energies

Article

Restoring pre-industrial CO_2 levels while achieving Sustainable Development Goals

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Abstract: Unless humanity achieves United Nations Sustainable Development Goals (SDGs) by 2030 and restores the relatively stable climate of pre-industrial CO_2 levels (as early as 2110), species extinctions, starvation, drought/floods, and violence will exacerbate mass migrations. This paper presents conceptual designs and techno-economic analyses to calculate sustainable limits for growing high-protein seafood and macroalgae-for-biofuel. We review the availability of wet solid waste and outline the mass balance of carbon and plant nutrients passing through a hydrothermal liquefaction process. The paper reviews the availability of dry solid waste and dry biomass for bioenergy with CO_2 capture and storage (BECCS) while generating Allam Cycle electricity. Sufficient wet-waste biomass supports quickly building hydrothermal liquefaction facilities. Macroalgae-for-biofuel technology can be developed and straightforwardly implemented on SDG-achieving high protein seafood infrastructure.). The analyses indicate a potential for (1) 0.5 billion tonnes/yr of seafood; (2) 20 million barrels/day of biofuel from solid waste; (3) more biocrude oil from macroalgae than current fossil oil; and (4) sequestration of 28 to 38 billion tonnes/yr of bio-CO_2. Carbon dioxide removal (CDR) costs are between 25–33% of those for BECCS with pre-2019 technology or the projected cost of air-capture CDR.

Keywords: sustainable development goals (SDGs); carbon dioxide removal (CDR); carbon sequestration (BECCS); renewable energy; waste-to-energy; Allam Cycle; hydrothermal liquefaction (HTL); macroalgae (seaweed) biofuels

Supplemental document and spreadsheet: https://osf.io/rjta8/quickfiles

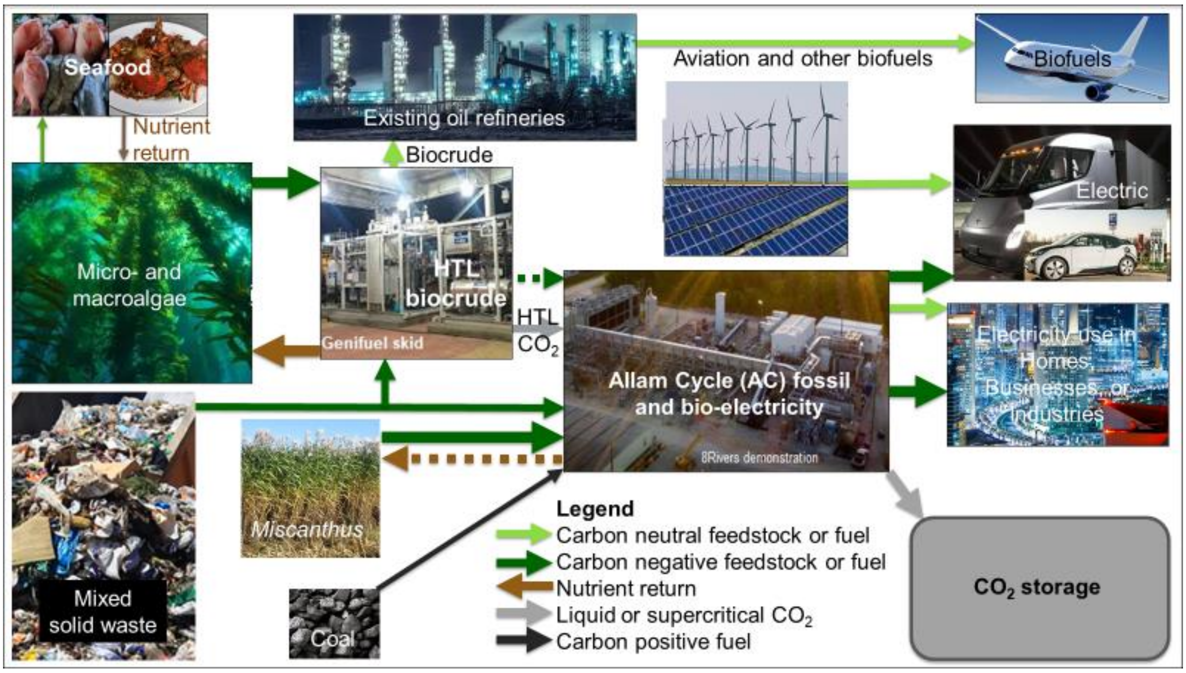
Key Points:

Feeding the world with sustainable seafood from artificial reefs that also restore ocean biodiversity and support marine protected areas

Sustainable development for all while reducing atmospheric CO_2 below 300 ppm by the 2100s and keeping global temperature rise below 1.5ºC

Quadrupling global electricity production, all carbon-neutral or carbon-negative, while replacing oil with carbon-negative biofuel

Graphical Abstract



1. Introduction

People face interrelated crises impacting basic human needs for food, shelter, and health, while at the same time maintaining aspirations for education and meaningful work. Crises involving food and shelter (e.g., droughts, floods, sea-level rise, groundwater depletion, and diminished glaciers/snowpack, which store fresh water for use during dry periods) are exacerbated by increasing greenhouse gas concentrations. Crises involving health (e.g., pandemics and the increasing range of disease-transmitting organisms) are also intensified by climate change.

The need to find interconnected opportunities within the interrelated challenges is critical. Indeed, Pope Francis (2015) and others (see Sorondo & Ramanathan (2016)), wish to "...bring the whole human family together to seek a sustainable and integral development…" The 2015 Paris Agreement recommends that "rapid reductions" of greenhouse gases be achieved "on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty" (IPCC, 2014).

Planning horizons account for much of the differences in integrated approaches to sustainability. Perhaps as much as 70 percent of humanity urgently need improved food, shelter, health, education, and opportunity. Many of these people see accomplishing United Nations Sustainable Development Goals (SDGs) (United Nations, 2016b) by 2030 as more urgent than zeroing greenhouse gas emissions by 2050. Some of the others agree, seeing the SDGs as the best way to mitigate violence, migrations, and unsustainable population growth. The IPCC 1.5°C report looks out to 2100. "All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century" (IPCC, 2018). Simply eliminating fossil fuels (on timelines acceptable to everyone) is insufficient to ensure warming of <1.5°C. Thus, zero-carbon electricity sources such as wind, hydro, solar, geothermal, and nuclear are necessary, but not sufficient.

There are a variety of CDR methods (also called negative emissions technologies or NETs). Some explicitly consider societal challenges: the U.S. National Academies of Sciences, Engineering, and Medicine (2019) plus the comprehensive literature reviews by Minx et al. (2018), Fuss et al. (2018) and Nemet et al. (2018), as well as Tim Flannery's books (2015, 2017) and the recent Project Drawdown Review (2020). Three emerging technologies, considered insufficiently proven in these reviews, are now viable and warrant analyses of their potential impacts:

a. Total ecosystem aquaculture (TEA) (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b, 2020c; Chambers, 2013; Lucas et al., 2019a, 2019b; Knowler et al., 2020) was refined during a techno-economic analysis funded by the U.S. Department of Energy (DOE). TEA systems consist of permanent, flexible reefs floating at ocean depths for optimal growth of the macroalgae species under culture. Primary productivity is optimized by returning just as much nutrients as extracted, unless the reef is extracting excessive anthropogenic nutrients. That is, primary productivity is not nutrient limited. Initially TEA produces finfish, shellfish, crustaceans, and other high-protein seafood with some boutique harvesting of macroalgae. Seafood-producing reefs directly address SDGs 1–3, 8, 10, and 14 and indirectly address most of the others. Some seafood reefs can expand tropical fisheries in the face of climate change, substitute for natural reefs so that natural marine areas can be protected and facilitate research and development on growing macroalgae-for-biofuel. Macroalgae-for-biofuel requires an energy conversion process that recycles nutrients to support complete ecosystems similar to seafood-production reefs. Although full TEA is not yet demonstrated, most components and technologies are proven in other forms of aquaculture, including integrated multi-trophic aquaculture (Knowler et al. 2020 and references therein). In addition, Laurens et al. (2020) make the case for greatly expanded biofuels production from macroalgae.

b. Hydrothermal liquefaction (HTL) (Jiang et al. 2019; Jiao et al. 2017; Pichach 2019) uses a combination of high temperature (350°C, 660°F) and pressure (2 MPa, 3,000 psi) to convert wet biomass and some plastics to a biocrude oil in about 30 minutes. Because the reaction temperature is <400°C, all nutrients can be recovered and used to grow more plants. Several companies have systems operating at 1–10 wet tonnes of biomass/day. Using wet organic wastes mixed with select plastics to make biofuels addresses SDGs 7, 12, 13, and 14. Like many biofuel technologies, HTL's commercial scale-up was interrupted by the 2020 drop in global oil prices.

c. Allam Cycle electricity production (8 Rivers Capital, 2020; Allam et al., 2017; Fernandes et al., 2019; McMahon, 2019) combines pure O_2, gaseous fuel, and recirculating CO_2. The combustion product is a supercritical fluid (viscosity like a gas, density like a liquid) that exits the turbine at 3 MPa (as a gas). The CO_2 is compressed to become a sequestration-ready gas or supercritical fluid at 10 MPa with no efficiency penalty. Economic costs or benefits depend primarily on fuel price. The fuel can be natural gas, gasified coal, or gasified dry biomass (including crop residues and other dry wastes). With fossil fuel, electricity production can be carbon-neutral, addressing SDGs 7, 12, and 13. With gasified dry biomass, the electricity produced can be carbon-neutral or carbon-negative. 8 Rivers Capital (2020) has operated a 50-MW natural gas Allam Cycle plant for over a year. They plan to be mass-producing 300-MW natural gas units by 2022 (McMahon, 2019), and gasified coal units after demonstration of a 300-MW unit expected by 2026 (8 Rivers Capital, 2020).

These three technologies can be sequentially deployed as shown in Figure 1 (see Section 3 for details). Infrastructure built to produce food prior to 2030 is expanded for biomass feedstocks and carbon capture after 2030:

(1) Install TEA on floating, flexible, fishing reefs with macroalgae forests to produce seafood while returning nutrients for sustainability.

