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CO_2-to-food pathways via synthetic fat and H_2 microbial protein outperform alternatives on energy, cost and land use

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Abstract

Power-to-food technologies could transform food systems by reducing CO_2, land, and water footprints while enhancing food security and global resilience. CO_2-to-food pathways span chemical synthesis (fats, sugars, starches) and fermentation routes using electrochemical feedstocks (acetate, sugars) or gases (e.g. hydrogen). Cost and environmental impacts are dominated by energy demands, making prioritization critical, yet comparisons are convoluted by inconsistent methods and assumptions across studies.

We develop a framework comparing energy efficiency, land productivity, and cost across twelve CO_2-to-food pathways, while providing future projections. Power-to-food efficiencies vary by ~10×, with synthetic fats and hydrogen microbial protein dominating: ~90% less land than conventional crops and ~99% less than animal products, ~5× more efficient than competing pathways (vertical farming, photobioreactors, heterotrophs), and considerable economic potential (~$2–8/kg dry)—against butter (~$4–7/kg), egg (~$5–32/kg), milk proteins (~$5–14/kg), or plant protein isolates (~$2–9/kg)—potentially unlocking massive sustainability, security, and animal welfare gains.

1 Introduction

The global food system is a major driver of adverse environmental changes, accounting for a large share of worsening trends in climate change, land degradation, water scarcity, deforestation, and biodiversity loss[1]. Reducing consumption of resource-intensive foods, especially animal-based products[2], and developing new approaches to food production[3] are now increasingly recognized as critical. While industrial agriculture has boosted yields to feed a global population of over eight billion, its heavy reliance on fertilizers, pesticides, liquid fuels, animals, and expanding land has led to massive increases in greenhouse gas emissions, eutrophication, freshwater depletion, biodiversity decline, animal suffering and antibiotics use[1]. With limited prospects to expand agricultural land and climate change threatening future yields[4,5], feeding a rapidly increasing and wealthier population without further environmental harm demands radically different methods.

A growing number of academics and for-profit businesses are now turning their attention to an understudied, next-generation approach to address the downsides of modern food systems: using industrial technologies to make food directly from CO_2, bypassing the notorious inefficiencies of photosynthetic food production[1,6–20]. We call these "power-to-food", in some cases also known as artificial photosynthesis[19], or food without agriculture[1]. There are myriad possible ways to synthesize food from inorganic carbon, other than photosynthetic growth of plants and microalgae. All three macronutrients (proteins, fats, and carbohydrates) can be synthesized using CO_2 as the main input. To name some examples: carbohydrates can be obtained via bioenzymatic catalysis[21] or non-biological synthesis[22]. Proteins can be obtained biologically from cultivating microorganisms via electrosynthesized intermediates such as hydrogen[23,24], carbon monoxide[25], methanol[26], or acetate[19,27]. Reduction of CO_2 to syngas[28] enables a wealth of chemical and biological synthesis routes[1,6], including but not limited to: syngas→paraffins→fatty acids→triglycerides (abiotic); syngas→amino acids→proteins (abiotic), or microorganism cultivation. These technologies provide food without needing arable land, potentially unlocking massive sustainability, biodiversity, security, and animal welfare gains.

The main unsolved challenges to scaling these approaches are their high capital requirement and high energy consumption. To bring about their promised societal benefits, it is imperative to prioritize investment to those power-to-food technologies best suited to the task, such as those most efficient at converting renewable energy into edible calories. Unfortunately, comparisons are made hard by methodological differences in studies: different definitions of energy efficiency and use, different assumptions of CO_2 capture, conversion efficiency, post-processing, etc., different system boundaries, different units, key performance indicators, framings, and more.

Here we developed a harmonized framework to compare electricity-to-food efficiency, cost floors, and land use efficiency across multiple CO_2-to-food pathways. Then, we compared energy efficiency, land productivity, and cost to agricultural product benchmarks, both animal- and plant-based. We find that the top approaches—hydrogen single cell protein, and chemical synthesis of fat—provide food one to two orders of magnitude more efficiently than conventional agricultural products. In addition, we estimate that power-to-food production at scale could already compete on cost with target agricultural ingredients of interest such as milk whey, egg powder, plant protein isolates, or butter. This combination of results demonstrates a promising opportunity to free up vast amounts of land from agricultural production to other uses, such as rewilding for biodiversity recovery and carbon storage. Extended Data Figure 1 shows the maximum possible extent of this potential, indicating that using power-to-food systems to produce a modest share of global food could have outsized positive impact.

The goal of this study is to help researchers, policymakers, and entrepreneurs understand the value of these technologies and strategically decide which ones hold the most potential for the needs of society. Identifying the best-performing systems can help guide where time, capital and policy attention are most effectively directed. Given renewable energy projections of increasing capacity and decreasing cost in the coming years[29], now is a key time to understand which approaches are best suited to displace agricultural products as low-cost renewable energy increases. Capital investment now would make power-to-food technology ready for mass scale deployment, and help realize its societal benefits: food sovereignty[30], consistent supply[31,32], production in constrained environments—desert, arctic, space, underwater, etc.[22,31]—resilience to food system shocks[6,33], low land and water use[1,8,11,34–37], replacing imported strategic commodities, etc. Application niches that capitalize on the above strengths are of particular interest for early development of power-to-food; for example, its ability to produce food in extreme environments from little more than widespread CO_2, water, and electricity has already brought it to the attention of government agencies like NASA and DARPA[31]. For more information, see the supplementary section on "Applications of CO_2 power-to-food production".

2 Results

2.1 Power-to-food efficiency

The comprehensive but not exhaustive selection of candidate food production pathways considered in the study is summarized in Figure 1. Starting from CO_2, water, hydrogen, energy, and sometimes a modest amount of minerals (when microorganisms are involved), a rich set of pathways emerges: electrified controlled-environment crop production (e.g., artificial-light lettuce and wheat); photosynthetic microalgae systems (e.g., Spirulina photobioreactors); microbial food routes fed either by hydrogen and CO_2 (hydrogen oxidizing bacteria, HOB SCP) or via electrolytically-derived CO_2-based intermediates such as acetate, methanol, formate, carbon monoxide, or synthetic carbohydrates (including yeast and microalgae); chemical synthesis of fats from CO_2-derived intermediates; synthesis of products that can be consumed directly or used as platform intermediates such as carbohydrates or acetate, through chemical and/or electrochemical routes; or acetate via microbial electrosynthesis (MES). Prior comparative analyses indicate that electricity-to-SCP energy use is very similar for H_2 gas fermentation and for H_2-derived methanol- and formate-mediated bacterial SCP routes, all within a variation of ~10%[11]. For simplicity, we therefore focus on HOB SCP (H_2 gas fermentation) as a characteristic example that extends to other similar such approaches.

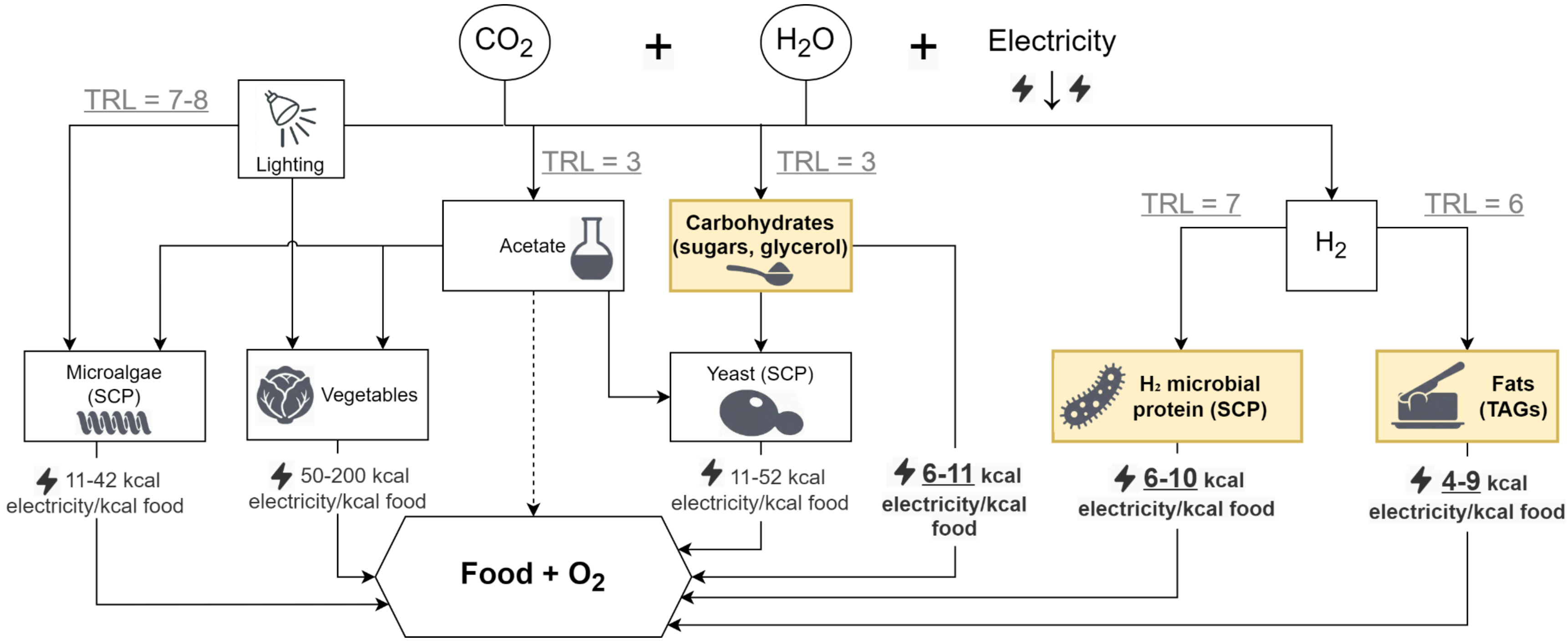

Figure 1. *Pathways for food production from CO_2 considered in the analysis, their energy use, and their Technology Readiness Level (TRL). The upper-bound values given for electricity use represent values achievable with current technology based on published systems ("base case"), while the lower-bound value represents a reasonably optimistic scenario for the potential of current or conceivable future systems ("optimistic case"). The "optimistic case" does not represent the maximum possible thermodynamic efficiency of these processes; future developments may therefore exceed the optimistic case value in some cases. Acetate can only be consumed as a food in very limited amounts in the form of dilute acetic acid (vinegar), and is shown here primarily as an intermediate. TRL estimates are taken from Supplementary Table S7. The items highlighted in bold and yellow indicate the three most energy-efficient routes by a notable margin.*

A summary of the power-to-food energy use results (i.e. electricity-to-food efficiency) for the current state of the technology is given in Figure 2. Each pathway's particular synthetic and metabolic mechanisms result in significant variations in energy consumption. For example, H_2SCP, synthetic fat and synthetic carbohydrates are 10+ times more efficient in electricity use per unit of protein/fat/kcal produced compared to vertical farming; and several times more efficient than fermentation pathways based on acetate or sugar intermediates. Full methodological details and additional results can be found in the Extended Data Table 1, Extended Data Figure 2, supplementary spreadsheet, and supplementary document, including "optimistic" electricity-to-food conversion values that represent reasonable upper bounds of the potential of future developments.

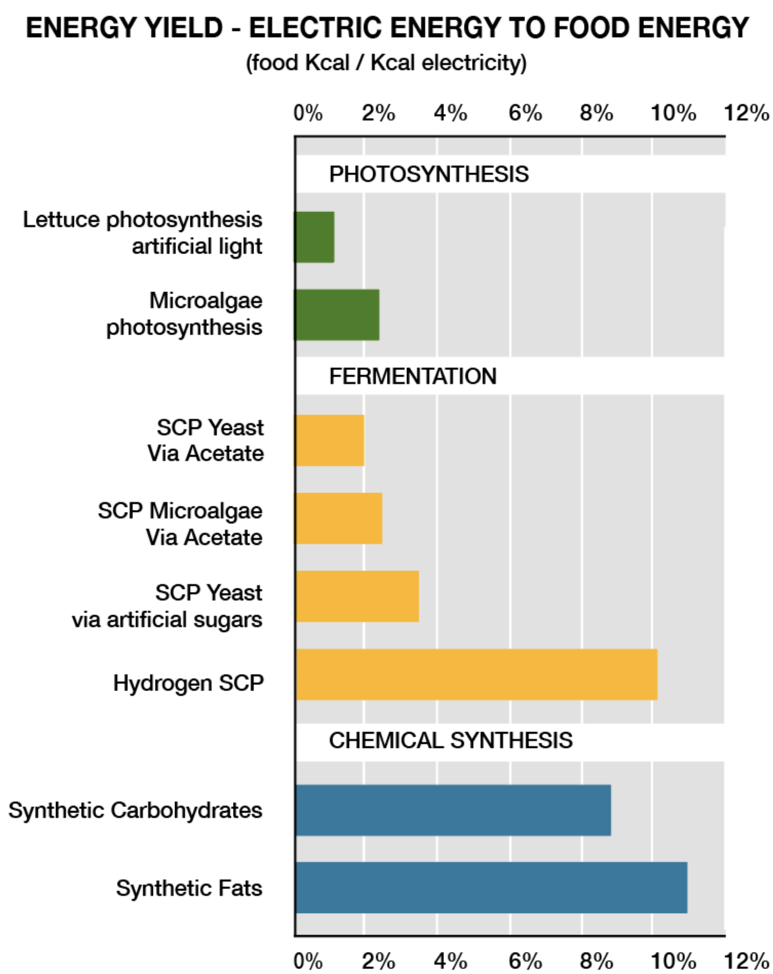

Figure 2. *Power-to-food conversion efficiency of existing CO_2-based power-to-food production methods, based on values reported for existing systems. Results are given in percentage of how many units of food energy are obtained per unit of electricity invested. Specific energy consumption values (kWh/kg food) can be found in Extended Data Table 1, while a comparison of energy efficiency vs TRL for all routes can be found in Extended Data Figure 2.*

2.2 Cost of CO_2 foods

A coarse-grained initial assessment of the broader economic viability of CO_2-based foods can be obtained through comparing their expected average energy cost and the commodity cost of comparable agriculture-based benchmark products. The energy cost is a robust, lower bound value that can be readily quantified to illustrate an initial order-of-magnitude product cost, and can be easily updated to reflect future developments. This thereby provides an initial, simple and transparent check for the economic viability of production. It would be very challenging for a CO2-based-food production process to compete economically if the cost of electricity alone (without additional operational and capital expenses) was higher than the wholesale price of a comparable competitor product. To estimate the cost of electricity per unit of CO_2 food product, the energy requirements estimated in the above section are combined with a base case electricity cost of $0.06/kWh—representative of values for large industrial customers in energy-intensive industries in the USA and China[38]—and an optimistic electricity cost of $0.03/kWh, which is approximately the expected lower end of levelized cost of electricity for solar energy with battery by 2040[39]. This is conservative compared to the levelized cost of solar photovoltaic electricity without batteries, which is projected to be lower than $0.02/kWh by 2040[39].

The results are shown in Extended Data Table 2. While the electricity costs alone suggest many power-to-food systems have, on average, limited economic viability at the current TRL, the "Optimistic case" results are promising for many technologies. The optimistic values represent future projected reductions in global electricity costs and improvements in process efficiency, indicating that electricity costs may cease to be a hard barrier for most power-to-food systems. Notably, production of H_2SCP and synthetic fat at scale does not appear to be limited by electricity costs even today, with electricity cost values around $3 and $6 per kg (dry) compared with benchmarks worth over $6/kg (dry). On the other hand, we see that even under the most optimistic assumptions used here, the electricity cost of synthetic carbohydrates alone ($1-3/kg dry) would make it unable to compete with average sugar costs ($0.4/kg dry), and yeast made with synthetic carbohydrates would similarly be unable to compete with yeast made using conventional sugar.

We can derive additional insights on total production costs based on known capital costs for some CO2-based food production processes and the expectation that all CO_2 foods are similarly capital intensive. This assumption is reasonable across non-photosynthetic food production methods as all of them are similarly based on water electrolysis or other electrosynthetic intermediates, most also involve fermentation, and when using renewables, they would probably also require feedstock balancing—equipment used to smooth variable renewable-electricity operation (e.g. batteries) and maintain stable input flows of hydrogen, CO_2, intermediates, and nutrients. The amortized/levelized CAPEX would be estimated at ~$1.9/kg of dry matter (DM) for 2030 and ~$1.0/kg (DM) for 2050 at large scale with continuous deployment, based on an H_2SCP model informed by pilot plant data and learning rates[14]. Other capital cost estimates exist in literature for H_2SCP[14] and synthetic fat[40], but they are notably lower than the aforementioned comprehensive end-to-end assessment that even includes power and feedstock balancing technologies. The results are summarized in Figure 3 and Supplementary Table S1, and they further suggest that H_2SCP and synthetic fats are poised to eventually compete with their benchmarks' current prices. Acetate-mediated SCPs may also be able to compete with benchmarks, but within the harmonized assumptions and literature bounds used in this study, acetate-mediated SCP never surpasses

H_2SCP. The rest of the approaches have more limited potential, even under the most optimistic assumptions used in this study.

Future research should evaluate these technologies comprehensively via techno-economic analyses including full capital costs and operational cost assessments to better characterize the potential of CO_2 foods.

	Base case (current efficiency, \$0.06/kWh, \$1.9/kg CAPEX)	Optimistic end (future efficiency, \$0.03/kWh, \$1.0/kg CAPEX)	Actual commodity cost of benchmark product (\$/kg food, dry)	Benchmark product
SCP Yeast via acetate	\$13	\$2	\$2-3	Yeast (agricultural sugar)
SCP Microalgae via acetate	\$11	\$2	\$4-6	Spirulina (open pond)
SCP Yeast via artificial sugars	\$9	\$3	\$2-3	Yeast (agricultural sugar)
Synthetic fats	\$8	\$2	\$4-7	Butter
Synthetic carbohydrates	\$5	\$2	\$0.2-0.6	Table sugar
Fat-rich engineered H_2SCP	\$5	\$2	\$4-7	Butter
Microbial protein from hydrogen (H_2SCP)	\$5	\$2	\$5-14 \$5-32 \$2-9	Whey protein concentrate Dried egg yolk Plant protein isolates

= Far from benchmark costs = Significant improvement needed = Close to benchmark

Figure 3. *Comparison between the estimated cost of electricity for CO_2-based power-to-food products and the actual wholesale cost of benchmark products of agricultural origin and fermentation based on agricultural inputs. The large-scale production cost ranges were based on the estimated ranges of 1) energy consumption for current vs potential future developments (see Extended Data Table 1 and supplementary information), 2) electricity costs between \$0.06/kWh (current price for electricity-intensive industries, "Base case") and \$0.03/kWh (price of future solar photovoltaic with batteries, "Optimistic case"), and 3) CAPEX cost contribution at different states of the technology, based on the same value as for H_2SCP. All values are given in 2025 USD. Power-to-food product cost estimates represent a dried, raw bulk product; they do not account for downstream extraction, purification, or upgrading, which can be significant when targeting refined animal or plant product substitutes. Supply chain costs are also not included, which typically increase retail prices several-fold for foods produced by conventional agriculture. Colors indicate the estimated degree of cost competitiveness relative to the benchmark: "Close to benchmark" indicates pathways that may already be able to approach benchmark costs at scale. "Significant improvement needed" indicates pathways that are currently much more expensive but could become competitive with major process improvements and lower electricity prices. "Far from benchmark costs" indicates pathways that remain far from competitiveness even under highly optimistic assumptions. An expanded version of this visualization can be found in the supplementary document.*

2.3 Land productivity of PV-driven CO_2-to-food technologies

The land productivity of CO_2-to-food technologies was estimated for solar photovoltaic (PV) driven systems as PV is projected to dominate future electricity supply and mirror the reliance of conventional food production on incoming sunlight. We define land productivity as the amount of food that can be produced per unit of land occupied by the infrastructure needed to produce the energy inputs and the factory floor, presented here in terms of food energy supply (kcal/m²/year), protein supply (g protein/m2/y), and fat supply (g fat/m2/y). We present the results in Figure 4.

