be used as a more sustainable alternative source of methane for SCP production compared to natural gas (Cumberlege et al., 2016). If the nearly untapped global biogas potential was leveraged in its entirety, it could substitute the equivalent of 26-37% of the current natural gas production (Jain, 2019). It is unclear, however, the extent to which this potential will be leveraged in the future, and how much of it would be available within an ASRS. For these reasons, only natural gas will be taken into account in the resource analysis to remain conservative and biogas will be left for future work.

Different types of natural gas reserves can be defined (Attanasi and Freeman, 2013). Apart from economically exploitable reserves there are stranded gas reserves, which cannot currently be economically exploited for typical industrial uses. Physically stranded reserves cannot be accessed with current drilling technology. In contrast, economically stranded reserves are either 1) too far from their end use to justify transport costs, 2) contained in wells that are too small to justify extraction costs, or 3) associated with oil reserves and thus requiring extraction before the oil can be exploited, but not resulting in profit as a product. The last type is often regarded as an undesirable byproduct of oil extraction and is commonly flared, reinjected or vented. This associated natural gas is ripe for exploitation via methane SCP production because the methane is already being extracted without the need for additional capital cost. This is of considerable value in a GCFS because the resources that would be spent on extraction of further natural gas could instead be spent on the construction of more SCP plants or other resilient foods. In current times, exploiting stranded methane for production of SCP is estimated to be both economically feasible and more sustainable than the current status quo (El Abbadi et al., 2022). Currently a yearly average of nearly 150 billion cubic meters at standard temperature and pressure (bcm) of natural gas is being flared globally at upstream oil & gas and natural gas liquefaction plants (EIA, 2019; Elvidge et al., 2016; World Bank, 2018). An estimated yearly average of around 450 bcm of associated natural gas is being reinjected into oil wells (EIA, 2019).

Ammonia is considered as the nitrogen source due to widespread global availability from the fertilizer industry; another nitrogen source could be urea. Other potential sources of ammonia include anaerobic digestion and biowaste pyrolysis or gasification (Matassa et al., 2015, 2020). During an ASRS, global agricultural production would most likely plummet, freeing up ammonia production capacity that could be used for SCP production instead. The oxygen is considered to be sourced from cryogenic air separation (Linde process), an industry standard process from which the majority of industrial oxygen is produced (FMI, 2019), as used by Calysta for methane SCP production (Cumberlege et al., 2016). It is recommended over other air separation processes (e.g. pressure swing adsorption or membrane separation) for a lower production cost in very large scale oxygen production (Alptekin, 2017; UIG, 2006). Using air directly as an oxygen source may be feasible but could significantly affect key performance parameters such as gas utilization, with major impact on the efficiency and economics of the process. Modeling and empirical studies, outside the scope of this work, could be required to clarify this. Instead, this work considers the use of pure oxygen as feedstock in line with the practices of major methane SCP companies Calysta and Unibio (Cumberlege et al., 2016; Unibio Group, 2020b).

The chemical reaction used as a reference is the one proposed for *Methylococcus capsulatus* based on the premises proposed by (Villadsen et al., 2011), namely a yield coefficient of methane to cellular biomass of $Y_{CH_4/biomass} = 0.8$ g biomass/g CH_4 and a biomass degree of reduction$k_x = 4.20$, defined as the number of equivalents of available electrons per mol of carbon . The reaction can be expressed in a general form as shown in Equation 1.

$$CH_4 + 1.453\,O_2 + Nitrogen\,source \rightarrow Biomass + 0.479\,CO_2 + Water \quad \textbf{(1)}$$

Given ammonia as a nitrogen source for microbial growth, the resulting overall reaction can be expressed as shown in Equation 2. The formula $CH_{1.8}O_{0.5}N_{0.2}$ stands for the simplified bacterial cell biomass, leaving aside sulfur and other minor components. The biomass is typically around 70% of protein and 30% of other compounds (e.g. fats, carbohydrates, ash).

$$CH_4 + 1.453\,O_2 + 0.104\,NH_3 \rightarrow 0.521\,CH_{1.8}O_{0.5}N_{0.2} + 0.479\,CO_2 + 1.687\,H_2O \textbf{(2)}$$

The relevant unit operations, mass and energy flows involved in the proposed reference process are shown in Figure 1. The natural gas and O_2 are fed together with ammonia and minerals to the bioreactor where the cell growth takes place in a continuous fermentation system, which gives a higher productivity than a batch fermenter. At the outlet of the reactor the fermentation broth contains an expected biomass concentration of 1-3% dry weight (i.e. bacterial cells), dissolved gasses and some unreacted ammonia and minerals. The water is removed via mechanical dewatering and drying steps, and the cells are disrupted in the homogenization step to increase digestibility by liberating the nutrients. The final SCP product is obtained in a powdered form, which may be subject to post-processing operations prior to storage. Water recycling, filters, pumps and heat exchangers are not shown.

A reduced nucleic acid content for the SCP product could be achieved via a number of processes, for example by applying a heat treatment (60-70 °C) to the effluent fermentation broth, or by using an alkaline treatment or chemical extraction (Ritala et al., 2017). Significant uncertainty remains as to which nucleic acid removal treatment would be employed in large-scale bacterial SCP production, but heat treatment is shown in Figure 1 in similarity to fungal SCP production. The heat treatment process activates endogenous, RNA-degrading enzymes for short time periods, while controlling for temperature and pH conditions (Anderson and Solomons, 1984). Once degraded, the nucleic acids diffuse out of the cell membrane and enter the liquid fraction, which has been previously separated from the SCP biomass through mechanical dewatering, for example through centrifugation. It may be possible to remove the need for heat treatments by instead using

RNA-degrading enzymes at ambient conditions over longer periods of time, but this process has not been considered in the industrial production studied in this work. Different or no cell disruption techniques may be used instead of homogenization, but the lack of these may reduce digestibility.

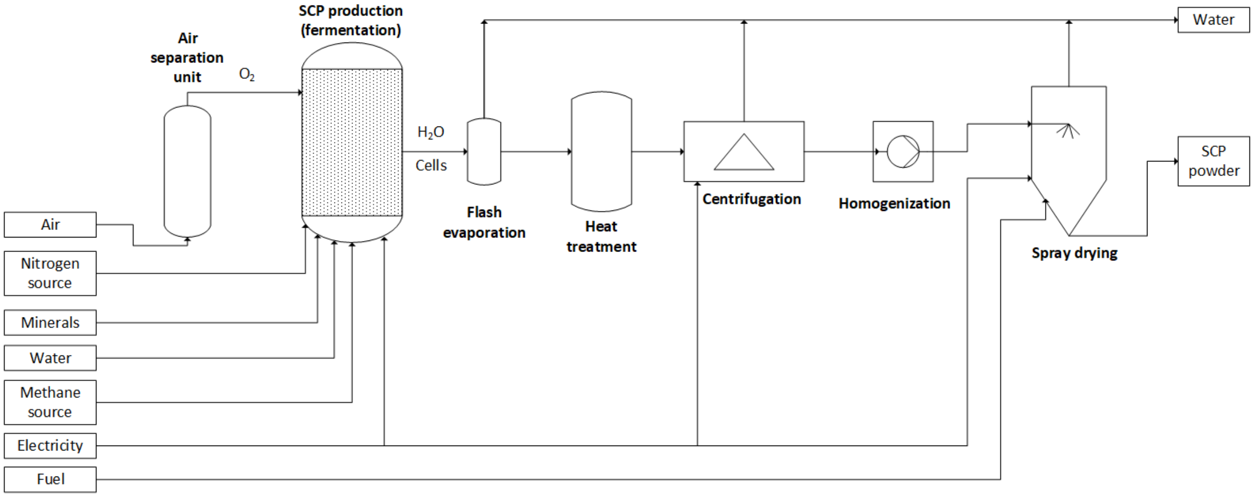

Figure 1. Simplified process flow diagram of the reference methane SCP production process, based on (Jorgensen, 2011).

The process can use thermophilic bacteria to avoid excessive cooling; see e.g. (Levett et al., 2016) for a techno-economic assessment of the biopolymer PHB by methanotrophic bacteria. Pure or mixed culture operation has been described. The process contains an explosive atmosphere of methane and oxygen, meaning safety precautions have to be taken particularly in the headspace area. The methane source can be purified upstream of the reactor, or higher hydrocarbons can be consumed by a bacterial consortium.

2.1 Methodology overview

Two key metrics characterize the potential of a resilient food for GCFS: the ramp up speed (how fast the production can be scaled over time) and the retail price per calorie (how affordable it would be during the catastrophe period). In addition, assessing the global availability of the relevant input resources is key to check for potential bottlenecks to fast production ramp-up. Figure 2 contains an overview of the methodology used to estimate these, which is described in depth in the following sections.

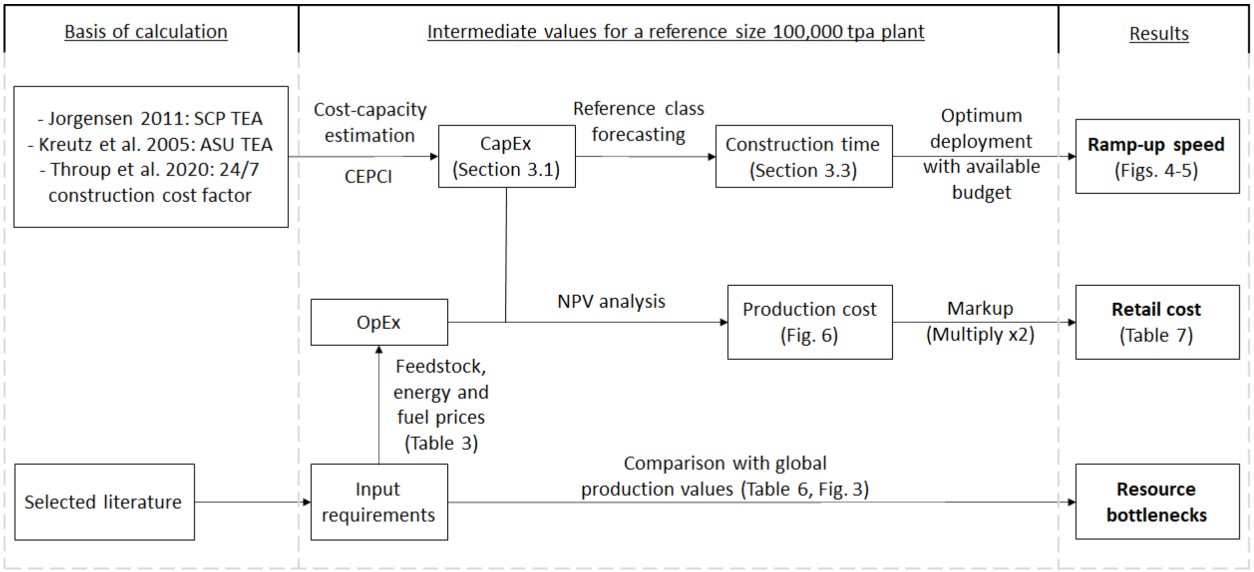

Figure 2. Methodology flowchart (TEA: techno-economic assessment, CAPEX: capital expenditure, OPEX: operating expenditure, NPV: net present value, CEPCI: Chemical Engineering Plant Cost Index).