(2) Install solid-waste collection systems that produce bioenergy (as opposed deposition in landfills). Simultaneously install electrical power plants that can be easily upgraded to capture and compress CO_2 emissions. As soon as possible, switch to capture-and-compression of CO_2 from biomass combustion.

(3) Sequester the captured fossil- and bio-CO_2. Increase the amount of biomass (such as macroalgae, *Miscanthus*, and other sustainable biomass crops) to make carbon-negative liquid fossil fuels (using the HTL process, which in itself captures some CO_2). Gradually increase the ratio of biomass-fueled electricity to fossil-fueled.

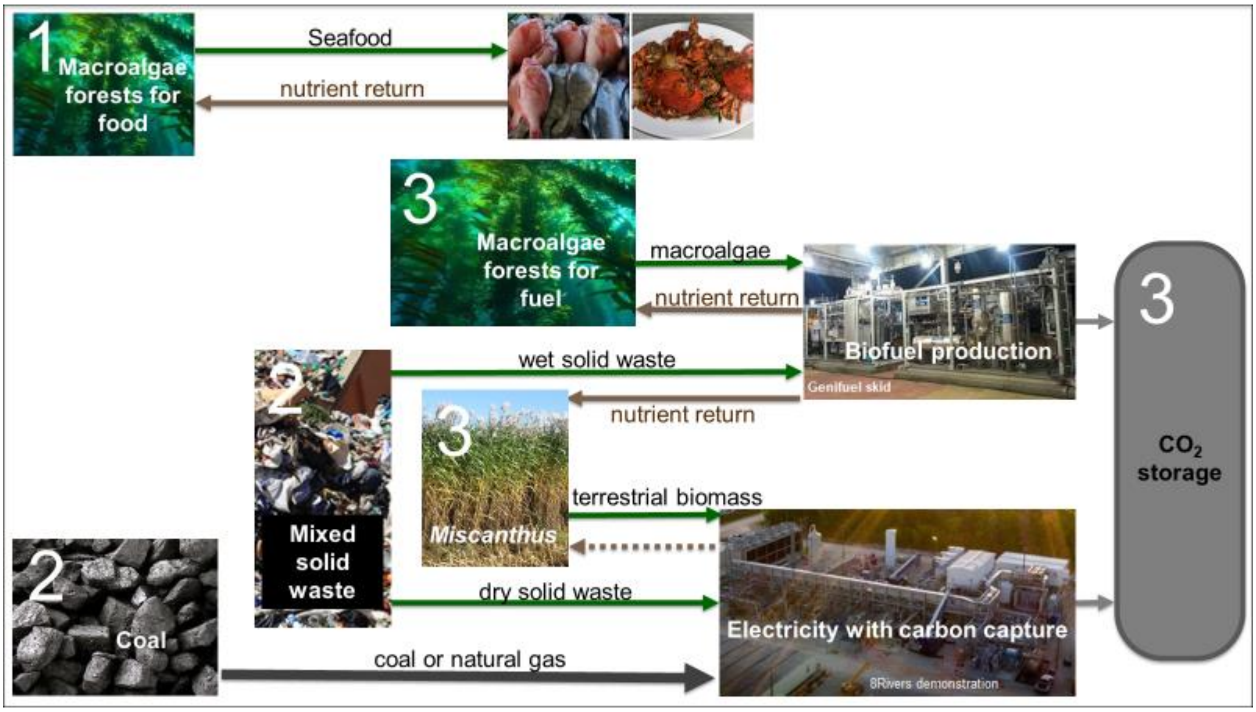


Figure 1. – Initial technologies to achieve SDGs while restoring 300 ppm CO_2. Gray arrows represent liquid CO_2. The nutrient-return arrow from electricity production is dashed because high-temperature processes such as gasification, incineration, and pyrolysis can return some nutrients from the ash, but convert most of the organic nitrogen into nitrogen gas and NO_x during combustion.

2. Methods

This project began as an update of "Negative carbon via ocean afforestation" (N'Yeurt, 2012), which used a mass balance of carbon and nutrient flows combined with a life cycle analysis of concept-level process designs to estimate the amount of energy and CDR that can be produced using macroalgae. The update was based on initial results from the U.S. DOE's Advanced Research Projects Agency-Energy (ARPA-E) MARINER program (2017b), which funded nine teams to address the economics of growing and harvesting macroalgae for energy conversion. Nine MARINER teams each generated techno-economic analyses for potential grow-harvest systems across a wide range of tropical and temperate macroalgae species in a variety of fixed and free-floating systems using novel substrates, paths to market, and autonomous operations. By directly involving members of six teams, with two other teams providing summary data, this research included insights from eight of the nine MARINER teams. The ARPA-E guidelines for the TEAs specified:

a. An integrated system design that includes seeding, growing, and harvesting.
b. Use of any reasonably foreseeable technology such as autonomous operation.
c. Use of local renewable power such as solar, wind, or current (the difficulty of estimating the cost of the equipment and its intermittent nature left most teams using biofuel for their TEA).
d. A minimum, but not necessarily continuous, 100,000-ha seaweed farm.
e. A location that will support the concept, including nutrients.
f. A reasonable expected economic life of the capital investment.

Early in the MARINER project, the plan was to improve the accuracy of the estimated carbon and nutrient demands and combine these with data on financing and energy costs to forecast the cost per dry tonne. The goal was to determine how much of global oil demand could be replaced with macroalgal biomass.

Gasified, coal-fired, Allam Cycle electricity generation data were made public as part of the U.S. DOE's coal FIRST program. Details of HTL carbon and nutrient flows combined with details of Allam Cycle processes revealed an opportunity for HTL to produce carbon-negative biofuel. This facilitated creation of a low-bioelectricity, high-biofuel path to global carbon neutrality with substantial sequestration (labeled P_{fuel} path).

Combining information on available wet (for HTL) and dry (for Allam Cycle gasification) waste and purpose-grown biomass and plastic with data on Allam Cycle power generation allowed another high-bioelectricity, low-biofuel path (P_{electric}). The estimates calculated over these two paths are presented in Section 3.1, Tables 1 and 2, and discussed throughout this paper.

In summary, the method combined theoretical studies from the MARINER program with other theoretical and experimental results including those for HTL and gasified, coal-fired, Allam Cycle power generation. The authors reviewed available research and calculations for waste and purpose-grown biomass. The method highlights first-order approximations, based on simplifications including:

a. Costs are estimated for production from the n^{th} macroalgae grow-harvest unit (after the learning curve to install automated harvesting and economies of scale).
b. Nutrient recycling calculations focus on nitrogen (N) (in protein, ammonium, nitrates, etc.). Phosphorus (P) and other nutrients are assumed to be roughly proportional when recycling waste (such as sewage or crop residues). However, if relying on excess nutrients (mainly N), as from a dead zone, the P may become a limiting factor)
c. Macroalgae productivity per area is not nutrient-limited (due to nutrient recycling), Of course, nutrient recycling per area is limited to less than that which would adversely affect local biodiversity and ecosystem balance.
d. High-protein seafood (shellfish, finfish, crustaceans, etc.) production per area is estimated from a mass balance of N and information on the insolation-limited primary productivity.
e. The technology issues and life-cycle cost for gasified dry biomass-fired Allam Cycle electricity will be like those for gasified coal-fired Allam Cycle electricity.
f. The paths shown in Figure 2 are based on values at three points: (1) 2018 emissions, (2) net zero CO_2 emissions (assigned to 2050), and (3) calculated maximum CDR (assigned to 2070).
g. Only CO_2 emissions and CDR from energy production are calculated. Other CO_{2eq} causes of climate change such as methane will need to be addressed separately from energy production (although the elimination of fossil fuel production will considerably reduce methane emissions).

All the above information was collated into the Supplemental Spreadsheet (SS), which shows the relevant data produced and collected as well as the calculations that produce the summary numbers in the tables. Instructions in the SS guide "what-if" calculations. Most of the data used in the spreadsheet come from published sources, which are referenced in the spreadsheet and displayed on tab 25. If there was a wide range of published data, that is reported with an indication why a particular average value was chosen. Since percentages of available biomass (such as municipal waste or crop residues) that can be collected at reasonable prices for bioenergy use vary widely by location and other variables, Tab 4 (Rows 12 -16 and 75, 78, 105) collection percentages can be varied to account for local situations (red text indicates a number that can be varied).

All the above information was collated into the Supplemental Spreadsheet (SS), which shows the relevant data produced and collected as well as the calculations that produce the summary numbers in the tables. The spreadsheet also allows "what-if" calculations by replacing the red numbers in the spreadsheet. Most of the data used in the spreadsheet come from published sources, which are referenced in the spreadsheet and displayed on tab 25. If there was a wide range of published data, that is reported with an indication why a particular average value was chosen.

Since percentages of available biomass (such as municipal waste or crop residues) that can be collected at reasonable prices for bioenergy use are expected to vary widely by location and other variables, Tab 4 (Rows 12 -16 and 75, 78, 105) collection percentages can be varied to account for local situations (red text indicates a number that can be varied).

However, the data for the MARINER macroalgae calculations have not been published. Only the techno-economic analysis spreadsheet (Capron et al. 2019a) and report (Lucas et al. 2019a) for AdjustaDepth are publicly available. Tab 6 (Rows 6 - 13) summarizes the calculations. One key number is available area (Gentry et al. (2017) reports 11 million sq km as appropriate for macroalgae and bivalve aquaculture with seafloor depth less than 200-m). Another is productivity (the spreadsheet uses 50 dry tonnes/ha/yr, based on Lapointe & Ryther (1978), Lapointe (1985), and Capo et al. (1999) who found values up to 125 dry tonnes/ha/yr). Cost per dry tonne harvested is calculated in the Capron et al. (2019a) spreadsheet based on the materials, energy, and labor needed to construct, deploy, plant, harvest, and maintain a structure modeled to survive a direct hit by a Category 5 hurricane.

These three numbers were provided by three other MARINER teams and shown on tab 6. The four sets of numbers were totaled to a potential of 60 billion dry tonnes/yr (D44) at a projected biomass-weighted average cost of $110/dry tonne (D45).