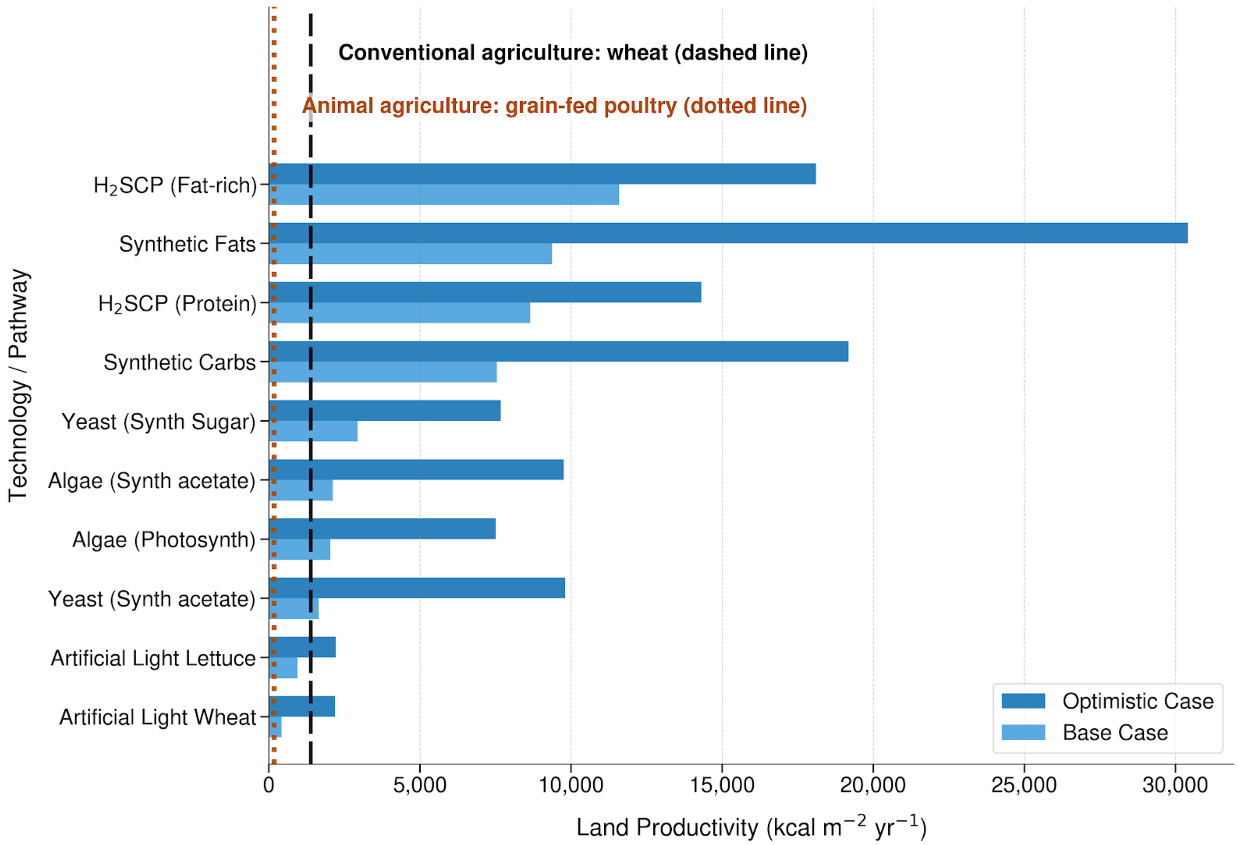

Figure 4. *Power-to-food systems produce much more food per unit of land than conventional agriculture. Land productivity (kcal/m²/year) of power-to-food production pathways driven by solar photovoltaic energy and CO_2 capture—for both current capabilities (base case) and future improvements (optimistic case); the multipliers on the right show how many times as land-efficient as wheat the optimistic case of each technology is. All comparisons with agricultural products here are based on current global average land productivity values[41]. These have significant variation worldwide; for comparison the highest measured crop yields can be found in Supplementary Figure S9 versus H_2SCP and synthetic fat.*

The most efficient systems are H_2SCP, synthetic fats, and synthetic carbohydrates, in terms of food energy per unit of land and food energy per unit of electricity used. These technologies are expected to be about one order of magnitude more land-efficient than wheat production, and about two orders of magnitude more efficient than animal production. The comparison is particularly dramatic between current PV-driven power-to-food systems and animal sources of protein and fat: the amount of land currently used for providing milk fat (e.g. butter) to one person could instead provide fat for ≈300 people using synthetic fat, see Figure 5. The amount of land that provides the protein requirement of a person with chicken meat can provide protein for ~100 people if using H_2SCP. This difference is only expected to widen in the future, as power-to-food systems and solar PV increase in efficiency.

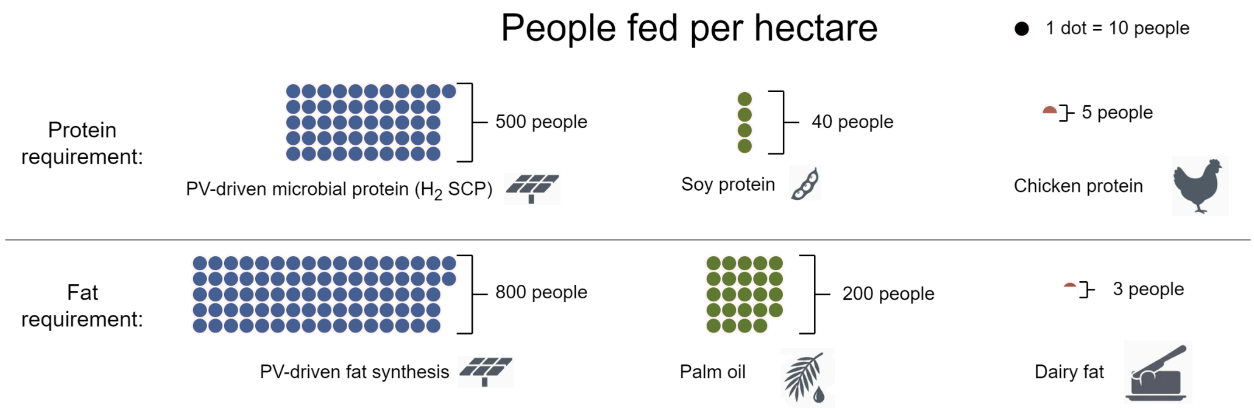

Figure 5. *Land productivity in terms of protein and fat supply per unit of land, comparing power-to-food systems (base case) with the most efficient plant-based and animal-based agricultural benchmarks; every dot represents 10 people. The protein requirement considered is 80 g/person/day, and the fat requirement is 35 g/person/day, both at 15% of dietary energy*[24,40].

Not only are power-to-food systems much more land-efficient than agricultural systems on average, they do not require any arable land. Most or all of their land requirement could be obtained from renewable energy located on marginal or barren land. This could potentially free up significant arable land for rewilding or other uses when displacing agricultural products. Extended Data Figure 3 illustrates this contrast by comparing the land productivity of power-to-food systems with that of wheat and grain-fed poultry, alongside each pathway's electricity-to-calories efficiency.

To better illustrate how the energy efficiency, land productivity, and production cost results were derived, we show an in-depth analysis of hydrogen oxidizing bacteria (perhaps the most well-studied power-to-food system) in the methods section "Case study: hydrogen oxidizing bacteria versus photosynthesis". Figure 6 summarizes the analysis as a comparison between HOB SCP and conventional wheat grain cultivation ("biological photosynthesis"). We estimated the H_2SCP to be nearly one order of magnitude more efficient at converting sunlight to digestible food energy than wheat, and almost two orders of magnitude more efficient than poultry. To illustrate the mechanisms behind this difference, we use energy flow diagrams comparing PV-driven H_2SCP versus conventional photosynthetic wheat cultivation in figure 6. The losses shown for each step of sunlight to edible food illustrate where improvements in each approach would make the biggest difference, as shown by Extended Data Figure 4.

We note that the efficiency of converting sunlight to food for HOB is one order of magnitude lower than the electricity to food efficiency value reported above for HOB. This is because the sunlight conversion efficiency additionally includes the efficiency of PVs for converting sunlight to electricity. We also emphasize that the efficiency of real-world solar farms is several-fold less efficient at converting incoming light to electricity than PVs measured under standard laboratory conditions. This is due to spacing between solar panels, dust and debris on the solar panels, and other inefficiencies [11,42].

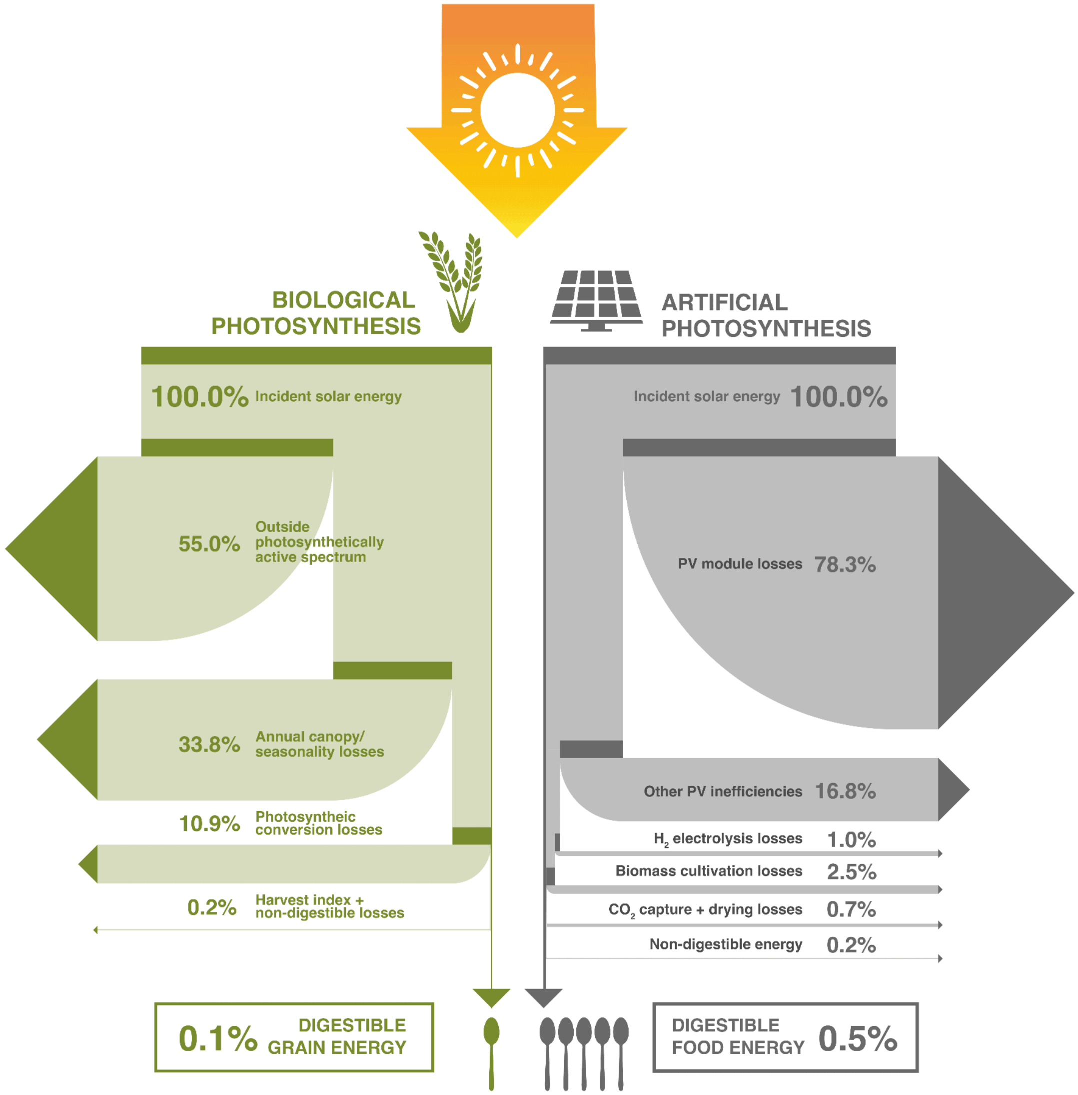

Figure 6. *Side-by-side energy flow comparison of PV-driven H₂SCP "artificial photosynthesis" versus biological photosynthesis of wheat. Sankey diagrams trace the conversion of incoming sunlight (100% solar energy) into food via plant-based and H₂SCP pathways. Conversion losses are shown as arrows with their width scaled to the energy lost, indicating as well the share of energy lost in each step. Green color denotes the biological photosynthesis process, while grey denotes the power-to-food H₂SCP process. The arrows reaching the bottom represent the fraction of solar energy retained in the final biomass; arrow widths are proportional to energy flow. For methodological details and references, see the supplementary section "Comparison between power-to-food systems and conventional photosynthesis".*

3 Discussion

Three of the processes studied have been estimated to have notably higher base case efficiencies than the rest: synthetic carbohydrates, H_2SCP, and chemical fat synthesis, all with an electricity-to-food efficiency around 10%. The rest of processes have notably lower efficiencies currently, all below a few %. The energy needed for producing the feedstock is the major driver of the energy cost, with CO_2 capture, drying and other supporting processes contributing minor additional energy demands. This makes the conclusions of the analysis robust to changes in CO_2 capture accounting and dewatering—see Extended Data Figure 5.

Combined with the economic assessment, we find that H_2SCP and synthetic fats are promising candidates for consumer market development, while synthetic carbohydrates are uneconomical. Of these, the H_2SCP options have the most interesting nutritional properties—with particularly significant amounts of protein and B vitamins[43]—while the synthetic fat process produces only saturated fat, but does have a higher ceiling of potential for highly integrated processes, estimated at ≈30% compared to the optimistic case of H_2SCP at ≈20%. Overall, the genetically modified H_2SCP seems to provide the most valuable nutrition per unit of energy invested for most applications.

Analyses of H_2SCP unit cost broadly agree with the current analysis, projecting that total production costs per kg of protein-rich H_2SCP could decline from ~$6 in the near future to ~$2 or less in 2050 (~$3-9/kg protein at 65% protein content), comparing favorably in price to soy and pea protein isolates (~$2–9 and ~$4–10 per kg of protein content, respectively)[14]. Techno-economic analyses of electro-microbial production of biomass (such as H_2SCP)[16] concur with this work in at least $1/kg in electricity costs, making these routes potentially viable for high value-added food production within a decade, but far from parity with lower cost commodities such as staple foods and fuels.

While both synthetic fat and fat-rich H_2SCP show promise for competing with dairy fat, the H_2SCP is not 100% fat, unlike the synthetic fat. Other oleaginous organisms contain around 60% fat[44]. The cost per unit of fat contained in the H_2SCP if it was 60% fat would be $4-8/kg fat, compared to $2-8/kg synthetic fat. However, other components of the H_2SCP (proteins, carbohydrates, vitamins, etc.) are also valuable, and it could potentially be modified to produce higher value unsaturated fats (e.g. EPA and/or DHA), while the synthetic fats are completely saturated. On the other hand, if a CO_2-based diesel Fischer-Tropsch industry existed, the synthetic fat cost could be lower by purchasing the by-product wax fraction of the Fischer-Tropsch process, which is cheaper and avoids the need to recycle the Fischer-Tropsch diesel products at additional hydrogen cost. This is consistent with molecular-complexity heuristics, which suggest that simple, non-chiral fats are generally more efficiently produced by thermochemical routes than by biomanufacturing synthesis[45].

In addition to low land use, power-to-food technologies have very low water use[1,8,11,34–37]. They could reduce food-system CO_2 emissions, ease pressure on freshwater resources, and free agricultural land for reforestation or other uses. They enable production of the proteins and fats we need with much lower environmental impacts than meat, butter, and oil palm, without the need to clear forests for palm oil plantations or livestock rearing, and without the animal suffering involved in factory farming. They could even help curb overfishing by displacing the use of wild-caught fish as fishmeal. Lastly, they provide access to virtually limitless resources for food production, for example: using about a quarter of the current global electricity capacity for H_2SCP production would cover the entire global protein requirement of the human population[24], requiring <1% of global land for solar farms[14] and no arable land at all. However, the benefits to society are conditional on the displacement of unsustainable foods and products[1]. To succeed, these technologies will need sufficiently good food functionality and consistently cheap, low-CO_2 energy. See the supplementary section "Applications of CO_2 food production" for illustrative estimates and discussion on sustainability.

On crewed space missions, the key promise of efficient power-to-food systems is integration with existing life support systems to curb food resupply needs. The three most promising pathways—H_2SCP, synthetic fat, and synthetic carbohydrates—are a particularly good fit, because the energy use of in-situ food production systems would be a pivotal contributor to launch mass and mission cost[22,23,46]. Given the high cost of moon launches at $1 million per kg of mass, power-to-food systems could result in billions of dollars in savings for large-scale space missions—see supplementary information. However, in order to take a central role in space food production they will have to prove capable of efficient byproduct recycling and production of the wide range of micronutrients that humans need to survive.

Finally, power-to-food systems are much more resilient to climate variability, environmental degradation and pollution, pests, pathogens, and trade restrictions[33]. Such processes could also be independent of sunlight (e.g. nuclear, geothermal, or fuel-based), making them resilient even to extreme food disruption scenarios, as long as the systems could be properly maintained. Such scenarios include abrupt sunlight reduction scenarios (volcanic winter, nuclear winter, asteroid/comet impact winter), severe climate shifts (e.g. abrupt changes in climate, even extreme change increasing global temperature over 10°C)[6,47], among others—more details in the supplement. Overall, market penetration of power-to-food technologies could provide a more sustainable and resilient mode of production, helping to feed humanity in the face of instability and uncertainty from changing agricultural and climatic conditions.

4 Methods

4.1 Selection of CO_2-based food systems

A literature review was undertaken to find candidate processes for food production from CO_2 with high efficiency for which enough public information is available to enable estimation of the energy consumption based on empirical data; full details are in the supplementary material. The comprehensive but not exhaustive selection of candidate food production pathways considered in the study is summarized in Figure 1. Then, the values taken from the literature are modified to allow for a fair, systematic comparison on the basis of how many units of electrical energy are required to produce a unit of chemical energy digestible by humans.

Energy conversion efficiency is relevant to all three applications (sustainable food production, space mission, and food resilience). Though it is not the only relevant metric, it is generally the highest contributor to greenhouse gas emissions on Earth and to launch costs in space missions.

Out of the foods found in the literature, those with a power-to-food efficiency potentially higher than 5% are selected for the analysis as high-efficiency food (in terms of electricity to digestible calories). This cutoff is relevant to both food affordability and space applications: it is roughly equal to a cost of just under $5 for fulfilling a person's energy intake of 2,500 kcal/person/day under base case assumptions ($0.06/kWh, $1.9), very close to the value for affording a healthy diet by FAO, at $4.46/person/day[48]; it is also roughly equal to the minimum energy efficiency needed to be able to compete in launch cost with prepackaged food in near-Earth orbit space missions[22,23].

4.2 Energy efficiency of CO_2-based food systems

Only existing technologies are included in the list, for which two values are estimated: a "base case" aiming to represent the current state of the art technology, and an "optimistic case" aiming to represent values that might be reasonably achievable with future development of the technologies involved over the coming decades, with upper bounds chosen below theoretical/thermodynamic maxima. The calculations performed to make the diversity of reported energy use values comparable on a common basis are described in depth in the supplementary spreadsheet and document. To make the comparison as balanced as possible, several variables are identical for the different food production processes. All of the processes—except for artificial light-based plants—require CO_2 capture to obtain a concentrated stream that can be converted to food. This is estimated at 2.17 kWh/kg CO_2, consistent with the capture costs in large-scale direct air CO_2 capture facilities on Earth[49] and CO_2 capture costs in the International Space Station[50]. Many of the processes involve H_2 generation via electrolysis, an energy-intensive step estimated at 49.25 kWh/kg H_2 (80% of thermodynamic efficiency) corresponding to values expected for large-scale electrolyzers in 2030[51] and for the systems in the International Space Station[52]. These two are further specified in Extended data Table 3, and are comparable to the values obtained in state-of-the-art industrial systems[53,54]. Equation 3 summarizes the estimation of energy efficiency for all pathways:

$$\eta_{electricity \to calories} = \frac{E_{food,\,digestible}}{e_{CO2,\,capture} \cdot r_{CO2} + E_{process}} = \frac{\frac{kWh\ digestible}{kg\ product}}{\frac{kWh\ CO2\ capture}{kg\ CO2} \cdot \frac{kg\ CO2}{kg\ product} + \frac{kWh\ process}{kg\ product}} \quad (3)$$

Where: $\eta_{electricity\text{-}calories}$ is the electricity-to-calories conversion efficiency of the power-to-food production pathway, $E_{food,\ digestible}$ is the energy of the food product in terms of digestible energy for the human body (kWh/kg product), $e_{CO_2,\ capture}$ is the energy required for CO_2 capture per unit of CO_2 (kWh/kg CO_2), r_{CO_2} is the amount of CO_2 required to produce one unit of product (kg CO_2/kg product), and $E_{process}$ is the total energy required to process the CO_2 into food per unit of product obtained (kWh/kg product). All values are used on a basis of dry matter. We can break this equation down further into a version specific to the biological SCP processes, where $E_{process}$ is decomposed into: the energy requirement of fermentation $E_{fermentation}$ (kWh fermentation/kg product), the energy requirement of drying E_{drying} (kWh drying/kg product), the specific energy requirement of producing a unit of feedstock $e_{feedstock}$ (kWh/kg feedstock), and the amount of feedstock required to produce one unit of product $r_{feedstock}$ (kg feedstock/kg product). See Equation 4:

$$\eta_{electricity \to calories\ (SCP)} = \frac{E_{food,\,digestible}}{e_{CO2,\,capture} \cdot r_{CO2} + e_{feedstock} \cdot r_{feedstock} + E_{fermentation} + E_{drying}} \quad (4)$$

Extended Data Table 4 summarizes the CO_2 requirements for all processes and scenarios, estimated based on mass balances as per the descriptions in the below subsections and the energy consumption in Extended data Table 3. A summary of the estimated drying requirements per step and production process is given in Extended data Table 5. The full details, including the estimations and sources specific to each process, can be found in the supplementary material, in particular section 2 of the supplementary document and in the supplementary spreadsheet.

The base case for artificial light lettuce was based on a state-of-the-art lettuce vertical farm, requiring 14.8 kWh/kg (wet)[55]. Other values for artificial light were derived from the maximum values of photosynthetic efficiency from sunlight observed for C3 plants of 3.5%[56]. For artificial light microalgae, the base case is based on a state-of-the-art spirulina factory requiring 140 kWh/kg (DM)[57], whereas the optimistic case was derived starting from the theoretical maximum value of sunlight to microalgae biomass of 9%[58].

