Supplemental Materials Document

Restoring Pre-Industrial CO2 Levels While Achieving Sustainable Development Goals

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Contents of this file

Text, Technical Supplemental Document, Pages: 1 - 60

Abbreviations used in this document and the main publication

Table of Contents with links to each section: p. 3 – 4

Figures S1 – S24 near where mentioned in this supplemental document

Table S1 of this supplemental document

The main publication "Restoring_pre-industrial_CO2_levels_while_achieving_Sustainable Development Goals" is referred to throughout this supplement as "the manuscript."

Additional Supporting Information (Files uploaded separately)

Supplemental Materials Spreadsheet (SMS) (Excel) containing the tables from the manuscript with formulas linked to calculations across 24 numbered tabs (aka worksheets). The left-most tab is a table of contents. The appropriate tab is referenced in the manuscript as SMS#X. The SMS allows "what if" calculations. (The SMS is in the Zip-Document under the Graphical Abstract.)

Abbreviations:

AFOLU = net emissions from Agriculture, Forestry and Land Use
ARPA-E = U.S. Department of Energy's Advanced Research Projects Agency-Energy

BECCS = bioenergy carbon capture and storage

C = carbon

CCGT = combined cycle gas turbines

CCS = carbon capture and storage

CDR = carbon dioxide removal

CDW = construction and demolition waste

EOR = enhanced oil recovery

EJ = exajoule = 10^{18} joules

GJ = gigajoule = 10^9 joules= 0.95 million British thermal units = MMBTU

Gt = billion tonnes

HTL = hydrothermal liquefaction

IPCC = International Panel on Climate Change

kWh = kilowatt-hours = 1,000 watt-hours

MARINER = MacroAlgae Research Inspiring Novel Energy Resources, ARPA-E project

MSW = municipal solid waste (i.e. trash)

MW = megawatts = million watts

MWh = million watt-hours

N = nitrogen, primary component of nutrients such as protein, ammonia, urea, and nitrate

NET = negative emission technology

NOMAD = Nautical Offshore Macroalgal Autonomous Device

$P_{electric}$ = high bioelectricity, low biofuel path

P_{fuel} = low bioelectricity, high biofuel path

SD = this Supplemental Document SDGs = United Nations Sustainable Development Goals

SPM = IPCC Summary for Policy Makers

SS = Supplemental Spreadsheet

Contents

1. Introduction

A. Background on need for carbon dioxide removal (CDR)

So far, national declared contributions (NDCs) to climate reductions under the Paris Agreement are insufficient [1] to achieve any of the four IPCC 1.5ºC pathways [2]. Manuscript Figure 2 shows IPCC pathways P1-P4 with our two paths (1) P_{fuel} and (2) $P_{electric}$ superimposed on the IPCC 2018 projections. Our paths are conservative in keeping with the maxim: "Plan for the worst. Hope for the best." Figure SPM.1c on the right of Figure 2 anticipates about 3 trillion tonnes of cumulative CO_2 emissions. After net zero emissions by about 2050, either path removes the 3 trillion tonnes of CO_2 by between 2140 and 2170. See SMS#10.

Limiting global average temperature rise to well below 2 °C above pre-industrial levels, in order to comply with the Paris 2015 Agreement [3], requires both that fossil carbon use is curtailed and large tonnages of CO_2 be captured and securely stored [4]. The IPCC special report on Global Warming of 1.5°C stated on SPM p. 6 [5]:

"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. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*)."

The 1.5°C IPCC report looked at two targets for net zero CO_2 emissions: by 2040 or by 2055. The total cumulative CO_2 emissions since 1750 from fossil fuels, cement, and land use changes (based on Friedlingstein et al. [6]) in the 2040 pathway reach 2,600 $GtCO_2$; in the 2055 pathway it totals 3,000 $GtCO_2$ ([5], p. 6). The manuscript projects net zero CO_2 emissions by 2050, implying that to return the planet to pre-industrial condition could require removal of as much as 2,900 $GtCO_2$.[1]

The UN Environment Programme (UNEP) Emissions Gap Report [1] "warns that unless global greenhouse gas emissions fall by 7.6 per cent each year between 2020 and 2030, the world will miss the opportunity to get on track towards the 1.5°C temperature goal of the Paris Agreement."

B. The manuscript scenarios compared to IPCC 1.5ºC pathways

The IPCC 1.5º Report ([5], SPM p. 13) presents four pathways to limit global heating to 1.5ºC, shown in these graphs in Figure S1. (Note AFOLU is net emissions from Agriculture, Forestry and Land Use, BECCS is net removal by BioEnergy (combustion) with Carbon Capture and Storage.)

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[1] The Global Carbon Project [6] reports of the 2,361 $GtCO_2$ total net CO_2 emissions from fossil fuels, cement and land use changes from 1750 to 2018, about 1,600 $GtCO_2$ have gone into the atmosphere and oceans, with 800 $GtCO_2$ into the land sink and 100 $GtCO_2$ unknown (net budget imbalance) (see calculations in SMS#21). Since it is unclear how much of the excess CO_2 into the land sink will re-emerge, it could be less than 2,900 $GtCO_2$ that will need to be removed, which could restore 300 ppm much sooner.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways

● Fossil fuel and industry　● AFOLU　● BECCS
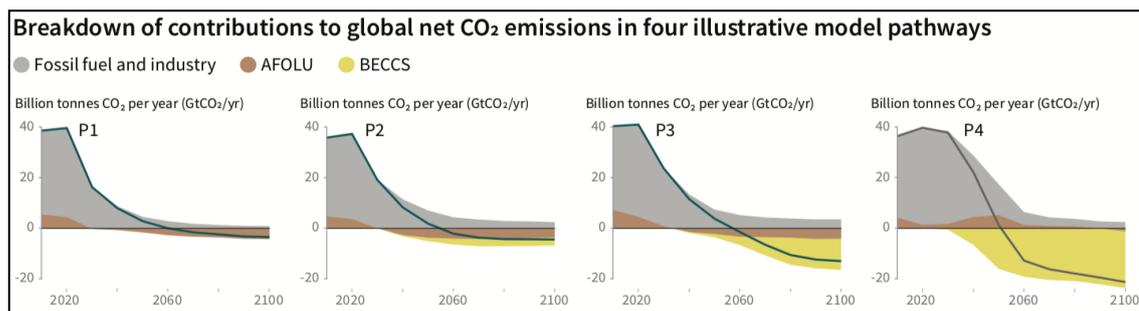
Figure S1: IPCC Pathways, excerpt from Figure SPM.3b, p. SPM 14 [5]

Summarized descriptions of the IPCC pathways shown in Figure S1:

P1:　A scenario in which a downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered.