2.2 CAPEX estimation

There is large uncertainty present in estimating the costs of a large scale "n-th plant" methane SCP production facility because currently no data on full-scale commercial size plants exist, "first of a kind" plants are costlier. The fixed capital expenditure (CAPEX) of the SCP plants was based on data from published industrial estimations by Unibio A/S. For a methane SCP production capacity of approximately 108,000 tonne dry product/year (tpa), the expected capital expenditure is $251 million USD (Jorgensen, 2011). The cost estimate is hereby assumed to represent an n-th plant estimation, meaning that significant cost reductions after the technology reaches a higher level of maturity are not considered in the analysis. This production capacity is representative of that of currently projected full-scale commercial SCP production plants (Calysta Inc., 2020; Lane, 2018; Rosenberry, 2019; Sefton, 2018). After including nucleic acid removal from 9% (Unibio Group, 2020a) to 2%, the installed production capacity of the reference plant becomes 100,800 tpa. Preferably, many (5-10) bioreactors would be present rather than a single massive one for easier construction and operation given this large capacity; compare to the 1,500 m^3 airlift reactor used to produce Pruteen (Chisti, 1989).

The cost reference does not include the capital cost of O_2 production. This cost is estimated separately based on the methodology and values proposed by (Kreutz et al., 2005), including fixed and operating costs. The option of buying O_2 from industrial suppliers is discarded given the quantities involved in producing enough SCP to feed a significant portion of humanity. The updated capital expenditure of this air separation unit (ASU) is added to that of the Unibio reference factory to obtain the final plant CAPEX.

In an ASRS, food is expected to be scarce after the first few months, as food reserves run out (Denkenberger et al., 2017), making it preferable to increase food production as soon as possible. Fast construction methods are hereby proposed to reduce plant construction time, at the expense of increasing the capital expenditure. The fastest reasonable cost construction method available is to implement 24/7 construction, reducing overall construction time to 32% of the original at an increased labor cost of 47% (Throup et al., 2022), according to the methodology and values of (Hanna et al., 2007). This value has been conservatively incorporated in terms of a 47% increase in the capital cost of the plant to account for labor constraints. State-of-the-art concurrent engineering could expedite the first steps of factory planning and engineering.

2.3 Assessment of required resources

Resource requirements are summarized in Table 1, and are calculated based on estimates published for methane SCP, microbial protein requirements more generally, and for chemical industrial equipment. The required utilities to operate a bacterial SCP production plant of reference size are estimated in terms of electricity and fuel energy requirements. Due to the variability in properties of natural gas from different locations, a range of variables has been considered for the methane and energy content of the gas, which will result in a ranged estimation of the natural gas required to fulfill the food requirements. A ranged value of gas utilization has also been considered, which also broadens the overall range. A reactor designed for SCP production would have a gas utilization of at least 80% to be economical, while values of up to 90% have been reported in U-loop reactors (Jorgensen, 2011). The gas utilization affects both the natural gas and O_2 input requirements of the reference plant. Conservatively, the energy requirement for air separation has been selected as corresponds to high purity O_2.

Table 1. Basis of calculation for the energy requirements of methane SCP production.

Variable	Value	Unit	Reference
Methane requirement	0.521	mol SCP/mol methane	(Villadsen et al., 2011)
Methane content of natural gas	87 - 98	%mole	(Enbridge Gas Inc., 2001)
Gas utilization of reactor	80 - 90	%	
Energy content of natural gas	35.4 - 42.8	MJ/m^3	(Engineering ToolBox, 2005)
Energy content of SCP	22	MJ/kg	(Unibio Group, 2020a)
Solid content of dryer inlet	20	%	(Sillman et al., 2019)
Energy consumption of spray dryer	4880	kJ/kg evaporated water	(Baker and McKenzie, 2005)
Electricity to thermal energy usage ratio of spray dryer	1:27	Electricity:thermal	(Baker and McKenzie, 2005)

Electricity use of fermentation step	1.6	kWh/kg SCP	(Pikaar et al., 2018)
Electricity use of air separation	0.357	kWh/kg O_2	(Aneke and Wang, 2015)

Assessing potential bottlenecks to the ramp up potential of methane SCP first demands estimating the amount of SCP required to fulfill the food requirements of the global population and the equivalent in terms of the number of reference production plants. The amount of protein and calories available in the SCP product, as well as the requirements for feeding one person, were compared to the number of people globally. Then the resources required to produce the required amount of SCP are quantified, which includes energy and material resources such as natural gas as main feedstock, coal for the thermal requirements (if adequate), ammonia as a nitrogen source and electricity to run the process. The decision of whether to use coal or natural gas is not trivial and would depend on the specific location, since using natural gas may be more convenient but would reduce the amount available for SCP production if natural gas was the limiting factor in the location. Some of the natural gas that remains unused after passing through the reactor could be burned to produce energy, but this has been conservatively ignored. Additionally, alternative potential sources of methane are presented for discussion. The values used as a basis for the analysis are summarized in Table 2.

*Table 2. Basis of calculation for the resource availability analysis. *Some amount of food waste throughout the system is unavoidable, regardless of food crisis severity. However, a reasonably low value of food waste, 12%, was considered in the proposed scenario. This value was chosen because food waste is expected to be lower due to increased food scarcity. Moreover, the final bacteria SCP product is a dry product, with a long shelf life, further reducing potential food waste* (Denkenberger and Pearce, 2014).

Variable	Value	Unit	Source
World population	7.8	billion people	(United Nations, 2019; Worldometers, 2020)
Recommended protein intake	60	g/person/day	(World Health Organization and United Nations University, 2007)
Expected food waste	12	% of calories produced	*
Average daily caloric requirement per person	2,100	kcal/person/day (=1.39 kWh)	(World Health Organization, 2004)

Global ammonia production	171	Megatonne/year	(Research and Markets ltd, 2020)
Global electricity consumption	2,551	GW (1 GWa = 8760, GWh = 8.76 TWh)	(Sönnichsen, 2020)
Global coal production	7,337	Megatonne/year	(Rob Smith, 2018)
Global natural gas production	4,198	bcm/year	(IEA, 2019)
Global natural gas flaring and venting	150	bcm/year	(EIA, 2019; Elvidge et al., 2016; World Bank, 2018)
Global associated natural gas reinjecting	450	bcm/year	(EIA, 2019)
Global biogas production potential	26-37	% of current NG production	(Jain, 2019)

An accurate estimate of the protein content in the final SCP product is central to estimates of how much of it would be necessary to fulfill the protein requirements of the global population. A protein content range of 50-80% per kg of dry SCP product resulted from a review of multiple sources (Ravindra, 2000). This range was considered directly when determining, for the required SCP product amounts, the required resource amounts of the four possible energy sources: natural gas, electricity, coal, and ammonia.

2.4 Ramp-up speed

The ramp up speed of methane SCP technology during a GCFS would mainly depend upon two variables: the economic resources that would be invested in global famine response and the physically available resources to carry it through, including but not limited to: raw materials, energy, and qualified labor. Regarding available funding, a relevant example could be found in the recent coronavirus pandemic in which governments around the world spent several trillion U.S. dollars combined on economic stimulus (Andrijevic et al., 2020). Given the much harsher severity of a sunlight reduction scenario, one could argue that monetary investment in response would not be a limiting factor.

Material, energy and human resources are more likely to be limiting to ramp up. There is a hard limit to how much construction material and chemical equipment production capacity can be leveraged in a limited amount of time without scaling up global production. In addition, even if enough people are willing to participate in construction and operation of food production facilities, it is uncertain how fast they could be trained. People currently working as construction workers and plant operators could conceivably be retrained as chemical plant construction workers and SCP plant operators much faster. Here these limitations have been dealt with by assuming that only the resources currently available yearly to related sectors could be leveraged for fast deployment of SCP production plants.

The methodology consists of finding the global capital expenditure on adjacent industries whose resources could be redirected such as chemicals, power, pulp & paper, utilities and beverages, which amounts to 489 billion USD per year (Damodaran, 2020). Based on this budget the number of reference SCP production facilities that could be built per year and the associated SCP production capacity is found. By artificially limiting the available budget in this manner, the resource limitations are roughly accounted for.

The time taken to construct a facility has been shown to be logarithmically related to the cost of the facility, and a reference class forecasting regression model based on this principle was used to determine the construction time based on data from previously built factories (Martin et al., 2006). From this the construction time of each "wave" of production plants can be estimated. The number of facilities that could be built per wave was calculated from the amount of plants that can be built per year divided by the number of waves per year. In combination with the known production capacity to be installed and the amount of food required by the global population, the ramp up speed of the technology can be estimated. That is, the speed at which the global food requirements are being fulfilled over time is calculated.

The startup period is defined as the time of reduced average production between mechanical completion and the start of operating capacity. During this period an average production capacity of 50% applies, and it is considered to last as much one fourth of the construction time at regular speed (Humbird et al., 2011). Any delays prior to construction beginning are also relevant to estimating construction timelines; during the COVID-19 pandemic, complex industries required 4 weeks to convert and scale production (Betti and Heinzmann, 2020). This delay could be reduced by investing in planning today. More details on this method can be found in (Throup et al., 2022) and (García Martínez et al., 2021b). Distributed production during the COVID-19 pandemic was far faster (Pearce, 2020a), but is left for future work.

2.5 Economic analysis

A net present value (NPV) analysis was performed by calculating the required revenue for a standard unit of the SCP product when NPV equals zero. This analysis enabled estimates of the break-even cost of the product. To estimate the timeframe of plant operation, six years was used. This timeframe is shorter than those typical of chemical plants, and represents the period in which industrial food production factories could operate during an extreme food shock. This is representative of the duration for a period with little sunlight caused by a nuclear winter. The increased capital cost from 24/7 construction applies. At the end of the six year period the equipment was considered to be depreciated, corresponding to the time of coldest temperatures. In reality, some lower priced food could be sold for longer, there would be some salvage value, or the systems could be built less expensively (less durably), so this is a conservative assumption. To account for the time value of money, a 10% discount rate was used, consistent with recommendations for economic analyses facing an absence of statistical data for the given technology (Short et al., 1995). For comparison, the same analysis was performed for normal conditions outside of a catastrophe, namely a typical plant lifetime of 20 years and regular construction cost.