The electrochemical synthesis of acetate reportedly requires 17.0 kWh/kg acetate[19] for the base case, and for the optimistic case we selected a value of 9.5 kWh/kg acetate from C2 electrolyzer projections[59] as a reasonable ceiling. The values estimated for hybrid inorganic-biological artificial photosynthesis processes using the aforementioned acetate as an intermediate to produce microalgae and yeast were based on recent empirical data reporting yields of 28.3 and 18.9 g biomass/g acetate respectively[19], for the base case. The optimistic case was instead derived from a value of 3.14 g biomass (DM) per electron from electron carriers for aerobic processes[7], as a reasonable ceiling for acetate-based processes.

The energy efficiency of synthetic carbohydrates is taken from a previous analysis of various pathways, resulting in a specific energy use range of 26.0-52.6 kWh/kg[22]. The efficiency of yeast from synthetic carbohydrates is estimated based on those and a well-established biomass yield of 0.51 g yeast/g glucose[60]. The energy efficiency of microbial protein from hydrogen is taken from a previous analysis resulting in a specific energy use range of 33.7–44.2 kWh/kg SCP[23]. For synthetic fats the optimistic case is based on a published estimate of 37.2 kWh/kg fat[1], while the base case was derived using transparent lower bound calculations from basic principles. The energy efficiency of microbial electrosynthesis of acetate is taken from a previous analysis resulting in a specific energy use range of 15.4–25.1 kWh/kg[46].

4.3 Land productivity of CO_2-based food systems

Using the electricity-to-calories efficiency, we can derive the land use of these technologies as well by incorporating the land use of the energy source. We select solar photovoltaic as the energy source, which after including module efficiency, land spacing, panels, dust and debris, and all other inefficiencies, results in a land footprint of ≈0.01 m2-year/kWh for utility-scale PV farms[11,42]. This representative value corresponds to just under 90,000 kcal electricity/m^2·year, which we can simply multiply by the electricity-to-calories efficiency values obtained previously to estimate the food yield per unit of module-occupied land for each pathway in (kcal/m^2/year). The analysis is analogous to Leger et al. 2021[11]. In addition, the optimistic case estimates of land productivity account for projected improvements in PV module efficiency by 2050, going 27% higher from current values[61], which would improve the footprint value to ~110,000 kcal electricity/m^2·year. Then, we add the comparatively very small land use of factory floor, which for this kind of system has been estimated at 0.003 m^2·year/kg product based on representative values of the chemical industry[1].

Finally, using the protein and fat content values of each food source, we can estimate the protein and fat production potential per unit of land, and compare them to a series of representative plant and animal products and their reported land use values. Supplementary Table S2 shows the values for conventional foods—representative of global averages—whereas Supplementary Tables S3 and S4 show the protein and fat production potential per unit of land for the power-to-food systems, for the base case and optimistic case values respectively. By dividing the land use of benchmarks with the land use results for power-to-food systems, we can estimate how much more land-efficient power-to-food systems are than agricultural products, as summarized in Supplementary Tables S5 and S6. For example, H_2SCP provides 13 times as much protein per unit of land as soybeans and 6 times as much food energy per unit of land as conventional wheat, for the base case representing the current state of the technology. Supplementary Figure S9 shows selected comparisons between H_2SCP and synthetic fats (the most land-efficient power-to-food pathways studied in this analysis) and relevant plant- and animal-based agricultural products. Supplementary Figure S9a and S9c compare the food energy supply of each food source, including to plant sources generally considered very high yielding in terms of food energy such as corn, oil palm, and sugar beets. Supplementary Figure S9b compares the protein supply of H_2SCP with the highest protein-yielding crop (soybeans) and animal protein sources.

4.4 Case study: hydrogen oxidizing bacteria versus photosynthesis

The electricity-to-calorie efficiency of HOB SCP has been estimated based on the method described in Alvarado et al. 2021[23] with minimal changes. Additional details are present in the supplementary spreadsheet and document, with Figure S4 showing a flow diagram of the production process. The water electrolysis, CO_2 capture, and drying energy requirements are adjusted upwards, as per the values in Extended Data Tables 3 and 4. The electrolysis energy consumption is the same (49.25 kWh/kg H_2) for the base case and optimistic case, since this value is already reasonably close to the theoretical maximum efficiency for this process (80%). This translates to 22.3 kWh/kg SCP based on a H_2 requirement of 0.45 kg H_2/kg SCP obtained from a model informed by pilot plant data[14].

The CO_2 energy requirement of 2.17 kWh/kg CO_2 used for all pathways[24] multiplied by a 2.4 kg CO_2/kg SCP requirement for HOB translates to 5.2 kWh CO_2 capture/kg HOB SCP. The H_2 and CO_2 mass requirements are the same for the base case and optimistic case. They are considered the lowest reasonable values, since the model considers ~100% gas utilization from continuous recycling of unreacted gas at the bioreactor outlet. Other pathways achieve considerably lower CO_2 gas utilization values, leading to many times higher CO_2 capture energy requirements per unit of product, such as the ~36 kWh CO_2 capture/kg SCP of yeast from synthetic acetate or the ~17 kWh CO_2 capture/kg SCP of yeast from synthetic sugars—see Extended data Table 4 and supplementary spreadsheet.

A fermentation energy requirement range of 1.5–4.5 kWh/kg SCP is used, somewhat higher than for a typical liquid fermentation process to account for the uncertainty of gas fermentation scale-up[23]. Adding the drying requirements from Extended data Table 5—which are more conservative than those of other analyses[14]—the resulting total requirement is 33.7–44.2 kWh/kg SCP. At a digestible energy content of 3,850 kcal/kg (DM) based on compositional data[62] and typical

Atwater factors[63]—4.5 kWh/kg (DM)—the electricity to calories efficiency is 10.1% for the base case and 13.3% for the optimistic case. Combining this 10.1% energy efficiency with ≈0.01 m^2-year/kWh[11,42] results in a land productivity of ~10 kWh food energy/m^2-year, or ~8,700 kcal/m^2-year. This is equivalent to ~2.2 kg SCP/m^2-year, or ~1.5 kg protein/m^2-year at a 65% protein content[14]. We can summarize the electricity-to-calories estimation for the HOB base case as per equation 1 (based on equation 4):

$$\eta_{electricity \to calories\ (SCP)} = \frac{E_{food,\ digestible}}{e_{CO2,\ capture} \cdot r_{CO2} + e_{feedstock} \cdot r_{feedstock} + E_{fermentation} + E_{drying}} =$$

$$= \frac{4.48 \frac{kWh\ digestible}{kg\ product}}{\frac{2.17\ kWh\ CO2\ capture}{kg\ CO2} \cdot \frac{2.41\ kg\ CO2}{kg\ product} + \frac{49.25\ kWh\ H2\ production}{kg\ H2} \cdot \frac{0.45\ kg\ H2}{kg\ product} + \frac{4.5\ kWh\ fermentation}{kg\ product} + \frac{12.1\ kWh\ drying}{kg\ product}} = 10.1\% \qquad (1)$$

Utility-scale solar PV systems overall capture ~4.9% of the sunlight reaching the solar farm area[11], resulting in a sunlight-to-calories efficiency of 0.5-0.7%, about an order of magnitude more efficient than that of wheat, and nearly two orders more than poultry (see Figure 4). To further illustrate the mechanisms behind this difference, we show energy flow diagrams comparing PV-driven H_2SCP versus conventional photosynthetic wheat cultivation in Figure 6 and Extended Data Figure 4. The estimate for wheat is summarized in equation 1, where: $\eta_{\text{PAR in sunlight}}$ refers to the fraction of light reaching a cropfield that is photosynthetically active, $\eta_{\text{PAR absorbed}}$ refers to the fraction of that light which the plants absorb, $\eta_{\text{photosynthesis}}$ refers to the fraction of that light which translates into biomass growth through photosynthesis, η_{grain} refers to the fraction of that biomass that is edible grain, and $\eta_{\text{digestible}}$ refers to the energy content of the grains that humans can digest. There is variation on these factors depending on the exact conditions, but these are illustrative of modern wheat cultivation worldwide. Crop losses to weeds, pests, disasters and other factors are not included. See the supplementary material for full details on this comparison. We can add one more step to represent animal products: chicken converts digestible grain energy into meat calories at an approximate ratio of 1:10[64], resulting in ~0.01% sunlight to food efficiency for poultry meat, as shown in figure S11.

$$\eta_{wheat} = \eta_{PAR\ in\ sunlight} \cdot \eta_{PAR\ absorbed} \cdot \eta_{photosynthesis} \cdot \eta_{grain} \cdot \eta_{digestible}$$
$$= 45\% \cdot 25\% \cdot 3\% \cdot 40\% \cdot 86\% \approx 0.1\% \qquad (2)$$

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Conflict of interest statement

Coauthor N. Lazouski works for Savor Inc., which develops one of the processes analyzed in this study. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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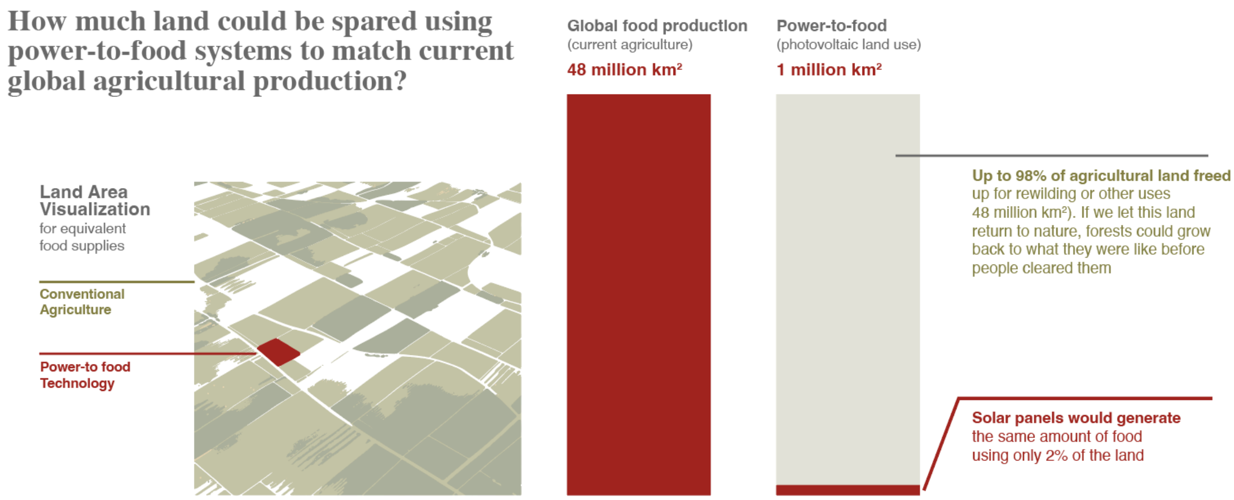
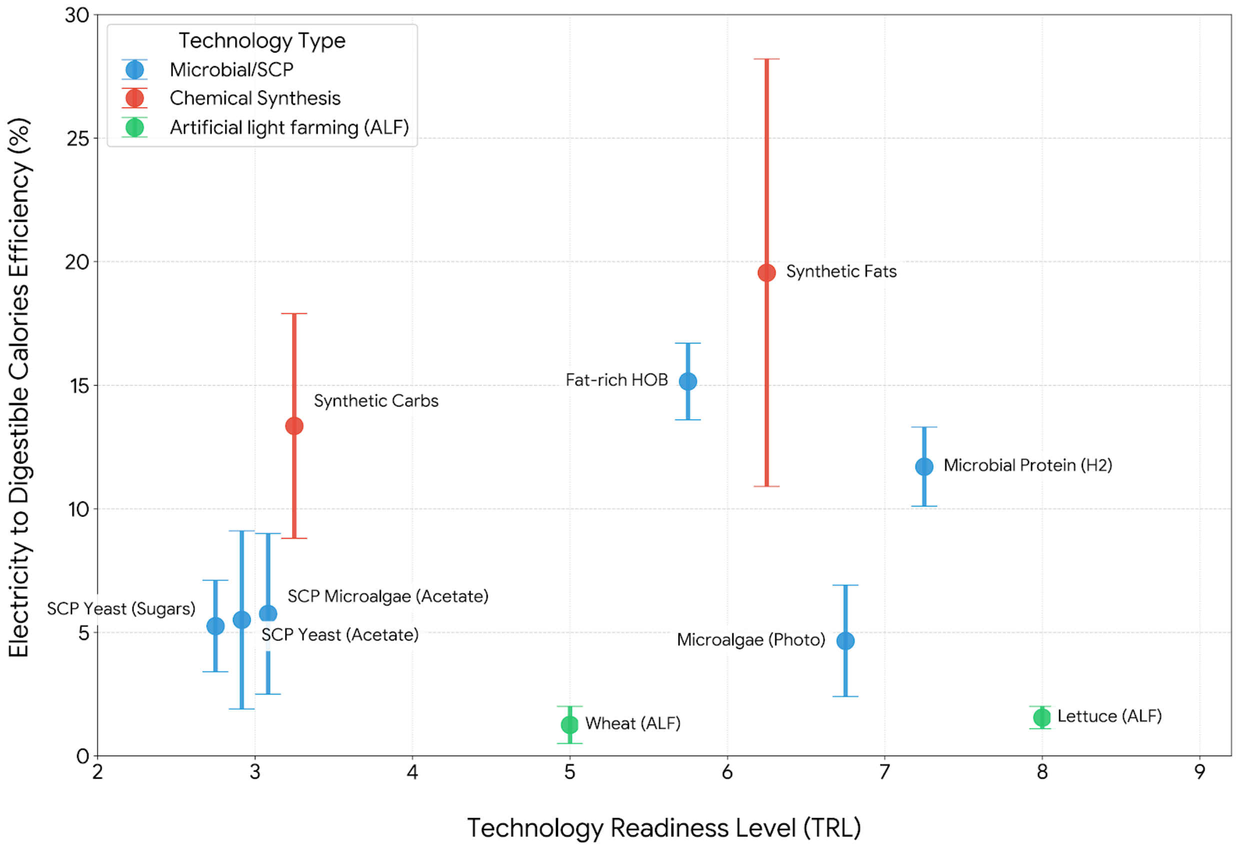
Extended data



***Extended Data Figure 1**. Land productivity of photovoltaic-based power-to-food systems vastly outperforms conventional agricultural production. Even a 10% displacement of global agricultural land use would spare nearly 5 million km^2 of land—an area roughly comparable to the European Union. Details of the analysis can be found in methods and the supplementary material.*

Extended Data Table 1*. Energy consumption of power-to-food pathways included in this work in terms of energy consumed per kg of target product.*

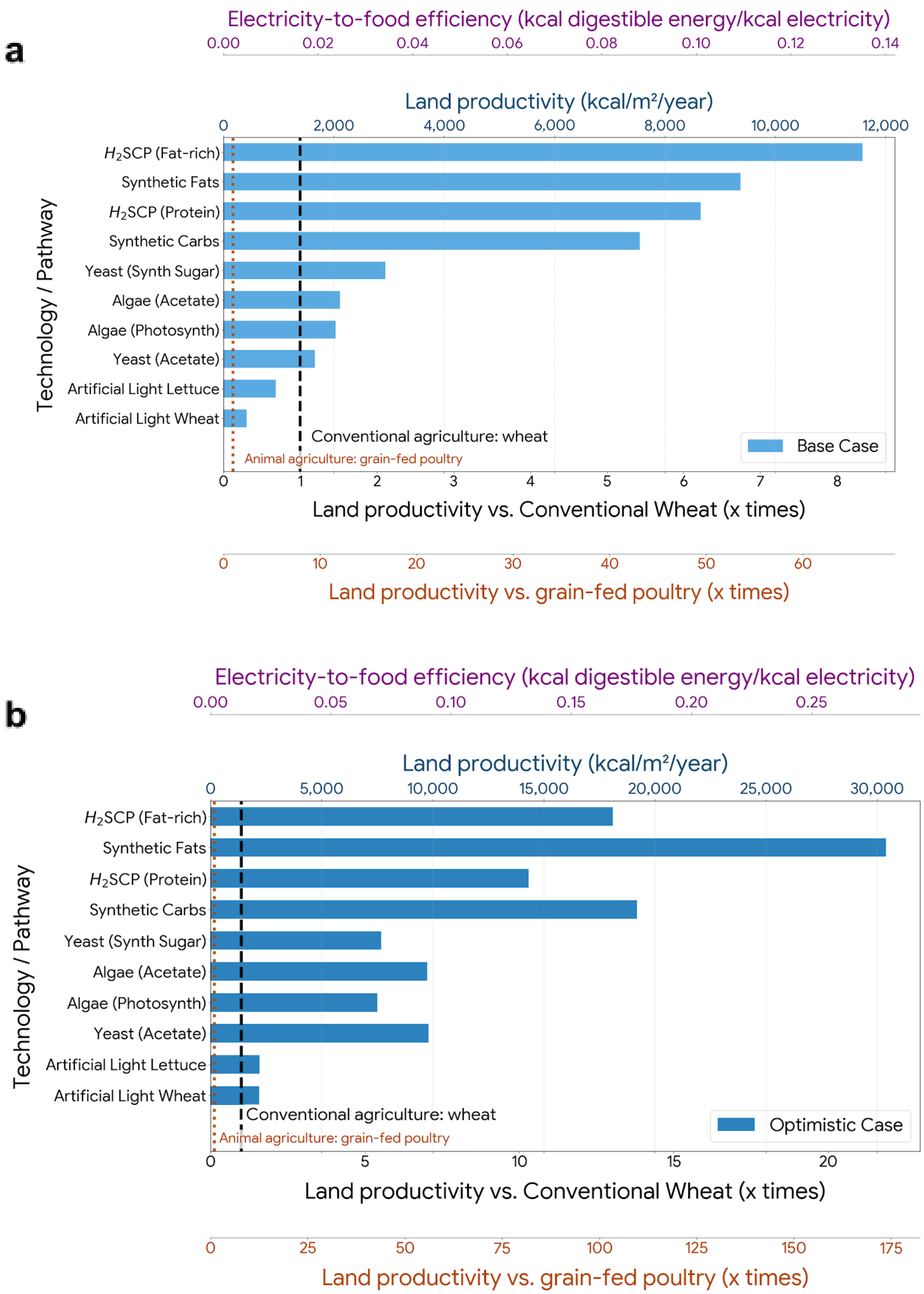
	Energy consumption per unit of food (kWh/kg)	
Food production pathway	Base case	Optimistic case
Artificial light farming (wheat)	901	222
Artificial light farming (lettuce)	328	178
Microalgae SCP via photosynthesis (Spirulina photobioreactor)	154	51
SCP Yeast via artificial sugars	117	56
SCP Yeast via acetate	183	39
SCP Microalgae via acetate	144	39
Microbial protein from hydrogen (H_2SCP)	44	34
Fat-rich engineered H_2SCP (~60% fat)	55	44
Synthetic carbohydrates	53	26
Synthetic fats	96	37
Microbial electrosynthesis of acetate (for comparison)	22	12
Electrochemical synthesis of acetate (for comparison)	31	14



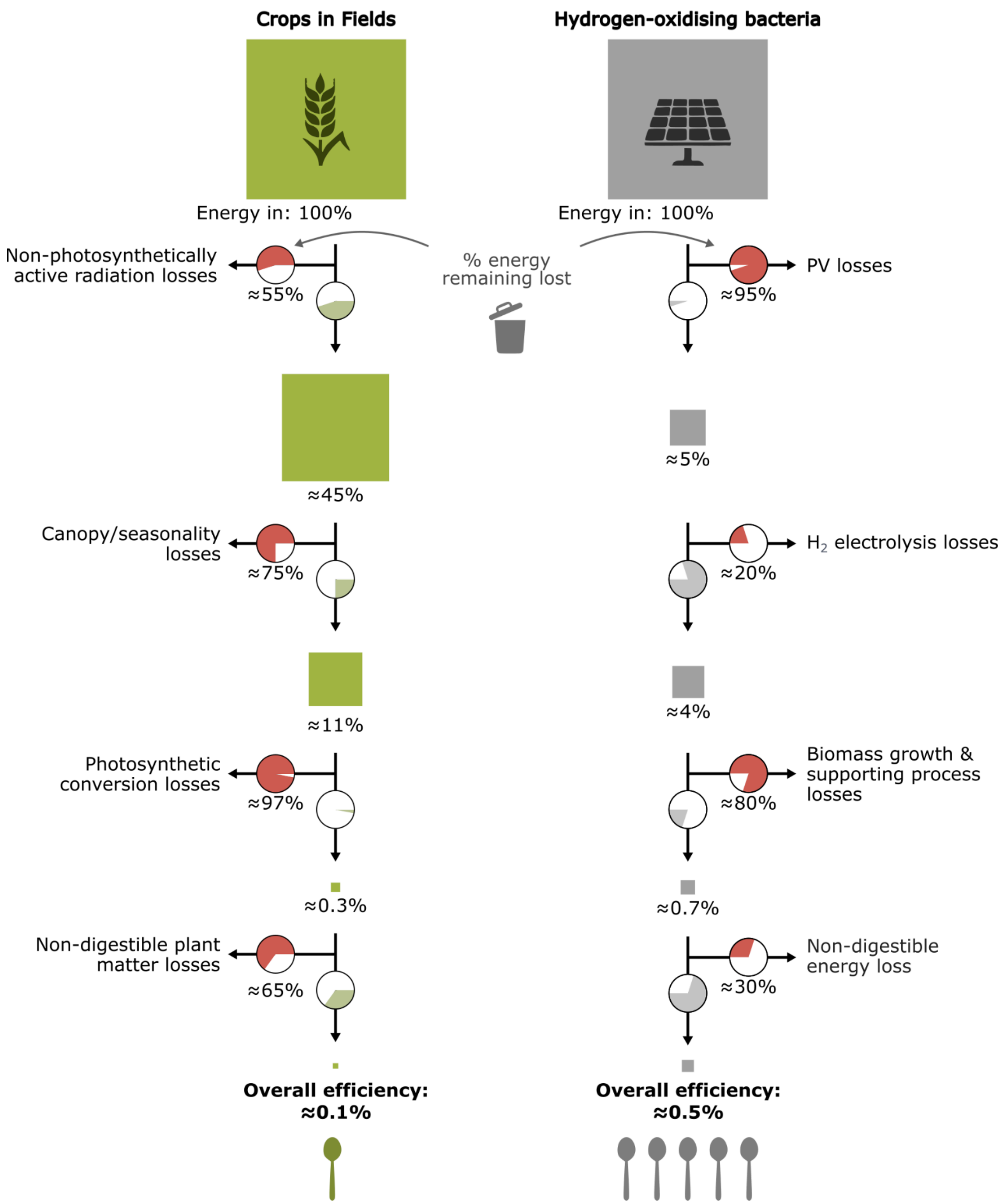
Extended Data Figure 2. *Power-to-food conversion efficiency of existing CO_2-based closed environment food production methods. The lower end of the range ("base case") represents values achievable with current technology based on published systems, while the "optimistic case" represents reasonable upper bounds of the potential of current or conceivable future developments. The "optimistic case" does not represent the maximum possible thermodynamic efficiency of these processes in any case, future developments may exceed the optimistic case value in some cases.*