The other important unpublished data are HTL cost projections shown in Tab 8, based on private communications from Craig Pichach, CleanCarbon Energy, including a site visit and calculations by Professional Engineer Mark E. Capron. Note these costs are based on an engineering design, not a physical demonstration. However, the fact that commercial HTL plants are currently being built by Licella for a plastic feedstock demonstration in the United Kingdom (ReNew ELP, 2019) and by Steeper Energy (2019) in Denmark and Canada indicate HTL prices are commercially viable and thus potentially in the ranges projected for CleanCarbon Energy.

3. Results

3.1 Overview of two bracketing paths

Calculating for both a primarily wet biomass-to-biofuel process versus a dry biomass-to-electricity process, allows showing CDR results on two contrasting paths. The two paths, shown in Figure 2 as P_{fuel} and P_{electric}, represent extremes of either mostly biofuel or mostly electricity. Presenting two paths provides options for communities and nations to consider as they develop their individual blend of technology and infrastructure to best fit their unique culture, people, natural resources, and needs. In terms of global impact, one path and/or technology is no better than any other; however, at the community level, some paths and technologies are better than others. At both global and community levels, all paths address global food demand before significant production of biomass for energy.

The P_{fuel} and P_{electric} lines in Figure 2 are hand drawn using values calculated in the supplemental spreadsheet (SS) tabs 1, 2, 10. They present smoothed paths between 2018 emissions, net zero emissions in 2050 (calculated in Table 1), and maximum net CDR starting about 2070 (calculated in Table 2).

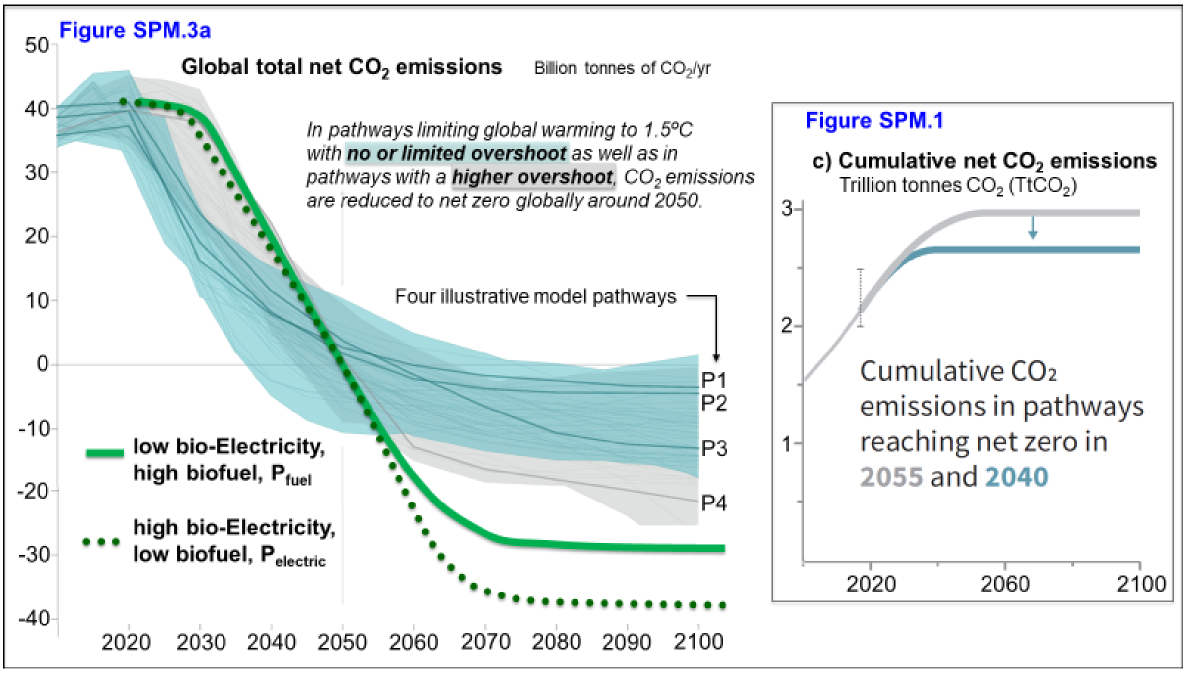


Figure 2. The two paths, P_{fuel} and $P_{electric}$, superimposed on the four pathways of the IPCC 1.5ºC target (IPCC, 2018) reflect annual emissions projections (Fig. SPM.3a) plus IPCC cumulative projections (SPM.1c). (Note: The P_{fuel} and $P_{electric}$ paths are smoothed lines between three calculated points. The IPCC Fig. SPM.3a pathways are smoothed lines with many calculated points. The original IPCC SPM.1c units were $GtCO_2$.)

3.2 Overview calculation results for net zero emissions and maximum net CDR

Tables 1 and 2 show the global energy, biomass, and CDR calculated in this paper. Table 1 (SS tab 2) outlines possible approaches to achieve net-zero emissions while using some fossil fuel by: (1) capturing and storing all CO_2 emitted by fossil-fuel electricity generation to make such electricity production carbon neutral, (2) capturing and storing some CO_2 from biofueled electricity production to offset some non-captured fossil fuel use, (3) capturing and storing most of the byproduct CO_2 produced when biomass is converted to biofuel to offset other fossil fuel emissions, and (4) carbon-negative biofuels and electricity replacing fossil-fueled transportation. Negative emissions from the captured and stored bio-CO_2 offset the use of fossil fuels (mainly natural gas) for heating and industry. After net zero CO_2 emissions, increasing biomass-fueled energy production with carbon capture removes CO_2 from the atmosphere at the rates indicated in Table 2.

Table 1. Balancing fossil fuel use, biomass-for-energy production, and bio-CO_2 sequestration for net zero emissions about 2050 (SS tab 1).

Metric	units	Low bio-electricity, high biofuel	High bio-electricity, low biofuel
Global fossil oil and natural gas use without sequestering the CO_2.	Billion barrels /yr (energy equiv.)	33	10
Global negative emissions biofuel production for non-electric use (transportation, industry, heating)		7	0
Global carbon neutral electricity (solar, wind, nuclear, fossil fuel with emissions capture, etc.)	Billion MWh/yr	15	56
Global carbon negative electricity (biomass with carbon capture and sequestration)		35	14
Biomass production **at net zero** (mix of waste, *Miscanthus* and similar, and macroalgae)	billion dry tonnes/yr	13	3

Resulting approximation of fossil- and bio-CO_2 sequestration **(at net zero)**	billion tonnes/yr	26	28
Computed net CO_2 emissions	**billion tonnes/yr**	**0.0**	**0.0**

Table 2 (SS tabs 1, 2) outlines the two alternative global energy demands used to calculate required bio-CO_2 sequestration by 2070 and beyond. The P_{fuel} path proposes a little more liquid biofuel than the 2018 demand for oil with relatively little bioelectricity. The $P_{electric}$ path assumes that the demand for bioelectricity is over twice the 2018 demand for electricity with one quarter of the 2018 demand for liquid fuel. Specifically, $P_{electric}$ involves mostly electric transportation, commercial, and residential energy use (little natural gas or biofuels).

Table 2 shows estimated plug-in values (in red) and computed numbers (in black). The variable plug-in numbers are illustrative of possibilities interpolated from 2018 global statistics. SS tabs 1 and 2 include more plug-in numbers, show the formulae, provide references, and offer opportunities for various "what if" calculations. The two paths in Tables 1 and 2 are designed to contrast: (1) P_{fuel}, the "low bioelectricity" path where most electricity is produced by conventional renewables and nearly all biofuel production is consumed by transportation; and (2) $P_{electric}$, the high bioelectricity path that maximizes Allam Cycle bioenergy with carbon capture and storage (BECCS) with most transportation electrified. P_{fuel} requires somewhat more biomass production than $P_{electric}$ with a slightly slower return to pre-industrial CO_2 levels.

Table 2. Two paths of energy demand and supply a few years (~2070) after net CO_2 emissions drop to zero around 2050 (SS tab 2).

Metric	Units	P_{fuel}: low bioelectricity, high biofuel	$P_{electric}$: high bioelectricity, low biofuel
Global population	Billion	10	10
Projected global average electricity generation in 2070* (2018 world average: 3.5 MWh/capita, China: 5.0, US: 13.6, Japan: 8.3 (BP, 2019))	MWh/yr/person	5	7
Projected global electricity generation in 2070 (2018 global electricity generation was 27 billion MWh per year (BP Statistical Review of World Energy, 2019))	Billion MWh/yr	50	70
Fraction of global electricity production projected to be BECCS with the remainder nuclear or renewable: solar PV, solar thermal, wind, hydro, wave, geothermal, etc.	%	22%	67%
Global non-electric HTL-produced biofuel use (transportation, industry, heating) (global oil demand of 100 million barrels/day (14 million tonnes/day) or 37 billion barrels/yr in 2018 (U.S. Energy Information Administration, 2020))	Billion barrels/yr	40	10
Global biomass production for Allam Cycle electricity BECCS	Billion dry tonnes/yr	4	17
Global biomass production for non-electric biofuel		35	9
Global biomass production for HTL bio-construction materials (asphalt, plastic, carbon fiber, textiles, etc.)		4	4
Total global biomass production (well past net zero, perhaps 2070)		**43**	**30**
Mass of bio-CO_2 captured and stored (well past net zero, perhaps 2070)	**Billion tonnes of CO_2/yr**	**28**	**38**
Year when 2 trillion tonnes of CO_2 are removed from atmosphere and ocean and permanently sequestered	**Year**	**2130**	**2110**

*Although the P_{fuel} path shows only a small increase in per-capita electricity from present levels, it assumes that the UN SDG goal of doubling the global rate of improvement in energy efficiency by 2030 continues so that universal access is achieved, but little additional energy is needed. The P_{fuel} path is an extreme case in that it assumes little increase in electric vehicles with most powered by carbon neutral biofuels.

Tables 1 and 2 quantify the steps in Figure 3 to demonstrate how net-zero emissions are technically feasible by 2050. Every component of Figure 3 can scale quickly using existing demand and supply chains.