P2:　A scenario with low-carbon technology innovation, and well-managed land systems with afforestation and limited BECCS (151 $GtCO_2$ by 2100).

P3:　A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand, plus BECCS (414 $GtCO_2$ by 2100).

P4:　A resource- and energy-intensive scenario with high economic growth, high demand for transportation fuels and livestock products, with high BECCS (1191 $GtCO_2$ by 2100).

Note that the first three pathways require that CO_2 emissions peak in 2020 and fall rapidly to net zero by 2060. P4 also peaks in 2020, but falls more slowly to 2030, then falls rapidly to net zero by 2050. Because the P4 scenario emits much more carbon before reaching net zero in 2050, it requires much more BECCS than the other scenarios. The first three pathways also have a 66% chance of no or limited overshoot of 1.5ºC, while P4 is expected to exceed 1.5ºC before returning to 1.5ºC by 2100.

However, so far national declared contributions (NDCs) to climate reductions under the Paris Agreement [1] are not even sufficient to achieve P4. The manuscript rises to meet that global challenge by presenting a practical, cost-effective way to achieve the IPCC 1.5ºC goals by severely limiting any overshoot of 1.5ºC, returning the temperature to 1.5ºC well before 2100, and then continuing the BECCS beyond 2100 to return the planet to preindustrial levels of CO_2 if desired.

The manuscript outlines two paths that seem more realistic than IPCC Pathways for achieving net zero emissions by 2050. This because both paths more gradually reduce fossil fuels with a lower reliance on purpose-grown terrestrial biomass (the only biomass source considered by the IPCC) in favor of waste and ocean biofuels. The trajectory of the Figure 2 manuscript paths is somewhat similar to P4's trajectory in that they support an increase in energy demand similar to the P4 44% increase by 2050. Both of the technologies in the manuscript paths can be carbon negative. The carbon negative biofuel offsets emissions from hard-to-eliminate fossil transportation fuels.

Allam Cycle [7–9] with fossil-fueled CCS enables quickly attaining carbon neutral electricity with a combination of CCS and other carbon neutral electricity (wind, solar, hydro, etc.). Even modest

amounts of Allam Cycle with biofuels (BECCS) offset emissions generated when mining and transporting coal and natural gas making net zero emissions possible.

In contrast to the P4 scenario, which requires 1191 $GtCO_2$ removed by BECCS by 2100, the manuscript removes 2000 $GtCO_2$ by between 2110 and 2130. However, the manuscript paths provide much more rapid startup of CO_2 capture and sequestration (CCS) by having all new electricity plants be Allam Cycle plants, even if powered by fossil fuels. This immediate large increase in CCS means far less CO_2 is emitted before net zero in 2050, so the overshoot (if any) should be much less than P4.

2. Methods: Bracketing the choice between bio-electricity and biofuel

A. Potential transition sequences

The panels in Figure S2 are another way to illustrate how the global energy situation could transition based on the manuscript paths. 2020 represents the current situation. 2050 represents the situation at net zero emissions. 2060 represents the time after negative emissions level off to a constant removal rate of between 30 and 40 Gt/yr. In 2050, the thicker black arrow from "Biomass" to "Transportation" indicates a path closer to P_{fuel}. In 2060, the slightly thicker black arrow from "Biomass" to "Electricity" and the thick green arrows from "Electricity" suggest a path closer to $P_{electric}$. Either path and any path between the two extremes accomplishes the same atmospheric CO_2 reductions, albeit at different times.
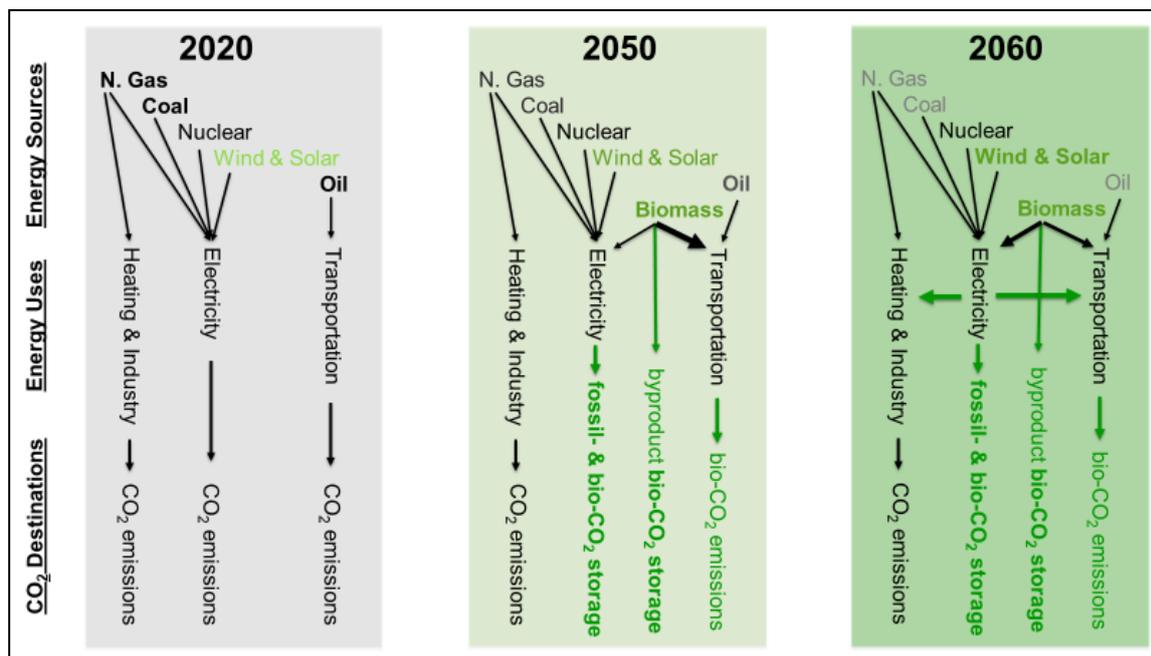
Figure S2. Stages of transition from current CO_2 emissions to significant capture and storage of CO_2 with biofuels. Note: Only primary fuels and technologies are considered; others are implied. For example, "Wind & Solar" includes every renewable energy (hydro, geothermal, wave, tidal, etc.) not generally considered suitable for transportation fuel. "Biofuel" includes manure, wastewater, and landfill methane plus biofuels such as *Miscanthus* and solid waste – used for heating and industry or gasified for electricity production or processed

through hydrothermal liquefaction (HTL).