***Extended Data Table 2**. Comparison between the estimated cost of electricity for CO_2 foods and the wholesale cost of benchmark products of agricultural origin or traditional fermentation. The electricity cost range considered is $0.03 ("Optimistic case") and $0.06/kWh ("Base case"). All benchmarks updated to 2025 USD. Note that benchmark costs do not include supply chain costs, which typically increase retail prices several-fold for foods produced by conventional agriculture.*

Energy efficiency	Base case: current technology	Optimistic case: with future improvements	Actual commodity cost of benchmark product ($/kg food, dry)	Benchmark product
Electricity cost ($ electricity/kg food, dry)	$0.06/kWh	$0.03/kWh		
Artificial light farming (wheat)	$54	$7	$0.2-0.4	Wheat grain (open field, USA)
Artificial light farming (lettuce)	$20	$5	$13-20	Fresh Lettuce Leaf (open field, USA)
Microalgae SCP via photosynthesis (Spirulina photobioreactor)	$9	$2	$4-6	Spirulina (open pond production)
SCP Yeast via artificial sugars	$7	$2	$2-3	Yeast (from agricultural sugar)
SCP Yeast via acetate	$11	$1	$2-3	Yeast (from agricultural sugar)
SCP Microalgae via acetate	$9	$1	$4-6	Spirulina (open pond production)
Microbial protein from hydrogen (H_2SCP)	$3	$1	$5-14 $5-32 $2-9	Whey protein concentrate, USA, 80% (2020-2025) Dried egg yolk, USA (2020-2025) Plant protein isolates
Fat-rich engineered H_2SCP (~60% fat)	$3	$1	$4-7	Butterfat/milkfat, USA (2020-2025)
Synthetic carbohydrates	$3	$1	$0.2-0.6	Table sugar, (2020-2025)
Synthetic fats	$6	$1	$4-7	Butterfat/milkfat, USA (2020-2025)



Extended Data Figure 3. *a) Land productivity (kcal/m^2/year) of power-to-food production pathways driven by solar photovoltaic energy and CO_2 capture—for both current capabilities (base case) and future improvements (optimistic case)—including comparisons to wheat and grain-fed poultry as agricultural benchmarks; b) Land productivity in terms of protein and fat supply per unit of land, comparing power-to-food systems (base case) with the most efficient plant-based and animal-based agricultural benchmarks. All comparisons with agricultural products here are based on current global average land productivity values*[41].



Extended Data Figure 4. *Solar energy use comparison of PV-driven H_2SCP production versus conventional wheat cultivation, focusing on the energy losses between each step. The most inefficient step in photosynthetic production is the conversion of absorbed photons to plant biomass (~3% efficient). In comparison, the most inefficient step in power-to-food systems are the losses involved in obtaining electrical energy from incident photons (~5% efficient). PV-driven SCP systems have significant room for advancement in land productivity by improving the PV electricity generation and biomass growth steps.*

Extended data Table 3. *Energy consumption of carbon capture and hydrogen generation per unit of CO_2 or H_2 mass for all processes.*

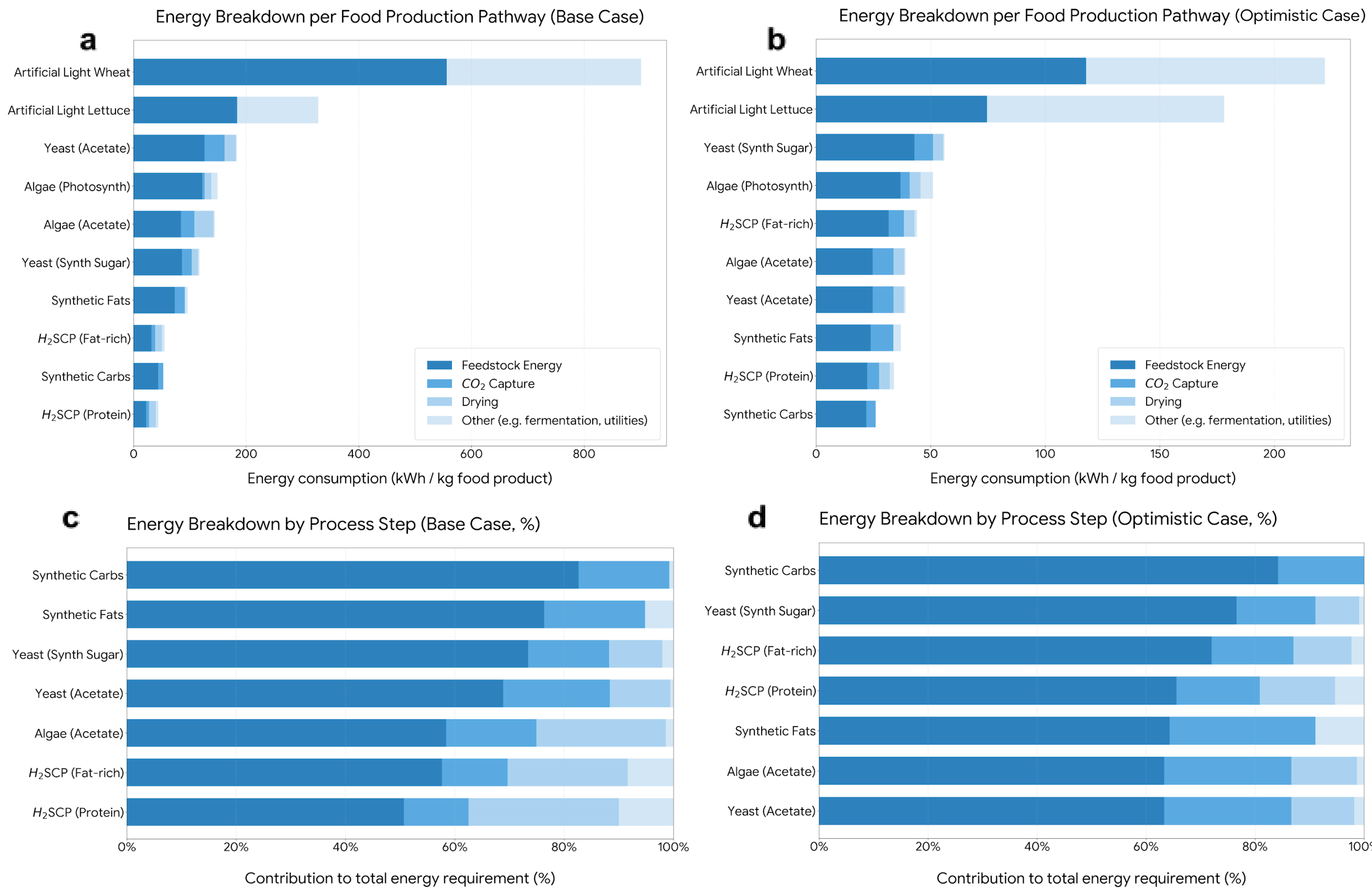
Unit	Thermodynamic energy (kWh/kg product)	Energy efficiency (% of thermodynamic value)	Energy consumption (kWh/kg product)
Electrolysis (H2)	39.4	80%	49.25
CO2 capture	0.13	6%	2.17

Extended data Table 4. *Summary of the CO_2 requirements of all processes, in terms of the units of CO_2 required per unit of food produced and in kWh of CO_2 capture energy per unit of food, for both the base case and optimistic case values. Notes: (*) Assumes unreacted CO_2 in bioreactor outlet can be perfectly recycled with no losses requiring additional capture; (†) Assumes CO_2 conversion byproducts are combusted and recycled, and the recycled CO_2 has to be recaptured at the same original energy cost; (§) Assumes crop growth is performed at ambient CO_2 concentration; (‡) base case assumes recycling of non-wax FT byproducts, while other byproducts are combusted and recycled, and the recycled CO_2 has to be recaptured at the same original energy cost—optimistic case assumes near-total recycling of organic byproducts through additional steps, reducing CO_2 capture requirements. Full details can be found in the supplementary spreadsheet.*

Process	CO2 capture requirement r_{CO_2} (kg CO2/kg food product)		Energy required for CO2 capture E_{CO_2} (kWh/kg food product)	
	Optimistic case	Base case	Optimistic case	Base case
Microalgae SCP via photosynthesis (Spirulina photobioreactor)*	1.9	1.9	4.1	4.1
Microbial protein from hydrogen (H_2SCP)*	2.4	2.4	5.2	5.2
Fat-rich engineered H_2SCP*	3.0	3.0	6.6	6.6
Electrochemical synthesis of acetate (for comparison)†	1.8	3.1	3.9	6.7
SCP Yeast via acetate†	4.2	16.4	9.1	35.7
SCP Microalgae via acetate†	4.2	11.0	9.1	23.8
Synthetic carbohydrates†	1.9	4.1	4.1	8.8
SCP Yeast via artificial sugars†	3.7	8.0	8.1	17.3
Microbial electrosynthesis of acetate (for comparison)*	1.5	1.5	3.4	3.4
Synthetic fats‡	4.5	8.1	9.9	17.7
Artificial light farming§	N/A	N/A	N/A	N/A

Extended data Table 5. *Drying requirements for single cell protein products, given per step and production process. Full details can be found in the supplementary spreadsheet.*

		Fermenter outlet solid concentration (kg dry biomass/kg liquid medium)	Water to be removed (kg water/kg dry biomass)	Centrifugation energy requirement (kWh/kg biomass)	Spray drying energy requirement (kWh/kg biomass)	Total drying requirement (kWh/kg biomass)
H_2SCP	Base case	1%	95	0.8	11.3	12.1
	Optimistic case	3%	29	0.2	4.4	4.7
Microalgae (PBR)	Base case	0.5%	195	1.6	11.3	12.9
	Optimistic case	3%	29	0.2	4.4	4.7
Microalgae (via acetate)	Base case	0.035%	2,853	22.8	11.3	34.1
	Optimistic case	3%	29	0.2	4.4	4.7
Yeast (via acetate)	Base case	0.090%	1,107	8.9	11.3	20.2
	Optimistic case	10%	5	0.0	4.4	4.5
Yeast (via sugar)	Base case	5%	15	0.1	11.3	11.4
	Optimistic case	10%	5	0.0	4.4	4.5



Extended Data Figure 5. *Breakdown of the contributions to the energy requirement of each pathway, distributed among: CO_2 capture, feedstock synthesis, drying, and other. a) Energy breakdown per step (base case, kWh/kg food); a) Energy breakdown per step (optimistic case, kWh/kg food), c) Energy breakdown per step (base case, %); d) Energy breakdown per step (optimistic case, %).*

SUPPLEMENT

CO_2-to-food pathways via synthetic fat and H_2 microbial protein outperform alternatives on energy, cost and land use

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1. Literature review of CO_2-based food systems

Crop production is an important benchmark for comparisons with CO_2 food systems using non-photosynthetic routes, and could be important in space missions for the production of phytonutrients and positive crew morale [1]. However, artificial light-based controlled environment agriculture was previously estimated to have very low energy efficiency, estimated at ~0.4% [1]. Here a range of efficiencies is estimated for two crops with very different suitability to artificial lighting: wheat, which is an agricultural staple but is not typically produced via artificial lighting; and vertically farmed lettuce, which is already being sold. Lettuce is a particularly good fit for production with artificial lighting thanks to its short growth cycle and moderate light requirements which imply a relatively small amount of artificial lighting compared to other plants, as well as a high percentage of edible biomass and favorable market value. On the other hand, vertical farming of wheat has been explored by companies but is not performed at industrial scale due to lower market prices and longer growth cycles, requiring intense lighting over a longer time to support seed production and associated biomass.

Recently developed hybrid inorganic-biological artificial photosynthesis processes using acetate as an intermediate have been used to generate a variety of food products, including microalgae SCP (Chlamydomonas), yeast SCP, mushroom-producing fungus, and even plant crops [2]. We estimated the power-to-food efficiency of this system for the microalgae SCP and the yeast SCP. These systems might be able to obtain the same benefits of crop cultivation with higher efficiency than artificial light photosynthesis, but not enough data were found to test this. A different hybrid inorganic-biological system has biosynthesized glucose and fatty acids via acetate-digesting genetically modified organisms, with self-declared efficiencies of 0.7–1.2% [3].

Microalgae SCP cultivation in artificial light photobioreactors was previously estimated to have an efficiency between 1–9% [4], when comparing current vs expected high-end values. Direct sunlight photosynthesis systems might have the potential to reach higher electricity-to-calories values in space applications, but this remains challenging due to damaging space radiation [5], and may not be efficient due to insufficient photons [1].

Microbial protein from bacteria was included due to high power-to-food conversion efficiency, which was previously estimated at approximately 12-17% for hydrogen oxidizing bacteria (HOB) [4], and others have also estimated high values for a similar process based on methanotrophic bacteria [1]. Genetic modification of these organisms could improve their efficiency, for example companies like Circe are using this to produce fat-rich H_2SCP, which was selected for study in the current work. Another interesting biological route to food production from CO_2 and H_2 is the biosynthesis of amino acids excreted by archaebacteria [6], but not enough data on this route was found to incorporate it into the current study.

The value for synthetic carbohydrates was estimated by the authors to be approximately 10-20% [7], while others have argued it could become even higher [8], [9]. The efficiency of converting these carbohydrates into SCP products of higher nutritional value was also selected for study, using yeast as a reference organism. Air Company has demonstrated the production of yeast via CO_2-derived ethanol [10], using a proprietary CO_2 conversion process [11], but not enough publicly available data were found to make a robust estimation in this study.

Fatty acids can be synthesized nonbiologically from CO_2 via several steps: briefly, CO_2 can be reduced into syngas, then converted into paraffin wax via the Fischer-Tropsch or Ziegler processes, which, followed by paraffin oxidation, results in fatty acids. These free fatty acids can be esterified with glycerol into triglycerides like those found in natural fats. The energy consumption of this process has been estimated at 142 MJ/kg, or a power-to-food efficiency of 26.5% [12].

Microbial electrosynthesis has a high power-to-food efficiency (estimated previously at 15–20% for acetic acid production) [13] but only short chain fatty acids have been produced in significant quantities so far [13], [14]. These are mostly acetic acid, which provides no micronutrients and limited energy, because it is unlikely to be healthy for humans when consumed in quantities large enough to make a meaningful caloric contribution to a diet [15]. There could be potential for future MES technologies to produce more nutritionally valuable molecules such as medium chain and long chain fatty acids [14] or SCP [13]. However, this possibility was not included due to uncertainty in the energy efficiency values and speculative nature of these processes. Acetic acid can also be efficiently produced through non-biological methods [2].

2. Energy efficiency of CO_2-based power-to-food systems

This section describes the calculations done to estimate the electricity-to-calories efficiency of the selected CO_2 to food processes. The full calculations performed to estimate electricity-to-calories values can be reviewed in the supplementary spreadsheet. For the processes in which the CO_2 is converted in one step and no significant volatile byproducts are generated (microalgae and H_2SCP), any unreacted inputs are assumed to be directly recycled with negligible losses—in practice, a small purge (and corresponding makeup CO_2) would probably be needed to remove trace accumulations (e.g., water vapor, inert gases, or minor off-gases), maintain the correct ratios and/or avoid explosive mixtures. For the processes where significant amounts of CO_2 conversion byproducts are obtained, it is assumed that the byproducts are combusted and recycled, and the recycled CO_2 has to be recaptured at the same original energy cost, as in a previous study [7]. In terms of energy consumption this is a conservative simplification, since the mixture obtained from complete combustion would have higher CO_2 concentration than the ambient air in the ship and thus would likely have a lower energy requirement per unit of CO_2 captured. To illustrate: for the base case, this would mean the energetic equivalent in a regular factory of disposing of or selling the byproducts and capturing new CO_2 for food production. In comparison, due to higher mass conversion efficiencies, the optimistic case values have much lower CO_2 mass requirements, leading to low values of total CO_2 energy capture per unit of food, comparable to what would be obtained if recycling the CO_2 from byproducts took no energy.

Finally, the processes involving SCP production includes drying of the final product, for preservation and palatability purposes. A closed loop food system would require some amount of shelf-stable, dry storage of food as a security measure and to deal with maintenance periods. Drying also makes the product easier to store and transport when produced industrially on Earth. The values of efficiency not including drying are given as well since technically the suspension of food in water can also be consumed with limited drying, analogous to a shake or soup (which typically contain around 90% water [16], compared to the 90–99.965% water content of the bioreactor outlets). All SCP drying energy requirements are conservatively estimated for a compact centrifuge (between 0.7 to 8 kWh per m^3 of water removed [17], [18]) and spray drying (1.3–3.2 kWh/kg water [19]) system. More energy-efficient dewatering systems are possible such as membrane-based processes (e.g. rotational sieves, microfiltration, ultrafiltration) but are conservatively not included.

1.1.1 *Artificial light (lettuce)*

Base case: Figure S1 shows a flow diagram of the process. The reported energy consumption on a state-of-the-art lettuce farm based on artificial light was 14.8 kWh/kg (wet), reportedly covering all of the energy use of the production system (lighting, heating, ventilation, pumping, controls) [20]. At a 95.5% water content [21], this is equivalent to 328 kWh/kg dry matter (DM). The reference farm does not report the share of energy consumed in non-lighting applications; a vertical farm industry survey reported an average of 45%, and a study with a comparable setup and reference reported it was 43.9%, so this latter value—144 kWh/kg (DM)—is used as the value for energy use in non-lighting applications. The energy content of lettuce is 140 kcal/kg (wet) [21], equivalent to 3.62 kWh/kg (DM). Therefore the electricity to calories efficiency of the process is 3.62/324 = 1.1%.

The energy required for carbon capture, if any, is assumed to be negligible since it would be a tiny fraction of the total energy, and if the plants shared the same atmosphere as the crew, they would take the CO_2 directly from the air without the need to concentrate it.

Optimistic case: Values of 3.5% have been observed in C3 plants, which is not far from the maximum possible sunlight conversion efficiency (4.6%) for C3 plants like wheat [22], but only during the rapid growth phase—overall they do not typically exceed 1% [23]. Considering that about 50% of sunlight is photosynthetically active radiation (PAR) [24], the corresponding maximum efficiency of PAR to biomass is 7%. Modern LED lamps could reach a higher share of PAR than sunlight, at 90–95% PAR [25], meaning that a light to biomass efficiency of 6.7% would correspond to the maximum observed in C3 plants if this lamp was used, instead of sunlight's 3.5%. State-of-the-art red LED lamps have shown electricity to light conversion, commonly known as wall-plug efficiency, of 81% [26], [27]—at least in special conditions such as low temperatures—resulting in an overall electricity to biomass efficiency of 5.4% (other spectra are needed for good plant growth, but this demonstrates it is plausible). When accounting for the fact that ~90% of the lettuce biomass generated is edible (e.g. the roots are not consumed), the result is a 4.8% overall electricity to digestible biomass efficiency, or 87.5 kWh/kg (DM). For the rest of the energy consumption it is assumed that with future developments it could be reduced to the same value as the average energy use in a typical greenhouse for processes other than lighting, resulting in 5.4 kWh/kg (wet) [28], or 104 kWh/kg (DM). The total consumption of 178 kWh/kg (DM) converts to an electricity to calories efficiency of 3.62/178.3 = 2.0%

In summary, for artificial light lettuce the base case value is 1.1% and the optimistic case is 2.0%.