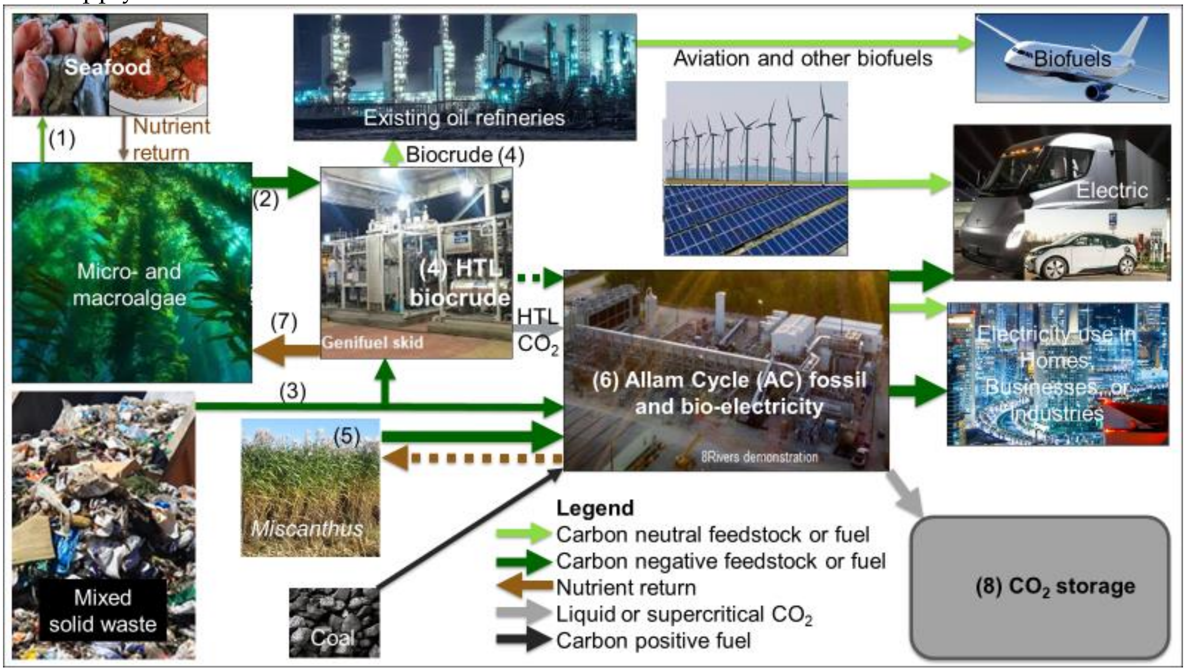


Figure 3. Process overview for mature (2070 and beyond) production of food, energy, and CO_2 sequestration. It is a simplified representation of the future global energy system with future oceanic integrated food and energy systems. It does not show terrestrial food systems. Each country and community will determine how much of each component is appropriate depending on local economics. (Note: *Miscanthus* represents all terrestrial biomass including wood waste, agricultural residues, etc. that might be gasified directly at the Allam Cycle electricity facility or fed to HTL. Solid waste represents organic sludges, food waste, paper, and plastics that are not recycled some other way. Micro- and macroalgae represent all watery biomass including seagrass and freshwater plants. The darker green and thicker arrows are paths to more bio-CO_2 storage (CO_2 removed from the environment, i.e., negative emissions). The lighter green and thinner arrows lead to carbon-neutral emissions, including bio-CO_2 emissions from combustion by airplanes, or wind and solar power.

The costs, values, and relative local scale for each process and arrow in Figure 3 can be modified in the supplemental spreadsheet for any given time and location. Potential variations and uncertainties include how fast will oil prices recover after the COVID-19 pandemic and what are the effects of millions of barrels per day of inexpensive HTL biocrude made from solid waste? Price unknowns arise in the early learning curve for employing new technologies. Some carbon neutral fossil-fueled electricity with 97%+ CO_2 sequestration could continue. Economics are explained in more detail in the Supplemental Document (SD) and Spreadsheet (SS). Numbered economic and sustainability considerations labeled in Figure 3 include:

1) Increasing seafood production can start now with excess and artificial nutrients (subsection 3.3, SS tab 18).
2) Ocean (aquatic) plants produce wet biomass feedstock for food and energy (subsection 3.3, SS tabs 4 and 6).
3) Wet solid waste is the initial feedstock for HTL biofuel. Dry solid waste can be the initial biomass feedstock for Allam Cycle electricity.
4) About 60% of the carbon in biomass or most plastics becomes biocrude oil during HTL (subsection 3.3). Biocrude can be refined at existing refineries. About 40% of the

carbon can be recovered as a mixture of fuel gas and CO_2 for Allam Cycle (or other) electricity and heat co-generation or the CO_2 can be separated and sequestered.

5) Dry terrestrial biomass can be gasified for Allam Cycle electricity production with carbon capture and sequestration.
6) The Allam Cycle (subsection 3.6) produces electricity from gasified coal, gasified biomass, or natural gas at 40−60% efficiency while also producing pure CO_2 compressed to 100-bar ready for sequestration.
7) Nutrient recycling is essential for sustained production of seafood and energy (subsection 3.4).
8) There are many ways to permanently sequester CO_2 (subsection 3.7).

3.3. Biomass production details

Tables 1 and 2 indicate the necessary scale of total biomass production. A higher proportion of the biomass for the "low bioelectricity, high biofuel" path will be "wet" such as macroalgae, food and green waste. A higher proportion of the biomass for the "high bioelectricity, low biofuel" path will be "dry" such as *Miscanthus*, paper and plastic.

Wet biomass production starts with seafood grown in total-ecosystem aquaculture (TEA) or other systems (Buschmann et al., 2017; Kim et al., 2017a, 2017b; Knowler et al., 2020; Park et al., 2018; Radulovich et al. 2015; Shi et al., 2018) provides food and oxygen for traditional seafoods (i.e., finfish, crabs, oysters, and the like). Gentry et al. (2017), Froehlich et al. (2019), and Theuerkauf et al. (2019) provide global overviews of potential locations. The SD explains that TEA adaptation research is needed to ensure seafood and biomass productivity with biodiversity in warming tropical waters. Fish are currently migrating toward Earth's poles to escape marine heat waves (Hastings et al., 2020).

While harvesting seafood, macroalgal biomass-for-energy production would be demonstrated and improved. Fish and shellfish production should cost less than \$2/kg on average. Domestic sales might be \$1−2/kg while exports earn \$4/kg or more at the dock. At \$2/kg, one billion wet shell-on tonnes of seafood would be worth \$2 trillion/yr. When demand for biomass-for-biofuel rises, aquaculture ecosystems can be managed to simultaneously produce both a 0.5 billion wet tonnes of seafood and 3 billion wet tonnes (0.3 billion dry tonnes) of macroalgae for energy. At \$100/dry tonne (Lucas et al. 2019a), this start-up macroalgae-for-energy would be worth \$30 billion/yr.

Expected GHG emissions from TEA-grown seafood is 2.7 tonnes CO_{2eq}/tonne live weight (the average of wild marine fishery emissions (Parker et al. 2018) and aquaculture emissions (MacLeod et al. 2020) (see more discussion in SD, plus SS tab 24).

The P_{fuel} path presumes increasing ocean net primary productivity by 40% or about 40 billion dry tonnes/yr. The $P_{electric}$ path projects increasing terrestrial net primary productivity by 15% or about 17 billion dry tonnes/yr. Currently, the world's net primary productivity is near 210 billion tonnes/yr of biomass (Field et al., 1998). Total land productivity is about 110 billion tonnes on an area of 150 million km^2. Ocean productivity is about 96 billion tonnes on 360 million km^2. This suggests that oceans are under-producing relative to land; this could be remedied by ensuring nutrient recycling and building structures supporting macroalgae or seagrass production in the photic zone. See SD Section 3.3 for a discussion of how macroalgae-for-fuel expansion into "nutrient deserts" can amplify ocean biodiversity more than traditional marine protected areas.

Primary conclusions from Table 3 include:

- Globally, there is excess potential additional biomass, 60−100 billion dry tonnes/yr, much more than the 30−40 billion dry tonnes/yr needed in these projections. Thus, there is no need to use wood from forests, which is often regarded as unsustainable (Hudiburg et al., 2013). More discussion in SD.
- There is more than enough organic solid waste (including mixed biosolids, paper, plastic, food waste, etc.) (Kaza et al., 2018) for 20 million barrels/day (by 2050) of sweet biocrude oil (SS tabs 4, 7, 11, 12).
- Every kind of biomass or waste (wet or dry) can contribute, which means every country can participate in some form of biomass production.

- While there are obvious differences in maximum scale and cost, most biomass sources can be turned into a viable industry.
- These numbers are speculative in that macroalgae projections are based on theoretical studies, not physical demonstration projects.

Table 3. Estimated global biomass production possibilities for some biomass sources (SS tab 3).

Metric	Estimated global scale at indicated cost[1]	Estimated cost delivered to energy process	Estimated energy-return ratio[2]
	Billions of dry tonnes/yr	$/dry tonne	E_{out}/E_{in}
Organic waste including mixed biosolids, paper, plastic, food waste, etc.[3]	5−7	$(200) −20	4−20
Terrestrial agriculture residues and purpose-grown biomass-for-energy (*Miscanthus*, etc.)[4]	6−20	$0−400	1−50
Macroalgae with total ecosystem aquaculture[5] paying for the structure	0.1−0.3	$40−70	20−50
Microalgae, mixed species, microbes, and plants[6]	Small, due to high cost	$400−2,000	0.4−1.1
Macroalgae, anchored systems[7]	10−15	$125−145	8−20
Macroalgae, free-floating systems[8]	40−60	$75−180	4−12

[1]Terrestrial material scale and cost are from references in SS tab 4. Macroalgae scale and cost are interpolated from TEAs anticipating technologies and systems (SS tab 6). The analyses were funded by the U.S. DOE's ARPA-E MARINER Program (2017b).