B. Updating process overview since N'Yeurt, et al. [10]

Figure S3 was developed based on the N'Yeurt, et al. 2012 paper [10]. It shows the complete ecosystem when using anaerobic digestion (the least expensive at that time) for the biomass-to-energy with byproduct CO_2 capture. The ecosystem includes sustainable (ocean health and biodiversity improving) food and energy production plus recycling nutrients and carbon sequestration.

The manuscript updates the biomass-to-energy technologies and the techno-economic analysis as follows:

- The anaerobic digester is replaced with hydrothermal liquefaction (HTL) to make biocrude oil [11,12]. After biooil production, HTL may be followed by anaerobic digestion or a hydrothermal gasification process to convert carbon in the leftover water into CH_4 and CO_2. (See Section 3.3 for hydrothermal gasification.) Both anaerobic digestion and HTL work best with wet[2] biomass.

- The steam- or gas turbine-electricity production is replaced with Allam Cycle electricity. Solids input to the Allam Cycle must be gasified. Gasification, like incineration and pyrolysis, works best with dry[3] biomass. The mix of CH_4 and CO_2 from HTL and/or anaerobic digestion can be combusted directly in Allam Cycle plants.

- Ideally, the HTL and Allam Cycle facilities are co-located so that the byproduct carbon from HTL biofuel production can be fuel gas for Allam Cycle electricity production. Co-location allows the byproduct carbon to become pure liquid CO_2 at 100-bar for $1 - $2/tonne.

Other technologies are being developed and may augment or supplant Allam Cycle electricity and HTL biofuel production. For example, hydrogen made from carbon neutral or carbon negative electricity may be important for replacing natural gas and perhaps other transportation fuels. The UK is currently demonstrating 20% by volume hydrogen in the natural gas grid [13]. Hydrogen made from carbon negative electricity or HTL (see below) is a renewable offset. Similarly, Allam Cycle carbon negative electricity can be used to make doubly "green ammonia" for fertilizers and fuels, as well as a hydrogen carrier [14].

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[2] Wet biomass is input with 60% to 95% water content: macroalgae, microalgae, leafy greens, food waste, and blends of too-wet with dry materials. Water-shook-off macroalgae is about 90% water.

[3] Dry biomass is input with 0 to 20% water content: wood, switchgrass, paper, and plastic. When harvested, miscanthus is 20% to 52% water, poplar is 9% to 52% water (so the high water content materials must be dried before gasification).
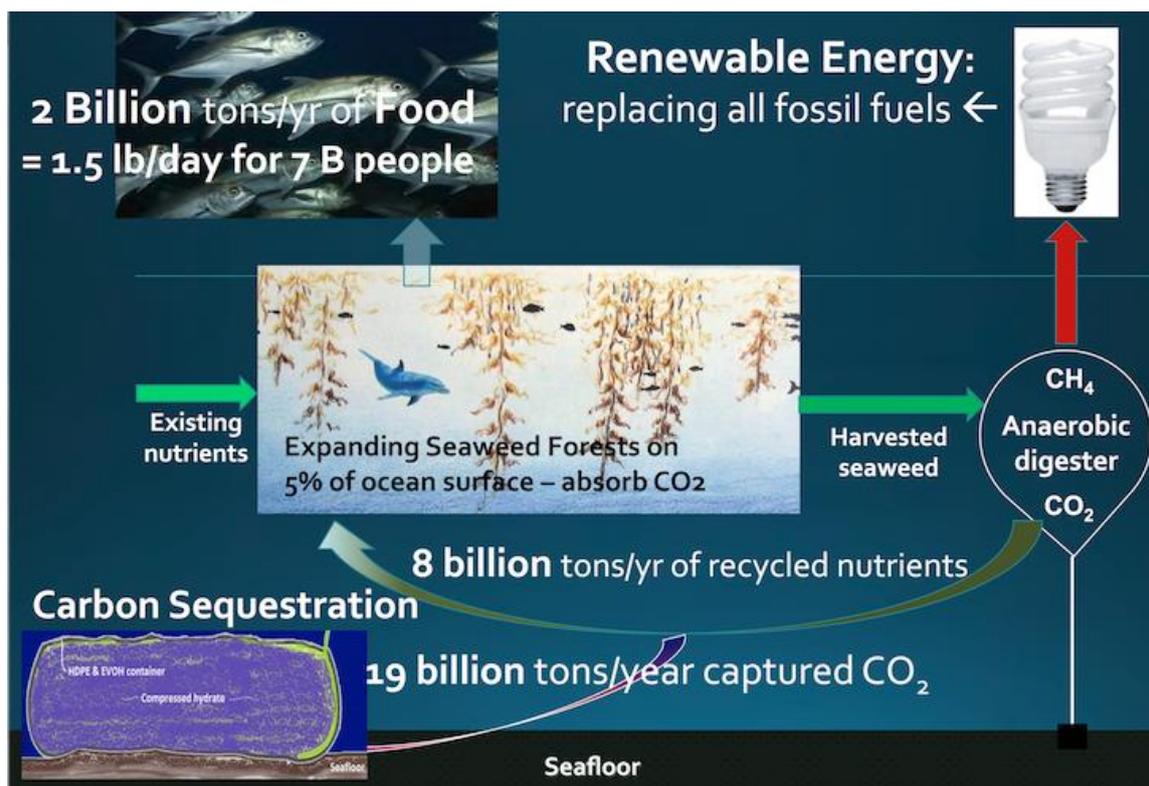
Figure S3. This figure illustrates the main features of the approach presented by N'Yeurt, et al. [10],which relied on anaerobic digestion, rather than HTL and Allam Cycle.