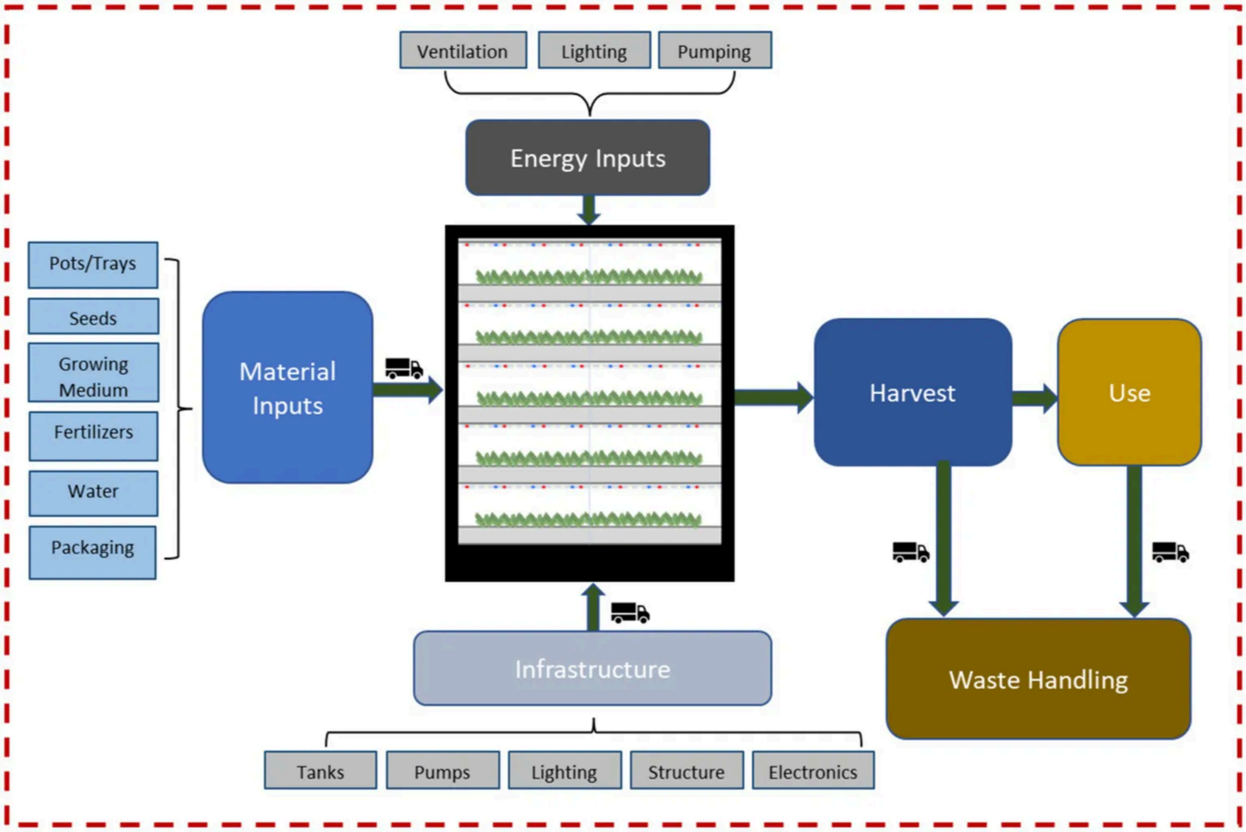

Fig S1. Process flow diagram for artificial light-based vertical farming including inputs and outputs. Material reprinted from: Michael Martin, Maria J. Bustamante, Ilaria Zauli, Francesco Orsini, Environmental life cycle assessment of an on-site modular cabinet vertical farm, Frontiers in Sustainable Food Systems, published 2024 by Frontiers (CC BY 4.0 license, no changes made).

1.1.2 *Artificial light (wheat)*

The values for wheat are estimated analogously to the optimistic case of lettuce described above. The selected values are: 1) a sunlight to biomass conversion efficiency of between 1.9% (mean for wheat) and 3.5% (maximum for C3 nonlegumes observed in special conditions) [22], 2) a PAR value of LEDs between 90–95% [25], and 3) a wall-plug efficiency between 50% [29] and 81% [26], [27]. Putting this together results in a light-to-biomass range of 1.7–5.4%. Out of the biomass obtained, the best wheat cultivars today obtain 47% in the form of grain, while the rest is mostly stems, leaves, roots, and chaff. Breakthroughs to optimize wheat for artificial light farming, such as genetic modification or artificial selection, might push this fraction higher. We consider 70% to be a generous assumption. This lowers the range to 0.2–3.8% light-to-edible-biomass, for a lighting requirement between 118–556 kWh/kg (DM). Adding the additional energy requirements of 104–346 kWh/kg (DM) [28], and comparing to a digestible energy content of 3,821 kcal/kg (dry) [30]—4.44 kWh/kg—results in an electricity to calories efficiency of 0.5–2.0%.

Note that the indigestible parts of the plant (e.g. leaves, stems, roots) can also be converted into food through enzymatic or thermochemical processes [31], but this was not included in the analysis.

1.1.3 Microalgae SCP via photosynthesis (Spirulina photobioreactor)

Figure S2 shows a flow diagram of the process. In the base case, the reported energy consumption on a state-of-the-art spirulina factory based on artificial light was 140 kWh/kg (DM), of which 122 is lighting electricity, 6 is from pumps (used in both cultivation and downstream processing), 8 from blowers, and 3.7 from harvesters, water treatment, pasteurization and packaging [29]. The base case process considered here calculates downstream processing differently as per the drying energy in Extended Data Table 5, but includes this energy requirement value from lighting and blowers, and assumes that half the energy from pumps is applied upstream for cultivation, for a total 133 kWh/kg [29]. After adding drying and CO_2 capture costs (see Extended Data Table 4) this results in 150 kWh/kg (DM). At a digestible energy content of 3,042 kcal/kg (DM) [32]—3.54 kWh/kg—the resulting electricity to calories efficiency is 3.54/150 = 2.4%.

The optimistic case is estimated analogously to the artificial light crops. In this case we start with a value of PAR to biomass of 12.5% [33], not far from the theoretical maximum of ~19%. This is one of the highest values reported for cyanobacteria, in carefully controlled lab conditions. Then from a 95% PAR from LEDs and a wall-plug efficiency of 81%, an overall electricity to biomass efficiency of 9.6% results, corresponding to a lighting electricity requirement of 36.8 kWh/kg (DM). We then assume that the energy consumption of the rest of the steps to obtain edible spirulina biomass can be halved (pumps, blowers,) from 11.0 kWh/kg (DM) to 5.5 kWh/kg (DM). After adding the drying and CO_2 capture energy (see Extended Data Table 5) the total energy is 51.0 kWh/kg (DM), corresponding to 6.9% electricity to calories efficiency.

In summary, the electricity to calories efficiency of microalgae (via artificial photosynthesis) is estimated to be 2.4% for the base case and 6.9% for the optimistic case. If drying were not required, the corresponding values would be 2.6%–7.6%.

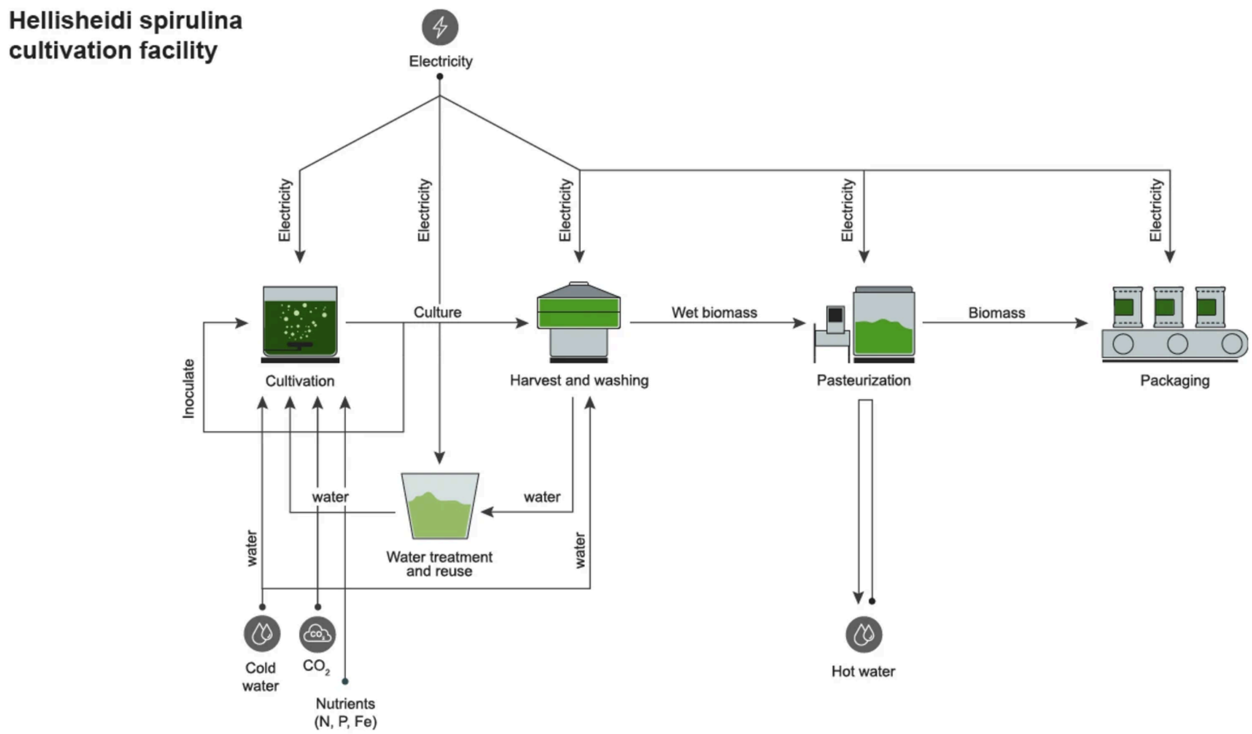

Fig. S2. Process flow diagram for photobioreactor-based Spirulina production including inputs and outputs. Material reprinted from: Asaf Tzachor, Asger Smidt-Jensen, Alfons Ramel & Margrét Geirsdóttir, Environmental Impacts of Large-Scale Spirulina (Arthrospira platensis) Production in Hellisheidi Geothermal Park Iceland: Life Cycle Assessment, Marine Biotechnology, published 2022 by Springer Nature (CC BY 4.0 license, no changes made).

1.1.4 Microalgae SCP via acetate

Figure S3 shows a block diagram of the process. Hann et al. [2] reported the energy consumption of producing microalgae, yeast, and certain crops using acetate instead of CO_2 as the carbon source. The first step is converting the CO_2 to acetate, which can be done at an energy cost of 14.4–30.5 kWh/kg acetate, including the cost of capturing CO_2 (see section on *Electrochemical synthesis of acetate*).

Base case: The biomass yield of microalgae from acetate was reported at 23.81% [2], which at 30.5 kWh/kg acetate implies a need of 107.9 kWh of electricity to produce the acetate required to obtain a kg of dry microalgae biomass. Incorporating a conservative fermentation energy requirement (e.g. pumping and mixing) of 1.5 kWh/kg (DM) [34] and the drying requirement (see Extended data Table 5), the resulting overall requirement is 143.5 kWh/kg (DM). At a digestible energy content of 3,042 kcal/kg (DM) [32]—3.54 kWh/kg—the resulting electricity to calories efficiency is 3.54/143.5 = 2.5%.

Optimistic case: the maximum reasonable yield of biomass from acetate is estimated at 42.5% based on a relatively efficient value of biomass growth yield per electron of 3.14 g biomass per mole of electrons for aerobic processes like this one [35], [36]. Acetate can be a source of up to 8 electrons when oxidized to CO_2, and furthermore has a molar mass of 59.0 g/mol, this results in 8*3.14/59.0 = 0.425 g biomass/g acetate. Coupled with the aforementioned 14.4 kWh/kg acetate, the energy requirement of the electrochemical acetate production is 33.8 kWh/kg biomass (DM). Finally, we add a more optimistic requirement for the fermentation process of 0.8 kWh/kg [34] and the CO_2 capture requirement (see Extended data Table 4) to obtain an overall energy requirement of 39.2 kWh/kg microalgae (DM), or 9.0% electricity to calories efficiency. Note that the high selectivity implicit in the optimistic case acetate synthesis results in efficiency values similar to what would be obtained if system byproducts (ethylene, propionate, and alcohols) were used as carbon sources for SCP as well.

In summary, the electricity to calories efficiency of microalgae (via nonbiologically electrosynthesized acetate) is estimated to be 2.5% for the base case and 9.0% for the optimistic case. If drying was not required, the corresponding values would be 3.2%–10.2%.

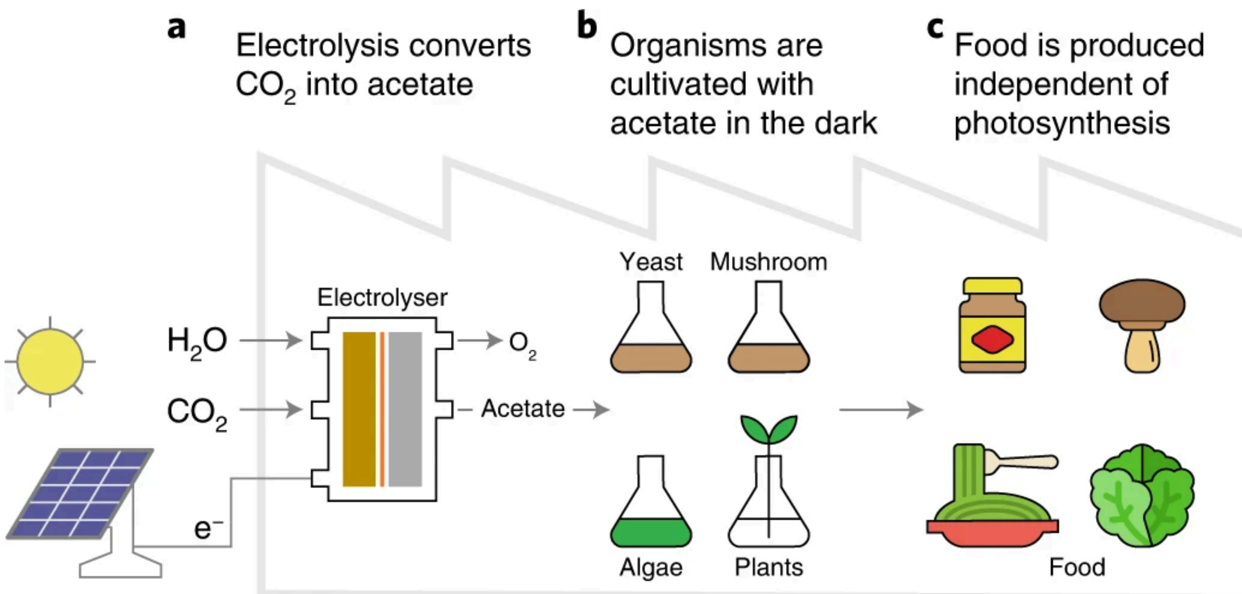

Fig. S3. Simple block flow diagram for food production using electrochemical synthesis of acetate as an intermediate. Material reprinted from: Elizabeth C. Hann, Sean Overa, Marcus Harland-Dunaway, Andrés F. Narvaez, Dang N. Le, Martha L. Orozco-Cárdenas, Feng Jiao & Robert E. Jinkerson, [A hybrid inorganic–biological artificial photosynthesis system for energy-efficient food production](), Nature Food, published 2022 by Springer Nature (CC BY 4.0 license, no changes made).

1.1.5 *Nutritional yeast SCP via acetate*

The energy use for production of yeast obtained via nonbiologically electrosynthesized acetate is estimated analogously to that of the microalgae in the previous section. Starting from acetate to yeast biomass values between 18.89% (as reported by Hann et al. [2]) and 42.5%, the requirement is 33.8–161.7 kWh electricity/kg yeast biomass (DM). After adding the 0.8–1.5 kWh fermentation energy requirements and the drying energy (see Extended data Table 5), the resulting total energy requirements are 39.0–183.4 kWh electricity/kg yeast (DM). At a digestible energy content of 3,430 kcal/kg (DM) [37]—4 kWh/kg—the resulting electricity to calories efficiency is 1.9% for the base case and 9.1% for the optimistic case. Disregarding the drying energy, the corresponding values would be 2.2%–10.2%.

1.1.6 Nutritional yeast SCP via synthetic carbohydrates

Carbohydrates such as sugars are a more traditional feedstock for biomass production in industry, allowing for the production of more nutritionally rich foods than plain sugar. In this case, synthetic carbohydrates are considered as the feedstock, in order to allow for in-situ production of SCP biomass from CO_2. The energy cost of glucose production from CO_2 is estimated as 52.6 kWh/kg glucose for the base case and 26.0 for the high efficiency end, including the cost of capturing CO_2 (see section on *synthetic carbohydrate synthesis*). The expected biomass yield from glucose is 51%, which although very close to the theoretical maximum has been demonstrated empirically and obtained in industrial scale operation, as it is one of the most developed bioprocesses in industry [2], [38]. Thus, it is considered both achievable and hard to improve upon, and is used here for both the base case and optimistic case estimates. The resulting energy cost of glucose production from CO_2 per unit of SCP is 51–104 kWh/kg yeast (DM). After adding the 0.8–1.5 kWh fermentation energy requirements and the drying energy (see Extended data Table 5), the resulting total energy requirements are 56–117 kWh/kg yeast (DM). Considering a digestible energy content of yeast of 4 kWh/kg, this makes for an electricity to calories efficiency range of 3.4–7.1%, or 3.8–7.7% without drying.

1.1.7 Microbial protein from hydrogen (H_2SCP)

Figure S4 shows a flow diagram of the process. The energy efficiency of H_2SCP, in particular HOB SCP, has been estimated based on the method described in Alvarado et al. 2021 [4] with minimal changes. The water electrolysis, CO_2 capture, and drying energy requirements are adjusted upwards, as per the values in Tables 1 and 3. The electrolysis energy consumption is the same (49.25 kWh/kg H_2) for the base case and optimistic case, since this value is already reasonably close to the theoretical maximum efficiency for this process (80%). This translates to 22.3 kWh/kg SCP based on a H_2 requirement of 0.45 kg H_2/kg SCP obtained from a model informed by pilot plant data [39]. The CO_2 requirement of 2.4 kg CO_2/kg SCP [40] translates to 5.2 kWh/kg SCP based on Extended data Table 4. The H_2 and CO_2 mass requirements are the same for the base case and optimistic case. They are considered the lowest reasonable values, since the model considers 100% gas utilization from continuous recycling of unused gas at the bioreactor outlet. A fermentation energy requirement range of 1.5–4.5 kWh/kg SCP is used, somewhat higher than for the liquid fermentation processes to account for the uncertainty of gas fermentation scale-up [4]. Adding the drying requirements from Extended data Table 5, the resulting total requirement is 33.7–44.2 kWh/kg SCP. At a digestible energy content of 3,850 kcal/kg (DM) based on compositional data [41] and typical Atwater factors [42]—4.5 kWh/kg—the electricity to calories efficiency is 10.1% for the base case and 13.3% for the optimistic case, or 14.0–15.4% if drying is not included.

Genetically engineered HOB can achieve higher energy efficiency values by increasing the fat content. An HOB containing 60% fat (comparable to oleaginous yeasts [43]) would make for an estimated energy content of 640 kcal per 100 grams (7.44 kWh/kg SCP). Since fats have a higher content of hydrogen than other components of the cell, the hydrogen and carbon requirements per unit product of the process is necessarily higher, around 37% more than the previously discussed HOB (see supplementary spreadsheet) for hydrogen, or 31.7 kWh/kg HOB, as well as 6.6 kWh/kg HOB for carbon capture (up 25%). All else equal, a simple extrapolation based on these values results in an overall energy requirement of 44.4–54.9 kWh/kg SCP, or 13.6–16.7% electricity to calories. Despite the higher energy requirement compared to normal protein-rich HOB, the efficiency is higher thanks to the higher dietary energy content of fats compared to proteins.

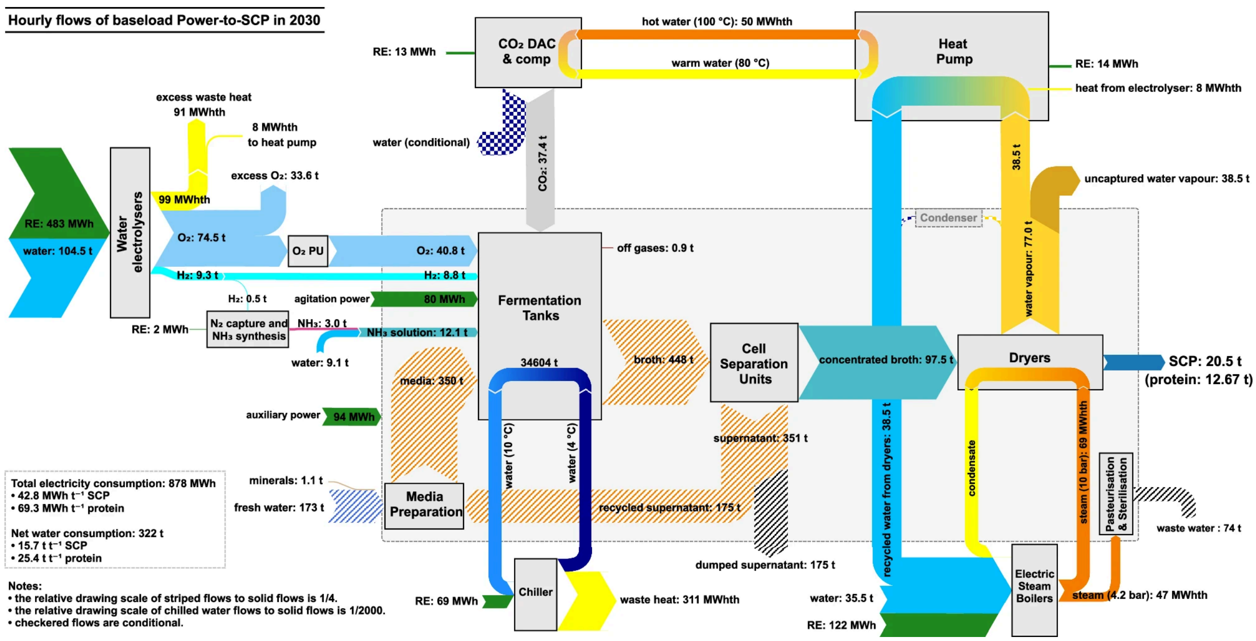

Fig. S4. Power-to-SCP flow diagram for a proposed full-scale e-SCP plant in 2030, including mass flows. Material reprinted from: Mahdi Fasihi, Fatemeh Jouzi, Petri Tervasmäki, Pasi Vainikka & Christian Breyer, [Global potential of sustainable single-cell protein based on variable renewable electricity](), Nature Communications, published 2025 by Springer Nature (CC BY 4.0 license, no changes made).