[2]Terrestrial material energy-return ratios are from references in SS tab 4. Macroalgae energy-return ratios were defined as the lower heating value of macroalgae for the energy out (E_{out}) and the energy required for planting, growing, harvesting, and transporting to the energy processor for energy in (E_{in}). The embedded energy in the structure, ships, etc. is approximated by the capital cost of those items converted to $/dry tonne. The operating energy is approximated as the cost of biofuel or the capital cost of ambient energy (solar, wave, wind) converted to $/dry tonne.

[3]Solid waste pays a disposal fee as if the HTL unit was a landfill. Landfill fees in the U.S. range from $30−100/wet ton ($120−400/dry tonne) (Environmental Research & Education Foundation, 2019). Negative values (because solid waste has a disposal fee) could produce oil for $0/barrel. E_{in} is the difference between the energy expended now to collect and transport solid waste to landfills compared to the energy expended to collect, transport, and process it at HTL facilities. Quantity from Kaza et al. (2018).

[4]Based on data from Kaza et al. (2018); Turner et al. (2018); REN21 (2019); U.S. Department of Energy (2018); Eisentraut (2010); Daly &Halbleib (2014); Das et al. (2019); Pandur et al. (2015). (SS tab 4). Significant dry biomass could be delivered to the electricity process (Allam Cycle) for $50/tonne about the same price as US coal at $2.5/GJ ($2.6/MMBTU) (SS tab 4).

[5]The scale of high-protein products paying for the structure (so that the cost of biomass-for-energy can be as low as $40/DMT) is limited by the demand for high-protein seafood (Capron & Piper, 2019; Capron et al., 2019, 2020a, 2020b)

[6]U.S. Department of Energy (2018) and Jiang et al. (2019) projected a range of $400−2,000 per dry ash-free tonne of microalgae in their techno-economic uncertainty analysis. Energy return on investment (EROI) from Zaimes & Khanna (2013).

[7]The area available for anchored macroalgae systems assumes seafloor depths from 0−200 m, generally on relatively flat continental shelves (Lucas et al., 2019a). There are moored systems appropriate for deeper seafloors and steep slopes (Sims et al., 2019). Figure 11 in SD suggests that wet biomass delivered to the biofuel process (HTL) for less than about $120/dry tonne would produce biocrude oil for less than about $70/barrel.

[8]Free-floating deep-ocean systems access large open-ocean areas by floating in currents, eddies, and gyres with minor steering inputs. Individually free-floating plants include *Sargassum* (*S. fluitan*s and *S. natans*) (Sherman et al., 2018). Attached growth plants on free-floating structures (Huesemann et al., 2017) include *Saccharina japonica*, *Saccharina latissima*, *Undaria pinnatifida*, *Nereocystis luetkeana*, *Gracilaria tikvahiae*, *Gracilaria edulis*, *Gracilariopsis lemaneiformis* and *Sargassum polycystum*. (SS tabs 4 and 6)

The bottom line is that there is more biomass potentially available at reasonable prices than is needed for either the $P_{electric}$ path, which uses 17 billion dry tonnes of dry biomass for Allam Cycle and 13 billion dry tonnes of wet biomass (food/green waste + macroalgae) for HTL, or the P_{fuel} path, which uses 4 billion dry tonnes of dry biomass and 39 billion dry tonnes of wet biomass (see SS Tabs 2, 3, 4).

The availability of large quantities of ocean biomass relieves pressure on terrestrial sources of biomass, which are increasingly limited by demands for food as well as climate impacts. TEA could grow 1 billion tonnes/yr of seafood on less than 10% of the suitable continental shelf less than 200-m seafloor depth (identified by Gentry et al., 2017). That would be about 0.3% of the world's oceans (SS tabs 6 and 18). TEA could grow 39 billion dry tonnes of oceanic biomass-for-energy on 7% of the world's oceans, including some deep ocean areas (SD 3.3 and SS tab 6). The remaining 93% of ocean area would not be needed for food or bioenergy production.

3.4. Nutrient recycling details

The 17 billion dry tonnes/yr of terrestrial biomass for the $P_{electric}$ path (Table 1) requires about 50 million tonnes/yr of nitrogen (SS tab 12) and proportional amounts of phosphorus, potassium, iron, boron, copper, manganese, molybdenum, zinc, nickel, and other micronutrients. Gasification (start of the Allam Cycle process for coal and dry biomass) converts the nitrogen to N_2 gas. Lost nitrogen might be made up with advances in nitrogen-fixing crops or increased artificial nitrogen production. Other nutrients can be recovered from the solid residues.

The 39 billion dry tonnes/yr of oceanic biomass for the P_{fuel} path, requires cycling 1.2 billion tonnes/yr of nitrogen (SS tabs 12 and 18) from the ecosystem-to-energy process and back. Proportional amounts of phosphorus, potassium, iron, boron, copper, manganese, molybdenum, zinc, nickel, and other micronutrients cycle along with the nitrogen. HTL recovers virtually all N as ammonia in the "leftover" water. Other nutrients are recovered in the solid residues. Because recycled nutrients (such as sewage biosolids) contain a complete array of micronutrients, they are also more beneficial to biomass growth than commercial fertilizer (Wesseler, 2019; Pan et al., 2017).

Other reasons for recycling nutrients (computations and references in SS tab 18):

- Buying ammonia would add $24/tonne to the cost of oceanic biomass, (i.e., add US$22/barrel to the cost of biocrude oil produced by HTL) based on values used by Jiang et al. (2019). There are additional costs for other nutrients, such as phosphates.
- 2018 global artificial nitrogen production of 176 million tonnes of N, production of which emitted 505 million tonnes of CO_2. Between 75 and 90% of manufactured ammonia is used for agriculture. Artificial nitrogen fertilizer production already produces ~1% of global CO_2 emissions (Brown, 2016).
- If nutrients after energy production were not recycled, waste-treatment costs using conventional "wastewater" biologic nutrient removal processes would increase the cost of bio-oil by $60/barrel.
- 1.2 billion tonnes of inorganic nitrogen is available in 2–3 million km^3 of deep ocean water. Removing the inorganic nitrogen (and other nutrients) from a few million km^3 of deep ocean water each year is not sustainable. Temporarily upwelling a smaller amount of deep ocean water to start and expand primary production may be acceptable.
- Upwelling deep ocean water for nutrient supply brings up CO_2, drops surface water pH (ocean acidification), and might increase the amount of CO_2 in the air (Chan et al., 2008; Feely et al., 2008; Köhn et al. 2017; Ries, 2010).
- Several processes (in addition to HTL, such as anaerobic digestion (Laurens et al. 2020)) convert macroalgae to energy with good efficiency while separating most of the carbon from the nutrients. These separated nutrients can be returned to the macroalgae ecosystem during harvesting without significant cost (Lucas et al. 2019b).

3.5. HTL details

Recent innovations and cost reductions with HTL (Genifuel, 2019; Jiang et al., 2019; Jiao et al., 2017; Pichach, 2019; ReNew ELP, 2019; Steeper Energy, 2019; Watson et al., 2019) make it practical to scale up as a solid waste-collection system that pays for itself. HTL converts to bio-oil any blend of wet plants, paper, wax, and most plastics (except thermosets, about 14% of total plastics (American Chemistry Council, 2019). This could include expired juice in plastic bottles, newspaper, expired packages of meat, seaweed, microalgae, switch grass, feces, biohazard wastes in plastic – all chopped and blended together. The process is analogous to the way algae became oil when buried deep in the Earth. By using a combination of high temperature (350ºC, 660ºF) and pressure (200 atmospheres, 3,000 psi) the conversion to oil is complete in about 30 min. Because the reaction temperature is less than 400ºC, all plant nutrients can be recovered and used to grow more plants (see SD 3.5).

There are many processes that convert wet biomass or wet organic waste to energy. There are many processes that convert most plastics (a dry material) to the raw material for new plastics or energy. HTL is the only process that converts both as a blended feedstock into energy. Eventually, all the plastic will be made from plants or biocrude and become biocrude or new plastics in a circular economy.

Because it produces biocrude, oil companies view an HTL facility as if it were a large oil well. All the existing oil handling and consumption infrastructure mean the transition from fossil fuel to biofuel is as fast as the waste collection, macroalgae production, and HTL facilities can scale. Even so, many factors, which vary with location, will determine which of the variety of processes is best for that location.

In the CleanCarbon Energy (CCE) HTL process (Pichach, 2019) about 60% of the carbon in the biomass becomes biocrude. The other 40% becomes byproduct carbon in the forms of biochar, CH_4, and CO, all of which can be converted to energy, plus CO_2, which can be captured for sequestration. SS tab 11 quantifies the amounts of sweet biocrude and the byproduct carbon.

HTL technology is nearly commercial now based on substantial research and development in many countries. Recent examples include work at the U.S. Pacific Northwest National Laboratories with U.S. DOE funding (Jiang et al., 2019). Aarhus University (Denmark) has investigated using HTL to recover phosphorus and carbon from manure and sewage sludge with Horizon 2020 funding (Bruun, 2019). Several companies are preparing ever larger demonstrations of HTL devices including Genifuel in the USA (2019)[4], Licella (based in Australia) with a plastic feedstock demonstration in the United Kingdom (ReNew ELP, 2019), Steeper Energy (2019) in Denmark and Canada[5], and CleanCarbon Energy in Canada (Pichach, 2019).

Developed countries could accelerate deploying commercial HTL with commercial scale demonstrations (100 to 4,000 wet tonnes/day). Demonstrations are needed because HTL processes have been developed so far for less-than-commercial scale with single consistent feedstocks. Solid waste will be a mixed and inconsistent feedstock requiring more sensors to predict its properties and controls to produce a consistent refinery-ready biocrude product. Developed country communities could pay for demonstrations using the disposal fees they collect to safely recycle and dispose of solid waste. After demonstrations clarify costs, HTL could be deployed in both developed and developing countries to replace landfills. Each community would determine their optimum balance between the amount of collected (and uncollected) waste, their disposal fees, and their resulting income from the sale of biocrude oil, electricity, and other products. See discussion in Table 3, Note 3, with details and graph in SD section 3.5.