The operating costs are estimated based on the energy resource requirements for a reference plant from Table 4 and the prices from Table 3. For the electricity cost, the typical cost for the aluminum industry was taken to represent the low end of the uncertainty range, and the higher end of the uncertainty range was represented by the current European industry average. Thermal energy costs were calculated based on the cost of the amounts of coal required to reach thermal energy requirements. The total variable operating costs included the electricity and thermal energy costs described above, plus a further $10.6 million USD for other operating costs, as well as a further 6.5$ million USD for overheads (Jorgensen, 2011). Working capital was presumed at $32.6 million USD. The financial parameters, with a federal tax rate of 35%, are based on the analysis of (Humbird et al., 2011). Financing sources were taken to comprise 70% equity (with an assumed 10% return on investment) and 30% loaned capital, assuming an interest rate of 8% per annum and a 10-year repayment period.

Table 3. Energy resource cost ranges considered.

Price range	**Low**	**Middle**	**High**
Electricity price	Global low (Burns, 2015)	U.S. average (EIA, 2020a)	Europe average (Eurostat, 2019)
($/kWh)	0.03	0.07	0.13
Natural gas price	Flared, vented or reinjected NG	10-year average (Markets Insider, 2020a)	10-year maximum (Markets Insider, 2020a)
($/MWh NG)	0.00	11.26	16.51
Coal price	Global low (EIA, 2020b)	Average (Markets Insider, 2020b)	10-year high (Markets Insider, 2020b)
($/tonne)	11.60	45.80	80.00

3 Results

3.1 CAPEX estimation

The updated capital cost of the air separation unit required to fulfill the plant's O_2 requirements is estimated at $67 million USD based on (Kreutz et al., 2005). Together with the other capital costs the total amounts to $329 million USD for regular construction, or $481 million for 24/7 construction. This would be equivalent to a CAPEX per unit of installed capacity of $3,300/tpa and $4,800/tpa, respectively. All costs are updated to 2020 values using the Chemical Engineering Plant Cost Index (CEPCI). These figures are conservatively estimated from the "first of a kind" plant proposed by Unibio; n-th plant facilities are at least 15% cheaper, in the authors' experience.

3.2 Required resources and operating expenditures

The energy requirements estimated for each step are shown in Table 4. All values are calculated from Table 1: the natural gas requirement is obtained based on the proposed reaction stoichiometry, range of methane content, energy content of natural gas and gas utilization. The air separation energy requirement is calculated based on the energy use of the separation system from literature, the gas utilization and the reaction stoichiometry. The fermentation and centrifugation energy requirements are taken from a resource analysis study. Spray drying energy requirements are obtained from the industry average of a study on industrial spray drying data and the expected solid content of the inlet stream. The median energy requirements of spray drying were lower, but the average was selected as a more conservative assumption. All values are corrected for nucleic acid removal.

Table 4. Energy requirements of methane SCP production per step in kWh over dry mass of product.

	Energy requirement (kWh/kg SCP)	
Step	**90% gas utilization, low NG energy content**	**80% gas utilization, high NG energy content**
Fermentation	1.6	
Centrifugation	0.8	
Spray drying	5.8	
Air separation	1.5	1.7
Energy equivalent of required natural gas	21.2	32.5
Total energy requirements for methane SCP production	31.0	42.5

The energy analysis results for a reference plant are shown in Table 5. The values are estimated based on Table 4 and the production capacity. The caloric energy efficiency is estimated as the amount of energy invested in producing the SCP in comparison with its caloric content. The actual energy and efficiency values vary depending on the gas utilization and energy and methane contents of the gas. The estimated methane requirements have been compared against the value proposed by Bio Protein A/S (now part of Calysta). They stated a utilization of 2 m^3 of methane per kg of SCP produced (Babi and Price, 2010), in accordance with the value obtained here for high gas utilization, high methane content and no nucleic acid removal, which denotes the conservativeness of the present estimations.

Table 5. Energy analysis results for a reference plant. The ranges are based on the intervals of gas utilization and energy content of the natural gas input considered.

Variable		**Low end**	**High end**	**Unit**
Total energy requirements of reference plant		359	489	MW
Of which electricity is		48	50	MW
Overall energy efficiency		20.0	14.6	%
Natural gas requirement of SCP production		0.218	0.276	bcm/year
Thermal energy requirements in terms of:	Coal	62,039		tonne/year
	Natural gas	0.048	0.058	bcm/year

The share of global resources that would be required to fulfill the protein requirements of the global population via methane SCP is shown in Table 6 for both ends of the expected protein content range and gas utilization. The ammonia requirements are estimated based on the reaction stoichiometry. No resource bottlenecks are identified in comparison to the current availability.

Table 6. Range of the share of global resources required to fulfill the minimum global human protein requirements, while accounting for 12% food waste.

	Low end	**High end**	
Protein content of methane SCP	80	50	%
Gas utilization	80	90	%
Methane SCP requirement	243	388	Megatonne/year
Electricity capacity required	114	192	GW

Share of global electricity consumption		4.5	7.5	%
Natural gas required		524	1,062	bcm/year
Share of global natural gas production		12.5	25.3	%
Ammonia required		45		Megatonne/year
Share of global ammonia production		26.3		%
Thermal energy requirements in terms of:	Share of global natural gas production required	3.3	4.4	%
	Share of global coal production required	2.0	3.3	%

Even when accounting for fulfilling the entire global caloric requirements, the share of global natural gas that would have to be leveraged does not exceed 100%. At most it would be 97%, when assuming low gas utilization and use of natural gas for fulfilling the thermal requirements of the plants. The share of global electricity required in this case would be at most 25%. In comparison, the share of global ammonia production capacity required would be 110% of current values.

The amounts of natural gas required to fulfill global caloric and protein requirements via methane SCP are shown in Figure 3 in comparison to different available sources of methane. If current production of flared, vented and reinjected gas could be leveraged in its entirety for methane SCP production, it could cover 56-100% of the methane needed to fulfill global protein requirements, depending on protein content of the SCP, methane content of the gas and gas utilization. The nitrogen contained in the current production of sewage and manure is estimated between 3-13 megatonne/year (Matassa et al., 2020), equivalent to 8-36% of the nitrogen requirements for fulfilling the global protein requirements. However, it is unclear whether this could be leveraged for SCP production during a GCFS.

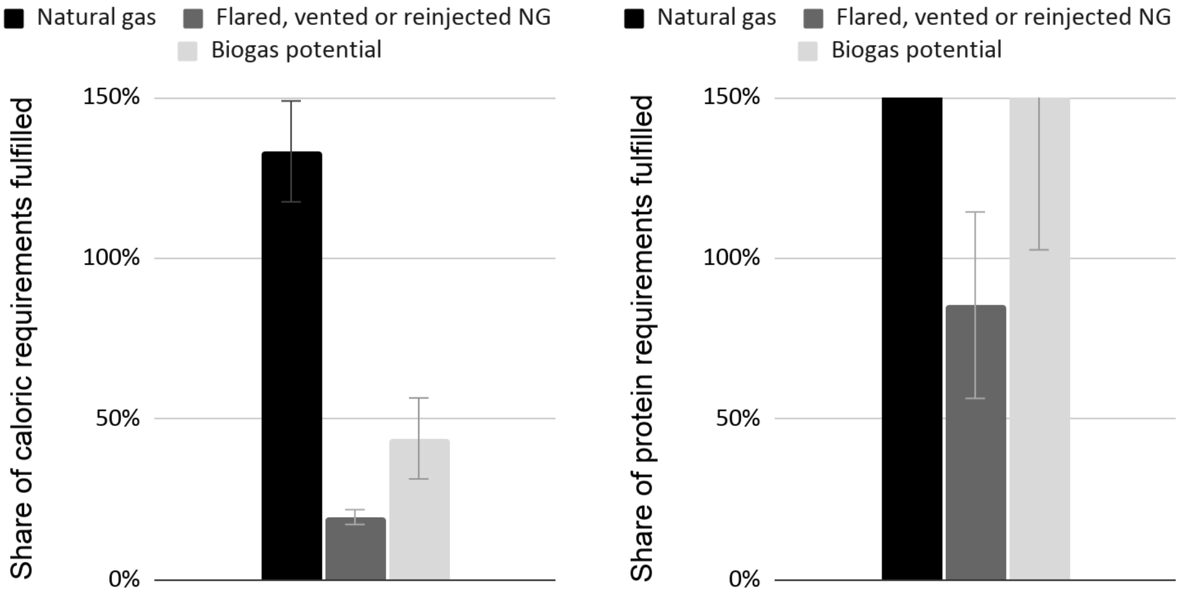

Figure 3. Share of global caloric requirements that could be fulfilled by different potential methane sources (left) in comparison with the share of global protein requirements that could be fulfilled using the same sources (right).

Bacterial SCP production also requires a number of minerals for cell growth metabolism. These include calcium, iron, phosphorus, sulfur, sodium, chlorine, potassium, and magnesium, among others. Out of these, magnesium was the only one identified as a potential bottleneck to SCP production ramp-up (García Martínez et al., 2021b), but only when aiming to fulfill global caloric requirements.

3.3 Ramp-up speed

The construction time for a reference size plant is estimated at 87 weeks, and at 27 weeks when using 24/7 construction. The ramp up speed for the scenario in which the global budget for chemical and related industries can be effectively redirected to fast construction of methane SCP factories is shown in Figure 4 for the global caloric requirements and Figure 5 for the global protein requirements. For the fast construction scenario at the end of the first year around 2% of the caloric requirements could be fulfilled, translating to 7-11% of the protein requirements. The global protein requirements could potentially be covered in approximately 2.5-4.5 years. Note that the regular construction speed eventually overtakes 24/7 construction due to its lower resource intensity, but takes much longer to start producing food which makes it much worse in the advent of a GCFS.

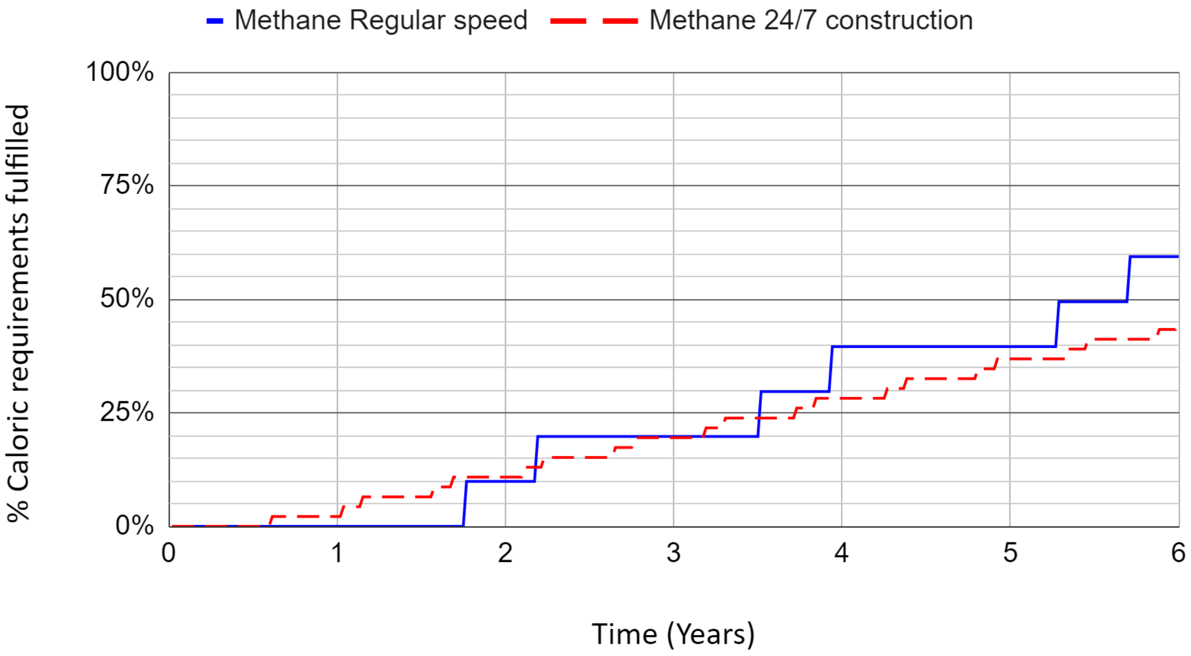

Figure 4. Expected ramp up speed of methane SCP production in terms of the global caloric human requirements fulfilled over time. The results shown reflect the use of the budget of similar industries, including regular and fast construction speeds.