1.1.8 Carbohydrate synthesis

The energy efficiency of synthetic carbohydrates has been estimated based on the method described in García Martínez et al. 2021 [7] with minimal changes, only the CO_2 capture has been increased as per Extended data Table 4 to an energy requirement of 2.17 kWh/kg CO_2.

Base case: Figure S5 (route C) shows a flow diagram representative of the process steps. The synthesis route of CO_2 to glycerol is selected as the base case representative of synthetic carbohydrate synthesis. It can be achieved at a 35% carbon yield based on established technologies, resulting in a CO_2 capture requirement of 4.1 kg CO_2/kg glycerol, or 8.8 kWh/kg glycerol in terms of energy. Then we add the value of energy required for each step to convert the captured CO_2 to glycerol, for a total of 52.6 kWh/kg glycerol (of which: 20.7 from converting CO_2 to formic acid, 5.3 from converting that to formaldehyde, and 17.8 to convert that to glycerol) [7]. At an energy content of 4.31 kcal/g [44]—5 kWh/kg—the corresponding electricity to calories efficiency is 8.8%.

Optimistic case: Figure S5 (route A) shows a flow diagram representative of the process steps. The selective synthesis route of CO_2 to digestible sugars, as achieved by Air Company [7], is selected as the optimistic case representative of synthetic carbohydrate synthesis. A carbon yield of 77% is proposed as a reasonable optimistic case potentially achievable in future developments [7], resulting in a CO_2 capture requirement of 1.9 kg CO_2/kg sugar, or 4.1 kWh/kg sugar in terms of energy. Then we add the value of energy required for each step to convert the captured CO_2 to glycerol, for a total of 26.0 kWh/kg sugar (of which: 10.8 from converting CO_2 to formic acid, 4.3 from converting that to formaldehyde, and 6.8 to convert that to sugar) [7]. At an energy content of 4 kcal/g [44]—4.7 kWh/kg—the corresponding electricity to calories efficiency is 17.9%.

The overall energy efficiency is thus estimated here at 8.8–17.9%. It is worth noting that the theoretical limit of efficiency is closer to 31–73% [8].

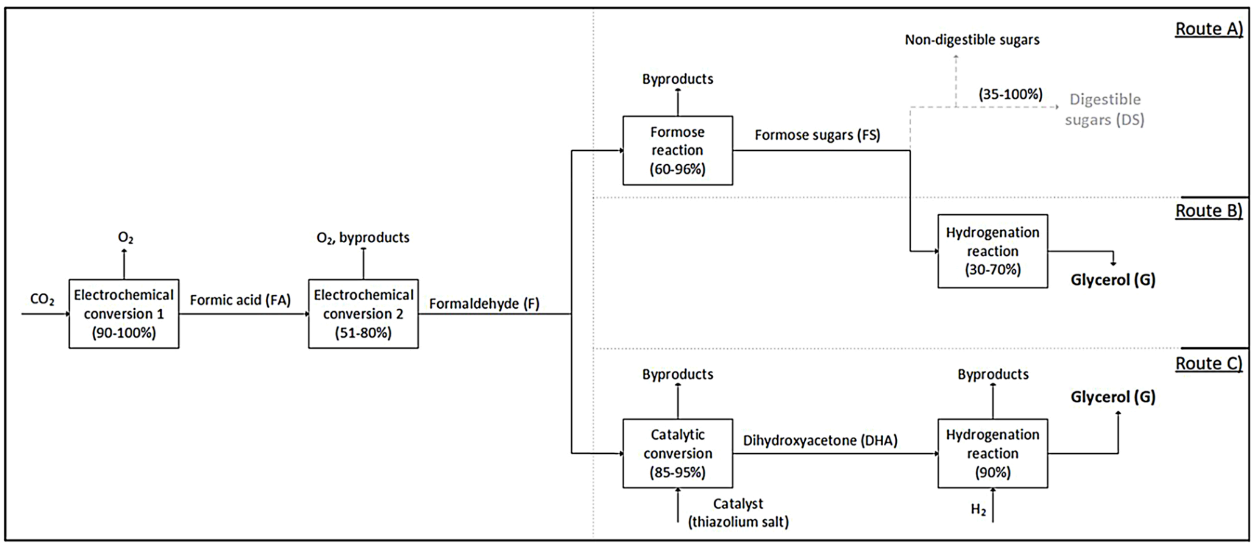

Fig. S5. Simplified block diagram of the proposed NBS routes for food production from CO_2. Separation steps, recycles and reaction media are not shown. The percentage values inside the blocks express the expected carbon yields. The bolded words indicate target food products. The dashed grey lines represent currently unproven process steps. Material reprinted from: Juan B. García Martínez, Kyle A. Alvarado, Xenia Christodoulou, David C. Denkenberger, [Chemical synthesis of food from CO_2 for space missions and food resilience](), Journal of CO_2 Utilization, published 2021 by Elsevier (reprinted with permission, no changes made).

1.1.9 *Chemical fat synthesis*

Base case: The first step of this process is converting CO_2 and H_2 to syngas (~90% overall carbon yield [45]). This is then converted to hydrocarbons through the Fischer-Tropsch (FT) process, at a corresponding 3.50 kg CO_2/kg FT products (the latter represented as CH_2) as per equation 1 and the abovementioned yield. However, not all FT products are wax; a pilot system optimized for wax production obtains about 35% of the FT products as paraffin wax [46] (see supplementary spreadsheet). Then, the FT products which are not suitable for fat synthesis (C1-C19 hydrocarbons) can be partially oxidized back to CO and H_2, and recycled to the FT reactor, pushing the overall yield significantly—only 10% is assumed to be lost due to recycling inefficiencies, for an overall 90% FT mass yield of FT product obtained as C20+ paraffins. The overall chemical equation 2 is then proposed to describe the CO_2 to paraffins process instead, obtained by combining the stoichiometry of CO_2 to FT products (represented by equation 2) with a conservatively high H_2 makeup of 1 unit per unit of input CO_2 to account for recycling.

$$n{\cdot}CO_2 \; + \; 3n{\cdot}H_2 \; -> \; (CH_2){\cdot}n \; + \; 2n{\cdot}H_2O \qquad (1)$$

$$n{\cdot}CO_2 \; + \; 4n{\cdot}H_2 \; + \; 1/2O2 \; -> \; (CH_2){\cdot}n \; + \; 3n{\cdot}H_2O \qquad (2)$$

Using proven technologies, the paraffin wax can be converted to fatty acids at a mass yield of 80%, and of those 63% can be obtained as a fraction of the target fatty acids most relevant for food use, which can be esterified into triglycerides at a mass yield of 95% [47]. All together, the CO_2 requirement is 8.1 kg CO_2/kg triglyceride (34% of the stoichiometric theoretical minimum even with FT byproduct recycling), and the energy required to capture that CO_2 is 17.7 kWh/kg fat (Extended data Table 4). However, the most energy consuming part is H_2 generation, which based on a 0.43 kg H_2/kg fat minimum stoichiometric requirement and assuming the same conversion yields for H_2 as for CO_2, we can roughly estimate a requirement of 1.49 kg H_2/kg fat (95.7 kWh/kg fat). For simplicity, the final values assume that either the free fatty acids are consumed directly or the glycerol needed for esterifying them into triglycerides is produced at the same value of electricity-to-calories efficiency. At an energy content of 9 kcal/g [44]—10.5 kWh/kg—the corresponding electricity to calories efficiency is 10.9%. Figure S6 shows a process flow diagram of the process (except for CO_2 to wax).

Optimistic case: The optimistic case value is based on the model of Davis et al. [12], whose results translate to a 26.7% electricity to calories efficiency (see supplementary spreadsheet). They projected a CO_2 requirement as low as 4.55 kg CO_2/kg fat was feasible (corresponding to 60% yield compared to the minimum stoichiometric value of 2.75 kg CO_2/kg fat based on palmitic acid), which results in a CO_2 capture requirement of 9.9 kWh/kg fat as per Extended data Table 4. Note that these high yields would require recycling of byproducts, such as non-wax Fischer-Tropsch byproducts and low-quality fatty acids back to the FT chain growth step, through conversion processes such as partial oxidation, cracking, hydrotreating, and/or reforming. Further, they estimated a H_2 energy requirement of 83 MJ/kg fat at an energy cost of 171.4 MJ/kg H_2, implying a requirement of 0.48 kg H_2/kg fat (just over the minimum stoichiometric value of 0.38 kg H_2/kg fat based on palmitic acid), which updated to the H_2 requirement of Extended data Table 3 results in 23.8 kWh/kg fat. Finally, the utilities required could potentially be brought down from the original 4.7 kWh/kg fat to 3.4 kWh/kg fat[1]. The resulting total is 37.2 kWh/kg fat for an electricity to calories efficiency of 28.2%—just slightly higher than Davis et al. estimated. Comparing this to the base case shows how large of a difference byproduct recycling would make in this process.

The overall energy efficiency is thus estimated here at around 10.9–28.2%.

[1] Personal communication with Kathleen Alexander from Savor (a company developing edible fats from CO_2), regarding the 4.7 kWh/kg fat value: "30+% of this energy is for a distillation system to separate all the fatty acids into different cuts; you could neglect about 90% of this if you don't need premium fats", therefore by subtracting 30% of 90% of the total, the value can be brought down to 4.7*(1-30%*90%)=3.4 kWh/kg AA.

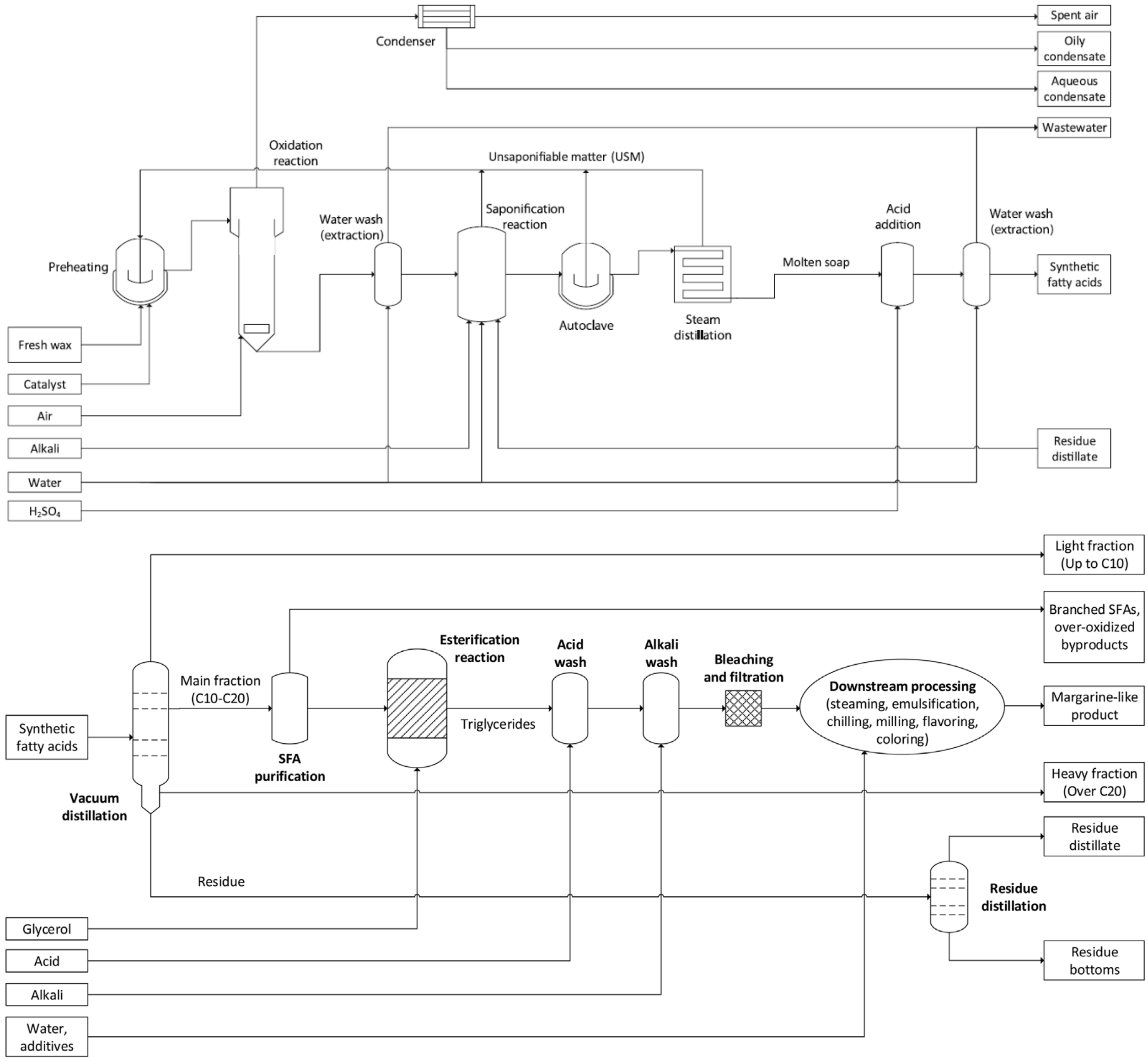

Fig. S6. Process flow diagram of the synthetic fat production process from paraffin wax; the process for converting CO_2 to wax is not shown here. Material reprinted from: Juan B. García Martínez, Kyle A. Alvarado, David C. Denkenberger, Synthetic fat from petroleum as a resilient food for global catastrophes: Preliminary techno-economic assessment and technology roadmap, Chemical Engineering Research and Design, published 2022 by Elsevier (reprinted with permission, no changes made).

1.1.10 *Electrochemical synthesis of acetate*

Figure S7 shows a process flow diagram of the process. Hann et al. [2] reported an energy requirement of 61.36 kJ/g C2 products to synthesize acetate from CO_2 gas at 0.716 g acetate/g C2, resulting in 85.7 kJ/g acetate or 23.8 kWh/kg acetate (we explicitly allocate all energy use to acetate and consider the rest as waste). For the optimistic case value, it is considered that this electrochemical process could reach a thermodynamic energy efficiency of 39%, based on 2050 projections for another challenging C2 molecule, ethylene [48]. This combined with a higher selectivity to acetate (0.9 g acetate/g C2) reduces the energy requirement of acetate synthesis to 34 kJ/g acetate. This would result in an electrochemical conversion step requirement of 10.5 kWh/kg acetate. The energy cost of the potassium salt scrubbing step is assumed negligible.

The carbon selectivity of CO_2 to acetate was reported as 57% [2], and for the optimistic case it is estimated that 90% selectivity is achievable. The alcohol byproducts and propionate generated on the side could in theory be converted into food as well through different processes, but here they are not, for comparison. Instead, they are assumed to undergo complete combustion, with the resulting CO_2 having to be recaptured at the same cost as it was originally captured, and recycled back to the CO_2 electrolyzer. The overall carbon conversion efficiency is reported as 90.5% [2], and for the optimistic case 100% conversion is assumed, by assuming that in an improved version of the system the CO_2 is fully converted or does not need to be scrubbed to be recycled. From these values we obtain a carbon yield of CO_2 to acetate between 51.6–90.0%, resulting in a CO_2 requirement of 1.78–3.10 kg CO_2/kg acetate.

In summary, the energy requirement of capturing the necessary CO_2 to generate this acetate as per Extended data Table 4 is between 3.9–6.7 kWh/kg acetate, making for a total energy between 14.4–30.5 kWh/kg acetate. Since acetate contains 3.49 kcal/g (4.1 kWh/kg) [44], the result is an electricity to calories efficiency of CO_2 to acetate between 13.3–28.3%. Drying is not necessary for human consumption, since the acetate solution is obtained at a concentration of 0.75 M, which is equivalent to an acetic acid solution of 4.5% acetic acid in water, a common concentration for table vinegar.

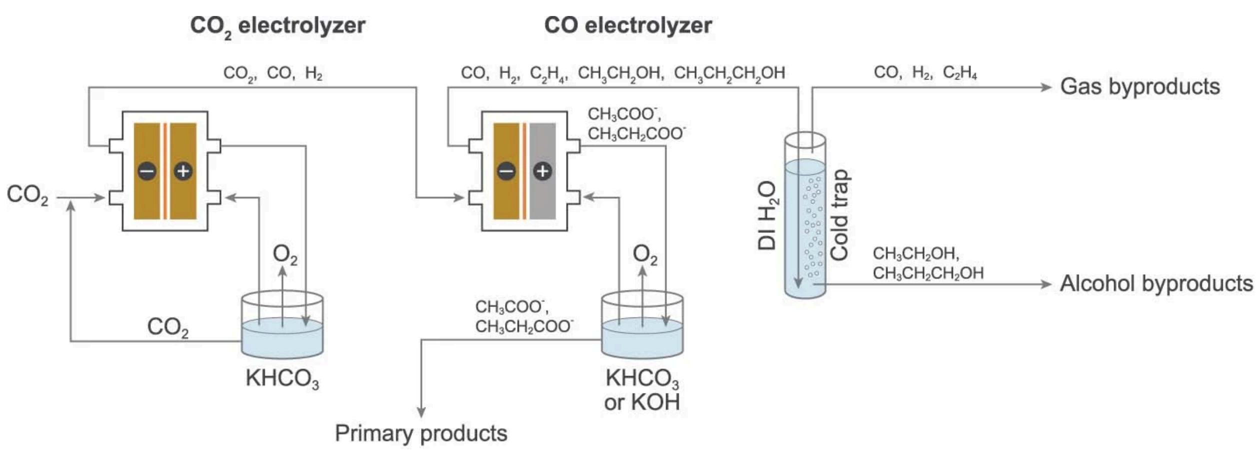

Fig. S7. Process flow diagram for electrochemical synthesis of acetate including inputs and outputs. Material reprinted from: Elizabeth C. Hann, Sean Overa, Marcus Harland-Dunaway, Andrés F. Narvaez, Dang N. Le, Martha L. Orozco-Cárdenas, Feng Jiao & Robert E. Jinkerson, A hybrid inorganic–biological artificial photosynthesis system for energy-efficient food production, Nature Food, published 2022 by Springer Nature (CC BY 4.0 license, no changes made).

1.1.11 *Microbial electrosynthesis of acetate*

Figure S8 shows a process flow diagram of the process. The energy efficiency of microbial electrosynthesis of acetate has been estimated based on the method described in Alvarado et al.

2023 [13] with minimal changes, only the CO_2 capture has been increased as per Extended data Table 4 to an energy requirement of 3.4 kWh/kg AA, and the acetate concentration is not considered necessary (the minimum expected outlet concentration is 1.8% [49], not far from vinegar's 4–6%). The range of coulombic efficiency considered is 50–90% [13], resulting in an energy requirement for the acetate bioelectrosynthesis step of 21.7 kWh/kg AA for the base case and 12.1 kWh/kg AA for the optimistic case. The corresponding total energy consumption is 15.4–25.1 kWh/kg AA, resulting in an electricity to calories efficiency of 16.2% for the base case and 26.3% for the optimistic case.

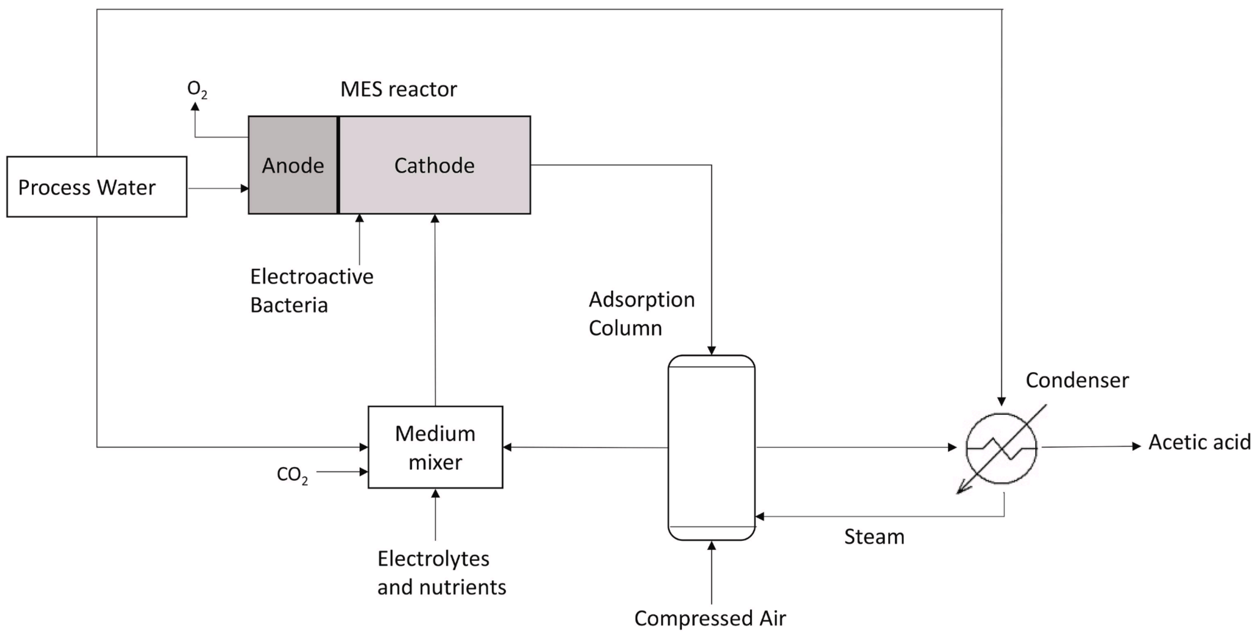

Fig. S8. Process flow diagram for microbial electrosynthesis of acetic acid. Material reprinted from: Juan B. García Martínez, Michael M. Brown, Xenia Christodoulou, Kyle A. Alvarado, David C. Denkenberger, Potential of microbial electrosynthesis for contributing to food production using CO_2 during global agriculture-inhibiting disasters, Cleaner Engineering and Technology, published 2021 by Elsevier (CC BY 4.0 license, no changes made).