3. Calculation, results, and discussion for key components

3.3 Biomass production details: start-up, eventual scale, cost, and infrastructure

A. Waste Details:

The first type of biomass that should be considered is waste (also called trash) that is not currently recycled onsite. The main categories of waste are:

o   Municipal solid waste (MSW) (which also includes household and business trash in rural areas)

o   Industrial wastes

o   Construction and demolition debris

o   Hazardous and medical wastes

o   Agricultural and forestry residues

MSW: The report for the World Bank by Kaza et al. [15] estimated global MSW at 2 billion wet tonnes/yr in 2016 rising to 3.4 billion by 2050. (Note this does not include industrial, construction/demolition or hazardous/medical wastes, which are discussed below.) Their global summary of MSW composition in 2016 is reproduced in SMS#4 and applied to their projected 2050 total. The result indicates that globally about 600 million (dry) tonnes of MSW food and green waste are too wet for Allam Cycle but could be fed into HTL plants. Some of this green waste is currently being composted, plus a small amount is used to generate methane from anaerobic digestion. About

half of the rest is put into landfills and the rest just dumped to avoid the cost of hauling and disposal fees in a landfill. How much could be collected and sent to HTL plants is dependent on the price that HTL could pay for such waste. Since Figure S8 indicates that HTL plants could pay up to $150/dry tonne and still produce biocrude for $70/barrel, we conservatively estimate that 80% of the wet organic MSW trash (480 dry tonnes/year) could be delivered to HTL facilities (at least until the market for liquid fuels is so saturated that the price per barrel drops). Note that all calculations use the percentages of water from US DOE [16].

Dry organics, including plastics, paper/cardboard, wood, rubber, and textiles can be either fed to HTL or efficiently gasified for use in Allam Cycle plants to produce bioelectricity. The current delivered price of coal in the US is only about $75/tonne ($100 internationally), which implies U.S. Allam Cycle plants may pay less than $50/dry tonne for the less dense dry organics from trash. So our spreadsheet projects that about 60% of dry organics (including some plastics that could be recycled) might be delivered to Allam Cycle plants for $50/dry tonne. But if HTL plants pay up to $150/dry tonne, perhaps a much higher percentage would be collected and delivered to HTL.

Industrial wastes: Global industrial waste totals were estimated by Kaza et al. [15] at 34 billion wet tonnes in 2016, which would be 59 billion tonnes in 2050 (using their formula for projecting MSW). Although most industrial waste is recycled on site, to our knowledge no global survey has been published. Jolly [17] reported that 85% of Dutch industrial waste is recycled. The rest finds its way either to incineration (7 percent) or dumping sites (6 percent). It is likely that the amount dumped is much greater in lower income countries, so we will estimate that 10% could readily be available for energy feedstock. (We discuss incineration below.)

The global characteristics of industrial waste sent to landfills been has not been comprehensively analyzed, so our spreadsheet uses as a proxy the data from California [18] of the "Commercial Self-Hauled Disposed Waste," which shows that about 12% are wet organics similar to yard trimmings, 7% are textiles, 27% wood, and 1% tires. Applying those percentages globally to the 10% potentially available for energy feedstock would produce 250 million dry tons of wet waste, and 1640 million dry tons of dry organic waste annually from industry (SMS#4).

Construction and demolition debris: Kaza et al. did not characterize components of construction and demolition debris, so our spreadsheet uses data from CalRecycle [18] which reports about 7% is wood products. Our spreadsheet estimates that 60% of this could be delivered to Allam Cycle plants for energy.

Hazardous and medical waste: Kaza et al. projects this at about 500 million dry tonnes in 2050, but do not report components. Indications are much of it is plastic-contained liquid materials that would be appropriate for HTL. Our spreadsheet estimates that 60% of this could be delivered to HTL for energy, about 300 million dry tonnes/yr.

Total MSW wastes: The rounded totals for 2050 from the spreadsheet SMS#4 are about 1,000 million dry tonnes/yr of wet wastes that could be delivered to HTL, plus about 5,000 million dry tonnes/yr of relatively dry wastes that could be delivered to either HTL or Allam Cycle plants. These could be delivered at negative or zero cost because much of these wastes currently pay disposal fees, which in the U.S. range up to $300/dry tonne for mixed MSW or over $1000/dry tonne for hazardous/medical wastes.

Agricultural residues: We consider two types of agricultural wastes: field residues (materials left in agricultural land after harvesting the crop) and process residues (materials left over when the crop is processed). These residues comprise more than half of the total bioproduction of the global food harvest [19].

These residues have a range of uses, including being left in the fields to provide cover and nutrients, feeding to livestock, composting, burning for household cooking and heating, burning in the fields, and using to make biofuels and energy. Devi et al [20] report 2 billion tons (about a quarter of the total) are burned. Most of this is burned in the fields, but some is burned in inefficient polluting unhealthy home cooking and heating stoves. Devi et al. report that in India, the disposal pattern of rice residue depends on its market value. Currently the value is so low that ¾ is burned in the field. The resulting pollution "has a severe impact on the environment including reduced soil quality, enhanced soil erosion, and increased air pollutants and greenhouse gases [21]." Ravinda et al. [22] report that in 2017 24% of India's crop residues was burned in the agricultural fields, resulting in emissions of a million tons of particulate matter and over 200 Mt of CO_2 equivalent greenhouse gases (CO_2, CH_4, N_2O).

Total agricultural residues was estimated by Kaza et al. [15] at 9 billion wet tonnes/yr in 2016, which would be 15 billion tonnes/yr in 2050, using their formula for projecting MSW to 2050. This would be 10 billion dry tonnes/yr (assuming 30% water content). Saini et al. [23]estimated 1.4 billion dry tonnes of residues from the four major crops of rice straw, wheat straw, corn stover and sugarcane bagasse. Analysis by Deng et al. [24] found the total potentially available in 2070 from residues from food crops, other agriculture, and forestry ranged from 10 to 88 exajoules (EJ). Daioglou et al. [25] estimated that globally about 40 EJ/yr (~2 billion dry tonnes/yr) of agricultural residues and wastes could be sustainably delivered to power plants at costs (including harvest, storage and transportation) of around USD $6/GJ (approximately USD $90/dry tonne) by 2050. We believe that this more conservative estimate of 2 billion dry tonnes is more reliable than the Kaza projection of potentially 15 billion dry tonnes, so SMS#4 uses 2 billion dry tonnes.

The most effective way to harvest residues is in the winter after it has naturally dried for a few months (and returned much of the nitrogen and other nutrients to the roots for natural regrowth). Thus, in contrast to all the other waste sources, agricultural residues are very seasonal, meaning they would have to be stored for many months to provide an even flow to the power plants.

Total Wastes: Our spreadsheet (SMS#4) estimates about 1 billion dry tonnes of food and green wet wastes plus 11.5 billion dry tonnes of dry organic wastes for a global total of 12 (± 4) billion dry tonnes per year.