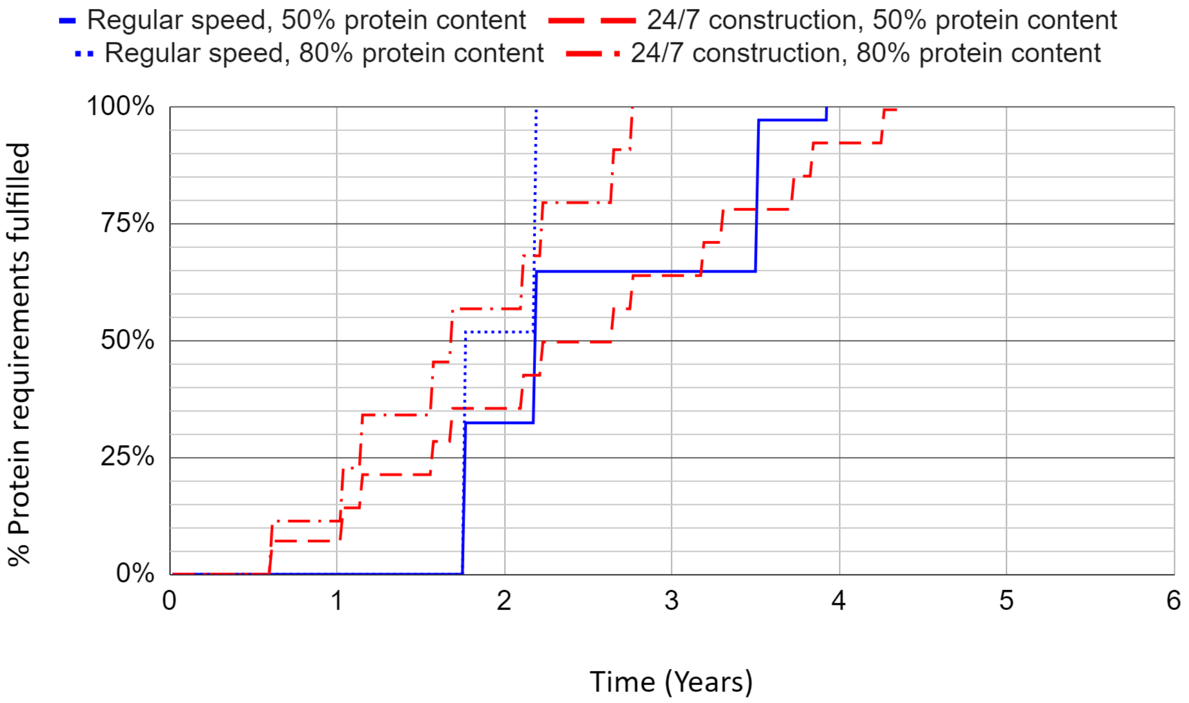

Figure 5. Expected ramp up speed of methane SCP production in terms of the global protein human requirements fulfilled over time, for different values of the protein content of the SCP product. The results shown reflect the use of the budget of similar industries, including regular and fast construction speeds.

For reference, if assuming unlimited capital and no bottlenecks, a capital cost of 6.1 trillion USD would be sufficient for building the amount of methane SCP factories required to fulfill the caloric requirements of humanity. This would take an amount of time equivalent to that of building one reference scale production plant at around 13 months to full production (see the second step in the curves from Figures 3 and 4). Assuming slow construction, the capital cost would amount to 4.1 trillion USD, corresponding to a timeframe of 27 months until full production levels would be achieved.

Humans are unlikely to survive by relying on methane SCP as their sole food source; aiming to fulfill all global human caloric requirements through SCP alone is unrealistic However, methane SCP could potentially fulfill the protein requirements of the global population over the duration of the proposed sunlight reduction scenario, approximately equivalent to 19-31% of caloric requirements. This amount of protein could be provided through SCP production on a construction budget of 1.2-1.9 trillion USD, a range that assumes fast construction methods and varies depending on the protein content per unit of SCP product. at a fast construction budget of around 1.2-1.9 trillion USD depending on protein content. The middle of the range of protein content, 65%, corresponds with the protein content expected from the Unibio SCP reference, assuming it has had nucleic acids removed, so it can be considered to constitute a ”best estimate” of the ramp-up speed. Based on it, the protein requirements would be fulfilled in 3.5 years with the limited construction budget. A similar calculation based on a 9.8% fat content of the methane SCP

(Silverman, 2020) and a minimum recommended fat intake equivalent to 15% of total energy intake (García Martínez et al., 2022) yields about 25% coverage of the global fat requirement when fulfilling the entire global protein requirement via methane SCP in this way. Other resilient foods could cover the rest of the nutritional requirements (Pham et al., 2022).

3.4 Food price

The NPV analysis was performed to estimate the break-even cost of the methane SCP product for different scenarios. The expected cost of the SCP in the ASRS was estimated by limiting the plant life to 6 years and accounting for the additional cost of 24/7 construction. For comparison, the product cost in regular conditions (20 years of lifetime and regular construction cost) was also obtained. For each of the two scenarios, the product cost was calculated for a scenario of high operating costs (high natural gas and electricity cost), and for an optimistic scenario using free natural gas (i.e. vented or flared) and low electricity cost, as lower and upper bounds for the cost. Results are shown in Figure 6.

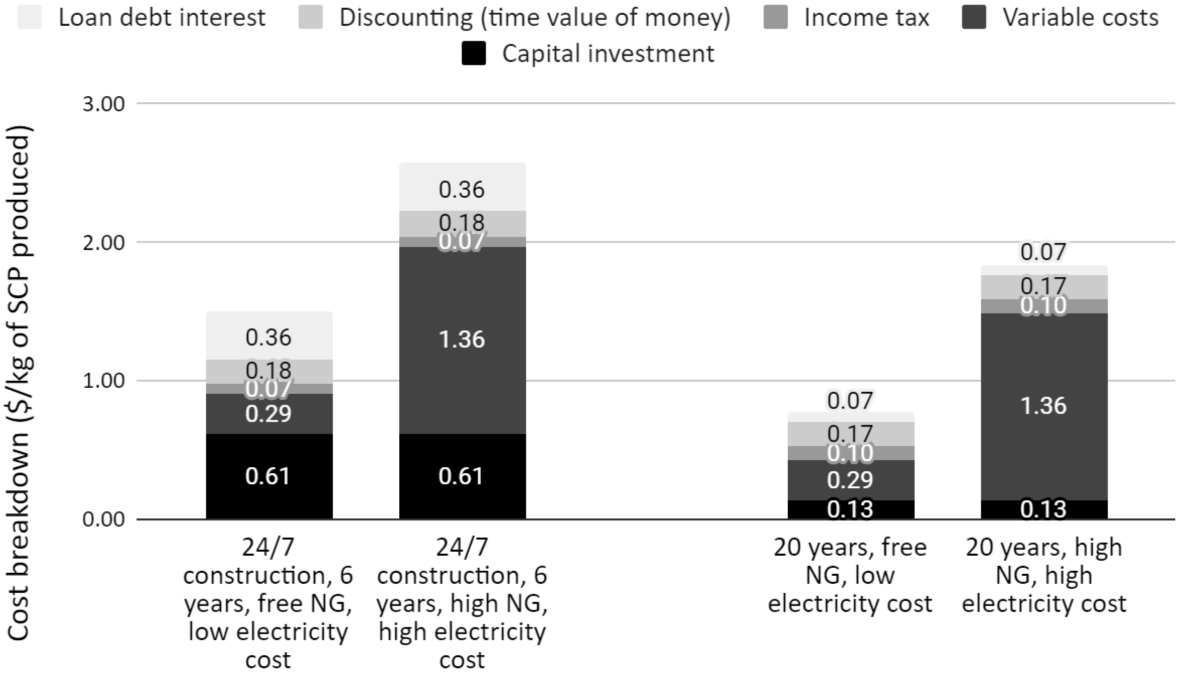

Figure 6. Breakdown of the contributions to the wholesale production cost incurred per unit of methane SCP produced.

A markup of 100% was applied to estimate the retail cost of the SCP product, accounting for distribution and other additional costs (McCray, 2010). We refer to these values as a retail cost instead of price due to the uncertain equilibrium of the market during a GCFS, which could alter the sale price. The result is shown in Table 7. The retail cost for fulfilling a person's daily caloric requirements would be $1.19-2.03.

Table 7. Retail cost of methane SCP for different cost scenarios in U.S. dollars per kilogram of dry SCP product.

Scenario	GCFS conditions (6 years plant lifetime, 24/7 construction)		Regular conditions (20 years plant lifetime, regular construction)	
Energy and feedstock cost	Free NG, low electricity	High	Free NG, low electricity	High
Wholesale price (USD/kg)	$1.51	$2.58	$0.77	$1.84
Retail cost (USD/kg)	$3.02	$5.16	$1.54	$3.68

4 Discussion

The product retail cost for GCFS conditions does not significantly increase when comparing the scenarios of low versus high operating cost, the difference being US$3-5/kg dry. The difference in retail cost between regular and GCFS conditions is estimated at approximately $2/kg. In an ASRS the sunlight levels could be reduced for longer than 6 years, but even with this longer delay before sunlight recovered to current levels, factories built later would still have fewer years of operation during which SCP products could command higher prices due to high demand. There would be lower demand for the SCP product after agricultural productivity recovers, although there could be some remaining opportunity for these plants to operate. The cost analysis is likely conservative for factories operating in the first year of the ASRS. At this price, it is expected that around 90% of the global population would be able to afford the SCP product for all calories with current incomes (Denkenberger et al., 2019).