3.6. Allam Cycle details

The Allam Cycle (8 Rivers Capital, 2020; Allam et al. 2017; Fernandes et al. 2019; McMahon, 2019) first makes pure oxygen separated from air. The left-over nitrogen and argon from air separation can be sold. Inside the Allam Cycle combustion chamber, pure O_2, the fuel (gasified coal, gasified biomass gasified plastic, or natural gas), and CO_2 (for cooling the combustion chamber) mix. After spinning the turbine, all the CO_2 is compressed and cooled. Most is recirculated. A little, 3 to 5%, depending on the type of fuel, is available as liquid or supercritical sequestration-ready CO_2. Its pressure, 100 to

150-bar (10 to 15 MPa, 1450 to 2,175 psi), will push it through a pipeline for direct injection into underground or underwater sequestration.

Allam Cycle power plants can produce electricity and byproduct liquid CO_2 using any biofuel or fossil fuel. Initially, we propose they run on fossil fuels (natural gas or gasified coal) but be converted to biofuels as rapidly as biofuels become available. Because the fossil-fuel supply chain and much of the electrical distribution system is already in place, fossil-fueled Allam Cycle carbon-neutral power plants can replace all expansions and replacements for fossil-fuel electricity production in less than two decades.

There are more designs for electricity with carbon capture and storage than just Allam Cycle. Several, including Allam Cycle, have detailed technical and cost analyses presented at the website for the U.S. DOE's Coal FIRST program (2020). Allam Cycle is used throughout this paper because its projected cost of electricity from gasified coal, with sequestration-ready CO_2 at 100-bar pressure is only $74/MWh, using typical US coal costs. The other six Coal FIRST program projects captured a lower fraction of produced CO_2 at 1-bar pressure. Adding $12/MWh for compression of CO_2 from 1 to 100-bar (SS tabs 14 and 15), their projected costs ranged from $118 to $243/MWh. (Fuel costs and byproduct sales differ, which complicates this comparison.)

James et al. (2019) prepared a standard baseline report for several power plant processes with CCS. The process with the least avoided cost, supercritical pulverized coal (SC-PC), showed a levelized cost of electricity is $64/MWh without CCS or $109/MWh with 90% carbon capture. (These are James' figures without transport and sequestration (T&S) costs with an added $3/MWh to compress from James' 15-bar to Allam Cycles' 100-bar.) Irlam (2017) reports similar values to James. See Section 3.6 for a discussion of costs in terms of $/tonne of CO_2 sequestered.

8 Rivers Capital (2020) explains that early adopters can sell gas products argon (Ar), nitrogen (N_2), and CO_2 and use the income to decrease the price of electricity to $55/MWh ($54 less than SC-PC coal with CCS).

Using the existing global coal supply chain combined with a design that facilitates mass production may mean that Allam Cycle electricity with CO_2 sequestration is the fastest way to net zero emissions. Funding agencies could purchase blocks of a thousand factory-built 300 MW power plants at a time. In addition to lower costs from mass production, this action will increase budget certainty for developing countries as they switch to Allam Cycle power. Fast start-up is encouraged while the oil industry is still buying CO_2 for enhanced oil recovery. Income from selling CO_2 for EOR will decrease the cost of electricity. (8 Rivers Capital (2020) estimated in early 2020 that the global demand for CO_2 used for EOR is equivalent to nearly 6,000 of the 300 MW Allam Cycle power plants or 1,800 GW.)

NET Power (a subsidiary of 8 Rivers) targets commercial deployment of 300-MW natural gas Allam Cycle power plants in 2022 (McMahon, 2019). 8 Rivers has proposed a demonstration of a 300-MW Allam Cycle with coal gasification at a Wyoming coal mine including selling all the argon and CO_2. The commercial operation date would be 2026 (8 Rivers Capital, 2020). Allam Cycle power plants are almost zero emissions and have operating flexibility that reduces the need for battery backup of solar and wind energy (8 Rivers Capital, 2020). They also provide "firm" power which has been calculated by Sepulveda et al. (2018) to reduce overall electricity costs in decarbonized scenarios. See discussion in SD Section 3.6.

3.7. CO_2 sequestration details

There are many options for liquid CO_2 sequestration start-up using the current 13 billion tonnes/yr of fossil-fueled CO_2 emissions from electricity generation. There are many more carbon and CO_2 storage techniques appropriate for situations other than low-cost liquid CO_2 not discussed in this paper. The options shown in Table 4 can retain acceptable costs while scaling for the safe sequestration of trillions of tonnes of liquid CO_2 produced by the HTL and Allam Cycle power plants. They include geologic CO_2 sequestration in depleted oil and gas wells and brine aquifers (Turner et al., 2018; Deng et al., 2017; Alcalde et al., 2018), basalt and other rocks on land and sub-seafloor (National Academies of Sciences, Engineering, Medicine, 2018; Kelemen et al., 2019; Snæbjörnsdóttir et al., 2020, Moran et al. 2020). Other authors have analyzed secure contained seafloor storage either as liquid (Caserini et al., 2017) or as CO_2-hydrate (Brewer, 2000; Capron et al., 2013).

SD includes more discussion of the concepts and results in Table 4, including how the different approaches to CO_2 storage complement each other.

Table 4. Liquid or supercritical CO_2 sequestration scale and cost (SS tab 13).

Metric	Global scale of potential storage[1]	Global scale of injection rate	Cost for injecting into sequestration process with permanent monitoring and occasional repairs[2]		Leakage rate[3]
	billions of tonnes of CO_2	billions of tonnes of CO_2/yr	US$/tonne[4] of CO_2	US$/MWh[5] with CO_2 from Allam Cycle	%
Geologic sequestration[6] in emptied oil wells, gas wells, and brine aquifers (negative costs are for enhanced oil recovery (EOR)	2,000 to 5,800	large uncertainty	-\$40 to \$56 most w/o EOR below \$8	-\$27 to \$40, most below \$5	< 0.9% of total per 1,000 years
Mineralization sequestration in on land basalt and peridotite rocks[7]	more than 1,000	more than 10	\$10 to \$30	\$7 to \$20	Negligible
Mineralization sequestration in subsea basalt rocks[7]	more than 20,000	much more than 20	\$200 to \$400	\$140 to \$300	Negligible
Contained CO_2-hydrate storage on the seafloor or liquid CO_2 in glass containers[8]	more than 20,000	much more than 20	\$5 to \$17	\$3 to \$12	<0.06% per 1,000 years

[1]Many countries have geologic resources for only one of the four options. Not every option guarantees the necessary scale.

[2]The cost range for geologic storage represents variations in geology, meaning some countries will have inexpensive storage sites and some will have expensive geologic storage. Mineralization costs depend on the characteristics of the local rocks and the depth of drilling required. The range for hydrate storage costs reflects the current situation of relatively little research and development.

[3]Leakage of 0.9% over 1,000 years (Alcade et al., 2018) applied to 2 trillion tonnes of CO_2 would be 18 million tonnes of CO_2/yr. Or 0.06% over 1,000 years (Capron et al., 2013) applied to 2 trillion tonnes is only 1 million tonnes of CO_2/yr. (SS tab 13).

[4]Costs do not include capturing, compressing, and transporting pure CO_2 (Compression from 30 to 100 bar is projected at \$1/t, from 1 to 100 bar at \$14/t in tab 14 of Supplemental Spreadsheet). Transportation costs are highly dependent on distance to suitable storage location estimated at \$2 to \$3/t for 100 km (National Academies of Sciences, Engineering, Medicine, 2019).

[5]Different fuels have different \$/MWh (with the same \$/tonne of CO_2) due to differences in their electrical efficiency and their carbon:hydrogen ratio. This column shows the \$/MWh using gasified coal into Allam Cycle plant. The Supplemental spreadsheet shows it for other fuels. Note that US\$10/MWh corresponds to 1 cent/kWh

[6]With geologic or mineralization storage, the injection rate of CO_2 should not exceed that which causes earthquakes or leaks due to high pressure in the ground near the injection point (Deng et al., 2017).

[7]The actual mineralization rate depends on the characteristics of the local rocks (McGrail et al., 2017; Snæbjörnsdóttir et al., 2020). See SD for maps and discussion of different types of rocks with more references (Gunnarsson et al., 2018; Kelemen et al., 2019; Moran et al., 2020).

[8]Contained seabed storage scale and injection rate is essentially unlimited. It may be the least expensive option for coastal communities with short distances to >500 m depths. From Capron et al. (2013) but updated in SS tab 17. Note that Caserini et al. (2017) project ~\$17/t storing liquid CO_2 at depths between 1000 and 3000 m (more in SD).

3.8. Costs of CDR

Legacy CO_2 is commonly thought of as CO_2 from emissions already in the atmosphere and ocean (Friedlingstein et al., 2019; Knutti & Rogelj, 2015). This paper's calculation includes future fossil-fuel

CO_2 uncaptured emissions in the total legacy CO_2 to be removed from the air and oceans. The total cost is a cost to society in the form of higher energy costs. The cost calculation below is an apples-to-apples comparison with:

- $150/tonne for direct air capture (in 2019 USD) (Baker et al., 2020);
- $74/tonne ($52/MWh) (James et al., (2019) breakeven emissions penalty (aka "avoided") cost when adding CCS to a SC-PC coal power plant, the lowest cost option in James' Exhibit ES-4). Costs may be slightly higher when biomass replaces coal (BECCS).

3.8.1. Capture

The first added cost and energy component of removing and storing legacy CO_2 is for capture. That is concentrating the CO_2 about 2,500 times from a little over 0.04% in air to >95%. Allam Cycle power plants always capture the combustion CO_2 when they produce electricity, so the added cost for capture is zero.