These global numbers provide hope for large quantities of inexpensive carbon neutral fuels that do not impact land use. When these fuels supply carbon capturing facilities, such as HTL and Allam Cycle plants, the processes accomplish huge amounts of CDR.

We note the actual distribution between HTL and Allam Cycle facilities will depend on the waste economics, amounts, and available facilities in any particular location. As data becomes available on the wastes in a location, facilities will be constructed to efficiently utilize them.

Distribution factors to consider include: (1) Only dry (agricultural, paper, plastic, etc.) biomass is appropriate for direct electricity production from Allam Cycle. This fuel is worth $3 to $8/MMBTU

($7.6/GJ) as feedstock for electricity generation depending on the local price of coal or natural gas. The corresponding values for biomass are roughly $56 and $150/dry tonne of biomass. (See calculation in SMS#4). (2) Dry and wet biomass can be mixed to make biofuel in HTL (worth $12/MMBTU when the global price of oil is $70/barrel)[4]. (3) Thus, HTL operators could pay people $10/dry tonne ($2 to $8/wet tonne) for mixed solid waste. Use the qualitative estimate of cost in Figure S10 to see that paying $10/dry tonne could produce oil for $20 to $50/barrel. Paying for solid waste would collect more trash (e.g. thus diverting more plastic from the ocean) than the current situation of people paying a trash disposal (tipping) fee. (4) If people pay a tipping fee to the HTL operators, the biocrude could cost less than coal to produce. But less trash may be collected, depending on the country. As Kaza et al. estimate, high income countries collect about 96% of MSW, while low income countries only 39%. Our spreadsheet SMS#4 provides a range of estimates for utilization of different waste sources for the high and low bioelectricity scenarios.

B. Existing terrestrial biomass for energy:

According to REN21 [26], current **traditional biomass** (primarily woody biomass or charcoal as well as dried dung and other agricultural residues,) used in developing countries for home heating and cooking is about 7.4% of total global energy or 27 EJ (7.5 billion MWh/yr) of carbon neutral energy, which is equivalent to about 1,400 million dry tonnes/yr of biomass. We estimate about half of this is unsustainable because it leads to deforestation. In addition, this use of biomass is very inefficient producing severe air pollution causing millions of deaths per year and should be phased out as rapidly as possible. The high bio-electricity pathway on our spreadsheet uses an average global electricity demand of 7 MWh per year per person. That means lifting developing countries from the present value near 2 MWh/yr/person to near 6 MWh/yr/person. 4 MWh/yr for 2 billion people is 8 billion MWh/yr, a little more than 27 EJ. Hopefully, the additional electricity displaces traditional uses of wood, charcoal, and dried dung. However, perhaps half of this waste could sustainably collected and be paid for by HTL and/or Allam Cycle plants to make biofuels and electricity.

REN21 reports **modern biomass** (primarily waste to energy, wood pellets, ethanol, and biomethane from landfills and sewage plants) used for heat, transportation fuel, and electricity is about 5% of total global energy or 19 EJ of carbon neutral energy, which is equivalent to about 900 dry tonnes of biomass. Some of the sources of this energy, such as corn ethanol, displace important food crops and must be phased out as soon as possible, to be replaced by more efficient, eco-friendly carbon-negative biofuels from HTL and Allam Cycle facilities, made from more sustainable sources such as wastes or others described below. Our spreadsheet assumes that no wood is cut for energy, but that option might be seen as sustainable in some locations.

C. New sources of sustainable purpose-grown terrestrial biomass:

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[4] At the time this paper is being written, the global price of oil is only about $30/barrel. But many analysts expect the price to climb once the COVID-19 pandemic is over (see Figure S15 for historical oil price fluctuations).

Turner et al. [27]estimate that annual global total biomass that could be sustainably available for biofuels for BECCS totals 20 billion dry tonnes from forests[5], 7 billion from savannas and marginal agricultural lands, and 0.5 billion residues from croplands for a total of 28 billion dry tonnes/yr. (This projection excludes 10 billion tonnes from croplands and grasslands that are and could conceivably be used for food production.) Then Turner et al. rule out the use of forests since many authors support leaving forests intact as carbon sinks (e.g. Hudiburg et al. [28]). They also ignore savannas and cropland residues. Finally, by only focusing on biomass sources on marginal lands located over high priority geological storage basins, they find only about 0.5 billion dry tonnes/yr readily available biomass for BECCS. Other authors project up to 20 billion dry tonnes/yr of potential biomass, including forests and not considering proximity to storage basins (U.S. Department of Energy [16], Das et al. [29]). Eisentraut [30] compares various authors' projections of the total bioenergy potential covering the various sources of biomass, including dedicated energy crops, as well as forestry and agricultural residues and waste. Results vary widely, ranging from a low estimate of 130 EJ (7 billion dry tonnes) (Hoogwijk et al. [31]) up to a maximum potential of more than 1,500 EJ (75 billion dry tonnes) in 2050 (Smeets et al. [32]). SMS#4 proposes a placeholder of 10 billion dry tonnes. The price of dedicated energy crops from plantations was estimated by Faaij [33] in the range of US$3-5/GJ (approximately US$45-75/dry tonne) and by US DOE [16]as US$40-100/dry tonne.

Faced with these large variations, we considered other factors in the calculation of how much terrestrial biomass is needed and available. Those calculations are in SMS#4. The P_{fuel} path uses 4 billion dry tonnes of terrestrial biomass (including all wastes plus purpose-grown crops such as *miscanthus*) for BECCS via the Allam Cycle. The $P_{electric}$ path uses 17 billion dry tonnes of terrestrial biomass (again including all wastes plus purpose-grown) for BECCS via the Allam Cycle. These volumes feed into the "Fraction of global electricity production projected to be BECCS…" in SMS#2 (at some future time a decade or so after net zero emissions). Changing the fractions of different types of terrestrial biomass (red numbers in SMS#4) will change the fraction of BECCS in SMS#2. The changed fraction of BECCS will change the amount of bio-CO_2 sequestered.