3. Energy efficiency estimation: comparison with literature and key uncertainties

The optimistic case efficiency of microalgae is derived from an electricity-to-light-to-biomass value of 13.9%, whereas the photosynthetic conversion efficiency of a microalgae bioreactor using sunlight is typically considered to have a theoretical limit of 12.6% (current photobioreactors often operate between 1-3%) [50]. The difference stems from the photosynthetically active radiation (PAR) value proposed for the LEDs at 95%, whereas the photosynthetic conversion efficiency is limited by natural sunlight, where only ~50% of the spectrum is usable. The corresponding power-to-food value of 8.9% is not far from the maximum achievable for microalgae photosynthesis, assuming no fundamental genetic modification breakthroughs on the organism's biological ATP/NADPH synthesis and carbon fixation systems. One interesting implication is that photosynthetic systems cannot surpass the power-to-food efficiency of H_2SCP without fundamental breakthroughs. The base case energy consumption is almost identical to that estimated by a pilot plant-informed model, at ~46 kWh/kg [39].

Current systems for artificial light vertical farming of lettuce have reportedly achieved energy consumption values equivalent to a 1.1% power-to-food, and an optimistic case value is estimated at 2.0%, indicating that current systems for lettuce are reaching values close to the efficiency ceiling that can be expected without new fundamental scientific breakthroughs, such as genetic modification to increase photosynthetic efficiencies [51].

The acetate intermediate hybrid inorganic-biological artificial photosynthesis systems have achieved efficiencies at small laboratory scale that surpass state-of-the-art photosynthetic systems for microalgae. This indicates potential for competing with modern microalgae photobioreactors, as long as the non-electricity costs of acetate-mediated microalgae production at scale (e.g. equipment) are not considerably larger than those of microalgae photobioreactor processes, and sufficiently long equipment lifetime is achieved.

One key uncertainty in the power to food efficiencies of photosynthetic options is the wall-plug efficiency of lighting. While 81% has been achieved in measurements, it could be very challenging to maintain during 24/7 operation due to various factors such as thermal degradation, LED aging/decay, power supply degradation, dust, etc. For example, if long-term operation wall-plug lighting efficiency was cut in half, the optimistic case power to food efficiency of microalgae would go down from 8.9% to 5.4%.

Two major uncertainties are present in the optimistic case power to food values of hybrid inorganic-biological food production systems mediated by acetate. The optimistic case of efficiency would be much lower if future work could not significantly improve the energy requirement of electrochemical acetate synthesis (from the experimental 61 kJ/g acetate to the proposed optimistic case for efficiency of 19 kJ/g) or the amount of biomass growth per unit of acetate (algae and yeast respectively obtained 28.3 and 18.9 g biomass/g acetate, and 42.5 is considered achievable). Combined, these two values would lower the achievable optimistic case power to food efficiency significantly: from 44.5% to 19.4% for electrosynthetic acetate, from 13.1% to 4.5% for algae, and from 13.2% to 3.1% for yeast. Another major uncertainty that may yet push the overall efficiency lower is the challenge of maintaining high acetate yields over time. Reported lifetimes for CO_2 to acetate tandem electrolyzer systems go as high as 125 hours of stable operation [52] but most applications require 1-3 orders of magnitude longer lifetimes.

For the synthetic fat process, the major uncertainty is probably the possibility of recycling the undesirable side products effectively, without requiring much additional energy. If that was not feasible, the base case of efficiency could not be significantly improved.

4. Production cost of CO_2-based power-to-food systems

Table S1. Large-scale production cost ranges for non-photosynthetic CO_2 foods based on the estimated ranges of 1) energy consumption for current vs potential future developments, 2) electricity cost (current price for electricity-intensive industries vs price of future solar photovoltaic with batteries), and 3) CAPEX cost contribution at different states of the technology, based on the same value as for H_2SCP. Note that costs here do not include downstream processing other than drying and supply chain costs.

CAPEX:	$1.9/kg (2030)	$1.0/kg (2050)	Actual commodity cost of benchmark product ($/kg food, dry)	Benchmark product
Energy efficiency:	Base case: current technology	Optimistic case: with future improvements		
Electricity cost:	$0.06/kWh	$0.03/kWh		
SCP Yeast via artificial sugars	$9	$3	$2-3	Yeast (from agricultural sugar)
SCP Yeast via acetate	$13	$2	$2-3	Yeast (from agricultural sugar)
SCP Microalgae via acetate	$11	$2	$4-6	Spirulina (open pond production)
Microbial protein from hydrogen (H_2SCP)	$5	$2	$5-14 $5-32 $2-9	Whey protein concentrate, USA, 80% (2020-2025) Dried egg yolk, USA (2020-2025) Plant protein isolates
Fat-rich engineered H_2SCP (~60% fat)	$5	$2	$4-7	Butterfat/milkfat, USA (2020-2025)
Synthetic carbohydrates	$5	$2	$0.2-0.6	Table sugar, (2020-2025)
Synthetic fats	$8	$2	$4-7	Butterfat/milkfat, USA (2020-2025)

The cost of growing wheat through artificial lighting is compared to open field wheat grain costs [53], indicating that it cannot compete even with the most optimistic assumptions. The cost of growing lettuce through vertical farming is compared to open field agriculture lettuce [53], suggesting that competition is possible with low enough electricity prices, in agreement with the fact that vertically farmed lettuce is already sold in some regions. The result agrees with other analyses of vertical farming [54], estimating that current best-practice vertical farms convert purchased electricity to edible plant matter at only ~1–2% efficiency, implying an electricity-only lower bound cost of ≈$10/kg dry plant matter—1–2 orders of magnitude above typical producer prices for staple crops like wheat (<$1/kg).

When the cost of synthetic carbohydrates is compared to normal table sugar [55], the ability of synthetic carbohydrates to compete can be completely ruled out unless sugar prices see a massive increase; a different study with a more optimistic energy efficiency (14 kWh/kg) estimated an electricity cost between $0.7–3/kg carbohydrate [9], which would still not be enough to compete. The cost of yeast made from CO_2-derived sugar or acetate is compared to nutritional yeast obtained industrially via traditional sugar fermentation [38] finding that current technologies are far from competing with the traditional process, and would require significant future developments to change this.

The cost of spirulina from photobioreactors and from CO_2-derived acetate is compared to that of open pond spirulina production [56] which is the major production method for the food market due to its lower costs, finding that competition is not out of the question if the technologies could be massively improved. Some authors have also called for practicing electro-agriculture, in which the CO_2-derived acetate is used to grow plants such as lettuce [36]. If electro-agriculture of acetate-grown lettuce reached an efficiency comparable to acetate-grown SCP—corresponding to electricity costs <$10/kg (DM)—it would have a chance at economically competing with vertically farmed lettuce, though not necessarily with conventional lettuce.

However, lettuce has a particularly high price, and competing with agricultural staples with much lower price per calorie would be extremely challenging. For example, even the most optimistic values expected for the electricity cost of acetate-derived SCP do not get close to current wheat prices. It appears very unlikely for electro-agriculture to replace anything but a minority of agricultural production in the mid-term future.

The cost of genetically modified fat-rich H_2SCP is compared to milkfat [57], since this is one of the applications explored for the technology by existing companies [58]. The cost of protein-rich H_2SCP is similarly [59], [60] compared to egg powder [61] and whey protein concentrate [62]. Finally the price of synthetic fat is compared to dairy butterfat [63]. For these products we find the same pattern: electricity costs are a much smaller barrier to competition since they are considerably lower than the benchmarks, indicating a potential opportunity in market viability. If the capital costs and other operational expenses are not too high, these products could compete with agricultural sources in the near future—especially if prices of dairy and eggs continue to rise.

5. Land productivity of CO_2-based power-to-food systems

Table S2. Global average food energy (kcal/m2/y), protein (g protein/m2/y), and fat (g fat/m2/y) supply values per unit of land for plant and animal product benchmarks relevant for comparison to power-to-food systems. The values for plant sources were obtained from Leger et al. [64] *combined with the FAO nutritional composition tables* [65]. *For animal products, the land use values estimated by Poore and Nemecek* [66] *were used instead.*

	Energy (kcal/m2/y)	Protein (g/m2/y)	Fat (g/m2/y)
Soybeans	1010	115	54
Oil palm	2650	5	300

Sugar beets	4520	84	6
Wheat	1390	51	10
Eggs (chicken)	222	17	16
Meat (chicken, fat and bone-free)	175	14	N/A
Milk (cow)	68	3.7	3.7
Beef (beef herd)	5	0.6	0.2
All animal products (world average)	41	2.6	not calculated

Table S3. Baseline food energy (kcal/m2/y), protein (g/m2/y), and fat (g/m2/y) production values per unit of land for power-to-food systems, derived from the energy efficiency analysis and the land footprint of solar photovoltaic energy and factory floor required. Cells marked with (-) indicate that the value is not of interest for the target comparison.

Food production pathway	Calorie yield per unit of land (kcal/m^2/year)	Protein content	Fat content	Protein yield per unit of land (g protein/m2/y)	Fat yield per unit of land (g/m2/y)
Artificial light farming (wheat)	424	15%	-	17	-
Artificial light farming (lettuce)	948	-	-	-	-
Microalgae SCP via photosynthesis (Spirulina photobioreactor)	2,024	60%	-	401	-
SCP Yeast via artificial sugars	2,932	55%	-	470	-
SCP Yeast via acetate	1,656	55%	-	266	-
SCP Microalgae via acetate	2,115	60%	-	419	-
Microbial protein from hydrogen (H_2SCP)	8,651	65%	-	1,461	-
Fat-rich engineered H_2SCP (~60% fat)	11,588	-	60%	-	773
Synthetic carbohydrates	7,547	-	-	-	-
Synthetic fats	9,374	-	100%	-	1,042

Table S4. Optimistic case food energy (kcal/m2/y), protein (g/m2/y), and fat (g/m2/y) production values per unit of land for power-to-food systems, derived from the energy efficiency analysis and the land footprint of solar photovoltaic energy and factory floor required. Cells marked with (-) indicate that the value is not of interest for the target comparison.

Food production pathway	Calorie yield per unit of land (kcal/m^2/year)	Protein content	Fat content	Protein yield per unit of land (g/m2/y)	Fat yield per unit of land (g/m2/y)
Artificial light farming (wheat)	2,186	15%	-	86	-
Artificial light farming (lettuce)	2,210	-	-		-
Microalgae SCP via photosynthesis (Spirulina photobioreactor)	7,508	60%	-	1,489	-
SCP Yeast via artificial sugars	7,676	55%	-	1,231	-
SCP Yeast via acetate	9,802	55%	-	1,572	-
SCP Microalgae via acetate	9,756	60%	-	1,934	-
Microbial protein from hydrogen (H_2SCP)	14,309	65%	-	2,416	-
Fat-rich engineered H_2SCP (~60% fat)	18,106	-	60%	-	1,207
Synthetic carbohydrates	19,186	-	-	-	-
Synthetic fats	30,409	-	100%	-	3,379

Table S5. Comparison of power-to-food technologies versus relevant plant-based agricultural benchmarks.

	Base case	Optimistic case	
Yeast SCP from CO2 via acetate vs soybeans	2x	14x	as much protein per unit of land as soybeans
Microalgae SCP from CO2 via acetate vs soybeans	4x	17x	as much protein per unit of land as soybeans
Microalgae SCP from CO2 via photosynthesis vs soybeans	3x	13x	as much protein per unit of land as soybeans
Yeast SCP from CO2 via synthetic carbohydrate vs soybeans	4x	11x	as much protein per unit of land as soybeans
H_2SCP from CO2 and H2 vs soybeans	13x	21x	as much protein per unit of land as soybeans
Synthetic carbohydrates from CO2 vs sugar beets	2x	4x	as much sugar per unit of land as sugar beets
Synthetic fats from CO2 vs palm oil	4x	11x	as much fat per unit of land as palm oil
Fat from engineered H_2SCP vs palm oil	4x	4x	as much fat per unit of land as palm oil
Vertical farming wheat vs	0.3x	2x	as much wheat per unit of land as

conventional wheat			conventional agriculture

Table S6. Comparison of power-to-food technologies versus wheat.

	Base case	Optimistic case	
Microalgae SCP from CO_2 via photosynthesis	1x	5x	as much food energy per unit of land as conventional wheat
Microalgae SCP from CO_2 via acetate	2x	7x	as much food energy per unit of land as conventional wheat
Yeast SCP from CO_2 via acetate	1x	7x	as much food energy per unit of land as conventional wheat
Yeast SCP from CO_2 via synthetic carbohydrate	2x	6x	as much food energy per unit of land as conventional wheat
H_2SCP from CO_2 and H_2	6x	10x	as much food energy per unit of land as conventional wheat
Synthetic carbohydrates from CO_2	5x	14x	as much food energy per unit of land as conventional wheat
Synthetic fats from CO_2	7x	22x	as much food energy per unit of land as conventional wheat
Fat-rich engineered H_2SCP (~60% fat)	8x	13x	as much food energy per unit of land as conventional wheat
Vertical farming wheat	0.3x	2x	as much food energy per unit of land as conventional wheat

Figure S9 compares the highest measured crop yields versus H_2SCP and synthetic fat. The values of highest yields ever obtained by any agricultural products were derived as follows: the highest yield of corn is ~624 bushels per acre in Virginia (USA) [67] at 15.5% moisture content, whereas corn has a calorie content of 3,650 kcal/kg [68] at 10.4% moisture, resulting in 13,478 kcal/m^2/y. The highest yield of sugar beets is 196.7 metric tons per hectare in Chile [69], which using a 17.2% sugar content (fresh mass basis) and an 80% sugar recovery [70] results in 10,826 kcal/m2/y. The highest yield of palm oil is ~10 tons per hectare in genetic field trials in South Asia [71] with a calorie content of 8,840 kcal/kg [72], resulting in 8,840 kcal/m^2/y.

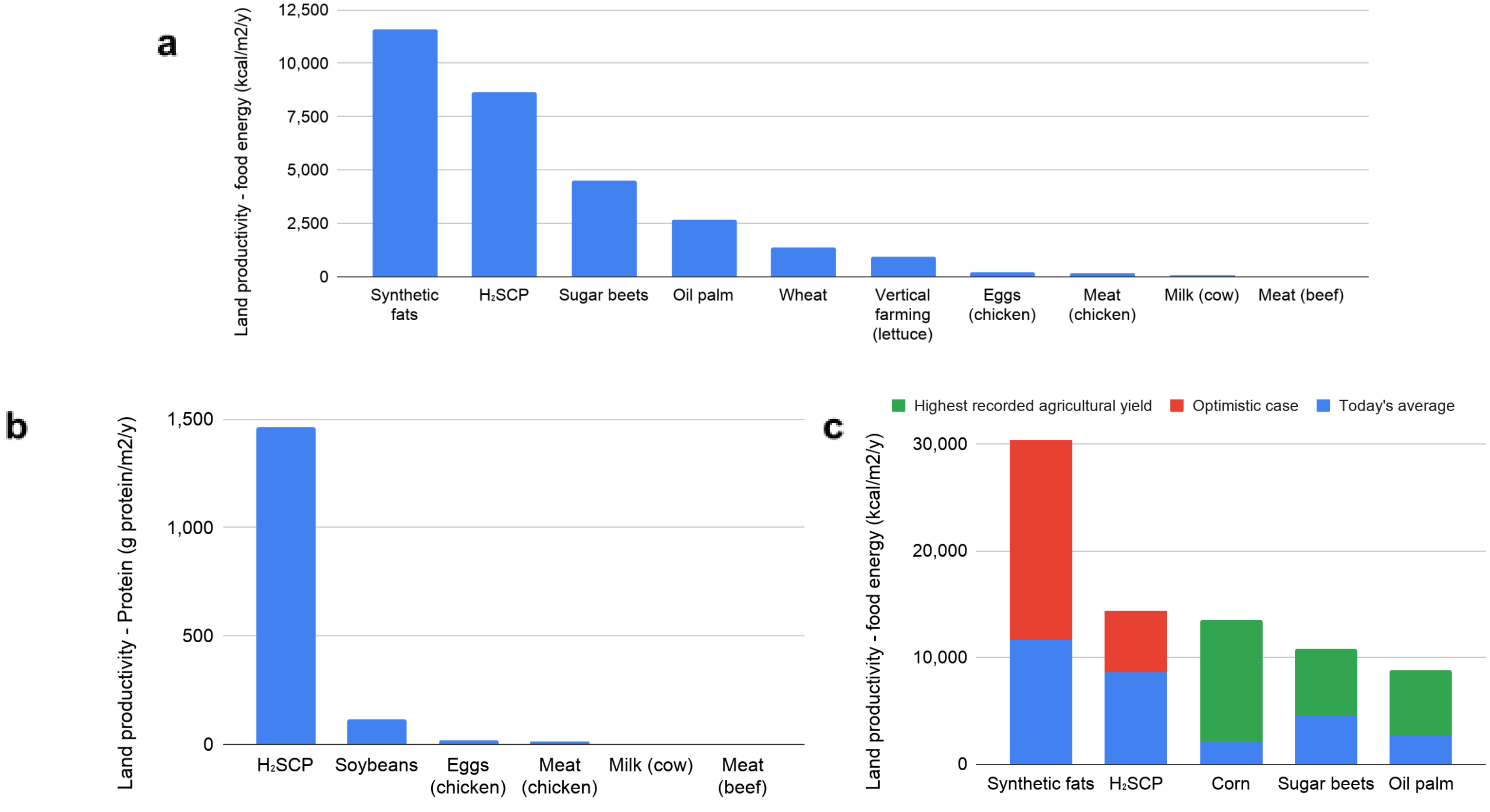

Figure S9. *Land productivity of the top performing power-to-food pathways studied in this analysis in comparison with relevant plant- and animal-based agricultural products. a) compares them in terms of food energy per m^2 and year; b) shows them in terms of protein supply per m^2 and year for H_2SCP in comparison with key plant- and animal-based protein-containing agricultural products; c) shows the base case and optimistic case values of food energy supply per m^2 and year of H_2SCP and synthetic fats as well as agricultural benchmarks and their highest recorded yields in optimized conditions. All agricultural values are based on global averages [73] (see Table S2 and supplementary document for details).*

6. Comparison between power-to-food systems and conventional photosynthesis

To better illustrate why the power-to-food technologies are more efficient than conventional agricultural photosynthetic systems, an energy flow analysis was performed, summarized in the Sankey diagrams in Figures S10 through S12. Sunlight-to-food conversions and losses are shown for the H_2SCP power-to-food pathway in S10, and for agricultural products like wheat in S11 and poultry meat in S12. Wheat and chicken are chosen as particularly efficient examples of agricultural products within their respective categories (plant products for wheat, meat products for chicken). Most other products within each category would be even further away from power-to-food systems in terms of land use and sunlight-to-food efficiency.

The energy flow diagram for HOB in figure S10 was derived starting from the sunlight to electricity efficiency of solar PV. A typical value is ~5%, whereby only about 5 out of every 100 units of sunlight hitting a solar PV plant are converted to electricity [54], [64]. Breaking that down even further: current PV module efficiency is famously above 20% (here we selected a value of 21.7% based on commercial cells [2]), on top of that the ~50% ground coverage due to panel spacing, imperfect solar tracking, cover by dust/debris, etc. causes further losses down to ~4.9%. Using the previously derived electricity requirement of 44.2 kWh/kg HOB SCP and a digestible energy content of 4.5 kWh/kg HOB SCP, the efficiency of solar to biomass energy is 4.9%*4.5/44.2 = 0.5%. Sequentially, these losses can be attributed:

- The electrolysis efficiency of 80% results in 1% losses (sunlight to H2 efficiency of ~3.9%).
- Biomass cultivation causes a loss of 2.5% out of the 3.9%, losing about two thirds of the energy contained in the H2. The required 0.45 kg H2/kg SCP imply a thermodynamic H2 need of 17.9 kWh (H2)/kg biomass, resulting in a solar to biomass theoretical efficiency of 3.9%*6.3/17.9=1.4%.
- In practice, the ancillary processing required to achieve this causes a further energy loss of ~0.7%, since this cost is roughly as large as the energy cost of electrolysis. This results in an actual solar to biomass efficiency of ~0.7%, with another ~0.7% lost as processing energy. Note that this is accounting for an ancillary energy loss starting from a total pool of captured sunlight, not contained in the biomass.
- A final loss of ~0.2% is due to the inefficiency of human digestive systems. Out of the gross biomass energy content of 6.3 kWh/kg for HOB SCP [41], we can digest the previously mentioned 4.5 kWh/kg, for a total solar to digestible energy conversion of 0.7%*4.5/6.3 ~ 0.5%.