An important caveat regarding the cost estimations is that the financial assumptions used are common during business as usual, but the financial conditions of an ASRS are complex and outside of the scope of this work. There is considerable uncertainty; although governments gave interest-free loans during the COVID-19 pandemic, raising capital during a GCFS could conversely become far more difficult in the financial ecosystem. Further research is needed on market equilibrium during an ASRS for more precise price estimations of resilient foods.

As shown in Figure 3, it is conceivable that most or all of the methane required to fulfill the global protein requirements could be sourced exclusively from a combination of biogas and natural gas associated with oil which is currently being flared or reinjected. This means that methane SCP production may require redirecting little or no additional natural gas production capacity from current or future uses in order to fulfill this goal. Locations with abundance of flared or vented natural gas should be prioritized for lower production costs. Additionally, these would not require redirecting the current natural gas production from its use as fuel, which would be a significant advantage during a nuclear winter. Using the natural gas feedstock as an energy source for fulfilling the thermal and electricity energy requirements of the plant could be more convenient than using other sources, but doing so would reduce the amount of feedstock available for further ramp-up. Additionally, further research on the availability of biogas during an ASRS would help provide more insight on the share of natural gas production capacity that would have to be redirected. Biogas produced from decaying plant biomass killed by an ASRS could be significant. Biogas could likely more efficiently be leveraged by co-cultivation of the methane-oxidizing bacteria with hydrogen-oxidizing bacteria (Kerckhof et al., 2021).

Methane SCP is generally faster to ramp up compared to other industrial solutions for resilient food production in ASRS, such as new construction of lignocellulosic sugar plants (Throup et al., 2022) or H_2 SCP plants (García Martínez et al., 2021b). Other non-industrial, low-tech resilient food solutions such as tropical greenhouses (Alvarado et al., 2020) and seaweed farming in the ocean (Mill et al., 2019) are expected to scale up production faster. However, the high protein content and quality of the methane SCP product far surpasses that of these faster scaling solutions, making it valuable as a protein supplementation food during a GCFS. For this reason, a recommendation would be to limit the ramp-up of methane SCP to the production capacity required to fulfill global protein requirements at most, while the rest of the calories and nutrients are fulfilled by faster scaling resilient food solutions that the SCP nutritionally complements (Pham et al., 2022).

Regardless of the ramp-up speed of methane SCP, it would be a great advantage to have multiple factories built and operating before the strike of a GCFS. This would imply a head-start in terms of food production, equivalent to shifting the ramp-up curves upward. If the factories had originally been built for producing animal feed, adding a nucleic acid removal treatment would allow obtaining valuable human food early in the catastrophe. For each plant (of the reference size) available at the onset of an ASRS, an estimated maximum of 620,000 people could meet their entire caloric needs with the SCP product; an estimated maximum of 2.6 million people could meet their minimum protein requirements through the product. Some potential interventions to expedite the ramp-up of SCP technology that were previously identified apply for the case of methane SCP. A coordinated response plan for materials and labor deployment to a collection of pre approved sites would accelerate the initial response to the GCFS. A readily available, generalist methane SCP plant front-end engineering design package, whether produced by industry or academia, could serve as a design basis for the new plants, similar to how (Humbird et al., 2011) serves as a benchmark case study for the biochemical ethanol production process. In addition, once the sector has reached maturity industry experts could create a guide on building and operating the plants, apart from sharing lessons on how to successfully reach and maintain production at scale (García Martínez et al., 2021b).

As shown in Figure 5, the protein content of the SCP product significantly influences the speed at which the global protein requirements can be fulfilled. If feasible, research on increasing the protein content would be of important use to this end, be it via optimization of operational parameters such as the methane to nitrogen ratio (Valverde-Pérez et al., 2020), use of thermophilic methanotrophs for reduced cooling requirements (El Abbadi et al., 2022), genetic modification of the microbes, or other means. These types of optimization, if performed prior to a GCFS, would increase the potential of SCP as a resilient food.

The basis of the ramp up model is the assumption that only the capital budget of chemical and related industries (489 billion USD) could be leveraged for construction of SCP factories, roughly accounting in this way for uncertainties in availability of construction materials, construction of chemical equipment and retraining of qualified labor. A previous order-of-magnitude estimate based on growth-rate values suggested that 100% of global human caloric requirements could be fulfilled by methane SCP at around 6 months (Denkenberger and Pearce, 2015), in comparison to the 10 years estimated in Section 3.3. However, the current estimate is considered to be conservative. If the potential of the global construction industry to provide these resources could be effectively leveraged in its entirety, methane SCP could potentially fulfill the entire global caloric requirements of humanity in the time it would take to build a single wave of factories using 24/7 construction, or just over a year. This is because the annual construction expenditure is estimated at 12 trillion USD (de Best, 2021), surpassing the capital requirements for fast construction of methane SCP at 6.1 trillion USD for fulfilling caloric requirements.

Even with the current conservative estimate, there seem to be no significant impediments to securing the global protein supply using methane SCP within a nuclear winter period. Nonetheless, the time this would take is still longer than the 3-6 months period that global food reserves are expected to last (Denkenberger et al., 2019), and would require unprecedented international cooperation. More research is needed on these labor, equipment construction and coordination constraints, so that the degree to which they would hinder the ramp up of methane SCP production (or production of other resilient foods for GCFS) is better understood. Similar to how a wide array of distributed production occurred to overcome supply shortages during the COVID-19 pandemic, it is expected that distributed production of SCP technologies would create greater resiliency in the food system. Similarly to the calls for open hardware to prevent medical shortages (Chagas et al., 2020; Pearce, 2020a, 2020b) the development of open source scalable components of the small-scale SCP production systems is possible. Some of the units are amenable to additive manufacturing and thus distributed open source production. There has already been substantial progress made on various heat exchangers (Arie et al., 2017; Denkenberger and Pearce, 2018; Tiwari et al., 2019). In addition, there are open source desktop centrifuges that could be scaled for this application (WareJoncas et al., 2018; Sule et al., 2019). Additional work is needed to develop low-cost open source and easily manufactured flash evaporators, spray dryers, cell homogenizers, gas compressors and appropriate bioreactors with high gas utilization.

Low-tech alternatives for downstream processing in small scale SCP production could be settling trays in a refrigerator instead of a centrifuge and boiling the resulting concentrate instead of using a cell homogenizer and spray dryer. Small scale production could use air as O_2 source to obviate the need for air separation, at the cost of reduced gas utilization. Though small scale production of methane SCP would be less efficient, it could have the feature of the waste heat heating the house (particularly advantageous in the case of nuclear winter). There would not be additional retailing costs in contrast to large scale production. Safety issues, and the impact of fugitive methane emissions from small, less controlled "home" or "community" SCP production facilities would have to be assessed. We consider large, industrial SCP production plants more realistic than small-scale efforts, as the process requires proper control. Supplying strains and nutrients for local small-scale productions also seems hard to achieve.

Repurposing existing infrastructure for SCP production could expedite GCFS response, and has already been studied for sugar production in the ASRS context (Throup et al., 2022). Similar to the methodology used in the sugar work, a unit to unit comparison of the methane SCP production process was made with several different industries, including breweries, instant coffee, milk powder, whey protein, washing powder, cheese powder, fertilizers and biorefineries, showing some overlap. Whey protein factories already have units present for centrifugation, spray drying, packaging and storage of powdered product, but the global whey production capacity is insignificant compared to that required to fulfill global protein requirements (~1% of 0.24-0.39 Gt SCP/year required). On the other hand, the global production capacity of cheese powder and fertilizer factories together amount to a larger tonnage than would be required to fulfill protein requirements via SCP production (0.093 and 0.317 Gt respectively (FAO, 2017; GIR, 2020)). If the drying process present in those factories could be leveraged in combination with the utilities, packing, power, steam, buildings and facilities, savings upwards of 40% of the total capital cost could potentially be obtained based on the Unibio reference plant (Jorgensen, 2011). The value is in accordance with a previously published analysis on repurposing paper mills to biorefineries, which similarly predicts capital savings of 40%, mostly from leveraging existing buildings and service facilities (Martinkus and Wolcott, 2017). However, the very specific nature of the equipment required for SCP production could make it impracticable to repurpose existing units, particularly some of the costliest ones such as reactors, centrifuges and spray dryers. Future research will study the potential of repurposing existing infrastructure for SCP production in depth given the significance of expediting GCFS response.

This needed future research can be viewed as a relatively high priority for GCFS mitigation and preparedness funding, but could also be viewed as a means of insurance for conventional methane infrastructure. As the science behind climate change becomes more granular, risks and liabilities for companies responsible for GHG emissions increase (Allen, 2003; Kunreuther and Michel-Kerjan, 2007; Faure and Peeters, 2011; Heidari and Pearce, 2016) and there is a mounting pressure to mitigate climate liability risk. Although natural gas is less carbon intensive than coal, natural gas pipelines have recently been identified as high priority targets for strategic lawsuits to act as GHG emissions bottlenecks (Pascaris and Pearce, 2020). Natural gas companies could argue that their infrastructure could provide security during GCFS events that impact food systems as they make the transition to hydrogen carriers in a green economy if the future work outlined here to make SCP viable and easily scaled is funded and deployed globally.

5 Conclusions

The estimated capital cost for a methane SCP facility for human food production is $4,800/tpa when built using 24/7 construction to quickly produce protein-rich food during a global catastrophic food shock. The expected retail cost of the product would be in the range of $3-5/kg (dry), depending on the cost of the natural gas feedstock and electricity.

The ramp up time of methane SCP is estimated at 2.5-4.5 years for fulfilling the protein requirements of the global population, within the duration of a nuclear winter scenario. No further scaling is recommended given the presence of faster scaling resilient foods. 7-11% of global protein requirements could be fulfilled at the end of the first year. Any facilities constructed prior to an abrupt sunlight reduction scenario would imply an important head start in food production capacity, given the sudden nature of the catastrophe and limited window for adaptation.

No significant resource bottlenecks have been found regarding the inputs of methane SCP required to fulfill global protein requirements. Potential bottlenecks regarding availability of construction materials, construction of chemical equipment and retraining of qualified labor were considered limiting. If these were not significant, protein requirements could potentially be fulfilled in little over a year. More research is needed on the degree to which these bottlenecks would affect SCP ramp-up speed.

Other important future research could include the repurposing potential of existing facilities, the economic conditions and biogas potential for methane production during an abrupt sunlight reduction scenario, or the creation of open source designs for small scale production. Recommended interventions include stimulating SCP production during business as usual, creation of a coordinated response plan for materials and construction and development of open generalist SCP front-end engineering design packages and guides.

In conclusion, methane SCP has significant potential to prevent global protein starvation during a global catastrophic food shock at a price affordable by most of the world's population.

Acknowledgements

Thanks to Dr. Silvio Matassa for his help and insights. Thanks to Megan Jamer for editing.

Funding

This research was supported by the Alliance to Feed the Earth in Disasters (ALLFED). Dr. Joshua Pearce is funded by the Witte Endowment.