D. Macroalgae:

The Advanced Research Projects Agency - Energy of the U.S. Department of Energy Macroalgae Research Inspiring Novel Energy Resources (MARINER) has provided over $30 million [34] for "developing advanced cultivation technologies that enable the cost and energy efficient production of macroalgal biomass in the ocean at a scale suitable as feedstock for the production of fuels and chemicals." One of the projects funded was called "AdjustaDepth" [35–37]. The AdjustaDepth team generated two results: a techno-economic analysis of a macroalgae grown on a flexible floating reef structure which submerges to avoid tropical storms; and a system now called "total ecosystem aquaculture (TEA)" (or "Marine Biodiversity and Productivity Reefs") [38–41]. TEA involves multi-product artificial reef ecosystems yielding free-range finfish, shellfish, crabs, abalone, lobster, and other seafood products in addition to macroalgae. The scale of high-protein products paying for the

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[5] Turner reports biomass in $GtCO_2$, which is roughly equivalent to 0.5 Gt of biomass, the conversion factor used here.

structure (so that the cost of biomass-for-energy can be as low as $40/dry tonne) is limited by humanity's demand for high-protein seafood, which is projected at up to 300 g/day[6] for 9 billion people (about 1 billion tonnes/yr). See SMD3.9.1 for details. Structures producing this quantity of food are estimated to also produce 100 to 300 million dry tonnes of macroalgae per year at $40 to $70/dry tonne.

Other MARINER designs [42] (see list in SMS#6) that can be anchored in water up to 200 m depth could produce 10 to 15 billion dry tonnes/year of macroalgae on locations identified by Gentry et al. [43]. Finally, MARINER free-floating deep-ocean systems access large open-ocean areas by floating in currents, eddies, and gyres with minor steering inputs. They include both free-floating and attached growth types of seaweed, which could produce vast quantities of biomass up to 60 billion dry tonnes/yr. Both moored and free-floating systems can employ TEA to simultaneously increase ocean biodiversity and reduce ocean acidity as they absorb CO_2 and produce food and biomass. Examples include Sherman et al. [44], Huesemann et al. [45], and other systems listed at ARPA-E [42]). See SMS#4, 6.

Proposed Macroalgal Design Based on U.S. Department of Energy Funding

The OceanForesters' open-ocean permanent floating submersible reef concept [35,38–40,46] for total ecosystem aquaculture builds on the research at the University of New Hampshire [47] plus University of Costa Rica's Dr. Ricardo Radulovich's near-shore multi-product sea-farms [48]. The U.S. Department of Energy Advanced Research Projects Agency for Energy (ARPA-E) MARINER program [42] funded nine teams refining reef structures each for different ocean conditions, service life, and economics. The OceanForesters-organized two teams, both led by the University of Southern Mississippi, including faculty from the University of New Hampshire, Texas A&M University, Baylor University, University of the South Pacific, U.S. Naval Academy, Florida Atlantic University, University of Alabama at Birmingham, and University of Louisiana at Lafayette. The team also had informal assistance from Dr. Radulovich, Dr. Alejandro Buschmann, Dr. Kevin Hopkins, NOAA, Samson Rope, and Applied Fiber. These designs are now ready for application elsewhere.

However, GESAMP ([49] p. 60) raises the following issues about macroalgal cultivation:
"There is little evidence, so far, of assessment of side-effects from either macroalgal cultivation or IMTA pilot studies (such as Chung et al., 2013). There is also little discussion of the need for, and implications of, upscaling cultivation, either in nearshore and/or offshore waters, to increase the magnitude of C sequestration, or how to detect and attribute sequestration. Clearly, modelling simulations could be used to further develop this debate.

Several studies have recently examined the wider ecological or societal implications of macroalgal cultivation for geoengineering (Aldridge et al. [50]; Cottier-Cook et al. [51]; Wood et al., [32]). Cottier-Cook et al. produced a policy brief which considers and debates 'how the production of seaweed affects and impacts our alternate source of safe food and nutrition supplement or our surrounding environment, with respect to pollution of coasts, our indigenous

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[6] People generally need about 50 grams of protein per day; 300 grams (0.7 lbs) of fresh fish would normally be 45 to 60 grams of protein.

biodiversity, disease outbreak (food safety standards, pet food, chocolate and toothpaste), climate change mitigation, fair trade and blue economy.' Wood et al. have recently raised a range of policy-relevant issues around the licensing of further work into this potential marine geoengineering approach."

In contrast, the new analyses by Capron et al. and Lucas et al. indicates that the progress on growing of macroalgae funded by the U.S. Department of Energy MARINER program makes massive increase in seaweed growing economical and feasible. In addition, if nutrient losses are sustainable, about 10% of the seaweed grown is likely to be sequestered for many hundreds of years in the deep ocean [52].

G. **Microalgae**:

Theoretically microalgae could contribute significant biomass, but currently its costs are projected over $400/dry tonne [16,53]. So our chart does not include any contribution.

H. **Scale of new-source terrestrial and ocean biomass**:

Many authors have looked at terrestrial biomass because its growth, harvest, and nutrient application technology are well tested, as well as low capital investment and low maintenance costs. The many authors differ widely on how much terrestrial biomass can be grown for energy. Scale-limiting issues include competing with food and other land uses, needing fresh water, affected by droughts and floods, and releasing CO_2 emissions from land use changes. Our research, reported on SMS#4, suggests there may be more than 17 billion dry tonnes of terrestrial biomass (including wastes, crop residues, and purpose grown crops) appropriate for gasification in Allam Cycle electricity production. The manuscript capped the need at 17 billion dry tonnes partly because that seems sufficient to meet the demand for bio-electricity (however, as the red (variable) percentages of utilization in SMS#4 indicate, more might be developed).

Ocean biomass growing and harvesting techniques are not as refined as for terrestrial biomass. There was large scale wild harvesting of kelp-for-potash off California from the 1910s through early 2000s by mowing the top meter of the water surface [54]. Since then, wild harvests have been limited and kelp farming techniques have become much more complex to produce a food-quality product. Our estimates of scale and cost are based on the techno-economic analyses from most of the nine teams awarded US$500,000 each in the U.S. Department of Energy, Advanced Research Projects Agency-Energy's MARINER program [42].

Ocean start-up can involve 400,000 seafood reefs, 20-ha each, providing a billion wet tonnes of seafood per year. However, 40 million such reefs are needed to provide the biomass to produce 100 million barrels of bio-oil per day (roughly 2018 global demand for oil) SMS#5. Biomass growth in tropical oceans can be nearly constant year-round, which minimizes the need for storing biomass. The remotely-controlled growing and harvesting systems will move slowly to minimize energy expended. Slow movement and safety considerations preclude putting people on the equipment.