This value corresponds perfectly with the previously derived land productivity of 8,716 kcal/m^2/y. At a typical solar irradiance of ~2,000 kWh/m^2/year and a conversion factor of 860 kcal/kWh, we estimate 8,716 kcal/m^2/y ÷ (2,000 kWh/m^2/year * 860 kcal/kWh) ≈ 0.5%.

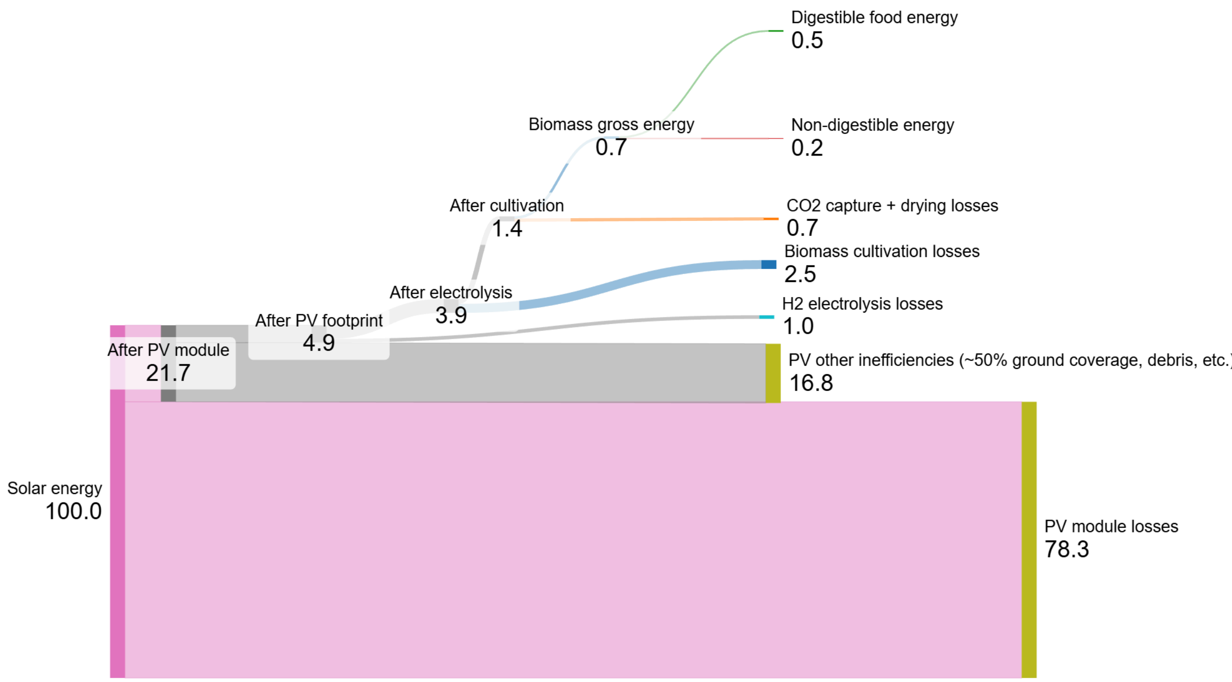

Figure S10. Sankey diagram of the sunlight-to-food energy flows and losses at each step of the H2 SCP power-to-food pathway, specifically the HOB variant (gas fermentation).

The energy flow diagrams for agriculture were derived from a simple back-of-the-envelope calculation, using wheat as a representative example. Agronomic data indicates that wheat production systems currently convert sunlight to food energy at a share of about ~0.1% of the sunlight reaching wheat croplands around the world [64], with examples including 0.074% in the USA, 0.101% in Russia, 0.081%, and 0.169% in China [74], to show a few regional measures. To illustrate how this value is often obtained, we start from the well-known fact that only about ~45% of sunlight reaching Earth is photosynthetically active radiation (PAR) [24]. Then out of this sunlight, only a small portion is typically absorbed by the plants for biomass growth, due to multiple phenomena, such as incomplete canopy cover, winter/dry season, and optical losses[2]. For example, in the Argentine Pampa wheat absorbs only 20–36% of annual incident PAR [75]. Then the vast majority of that absorbed PAR is lost in photosynthetic conversion losses; we choose a round value of ~3% not lost, just under the values reported in agronomic studies [22] (which typically focus on varieties more efficient than the global average). Then we use a typical wheat harvest ratio of ~40% [76] (grain mass divided by total plant biomass, including underground biomass such as roots). Finally, we used a digestibility ratio of ~86% based on a gross energy content of 4,419 kcal/kg (DM) [77] compared to a digestible energy content of 3,821 kcal/kg (DM) [30]. Putting it all together results in: 0.45 * 0.25 * 0.03 * 0.4* 0.86 ≈ 0.1% (See figure S11). We can add one more step to represent animal products: chicken converts digestible grain energy into meat calories at an

[2] (i) canopy cover is incomplete for much of the season and the field may be bare or have low leaf area index (the one-sided green leaf area per unit ground area) during sowing-establishment, senescence, and post-harvest/fallow periods, so much PAR reaches soil rather than vegetation; (ii) even when the canopy is present, geometric gaps and non-uniform leaf distribution reduce interception; and (iii) part of the intercepted radiation is not absorbed by green tissue due to optical losses—reflection from leaves/soil and transmission through the canopy—so the fraction of absorbed photosynthetically active radiation remains below unity.

approximate ratio of 1:10 [78], resulting in ~0.01% sunlight to food efficiency for poultry meat, as shown in figure S12.

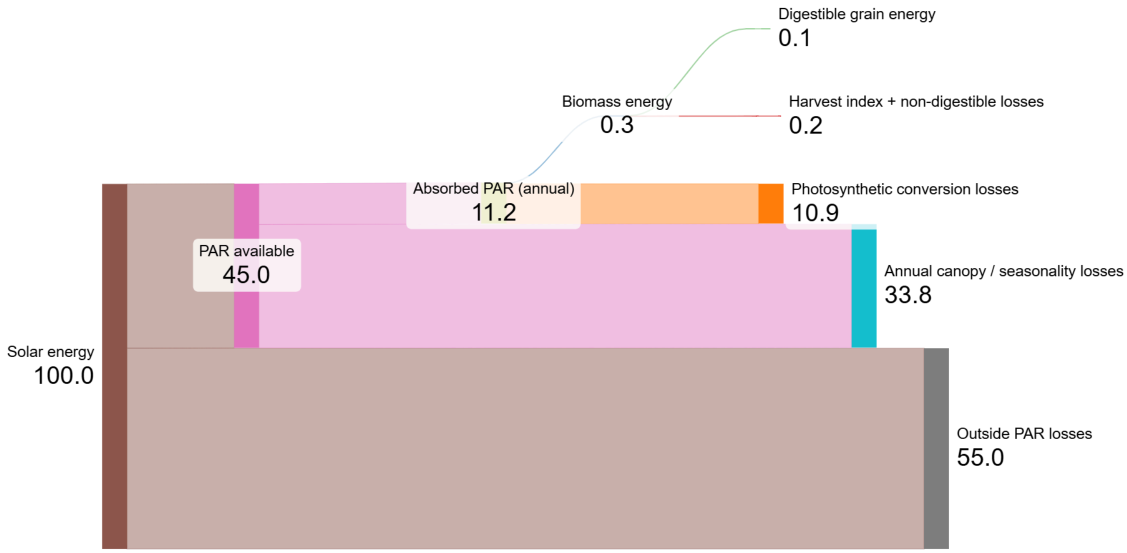

Figure S11. Sankey diagram of the sunlight-to-food energy flows and losses at each step of conventional agriculture using wheat cultivation as a representative example.

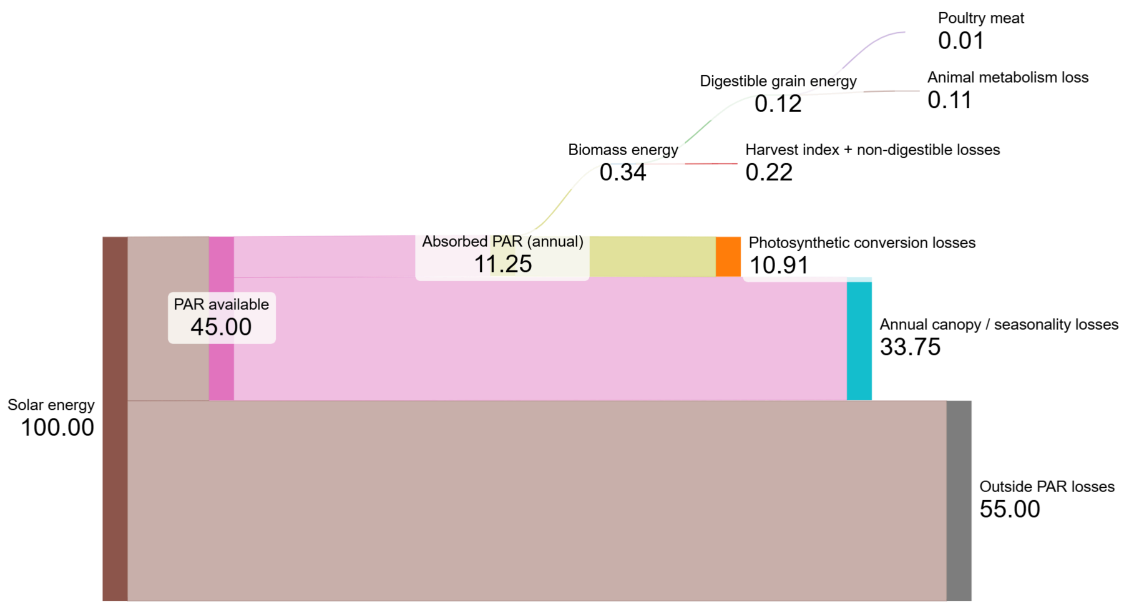

Figure S12. Sankey diagram of the sunlight-to-food energy flows and losses at each step of conventional agriculture using grain-fed poultry as a representative example.

7. Technology readiness Level (TRL) of CO_2-based power-to-food systems

Table S7. TRL of power-to-food pathways and rationale. The technologies studied in the current work span a wide range of technology readiness levels (TRLs). We analyze them based on the definitions of TRL put forth by the European Commission [79] and by Buchner et al. [80], extensions of the original scale from NASA modified to apply to any type of technology and to chemical technologies, respectively.

Food production pathway	**TRL**	**Rationale**
Artificial light farming (wheat)	5	Large scale prototype tested in intended environment: Infarm conducted trials that produced 117 kg of wheat per hectare equivalent per year (in a vertical stack) [81].
Artificial light farming (lettuce)	8	First of a kind commercial system: Companies such as Bustanica and Ljusgarda already produce limited amounts of lettuce that can be purchased by consumers in local grocery stores. Bustanica has the capacity to produce over 1,000 tons of produce per year [82].
Microalgae SCP via photosynthesis (Spirulina photobioreactor)	7	System prototype demonstration in operational environment: the Helliseidi spirulina photobioreactor plant has an installed production capacity of 150 tons of edible wet biomass per year, fulfilling Buchner et al.'s requirement for a TRL of 7 [29].
SCP Yeast via artificial sugars	3	Laboratory tests demonstrate proof of concept: synthesis of edible yeast from CO_2-derived sugars has been achieved at a laboratory scale by Air Company for NASA's Deep Space Food Challenge [83].
SCP Yeast via acetate	3	Laboratory tests demonstrate proof of concept: Hann et al. demonstrated the small scale synthesis of acetate from CO_2 using a tandem electrolyzer system, and successfully grew yeast, microalgae, and some plants from the acetate [2].
SCP Microalgae via acetate	3	Laboratory tests demonstrate proof of concept: Hann et al. demonstrated the small scale synthesis of acetate from CO_2 using a tandem electrolyzer system, and successfully grew yeast, microalgae, and some plants from the acetate [2].
Microbial protein from hydrogen (H_2SCP)	7	Demonstration system: Solar Foods has constructed factory 01, with a reported production capacity of 160 tons of protein annually, fulfilling Buchner et al.'s requirement for a TRL of 7 [84].
Fat-rich engineered H_2SCP	6	Large scale prototype: Circe Bioscience have demonstrated biomanufacturing of fats from CO_2 on their pilot plant facility, and they intend to build a demonstration facility with a 150 ton capacity that would take them to TRL 7 [85].
Synthetic carbohydrates	3	Laboratory tests demonstrate proof of concept: synthesis of digestible sugars from CO_2 has been achieved at a laboratory scale by Air Company for NASA's CO_2 Conversion Challenge [86].

Synthetic fats	6	Large scale prototype: Savor Inc. have demonstrated thermochemical production of fats from CO_2 at their pilot plant with a goal to achieve 5 tons/year [87].
Microbial electrosynthesis of acetate	4	Small scale prototype: Cabau-Peinado et al. have achieved relatively efficient microbial electrosynthesis of acetate at small scale [88].
Electrochemical synthesis of acetate	4	Small scale prototype: Crandall et al. demonstrated the small scale synthesis of acetate from CO_2 using a tandem electrolyzer system at a laboratory scale for 125 hours [52].

8. Applications of CO_2 power-to-food production

8.1. *Combating climate change, land degradation, and water depletion*

One major advantage industrial CO_2 food technologies have in common is their very low land and water use [9], [12], [64], [89], [90], [91], [92]. Thus, large-scale deployment of these technologies could facilitate reduction of CO_2 emissions, reforestation of agricultural land, and curbed freshwater depletion. However, the benefits to society are conditional on the displacement of unsustainable foods and products [12]. For example, some of these processes can provide quality proteins and fats with much lower CO_2 emissions than meat and some oil crops respectively, such as single cell proteins from CO_2. They enable us to produce the oils and fats we need without destroying forests for palm oil plantations or livestock rearing. Fermentation processes can reduce overfishing in the ocean by replacing the fish-based feed needed to farm salmon with SCP. When displacing animal products, they also reduce animal suffering from factory farming.

Let us consider the requirement of consistently cheap, low-CO_2 energy with an example. If the energy was not low-CO_2 (not from e.g. renewables, nuclear, or fossil fuels with carbon capture), the amount of CO_2 emitted could surpass the amount used to make the food many times over. Consider H_2SCP, which is among the most efficient foods studied: if it were made with U.S. grid energy, which in 2023 had a CO_2 intensity of ~0.37 kg CO_2/kWh electricity [93], at an estimated 34-44 kWh/kg H_2SCP that would release 12-16 kg CO_2/kg H_2SCP biomass or 18-23 kg CO_2eq/kg protein. This is lower than the greenhouse gas emissions per protein of animal products like eggs at ~42 kg CO_2eq/kg protein [73], milk at ~95 [73], and whey solids at ~100 [94], but higher than other comparable products such as soy protein isolate at ~6 [95], mycoprotein at ~5 [96], or natural gas-based SCP at ~8 [97]. Low-CO_2 energy is the only way to beat the latter, potentially going as low as ~1 CO_2eq/kg protein for H_2SCP [89].

It is worth clarifying that CO_2 food technologies do not permanently remove carbon from the atmosphere because we breathe out the CO_2 again after eating the product [89]. While it is possible to capture significant amounts of CO_2 through direct air capture and reforestation of agricultural areas—enabling the process to become carbon-negative—most environmental benefits come from agricultural displacement. For example: if Indonesian and Malaysian palm oil were replaced with net-zero CO_2 fats made exclusively with cheap renewable energy [12], ~400 million metric tons of

CO_2 per year could be avoided (~1% of global CO_2 emissions). Significantly reduced CO_2 emissions could be achieved even if the carbon to make these synthetic fats came from natural gas instead [12]. However, if the product was made with electricity coming from the U.S. energy mix, it would not be any better than the palm oil in terms of greenhouse gas emissions.

Consistency in energy supply is also important because capital-intensive factories such as those required to produce CO_2 foods at scale suffer economic penalties from periods of downtime. This normally makes it hard to use intermittent renewable power, even if it became virtually free and widely available in the near future, as some have theorized [98]. However, there are promising methods to address this such as a hybrid solar and wind power supply, flexible operation of subunits, and the integration of various energy and feedstock balancing technologies such as batteries, H_2 storage, and H_2 gas turbines [39]. These can be used to optimize unit cost by operating at maximum capacity at times of low electricity cost and at partial capacity the rest of the time, potentially enabling levelized costs of electricity just under the value of $0.03/kWh (for solar with batteries) used as a floor in the economic comparison here [39].

Lastly, technologies for conversion of CO_2 and water provide access to virtually limitless resources for food production. As an example, if one employed about a quarter of the current global electricity capacity into H_2SCP production, we could cover the entire global protein requirement of the human population [40], using <1% of global land with solar farms [39] and no arable land at all. As shown by Extended Data Table 2, CO_2 foods are currently disadvantaged in terms of cost due to the very high energy requirements of the process, but this could change in the future. They would be much more likely to be cost-competitive if the devastating environmental externalities of traditional agricultural products were incorporated in their price, such as deforestation and water pollution from animal products or palm oil.

8.2. Crewed space missions

Food production in space is also a compelling arena in which to apply these systems. Producing food on location is the only viable way to expand space travel into deep space, addressing challenges such as food quality degradation [99], nutritional degradation [100], and the large mass requirement of sustaining a crew in the long term [101]. One key advantage of CO_2-based food production systems is how they integrate with existing life support systems: they can use the hydrogen generated in-situ as part of oxygen generating systems to reclaim water for the crew, much like the Sabatier-based systems of today, but with the added benefit of food production. This results in considerable overall launch mass savings in the long term thanks to lower food resupply needs [4], [7], [13].

Let us consider the case of a moon base: suppose a prototype H_2SCP system weighed around 7,500 kg and produced 8,000–10,000 kg of food per year (enough for roughly a few dozen people, depending on ration size). If delivering cargo to the lunar surface costs on the order of $1,000,000 per kg, then producing food locally avoids transporting ~80,000–100,000 kg of food over a 10-year mission—an avoided delivery bill of ~$80–$100 billion on food mass alone, before counting packaging, safety stock, and food-system hardware that typically accompanies resupply. Even if delivered costs fell dramatically to $25,000/kg, the same avoided food shipments would still be worth ~$2.0–$2.5 billion over a decade. In short, because the marginal cost of imported mass is so extreme in large-scale space missions, closing the food loop with power-to-food can plausibly save billions to tens of billions of dollars, even after paying for a multi-ton production system upfront.

Additionally, intermediate or final products of these novel food production processes can serve as material for the synthesis of more complex molecules. Sugars can be converted into fuels or used as a substrate for precision fermentation, lubricants and butter substitutes can be produced from esterified glycerol and fatty acids, and the technology and bacterial strains used for fermentation can be used for bioplastics. Developing these technologies to fulfill basic human survival needs in space could also serve as the foundation on top of which a biotechnology-based circular industrial system can be built on any planet [102].

Despite achieving high power-to-food efficiencies, the lower selectivities often achieved for nonbiological synthesis systems (synthesis of acetate, fats, and carbohydrates) and their inability to produce fundamental micronutrients limit their applicability in closed environments such as space missions. Efficient byproduct recycling systems, as envisioned throughout the study, would need to be developed in order for them to make significant contributions to food production in space. Moreover, if nonbiological systems remain unable to produce the wide range of micronutrients that humans need to survive, it could be hard for them to take a central role in space food production. Future research should study the suitability of both biological and nonbiological CO_2 food production systems to contribute to or even become the basis of nutritionally complete diets for long-term deep space missions and off-world bases.

8.3. Preventing a global catastrophic food failure

This work has studied closed environment, modular, polycentric food production systems, which minimize or even remove key risks affecting modern food systems. When established in a location, they are nearly or completely immune to climate variability, environmental degradation and pollution, pests, pathogens, and trade restrictions [103]. If the energy source does not depend on sunlight (e.g. nuclear, geothermal, or fuel-based), they would not even need sunlight to work. These characteristics make the CO_2 food systems resilient even to extreme food disruption scenarios, at least as long as the systems could be properly maintained. For example: abrupt sunlight reduction scenarios (volcanic winter, nuclear winter, asteroid/comet impact winter), severe climate shifts (e.g. abrupt changes in climate, even extreme change increasing global temperature over 10°C), and other potential future threats that could lead to widespread plant collapse, perhaps through engineered plant diseases [104] or mirror biology [105].

A large set of life-preserving food solutions has been proposed in response to these catastrophes [106], including high-tech industrial food production systems similar to those described here but based on feedstocks other than CO_2, such as SCP from natural gas, synthetic fat from petroleum wax, or sugar from lignocellulosic biomass, which would currently have lower costs [104]. Considerable uncertainty remains about the possibility of producing CO_2 foods at costs comparable to these unless consistently cheap energy is widely available, but options like the H_2SCP or synthetic fats could make significant contributions to food catastrophe response in locations that have this [40], [47], [104]. Overall, market penetration of CO_2 foods would increase the resilience of the global food system to tail risks, keeping a stable supply of food in the face of instability and uncertainty from changing agricultural and climatic conditions.

The extreme degree of resilience of these technologies against adverse conditions, being able to produce food even in space, has led to their being proposed as food provision methods in isolated refuges (underground, underwater, or extraplanetary), in order to prevent an existential catastrophe from ending civilization or humanity itself [4], [7], [13], [107].

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