References

Adjei, A.A., Yamamoto, S., Kulkarni, A., 1995. Nucleic Acids and/or Their Components: A Possible Role in Immune Function. J. Nutr. Sci. Vitaminol. (Tokyo) 41, 1–16. https://doi.org/10.3177/jnsv.41.1

Ahn, S., Norwood, F.B., 2020. Measuring Food Insecurity during the COVID-19 Pandemic of Spring 2020. Appl. Econ. Perspect. Policy. https://doi.org/10.1002/aepp.13069

Allen, M., 2003. Liability for climate change. Nature 421, 891–892. https://doi.org/10.1038/421891a

ALLFED, 2017. ALLFED [WWW Document]. ALLFED. URL https://allfed.info/ (accessed 7.30.20).

Alptekin, G., 2017. Low Cost Air Separation Process for Gasification Applications [WWW Document]. URL https://netl.doe.gov/sites/default/files/event-proceedings/2017/crosscutting/20170320-Track-C/20170320_1330C_Presentation_FE0026142_TDAResearch.pdf (accessed 7.24.20).

Alvarado, K.A., García Martínez, J.B., Matassa, S., Egbejimba, J., Denkenberger, D., 2021. Food in space from hydrogen-oxidizing bacteria. Acta Astronaut. 180, 260–265. https://doi.org/10.1016/j.actaastro.2020.12.009

Alvarado, K.A., Mill, A., Pearce, J.M., Vocaet, A., Denkenberger, D., 2020. Scaling of greenhouse crop production in low sunlight scenarios. Sci. Total Environ. 707, 136012. https://doi.org/10.1016/j.scitotenv.2019.136012

Anderson, C., Solomons, G.L., 1984. Primary metabolism and biomass production from Fusarium, in: Moss, M.O., Smith, J.E. (Eds.), The Applied Mycology of Fusarium. Cambridge University Press, Cambridge.

Andrijevic, M., Schleussner, C.-F., Gidden, M.J., McCollum, D.L., Rogelj, J., 2020. COVID-19 recovery funds dwarf clean energy investment needs. Science 370, 298–300. https://doi.org/10.1126/science.abc9697

Aneke, M., Wang, M., 2015. Potential for improving the energy efficiency of cryogenic air separation unit (ASU) using binary heat recovery cycles. Appl. Therm. Eng. 81, 223–231. https://doi.org/10.1016/j.applthermaleng.2015.02.034

Arie, M.A., Shooshtari, A.H., Tiwari, R., Dessiatoun, S.V., Ohadi, M.M., Pearce, J.M., 2017. Experimental characterization of heat transfer in an additively manufactured polymer heat exchanger. Appl. Therm. Eng. 113, 575–584. https://doi.org/10.1016/j.applthermaleng.2016.11.030

Attanasi, E.D., Freeman, P.A., 2013. Role of Stranded Gas in Increasing Global Gas Supplies (No. USGS Open-File Report 2013–1044).

Babi, D.K., Price, J., 2010. Single Cell Protein from Landfill Gas. https://doi.org/10.4122/1.1000000046

Bailey, R., Benton, T.G., Challinor, A., Elliott, J., Gustafson, D., Hiller, B., Jones, A., Kent, C., Lewis, K., Meacham, T., Rivington, M., Tiffin, R., Wuebbles, D.J., 2015. Extreme weather and resilience of the global food system: Final Project Report from the UK-US Taskforce on Extreme Weather and Global Food System Resilience. UK Glob. Food Secur. Programme. https://www.stat.berkeley.edu/~aldous/157/Papers/extreme_weather_resilience.pdf

Baker, C., McKenzie, K., 2005. Energy consumption of industrial spray dryers. Dry. Technol. 23, 365–386. https://doi.org/10.1081/drt-200047665

Beasley, D., 2020. WFP Chief warns of hunger pandemic as COVID-19 spreads (Statement to UN Security Council) | World Food Programme [WWW Document]. URL https://www.wfp.org/news/wfp-chief-warns-hunger-pandemic-covid-19-spreads-statement

-un-security-council (accessed 5.18.20).
Betti, F., Heinzmann, T., 2020. COVID-19: How companies are changing track to join the fight [WWW Document]. World Econ. Forum. URL https://www.weforum.org/agenda/2020/03/from-perfume-to-hand-sanitiser-tvs-to-face-masks-how-companies-are-changing-track-to-fight-covid-19/ (accessed 5.27.20).
Bostrom, N., 2013. Existential Risk Prevention as Global Priority. Glob. Policy 4, 15–31. https://doi.org/10.1111/1758-5899.12002
Bostrom, N., Cirkovic, M.M., 2011. Global catastrophic risks. Oxford University Press.
Brosemer, K., Schelly, C., Gagnon, V., Arola, K.L., Pearce, J.M., Bessette, D., Schmitt Olabisi, L., 2020. The energy crises revealed by COVID: Intersections of Indigeneity, inequity, and health. Energy Res. Soc. Sci. 68, 101661. https://doi.org/10.1016/j.erss.2020.101661
Burns, S., 2015. Power Costs in the Production of Primary Aluminum [WWW Document]. Steel Alum. Copp. Stainl. Rare Earth Met. Prices Forecast. Met. URL https://agmetalminer.com/2015/11/24/power-costs-the-production-primary-aluminum/ (accessed 5.20.20).
Calysta Inc., 2020. Adisseo and Calysta establish a Joint-Venture to commercialize FeedKind® [WWW Document]. URL http://www.feedkind.com/adisseo-calysta-establish-joint-venture-commercialize-feedkind/ (accessed 5.23.20).
Chagas, A.M., Molloy, J.C., Prieto-Godino, L.L., Baden, T., 2020. Leveraging open hardware to alleviate the burden of COVID-19 on global health systems. PLOS Biol. 18, e3000730. https://doi.org/10.1371/journal.pbio.3000730
Chisti, M.Y., 1989. Airlift bioreactors. Elsevier Applied Science London.
Circe Biotech, 2021. Protein: feed & food [WWW Document]. URL https://www.circe.at/products/protein (accessed 2.16.22).
Cirkovic, M.M., 2008. Observation selection effects and global catastrophic risks, in: Global Catastrophic Risks. Oxford University Press Oxford, pp. 120–145.
Claassens, N.J., Sousa, D.Z., dos Santos, V.A.P.M., de Vos, W.M., van der Oost, J., 2016. Harnessing the power of microbial autotrophy. Nat. Rev. Microbiol. 14, 692–706. https://doi.org/10.1038/nrmicro.2016.130
Cotton‐Barratt, O., Daniel, M., Sandberg, A., 2020. Defence in Depth Against Human Extinction: Prevention, Response, Resilience, and Why They All Matter. Glob. Policy 11, 271–282. https://doi.org/10.1111/1758-5899.12786
Coupe, J., Bardeen, C.G., Robock, A., Toon, O.B., 2019. Nuclear winter responses to nuclear war between the United States and Russia in the whole atmosphere community climate model version 4 and the Goddard Institute for Space Studies ModelE. J. Geophys. Res. Atmospheres 124, 8522–8543. https://doi.org/10.1029/2019JD030509
Cumberlege, T., Blenkinsopp, T., Clark, J., 2016. Assessment of environmental impact of FeedKind protein 26. https://prod-drupal-files.storage.googleapis.com/documents/resource/public/Assessment%20of%20environmental%20footprint%20of%20FeedKind%20protein%20-%20REPORT.pdf
Damodaran, A., 2020. Global Capital Expenditures, Acquisitions and R&D and Sales/Invested Capital Ratios [WWW Document]. URL http://www.stern.nyu.edu/~adamodar/pc/datasets/capexGlobal.xls (accessed 9.3.20).
de Best, R., 2021. Construction industry spending globally [WWW Document]. Stat. Constr. Ind. Spend. Worldw. 2014 2019 Forecasts 2020 2035. URL https://www.statista.com/statistics/788128/construction-spending-worldwide/ (accessed 2.19.21).

Denkenberger, D., Pearce, J., Taylor, A.R., Black, R., 2019. Food without sun: Price and life-saving potential. Foresight 21, 118–129. https://doi.org/10.1108/FS-04-2018-0041

Denkenberger, D., Pearce, J.M., 2014. Feeding everyone no matter what: Managing food security after global catastrophe. Academic Press.

Denkenberger, D., Sandberg, A., Tieman, R.J., Pearce, J.M., 2021. Long-term cost-effectiveness of interventions for loss of electricity/industry compared to artificial general intelligence safety. Eur. J. Futur. Res. 9, 11. https://doi.org/10.1186/s40309-021-00178-z

Denkenberger, D.C., Cole, D.D., Abdelkhaliq, M., Griswold, M., Hundley, A.B., Pearce, J.M., 2017. Feeding everyone if the sun is obscured and industry is disabled. Int. J. Disaster Risk Reduct. 21, 284–290. https://doi.org/10.1016/j.ijdrr.2016.12.018

Denkenberger, D.C., Pearce, J.M., 2015. Feeding everyone: Solving the food crisis in event of global catastrophes that kill crops or obscure the sun. Futures 72, 57–68. https://doi.org/10.1016/j.futures.2014.11.008

Denkenberger, Pearce, J.M., 2018. Design Optimization of Polymer Heat Exchanger for Automated Household-Scale Solar Water Pasteurizer. Designs 2, 11. https://doi.org/10.3390/designs2020011

Duchene, L., 2016. Bridging the omega-3 gap with methane, microalgae [WWW Document]. Glob. Seaf. Alliance. URL https://www.globalseafood.org/advocate/bridging-the-omega-3-gap-with-methane-microalgae/ (accessed 1.14.22).

EIA, 2020a. Average retail price of electricity [WWW Document]. US Energy Inf. Adm. URL https://www.eia.gov/electricity/data/browser/#/topic/7?agg=2,0,1&geo=g&freq=M (accessed 5.20.20).

EIA, 2020b. Coal Markets [WWW Document]. US Energy Inf. Adm. URL https://www.eia.gov/coal/markets/ (accessed 5.20.20).

EIA, 2019. U.S. Energy Information Administration: International Energy Statistics database [WWW Document]. URL https://www.eia.gov/international/data/world (accessed 7.22.20).

El Abbadi, S.H., Sherwin, E.D., Brandt, A.R., Luby, S.P., Criddle, C.S., 2022. Displacing fishmeal with protein derived from stranded methane. Nat. Sustain. 5, 47–56. https://doi.org/10.1038/s41893-021-00796-2

Elvidge, C.D., Zhizhin, M., Baugh, K., Hsu, F.-C., Ghosh, T., 2016. Methods for global survey of natural gas flaring from visible infrared imaging radiometer suite data. Energies 9, 14. https://doi.org/10.3390/en9010014

Enbridge Gas Inc., 2001. Chemical Composition of Natural Gas [WWW Document]. URL https://www.uniongas.com/about-us/about-natural-gas/chemical-composition-of-natural-gas (accessed 8.27.20).