The scale of energy production, harvesting near 400 billion wet tonnes per year (13 billion tonnes of carbon/year), means increasing ocean net primary productivity by 26%. Currently, land net primary productivity is about 60 billion tonnes of C per year on land area of 150 million km^2 [55].

Ocean production is about 50 billion tonnes of C [56] on 360 million km². That is: oceans are under-producing relative to land. The result is the additional substrate in the photic zone combined with nutrient recycling will not be "taxing" the oceans primary productivity capacity. On the contrary, the increased substrate with carefully managed nutrient recycling, and reef nutrient cycling per Figs. S4 and S5, provides an opportunity to improve local ocean biodiversity.
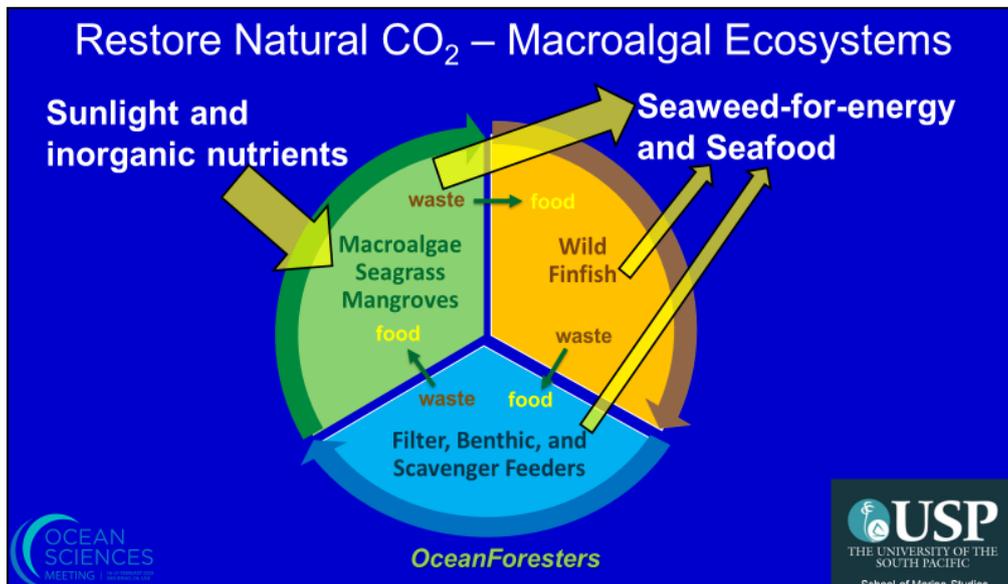
Figure S4 – Nutrient and energy (sunlight to food and energy) cycling in and around a reef structure built and managed for Total Ecosystem Aquaculture (TEA)

The nutrient cycling shown in Figures S4 and S5 can provide substantial productivity increase and biodiversity increase per area of ocean. For example, producing a billion wet tonnes/yr of seafood is projected to need less than 0.3% of world oceans (SMS#18). The 39 billion dry tonnes/yr of ocean plants (macroalgae and seagrass) for biofuel on the P_{fuel} path should require less than 7% of the world's ocean surface (SMS#18). However, fuel operations can resemble enhanced marine protected areas supporting biodiversity. The macroalgae or seagrass can be a perennial plant that is mowed so as to always leave at least 30% of the full-grown plant while allowing the fauna and the plants time and area to reproduce. (Actually, we would like to model the mowing and distribution of nutrients so that the plants (and the ecosystem) react as if the automated machinery were a green sea turtle or a dugong enjoying bountiful plants.)

One MARINER team proposed attached growth of temperate macroalgae (kelp) on a free-floating structure [57]. Two of the teams proposed free-floating and "corralled" *Sargassum* [44,58]. Three teams proposed attached growth of tropical macroalgae on moored structures [37,59,60]. Three teams proposed attached growth of temperate macroalgae (kelp) on moored structures [61–63]. Data from the teams that contributed suggest the potential for growing over 80 billion dry tonnes/yr. That is about twice the 42 billion dry tonnes/year needed to produce 110 million barrels of biocrude oil per day on the high biofuel pathway. Most teams determined their system eventual at-the-dock macroalgae price would enable producing biocrude oil for less than $100/barrel (SMS#4).

The MARINER program represents a tiny fraction of the effort spent on terrestrial biomass-for-energy. Unlike terrestrial biomass, oceanic biomass-for-energy is early on the learning curve. Even so, ocean biomass appears to scale up much better than does terrestrial biomass for reasons including: three times the global growing area, the opportunity for harvesting food while improving biodiverse ecosystems, and no land use and freshwater availability impacts. While ocean biomass is not affected by droughts and floods, there will be climate change impacts from marine heat waves (which may be avoided by submerging moored structures) and ocean acidification to manage.

Summary of benefits of sustainably increasing ocean biomass production:
- Major increases in global food production, especially of high protein food rich in micronutrients essential for the diets of developing countries [39,64,65].
- Reductions of deforestation and other terrestrial environmental impacts as seafood replaces terrestrial livestock, associated livestock crops, and land-based biofuels are replaced by ocean-based biofuels.
- Freeing land and freshwater for protection of terrestrial biodiversity.
- Freeing natural reefs for protection of ocean biodiversity. That is, communities achieve SDGs by building reef structures with carefully managed total ecosystem aquaculture, placed in currently low-producing areas. (Low productivity can be because the water is too deep, the seafloor does not support coral or macroalgae, excessive turbidity, excessive nutrients, etc.) The community might also achieve other SDGs by establishing marine protected areas where natural reefs are biodiverse and productive.
- Total ecosystem aquaculture's multitude of species may provide more robust food security while increasing ocean biodiversity, locally reducing ocean acidity, reducing dead zones, and clarifying the water for improved tourism.

Ocean biomass is wet (90 to 80% water) suited for energy conversion processes that return all the nutrients such as HTL, anaerobic digestion, or fermentation. This paper focuses on using HTL because of the high price obtained from biocrude oil, but anaerobic digestion could also produce biogas for Allam Cycle plants. These are discussed below.

G. How HTL and Allam Cycle can start with wastes and then increase the scale of BECCS (Bio-Energy with Carbon Capture and Sequestration):

Recent cost innovations with HTL [12] open the possibility of waste-to-biofuel projects that pay for collecting wet solid waste. That is, the HTL operator might pay people \$20/wet tonne to have their wastes delivered to the HTL facility.