3.8.2. Compression

The second added cost and energy component is for compressing the pure CO_2 to a liquid or supercritical state for permanent sequestration, which varies for the following different situations:

- <u>CO_2 capture from Allam Cycle</u> – Each 300-MW coal- (and likely biomass)-fired power plant compresses 4,600 tonnes/hr of CO_2 from 30 to 150 bar. Most of the CO_2 is recirculated working fluid. About 230 tonnes/hour is produced from coal for sale or sequestration. The energy required to compress CO_2 from a gas at 30 bar to a supercritical fluid at 100 to 150 bar is small, about 9 kWh/tonne (8 Rivers Capital, 2020). The combined energy plus other operating and capital costs are near $1/tonne of CO_2 for coal or $2/tonne for natural gas. This is based on data from Fernandes et al. (2019), Atlas Copco CO_2 compressors (2020), Allam et al. (2017), and 8 Rivers Capital (2020) (SS tab 14).
- <u>CO_2 capture from HTL</u> – HTL produces bio-crude plus fuel gas that could be combusted with air such that it produces gas with a high fraction of CO_2 (10 to 20%) at 1 bar. Capturing >95% of the CO_2 costs about $40/tonne of CO_2. Compressing CO_2 from 1 to 100 bar requires about 130 kWh/tonne of CO_2. The combined capture, energy plus other operating, and capital costs are near $65/tonne of CO_2. Most of the cost is for capture and compressing energy, which varies significantly by location, by technology, and over time, as indicated in Table 5.
- <u>Hybrid of HTL co-located with Allam Cycle</u> – HTL's byproduct fuel gas and CO_2 at 1 bar would be blended and provided as fuel (low-grade fuel gas) to the Allam Cycle. Its value as fuel should cover the cost of compressing it to the required fuel pressure. This situation's capture and compression cost should be similar to the $1 or $2/tonne of CO_2 for the Allam Cycle situation (SS tab 14).

3.8.3. Transportation

The third added cost component (relatively little energy needed because the CO_2 is a supercritical fluid with very little friction) is the capital cost for transportation, which has been projected by National Academies of Sciences, Engineering, Medicine (2019) as $2/tonne for a 100 km pipeline.

3.8.4. Storage

The fourth added cost is sequestration of the pure, compressed CO_2. Table 5 (SS tabs 13 and 14) values are based on transportation and storage costs of $10/tonne of CO_2. (We note that James et al. (2019) and Rubin (2015) used $9/MWh in SC-PC avoided cost calculations ($12 per tonne of CO_2) for transportation and storage.) This paper uses $8/tonne of CO_2 as an average cost of sequestering liquid or supercritical CO_2 because Turner et al. (2018), Deng et al. (2017) and others project costs for many saline aquifers as $1 - $8/tonne. In addition, Table 4 shows negative costs (a credit) for those able to sell CO_2 for EOR (see more discussion in SD).

3.8.5. Input fuel cost

A fifth cost component is the varying cost of fuels plus economics of the new and old technologies for converting fuel into liquid fuel and/or electricity and process heat. For example, if the new fuel source is less expensive (such as solid waste) than the old fuel (such as liquified natural gas), capturing and sequestering CO_2 might have negative additional cost (Table 5, first two rows). Similarly, if the new fuel source costs $11/GJ (such as HTL biocrude from macroalgae) instead of $2.5/GJ (U.S. coal), the additional cost might be $180/tonne of CO_2 (Table 5, bottom row).

3.8.6. Process cost

A sixth cost component is because different processes result in different levelized electricity cost ($/MWh) even with the same fuel cost ($/MMBTU). The process cost may also be expressed in $/tonne of CO_2 captured and compressed. The mainstream processes competing with Allam Cycle for fossil fuel or biomass electricity are supercritical pulverized coal (SC-PC) and combined cycle gas turbine (CCGT using natural gas). The Allam Cycle process cost with CCS appears to be $15/tonne of CO_2 higher than for SC-PC without CCS (based on statements in 8 Rivers Capital (2020), explained in SD, used in Table 5).

3.8.7. Total cost

Each row in Table 5 presents the sum of the six cost components to society of producing electricity, capturing CO_2, compressing it to liquid, transporting it, and permanently sequestering it, while showing the outcomes using the Allam Cycle process and varying fuel cost.

The transportation and sequestration cost of $10/tonne of CO_2 is included in all rows. (Rows 1 and 2 are negative because the cost is offset by income from waste disposal fees and sales of gases.) A local analysis is required to show the local cost differences for each technology with the local cost of fuel. The assumptions and variables in Table 5 include (see calculations and explanations in SS tab 14):

- Waste can be converted to inexpensive energy with CO_2 capture and sequestration because disposal fees decrease the cost of fuel.
- Terrestrial (dry) biomass (agricultural wastes and purpose-grown biomass) costs about the same as coal. That might be $1.9/GJ in some countries (such as US) and $4.7/GJ in other countries (such as Japan which is dependent on imported coal at about $100/tonne).
- The hybrid of HTL co-located with Allam Cycle has about the same added cost for sequestering CO_2 as does Allam Cycle alone (greatly reducing the sequestration cost for the byproduct fuel gas and CO_2 generated during HTL).
- HTL biocrude and biogas made from purpose-grown biomass are likely to cost much more than coal or natural gas as shown in the bottom two rows of Table 5. Therefore, we assume essentially no HTL biocrude-from-macroalgae will be fed into Allam Cycle plants for electricity production; it will be used for transportation fuels.

SS tab 16 includes a traditional calculation of "avoided" or "breakeven emissions penalty" costs. With SC-PC$_{ref}$ and Allam Cycle$_{CCS}$ the avoided cost is $22/tonne of CO_2. This compares well with the slightly more conservative $26/tonne of CO_2 shown in Table 1.

Table 5. Added cost to society for capturing, compressing, and sequestering CO_2, changing from various fossil fuels to biomass fuels, and changing to Allam Cycle. Each row reflects a different local situation. Negative numbers mean reduced costs but are limited to early adopters using dry waste for fuel and able to sell gases. "No gas sales" means demand for more CO_2, argon, or nitrogen has dropped to zero. Results are calculated in SS tabs 14, 16.

Metric	Additional $/tonne of CO_2	Comment
Allam Cycle power plant gasifying $0/GJ ($0/MMBTU) dry waste in place of $7.6/GJ ($8/MMBTU) LNG, including income from sales of argon and nitrogen plus CO_2 for EOR	**-$260**	Lower electricity fuel cost possible when retaining solid waste disposal fees to offset Allam capital and operating costs.
Allam Cycle power plant gasifying $0/GJ ($0/MMBTU) dry waste in place of $2.5/GJ Illinois coal delivered in US, including income from gas sales	**-$45**	
Allam Cycle power plant burning terrestrial biomass delivered for the same $2.5/GJ as for US coal, no gas sales	**$26**	When fuel costs the same, all the additional cost is process change ($15/tonne), compressing ($1/tonne), transporting, and sequestering liquid CO_2 ($10/tonne).
Allam Cycle power plant burning $11/GJ HTL biocrude instead of fossil oil for the same $11/GJ, no gas sales	**$26**	
Hybrid co-located HTL and fossil-fired (some HTL biogas) Allam Cycle capturing and compressing CO_2 from both processes. Same $/GJ for biomass or fossil fuel, no gas sales	**$26**	
Standalone HTL facility using by-product biogas internally with internal capture and compression of by-product CO_2, no gas sales	**$75**	Using historic capture and compression average cost of $65/tonne plus the same $10/tonne for sequestration.
Allam Cycle power plant burning $11/GJ HTL biocrude in place of $7.6/GJ LNG (approximate), no gas sales	**$90**	Higher fuel cost increasing electricity price is most of the added expense.
Allam Cycle power plant burning $11/GJ HTL biocrude in place of $2.5/GJ coal (approximate), no gas sales	**$180**	

Table 1 shows globally about 28 billion tonnes/yr of fossil- and bio-CO_2 being sequestered on either path at net zero emissions. With mostly co-located HTL and Allam Cycle facilities, the global cost is 28 billion tonnes/yr times $26/tonne, which rounds to $730 billion/yr.

A range of 28 to 38 billion tonnes/yr of bio-CO_2 is being sequestered in Table 1 on either path for reducing atmospheric CO_2 concentrations (carbon dioxide removal (CDR)). Suppose an additional 20 billion tonnes/yr of fossil-CO_2 is generated and sequestered. The average net mass sequestered between the two paths is 53 billion tonnes times $26/tonne (from Table 5), which rounds to $1,400 billion/yr with mostly co-located HTL and Allam Cycle facilities.

If HTL is not co-located with Allam Cycle facilities, both paths would use $75/tonne for HTL byproduct CO_2 capture, compression, and sequestration. The HTL-focused P_{fuel} path would cost about $2,300 billion/yr. The Allam Cycle-focused $P_{electric}$ path would total about $1,900 billion/yr (SS tab 14).

US$1,400 billion/yr ($26/t) is $175/person/year for 8 billion people, $700/yr for a family of four (much better than CDR at $150/tonne, which would cost a family of four nearly $4,000/yr). On the other hand, $1,400 billion is only 1.6% of the total global 2019 gross domestic product of $87 trillion (StatisticsTimes, 2019). The SD provides more discussion about the following:

- Process cost explained
- Putting the cost of sequestering CO_2 in perspective
- Lower costs for early adopters
- Allocating costs for removing legacy CO_2
- Examples of fossil-CO_2 fees and sequestration payments

3.9. SDGs details

These multiple interrelated systems can start by achieving UN SDGs and expand in scale to reduce CO_2 levels. These systems are interrelated in that the most circular economy (cradle-to-cradle manufacturing) and the best economics occur when the systems are co-located. Systems include the following nine items.

3.9.1. Food systems with lower CO_{2eq} emissions (SDGs 1, 2, 3, 13, 14, and 15)

Total ecosystem aquaculture systems are built-reef ecosystems with nutrient recycling that can provide abundant, inexpensive multi-species seafood. Distributed globally, seafood reefs (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b; Chambers, 2013; Lucas et al., 2019a, 2019b) can sustainably and economically produce a billion tonnes/yr of seafood by 2050. That is, the necessary ocean surface area and amount of recycled nutrients are available to produce an additional billion tonnes of seafood per year. Combined meat and seafood production in 2019 was about 500 million tonnes per year. The FAO (2018a) expects demand for meat and seafood may about double by 2050. That implies that a half billion tonnes of seafood could fill the gap. Average meat GHG impact is about 17 tonnes of CO_{2eq} per tonne of meat (Ritchie & Roser 2019; Poore & Nemecek 2018). Seafood GHG impact is about three tonnes of CO_{2eq} per tonne of seafood (including both wild-caught and aquaculture) (MacLeod et al. 2020; Parker et al. 2018). A business-as-usual increase in both meat and seafood production would mean 13 billion tonnes of $CO_{2eq.}$ Continuing 2018 meat and seafood production levels and adding a half billion tonnes of TEA seafood would total eight billion tonnes of CO_{2eq}, a savings of five billion tonnes of CO_{2eq} (see SS tab 24).