Engineering ToolBox, 2005. Fuel Gases Heating Values [WWW Document]. URL https://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html (accessed 8.27.20).

Eurostat, 2019. Development of electricity prices for non-household consumers, EU-28 and EA [WWW Document]. Eurostat. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Development_of_electricity_prices_for_non-household_consumers,_EU-28_and_EA,_2008-2019_(EUR_per_kWh).png (accessed 5.20.20).

FAO, 2017. World Fertilizer Trends and Outlook to 2020. http://www.fao.org/3/a-i6895e.pdf

Faure, M., Peeters, M., 2011. Climate change liability. Edward Elgar Publishing.

Finnigan, T.J.A., Wall, B.T., Wilde, P.J., Stephens, F.B., Taylor, S.L., Freedman, M.R., 2019. Mycoprotein: The Future of Nutritious Nonmeat Protein, a Symposium Review. Curr. Dev.

Nutr. 3. https://doi.org/10.1093/cdn/nzz021

Flanagan, S., 2022. Calysta appoints Chief Science and Sustainability Officer [WWW Document]. Calysta. URL https://calysta.com/calysta-appoints-chief-science-and-sustainability-officer/ (accessed 2.16.22).

FMI, 2019. Industrial Oxygen: Meeting Alternative Energy Demands (No. REP-GB-10071). Future Market Insights.

García Martínez, J.B., Alvarado, K.A., Denkenberger, D.C., 2022. Synthetic fat from petroleum as a resilient food for global catastrophes: Preliminary techno-economic assessment and technology roadmap. Chem. Eng. Res. Des. 177, 255–272. https://doi.org/10.1016/j.cherd.2021.10.017

García Martínez, J.B., Brown, M.M., Christodoulou, X., Alvarado, K.A., Denkenberger, D.C., 2021a. Potential of microbial electrosynthesis for contributing to food production using CO2 during global agriculture-inhibiting disasters. Clean. Eng. Technol. 4. https://doi.org/10.1016/j.clet.2021.100139

García Martínez, J.B., Egbejimba, J., Throup, J., Matassa, S., Pearce, J.M., Denkenberger, D.C., 2021b. Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios. Sustain. Prod. Consum. 25, 234–247. https://doi.org/10.1016/j.spc.2020.08.011

GIR, 2020. Global Cheese Powder Market Size, Forecast Report 2025 (No. PD021253).

Glencross, B.D., Huyben, D., Schrama, J.W., 2020. The Application of Single-Cell Ingredients in Aquaculture Feeds—A Review. Fishes 5, 22. https://doi.org/10.3390/fishes5030022

Hanna, A.S., Chang, C.-K., Lackney, J.A., Sullivan, K.T., 2007. Impact of Overmanning on Mechanical and Sheet Metal Labor Productivity. J. Constr. Eng. Manag. 133, 22–28. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:1(22)

Heidari, N., Pearce, J.M., 2016. A review of greenhouse gas emission liabilities as the value of renewable energy for mitigating lawsuits for climate change related damages. Renew. Sustain. Energy Rev. 55, 899–908. https://doi.org/10.1016/j.rser.2015.11.025

Henchion, M., Hayes, M., Mullen, A.M., Fenelon, M., Tiwari, B., 2017. Future protein supply and demand: strategies and factors influencing a sustainable equilibrium. Foods 6, 53. https://doi.org/10.3390/foods6070053

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., 2011. Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis of corn stover (No. NREL/TP-5100-47764). National Renewable Energy Lab.(NREL), Golden, CO (United States).

IEA, 2019. Natural Gas Information: Overview [WWW Document]. Nat. Gas Inf. Overv. URL https://www.iea.org/reports/natural-gas-information-overview

Jain, S., 2019. Global Potential of Biogas. https://www.worldbiogasassociation.org/global-potential-of-biogas/

Jenkins, G., 1988. SCP — The BP Protein Process, in: Greenshields, R. (Ed.), Resources and Applications of Biotechnology: The New Wave. Palgrave Macmillan UK, London, pp. 141–149. https://doi.org/10.1007/978-1-349-09574-2_15

Jensen, M., 2021. Unibio solutions for UFMSW valorisation from Valuewaste. https://hoopproject.eu/wp-content/uploads/2021/05/ValueWaste-Project-PPT-Presentation-26052021.pptx-pdf.pdf

Jorgensen, J.B., 2011. Exploiting Microorganisms for Animal Feed Production. The 7th Malaysia International Agro-Bio Business Conference : What Next Agriculture II, Kuala Lumpur, Malaysia. https://core.ac.uk/download/pdf/13790016.pdf

Kerckhof, F.-M., Sakarika, M., Van Giel, M., Muys, M., Vermeir, P., De Vrieze, J., Vlaeminck, S.E., Rabaey, K., Boon, N., 2021. From Biogas and Hydrogen to Microbial Protein Through Co-Cultivation of Methane and Hydrogen Oxidizing Bacteria. Front. Bioeng. Biotechnol. 9, 771. https://doi.org/10.3389/fbioe.2021.733753

Khoshnevisan, B., He, L., Xu, M., Valverde-Pérez, B., Sillman, J., Mitraka, G.-C., Kougias, P.G., Zhang, Y., Yan, S., Ji, L., Carbajales-Dale, M., Elyasi, S.N., Marami, H., Tsapekos, P., Liu, H., Angelidaki, I., 2022. From renewable energy to sustainable protein sources: Advancement, challenges, and future roadmaps. Renew. Sustain. Energy Rev. 157, 112041. https://doi.org/10.1016/j.rser.2021.112041

Kreutz, T., Williams, R., Consonni, S., Chiesa, P., 2005. Co-production of hydrogen, electricity and CO2 from coal with commercially ready technology. Part B: Economic analysis. Int. J. Hydrog. Energy 30, 769–784. https://doi.org/10.1016/j.ijhydene.2004.08.001

Kunreuther, H.C., Michel-Kerjan, E.O., 2007. Climate change, insurability of large-scale disasters and the emerging liability challenge. https://doi.org/10.3386/w12821

Laborde, D., Martin, W., Vos, R., 2020. Poverty and food insecurity could grow dramatically as COVID-19 spreads. Int. Food Policy Res. Inst. IFPRI Wash. DC. https://www.ifpri.org/publication/poverty-and-food-insecurity-could-grow-dramatically-covid-19-spreads

LaJeunesse, S., 2020. Research team to study food resilience in the face of catastrophic global events | Penn State University [WWW Document]. URL https://news.psu.edu/story/622541/2020/06/08/research/research-team-study-food-resilience-face-catastrophic-global-events (accessed 7.30.20).

Lane, J., 2018. Construction complete at Unibio/Protelux commercial scale methane to protein plant : Biofuels Digest [WWW Document]. URL http://www.biofuelsdigest.com/bdigest/2018/09/13/construction-complete-at-unibio-protelux-commercial-scale-methane-to-protein-plant/ (accessed 5.23.20).

Lee, A., 2021. Barriers to adopting alternative protein are decreasing, post-Covid-19: String Bio co-founder Ezhil Subbian [WWW Document]. Eco-Bus. URL https://www.eco-business.com/news/barriers-to-adopting-alternative-protein-are-decreasing-post-covid-19-string-bio-co-founder-ezhil-subbian/ (accessed 9.13.21).

Leger, D., Matassa, S., Noor, E., Shepon, A., Milo, R., Bar-Even, A., 2021. Photovoltaic-driven microbial protein production can use land and sunlight more efficiently than conventional crops. Proc. Natl. Acad. Sci. 118. https://doi.org/10.1073/pnas.2015025118

Levett, I., Birkett, G., Davies, N., Bell, A., Langford, A., Laycock, B., Lant, P., Pratt, S., 2016. Techno-economic assessment of poly-3-hydroxybutyrate (PHB) production from methane—The case for thermophilic bioprocessing. J. Environ. Chem. Eng. 4, 3724–3733. https://doi.org/10.1016/j.jece.2016.07.033

Manero, A., Smith, P., Koontz, A., Dombrowski, M., Sparkman, J., Courbin, D., Chi, A., 2020. Leveraging 3D Printing Capacity in Times of Crisis: Recommendations for COVID-19 Distributed Manufacturing for Medical Equipment Rapid Response. Int. J. Environ. Res. Public. Health 17. https://doi.org/10.3390/ijerph17134634

Manheim, D., Denkenberger, D., 2020. Review of potential high-leverage and inexpensive mitigations for reducing risk in epidemics and pandemics. J. Glob. Health Rep. 4, e2020010. https://doi.org/10.29392/001c.12530

Markets Insider, 2020a. Natural Gas PRICE Today [WWW Document]. Nat. Gas PRICE Today. URL https://markets.businessinsider.com/commodities/natural-gas-price (accessed 8.28.20).

Markets Insider, 2020b. Coal PRICE Today | Coal Spot Price Chart [WWW Document]. markets.businessinsider.com. URL https://markets.businessinsider.com/commodities/coal-price (accessed 5.20.20).

Marlow Foods Ltd., 2001. GRAS NOTIFICATION for MYCOPROTEIN [WWW Document]. URL http://wayback.archive-it.org/7993/20171031053437/https://www.fda.gov/downloads/Food/IngredientsPackagingLabeling/GRAS/NoticeInventory/UCM266876.pdf (accessed 7.30.20).

Martin, J., Burrows, T.K., Pegg, I., 2006. Predicting Construction Duration of Building Projects. Presented at the Shaping the Change: XXIII FIG Congress, Munich. https://fig.net/resources/proceedings/fig_proceedings/fig2006/papers/ts28/ts28_02_martin_etal_0831.pdf

Martinkus, N., Wolcott, M., 2017. A framework for quantitatively assessing the repurpose potential of existing industrial facilities as a biorefinery. Biofuels Bioprod. Biorefining 11, 295–306. https://doi.org/10.1002/bbb.1742

Matassa, S., Batstone, D.J., Hülsen, T., Schnoor, J., Verstraete, W., 2015. Can direct conversion of used nitrogen to new feed and protein help feed the world? Environ. Sci. Technol. 49, 5247–5254. https://doi.org/10.1021/es505432w

Matassa, S., Boon, N., Pikaar, I., Verstraete, W., 2016. Microbial protein: future sustainable food supply route with low environmental footprint. Microb. Biotechnol. 9, 568–575. https://doi.org/10.1111/1751-7915.12369

Matassa, S., Papirio, S., Pikaar, I., Hülsen, T., Leijenhorst, E., Esposito, G., Pirozzi, F., Verstraete, W., 2020. Upcycling of biowaste carbon and nutrients in line with consumer confidence: the "full gas" route to single cell protein. Green Chem. 22, 4912–4929. https://doi.org/10.1039/D0GC01382J

McCray, B., 2010. How to set retail prices and markups [WWW Document]. Small Biz Surviv. URL https://smallbizsurvival.com/2010/11/how-to-set-retail-prices-and-markups.html (accessed 9.22.20).

Mill, A., Harrison, C., James, S., Shah, S., Fist, T., Alvarado, K., Taylor, A., Denkenberger, D., 2019. Preventing global famine in case of sun-blocking scenarios: Seaweed as an alternative food source. https://www.researchgate.net/publication/337199859_Preventing_global_famine_in_case_of_sun-blocking_scenarios_Seaweed_as_an_alternative_food_source_Key_findings

Pascaris, A.S., Pearce, J.M., 2020. U.S. Greenhouse Gas Emission Bottlenecks: Prioritization of Targets for Climate Liability. Energies 13, 3932. https://doi.org/10.3390/en13153932

Pearce, J.M., 2020a. Distributed Manufacturing of Open Source Medical Hardware for Pandemics. J. Manuf. Mater. Process. 4, 49. https://doi.org/10.3390/jmmp4020049

Pearce, J.M., 2020b. A review of open source ventilators for COVID-19 and future pandemics. F1000Research 9. https://doi.org/10.12688/f1000research.22942.2

Pearce, J.M., Denkenberger, D.C., 2018. A National Pragmatic Safety Limit for Nuclear Weapon Quantities. Safety 4, 25. https://doi.org/10.3390/safety4020025

Pearce, J.M., Khaksari, M., Denkenberger, D., 2019. Preliminary Automated Determination of Edibility of Alternative Foods: Non-Targeted Screening for Toxins in Red Maple Leaf Concentrate. Plants 8, 110. https://doi.org/10.3390/plants8050110

Pham, A., García Martínez, J.B., Brynych, V., Stormbjorne, R., Pearce, J.M., Denkenberger, D.C., 2022. Nutrition in Abrupt Sunlight Reduction Scenarios: Envisioning Feasible Balanced Diets on Resilient Foods. Nutrients 14, 492. https://doi.org/10.3390/nu14030492

Pikaar, I., Matassa, S., Bodirsky, B.L., Weindl, I., Humpenöder, F., Rabaey, K., Boon, N., Bruschi, M., Yuan, Z., van Zanten, H., 2018. Decoupling livestock from land use through industrial feed production pathways. Environ. Sci. Technol. 52, 7351–7359. https://doi.org/10.1021/acs.est.8b00216

Rajesh, M., Kamalam, B.S., Sharma, P., Verma, V.C., Pandey, A., Dubey, M.K., Ciji, A., Akhtar, Md.S., Pandey, N., Sarma, D., Kaushik, S.J., 2022. Evaluation of a novel methanotroph bacteria meal grown on natural gas as fish meal substitute in rainbow trout, Oncorhynchus mykiss. Aquac. Res. https://doi.org/10.1111/are.15735

Ravindra, P., 2000. Value-added food: Single cell protein. Biotechnol. Adv. 18, 459–479. https://doi.org/10.1016/S0734-9750(00)00045-8

Research and Markets ltd, 2020. Ammonia Market - Growth, Trends, and Forecast (2020 - 2025) (No. 4773617).

Ritala, A., Häkkinen, S.T., Toivari, M., Wiebe, M.G., 2017. Single cell protein—state-of-the-art, industrial landscape and patents 2001–2016. Front. Microbiol. 8, 2009. https://doi.org/10.3389/fmicb.2017.02009

Rob Smith, 2018. These are the world's biggest coal producers [WWW Document]. World Econ. Forum. URL https://www.weforum.org/agenda/2018/01/these-are-the-worlds-biggest-coal-producers/ (accessed 5.14.20).

Robock, A., Oman, L., Stenchikov, G.L., 2007. Nuclear winter revisited with a modern climate model and current nuclear arsenals: Still catastrophic consequences. J. Geophys. Res. Atmospheres 112. https://doi.org/10.1029/2006JD008235

Rosenberry, B., 2019. NovoNutrients: Making Aquatic Feeds from Waste Products [WWW Document]. URL https://www.shrimpnews.com/FreeReportsFolder/SpecialReports/NovoNutrientsShrimpFeedsFromWasteProducts.html (accessed 5.23.20).

Sefton, B., 2018. NovoNutrients: Food from CO2. http://nas-sites.org/dels/files/2018/02/2-2-SEFTON-NovoNutrients-NAS.pdf

Shepon, A., Eshel, G., Noor, E., Milo, R., 2016. Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. Environ. Res. Lett. 11, 105002. https://doi.org/10.1088/1748-9326/11/10/105002

Shokrani, A., Loukaides, E.G., Elias, E., Lunt, A.J.G., 2020. Exploration of alternative supply chains and distributed manufacturing in response to COVID-19; a case study of medical face shields. Mater. Des. 192, 108749. https://doi.org/10.1016/j.matdes.2020.108749

Short, W., Packey, D.J., Holt, T., 1995. A manual for the economic evaluation of energy efficiency and renewable energy technologies (No. NREL/TP-462-5173). National Renewable Energy Lab., Golden, CO (United States).

Sillman, J., Nygren, L., Kahiluoto, H., Ruuskanen, V., Tamminen, A., Bajamundi, C., Nappa, M., Wuokko, M., Lindh, T., Vainikka, P., Pitkänen, J.-P., Ahola, J., 2019. Bacterial protein for food and feed generated via renewable energy and direct air capture of CO2: Can it reduce land and water use? Glob. Food Secur. 22, 25–32. https://doi.org/10.1016/j.gfs.2019.09.007

Silverman, J., 2020. Single Cell Protein: A sustainable approach to meeting the growing protein demand. AQUAFEED Adv. Process. Formul. 7, 10–14. https://www.aquafeed.com/article-files/file_1454440826_1.pdf

Solar Foods, 2021. Solein submitted to the European Commission for novel food approval [WWW Document]. Sol. Foods Oy. URL https://solarfoods.fi/our-news/solein-submitted-to-the-european-commission-for-novel-food-approval/ (accessed 2.17.22).

Sönnichsen, N., 2020. Electricity consumption globally [WWW Document]. Statista. URL https://www.statista.com/statistics/280704/world-power-consumption/ (accessed 5.14.20).

Southey, F., 2019. Solar Foods makes protein out of thin air: 'This is the most environmentally friendly food there is' [WWW Document]. foodnavigator.com. URL https://www.foodnavigator.com/Article/2019/07/15/Solar-Foods-makes-protein-out-of-thin-air-This-is-the-most-environmentally-friendly-food-there-is (accessed 5.8.20).

Sule, S.S., Petsiuk, A.L., Pearce, J.M., 2019. Open Source Completely 3-D Printable Centrifuge. Instruments 3, 30. https://doi.org/10.3390/instruments3020030

Switzenbaum, M.S., Giraldo-Gomez, E., Hickey, R.F., 1990. Monitoring of the anaerobic methane fermentation process. Enzyme Microb. Technol. 12, 722–730. https://doi.org/10.1016/0141-0229(90)90142-D

TEMASEK, 2020. The Unlikely Solutions to Close the Protein Gap [WWW Document]. Temasek Corp. Website Engl. URL https://www.temasek.com.sg/content/temasek-corporate/en/news-and-views/stories/future/the-next-food-revolution/the-unlikely-solutions-to-close-the-protein-gap (accessed 9.13.21).

Throup, J., García Martínez, J.B., Bals, B., Cates, J., Pearce, J.M., Denkenberger, D.C., 2022. Rapid repurposing of pulp and paper mills, biorefineries, and breweries for lignocellulosic sugar production in global food catastrophes. Food Bioprod. Process. 131, 22–39. https://doi.org/10.1016/j.fbp.2021.10.012

Tiwari, R., Andhare, R.S., Shooshtari, A., Ohadi, M., 2019. Development of an additive manufacturing-enabled compact manifold microchannel heat exchanger. Appl. Therm. Eng. 147, 781–788. https://doi.org/10.1016/j.applthermaleng.2018.10.122

Tzachor, A., Richards, C.E., Holt, L., 2021. Future foods for risk-resilient diets. Nat. Food 2, 326–329. https://doi.org/10.1038/s43016-021-00269-x

UIG, 2006. Universal Industrial Gases Inc. - Optimal System - Plant Selection and Supply System Design [WWW Document]. URL http://www.uigi.com/optimalplant.html (accessed 7.24.20).

Unibio Group, 2020a. Chemical Composition of Uniprotein [WWW Document]. Unibio. URL https://www.unibio.dk/end-product/chemical-composition-1/ (accessed 5.14.20).

Unibio Group, 2020b. Unibio process [WWW Document]. URL https://www.unibio.dk/technology/process/ (accessed 9.25.20).

United Nations, 2019. World Population Prospects 2019: Highlights (No. ST/ESA/SER.A/423).

U.S. Department of Agriculture, 2016. How many calories are in one gram of fat, carbohydrate, or protein? | Food and Nutrition Information Center| NAL | USDA [WWW Document]. URL https://www.nal.usda.gov/fnic/how-many-calories-are-one-gram-fat-carbohydrate-or-protein (accessed 7.30.20).

U.S. Food and Drug Administration, 2002. GRAS Notices: GRN No. 000091 (Mycoprotein) [WWW Document]. URL https://www.accessdata.fda.gov/scripts/fdcc/index.cfm?set=GRASNotices&id=91 (accessed 7.30.20).

Valverde-Pérez, B., Xing, W., Zachariae, A.A., Skadborg, M.M., Kjeldgaard, A.F., Palomo, A., Smets, B.F., 2020. Cultivation of methanotrophic bacteria in a novel bubble-free membrane bioreactor for microbial protein production. Bioresour. Technol. 310, 123388. https://doi.org/10.1016/j.biortech.2020.123388

Villadsen, J., Nielsen, J., Lidén, G., 2011. Bioreaction engineering principles. Springer Science & Business Media.

Volova, T.G., Barashkov, V.A., 2010. Characteristics of proteins synthesized by hydrogen-oxidizing microorganisms. Appl. Biochem. Microbiol. 46, 574–579. https://doi.org/10.1134/S0003683810060037

WareJoncas, Z., Stewart, C., Giannini, J., 2018. An Inexpensive, Open-Source Mini-Centrifuge. Am. Biol. Teach. 80, 451–456. https://doi.org/10.1525/abt.2018.80.6.451

Warner, M., 2019. Industrial Biotechnology Commercialization Handbook: How to Make Proteins Without Animals and Fuels Or Chemicals Without Crude Oil. Independently Published.

World Bank, 2018. Global gas flaring and oil production: 1996 - 2018 [WWW Document]. URL http://pubdocs.worldbank.org/en/182101560185376968/pdf/Global-gas-flaring-and-oil-produ

ction-1996-2018.pdf (accessed 7.16.20).
World Health Organization, 2004. Food and nutrition needs in emergencies. https://www.unhcr.org/uk/45fa745b2.pdf
World Health Organization, United Nations University, 2007. Protein and amino acid requirements in human nutrition, WHO Technical Report Series 935. ISBN: 92-4-120935-6.
Worldometers, 2020. World Population Clock [WWW Document]. Worldometers. URL https://www.worldometers.info/world-population/ (accessed 5.28.20).