Land-locked countries would not have direct access to seafood production, other than inland aquaculture. Land-locked countries could follow the high-bioelectricity path, which transitions to dry biomass-electricity-with-sequestration. The market for agriculture residue-to-electricity (corn cobs, corn stalks, chaff) may benefit land agriculture (better paying jobs, more robust food production, etc.). An additional half-billion tonnes of seafood per year should mean that inland people can still have high protein seafood to augment local agriculture. It may also reduce pressures to deforest land areas for more crops and livestock.

As temperatures rise in the tropics, more crops are failing (Porter et al. 2014; Tigchelaar et al. 2018), and especially important for developing countries, food micronutrient levels are dropping (Tirado 2017; Zhu et al. 2018; Chumley & Hewlings 2020). Thus, health can be improved with seafood, which has high micronutrient levels (FAO 2017; Mohanty et al. 2016). Ocean temperatures are rising slowly, but remain amenable to bivalves and fish. Moreover, temperatures along coasts are rising more slowly than inland, so refugees from inland droughts and floods can find work without leaving their home country. The hope is that this will lead to less migration and less violence. In fact, developing countries could earn income from developed countries by exporting seafood while accommodating refugees and migrants as temporary or permanent workers on their built-reef ecosystems. Aquatic-based organic fertilizers can replace chemical fertilizers. Scaling built-reef total ecosystem aquaculture provides more seafood, which makes it easier to reserve marine protected areas.

3.9.2. Human waste resource recovery systems (SDGs 3, 6, 12, and 14)

Improved human and livestock waste collection and recycling systems can maintain public health while recovering freshwater, energy, and nutrients to produce more food and improving ocean health. When nutrients are recycled effectively, the food-waste-food circular economy should cost less than current systems for treating human and livestock waste that destroy nutrients, necessitating production of artificial and mined nutrients.

3.9.3. Solid waste resource recovery systems (SDGs 3, 6, 12, and 14)

Municipal and industrial solid waste collection systems can recover resources safely and effectively while producing energy that more than covers the cost of collection. Paying people for their solid waste would greatly reduce future marine plastic pollution. Developing countries might earn income from developed countries by exporting carbon negative biofuels.

3.9.4. Sustainable energy systems (SDGs 7 and 13)

Install multi-fuel energy systems that produce sequestration-ready CO_2. The "multi-" includes coal, natural gas, and biomass. Include ways to recycle nutrients from the energy process to grow more food and biomass-for-energy. Developing countries might earn income from developed countries by growing terrestrial biomass to fuel the developing country's electricity production and sequestering the bio-CO_2 less expensively than can be done in developed countries. Co-locate the human and solid waste resource recovery plants with sustainable energy systems for cost and circular economy synergies.

3.9.5. Sustainable ocean biomass-for-energy (SDGs 7 and 13)

Gradually scale the seafood reefs with improvements in labor productivity appropriate for satisfying global demand for liquid biofuels. Developing countries might earn income from developed countries by exporting carbon negative biofuels.

3.9.6. CO_2 sequestration systems (SDG 13)

Employ location-appropriate CO_2 sequestration systems for the CO_2 produced and captured during energy production. Developing countries might earn income from developed countries by exporting negative carbon credits.

3.9.7. Floating land systems (SDG 11)

Floating land (Guarino, 2019) is a collection of systems that allows people to remain in place and/or move to living on the ocean as sea levels rise.

3.9.8. Other public health systems (SDG 3)

Both proposed paths help replace inefficient open-flame charcoal cooking with clean-burning fuel or electric stoves. They also eliminate air pollutants from electricity generation, yielding large co-benefits for air quality and human health. West et al. (2013) calculated local average marginal co-benefits of avoided mortality from air pollution ranging from \$50–380/tonne of CO_2.

3.9.9. All systems must be sustainable (all SDGs)

N'Yeurt et al. (2012) discussed sustainability criteria for growing macroalgae forests to reverse climate change. The technologies have evolved and the economics improved, facilitating additional sustainability across environmental, climate, political, social, energy, and economic pathways. (See SD for more discussion on how ocean forest reefs directly support twelve of the SDGs.)

4. Conclusions and Recommendations

4.1. Summary

This paper identified sustainable paths to realizing large negative carbon emissions and achieving food, employment, healthy oceans, and other SDGs while lowering the cost of oceanic-biomass-for-energy production. Integrated, globally just strategies for accomplishing these goals were proposed. So far, national declared contributions (NDCs) to climate reductions under the Paris Agreement are insufficient to achieve the IPCC pathway P4. This paper presented a practical, cost-effective way to achieve the IPCC 1.5º goal of net zero by 2050 and then continue BECCS beyond 2100 to return the planet to preindustrial levels of CO_2 if desired.

An additional 0.5 billion tonnes/yr of seafood (three times present seafood production and equal to the current total meat and seafood production) (FAO, 2018b) could be produced by recycling nutrients from humans back to the land and ocean. In the ocean, recycled nutrients are distributed to macroalgae or seagrass grown on floating, flexible fishing reefs positioned in the photic zone independent of seafloor depth. These fishing reefs form highly productive ecosystems supported by nutrients optimized for seasonal productivity and natural variations in endogenous nutrients and dissolved oxygen supply. Calculations suggested that a billion tonnes of seafood can be grown on less than 10% of the suitable continental shelf with water depths <200 m (Gentry et al., 2017) equating to about 0.3% of the world's oceans (see SS tabs 6 and 18). By growing more food in less ocean, marine protected areas could be increased. Production of high-protein food in the ocean could facilitate transition of grain-for-meat production to grain-for-people production as well as increased energy crops, forests, and wildlife habitat with lower GHG emissions. Structures supporting seafood-production reefs are similar to those used for macroalgae-for-biofuel production. Seafood production and macroalgae-for-biofuel equipment could be co-developed on a single structure.

All countries can benefit from safe handling of biohazard wastes and mixed-solid wastes in general with low, even negative, disposal fees using HTL to produce 20 million barrels/day (3 million tonnes/day) of biocrude oil from wastes by 2050. Additional benefits include less plastic trash reaching the ocean, less methane emissions from landfills, and profitably clearing beached *Sargassum*.

Allam Cycle power plants reduce the avoided cost (i.e., the economic penalty as defined by Rubin et al. 2015) to capture, compress, transport, and sequester one tonne of CO_2 from the >$60/tonne (in 2020) for other power plant CCS technologies to less than $0/tonne for early adopters (Table 5, SS tabs 14 and 16). (As "waste" sources become valuable and gases produced during Allam Cycle electricity production exceed commercial demand, the avoided cost could rise to $26/tonne.) This significant cost decrease for CCS, combined with developing-country needs for renewable, sustainable electricity, provides an opportunity for these countries to lead in mitigating climate change. Utilizing the existing global coal supply chain combined with significant construction of Allam Cycle power plants decreases the time to net-zero emissions. Fast start-up can be supported by the oil industry buying CO_2 for enhanced oil recovery.

When co-located, the HTL and Allam Cycle facilities synergistically produce carbon-negative biofuel. Both technologies can be co-located with other businesses and waste-handling facilities to maximize this closed-loop economy that demonstrates improved energy efficiencies (e.g., pasteurizing human and medical wastes with "waste" heat and manufacturing high-performance plastics from biocrude oil that when recycled more easily convert to biocrude or electricity).

Each country or community can consider which sustainable-development components and associated technologies best fit their resources and goals. Every sustainable development listed in Section 3.9 can start now and grow while achieving SDGs with high economic efficiency. These technologies can deploy to global scales while earning profits producing seafood in addition to energy and nutrient production from mixed-plastics and organic solid waste. This is consistent with Otto et al. (2020) in that major climate efforts must be "explicitly compatible with the Sustainable Development Goals, in the sense of positive social tipping dynamics." The health co-benefits of net-zero-emissions energy and waste recovery strongly support this approach by generating local support, especially because these benefits are primarily local and near-term (West et al., 2013).

4.2. Needed Research

The process of building, operating, and maintaining the needed commercial-scale infrastructure will involve needed technology refinements. Potential research topics include the following (see SD for additional examples):

- Life-cycle costs, planetary boundaries (Algunaibet et al., 2019), energy, and emissions analyses for all the mechanisms and technologies included, such as emissions during soil preparation, cultivation, collection and processing of dry biomass and the equivalent for oceanic biomass. Macroalgae-for-biofuel scale production requires a planetary boundary check on ozone layer depletion from gases emitted by micro- and macroalgae (Stemmler et al. 2015; Mehlmann et al. 2020 and references therein).
- Total-ecosystem aquaculture must be designed for continued biodiversity and seafood production even with some fish species moving toward the poles as the tropical oceans become too warm (Morley et al., 2018; Sumaila et al., 2019).

- Economics and governance – Economists and political leaders need to devise equitable ways to pay (Buck, 2020) for accomplishing net-zero CO_2 emissions and removing legacy CO_2 emissions from the atmosphere for a century or so after achieving net-zero CO_2 emissions.
- The United Nations Decade of Ocean Science for Sustainable Development (Intergovernmental Oceanographic Commission of UNESCO, 2019) could use the above framework to focus on supporting sustainable management of the oceans to achieve the UN SDGs.

Acknowledgments, Samples, and Data

Supplementary Materials: The following are available online at https://osf.io/rjta8/quickfiles: Supplemental Document and Supplemental Spreadsheet.

Conflict of Interest: The authors declare no competing interests. Authors Capron and Hasan acquired knowledge of HTL processes while considering HTL manufacturers Genifuel, Algae Systems, and CleanCarbon Energy for municipal biosolids and solid waste. Capron and Hasan provided pro-bono advice to all three companies on topics related to recycling nutrients and handling byproduct carbon (can be either fuel or food).

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