The Allam Cycle's high efficiency enables it to produce much more electricity from gasified dry wastes than other state-of-the-art power plant technology including supercritical pulverized coal (SC-PC) with woody biomass burned in place of coal or H-class combined cycle gas turbines (CCGT) with woody biomass gasified in place of natural gas.[7]

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[7] The high temperature of burning and gasifying release nearly all the organic nitrogen in the biomass to the atmosphere as N_2. That is the nitrogen fertilizer in the biomass cannot be recycled and would need to be made up with artificial fertilizer or a nitrogen-fixing growing system.

In either of those other state-of-the-art power plants, the energy (to compress from 1 to 100-bar uses 110 to 120 kWh/tonne of CO_2) and cost (US\$46 to \$87/tonne) of capturing and compressing CO_2 from the exhaust is significant. But the Allam Cycle generates pure liquid or supercritical CO_2 at 100 bar using 23 kWh/tonne for capture and compression with less than \$3/tonne total for related operating and capital costs (see Section 3.6 in the manuscript and SMS#16).

HTL expands BECCS' scale by including wet biomass (oceanic macroalgae, food waste) producing biocrude oil. During the HTL process, 60% of the input carbon becomes carbon neutral biocrude oil. The biocrude can be refined into every transportation fuel. It can also become asphalt, plastics, and other chemicals. About 40% of the input carbon becomes CO_2 and CH_4 that can be captured and sequestered. If the HTL facility sends the mixed CO_2 and CH_4 to Allam Cycle electricity generation, it becomes pure liquid or supercritical CO_2 at 100 bar at the Allam Cycle cost of \$3/tonne.

H. Calculation of biomass for low and high bioelectricity options

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 SMS#2, 3, 4.

S3.4 Nutrient recycling details: start-up, eventual scale, cost, and infrastructure

A. Need for nutrient recycling

Terrestrial and oceanic biomass increase food and reduce waste by moving to a circular economy. As explained in "The End of Trash" [66],

> "A typical farmer around the town of Velen (Germany), where I met Doris Nienhaus, might spend \$40,000 a year to truck nearly 2,000 tons of liquid manure more than a hundred miles away to a field that's not already manured up. "A some point it won't economically viable." Nienhaus said. Her solution is a plant that extracts the basic nutrients – phosphorus, nitrogen, and potassium – from manure."

Nienhaus is using anaerobic digestion. A combination of HTL, anaerobic digestion, and other nutrient concentrating technologies can be more cost effective for longer nutrient return travel distances.

Figure S5. The outer loop shows the recycling human wastes to sustain reef production, enabled by waste recycling in the inner loop detailed in Figure S4.

The outer cycle of Figure S5 shows how sustainability gets people involved in the aquaculture ecosystem. People harvest seafood. People consume seafood. People's "wastes" are collected (usually at a waste treatment plant), disinfected, and returned to the ecosystem to grow more plants. The plants are part of the nutrient recycling system within the reef (shown in the inner circle detailed in Figure S6).

The paths need to harvest up to 43 billion dry tonnes/yr of additional primary productivity biomass, which must be developed on land or ocean areas with adequate sunlight and water by supplying more nutrients than currently available at those areas. Also, *miscanthus* and other such land biomass contain relatively less plant nutrients per ton for recycling than does ocean biomass[8].

Recycling the nutrients, as opposed to removing them from the ecosystem and disposing of them, is important for containing costs as well as supporting sustainability at scale. Jiang, et al. [11] assigned these values to recycled nutrients: $0.85/kg ammonia ($NH_3$), $0.69/kg $(NH_4)_2HPO_4$. (Ammonia costs have varied from $200 to $900/tonne over time.) Also, artificial nitrogen fertilizer production already accounts for 1% of CO_2 emissions [67].

At this large scale, artificial upwelling of deep ocean water for mining the necessary nutrients is not practical. Production of 10 billion dry tonnes/yr of biomass in 10 million square kilometers of North Pacific Gyre would strip out all the inorganic N, and other plant nutrients, in 50 years,

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[8] Dry macroalgae is about 3% N, but varies a few percent by species and for the same species seasonally. Dry woody/terrestrial biomass is about 0.3% N, and also varies widely.

(SMS#19) although currents are always moving nutrients such that it might be a few decades before the absence of nutrients is noticeable at some distant location.

Therefore, nutrients can and must be recycled. Energy conversion processes appropriate for wet biomass, such as anaerobic digestion, fermentation, and hydrothermal liquefaction (HTL) produce nutrient byproducts in the water and ash, easily separated from the biogas, ethanol, or bio-oil. For example, one HTL facility producing 450 barrels of biocrude oil/day from 4,500 water-shook-off tonnes of macroalgae/day will have as much N in the leftover water as that excreted by 1 million people (SMS#12). The water and the ash will also contain some dissolved organic carbon and proportional amounts of phosphorous, potassium, iron, boron, copper, manganese, molybdenum, zinc, nickel, and other micronutrients to maintain healthy growth. If the nutrients are not recycled, disposal costs would be huge. Conventional "wastewater" biologic nutrient removal processes for 1 million people can cost US$10 million/yr[9] (equivalent to adding US$60/barrel of oil produced).

The HTL process leaves some organic carbon dissolved in the water in the form of short-chain fatty acids. When water with significant organic carbon is discharged into water bodies, microbes rapidly deplete dissolved oxygen while consuming the organic carbon. There are several ways to recycle the organic carbon from the HTL facility by turning it into food (through nutrient recycling) and/or energy, as described below.

Recycling the organic carbon, and all the plant nutrients to grow more seafood and micro- or macroalgae biomass, while enhancing biodiversity, may have the best economics. Suppose 10,000 water-shook-off wet tonnes of macroalgae biomass is harvested into a barge for transport to the HTL facility. The same barge can return to the macroalgae ecosystem with nearly all the plant nutrients needed to grow another 10,000 wet tonnes in the form of 9,300 tonnes of water, ammonia and dissolved solid residues from the HTL plant. When the nutrient-loaded water is in a collapsible bladder, the nutrients may be distributed at the same rate simultaneously while harvesting the biomass.

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[9] Biologic N removal involves supplying air to bacteria which convert NH_3 to NO_3. Other bacteria then convert NO_3 to N_2. Costs are very sensitive to scale and the cost of energy. Mark E. Capron, professional wastewater engineer, selected US$10/capita/yr as a reasonable average cost for biologic N removal capital and operating expenses.
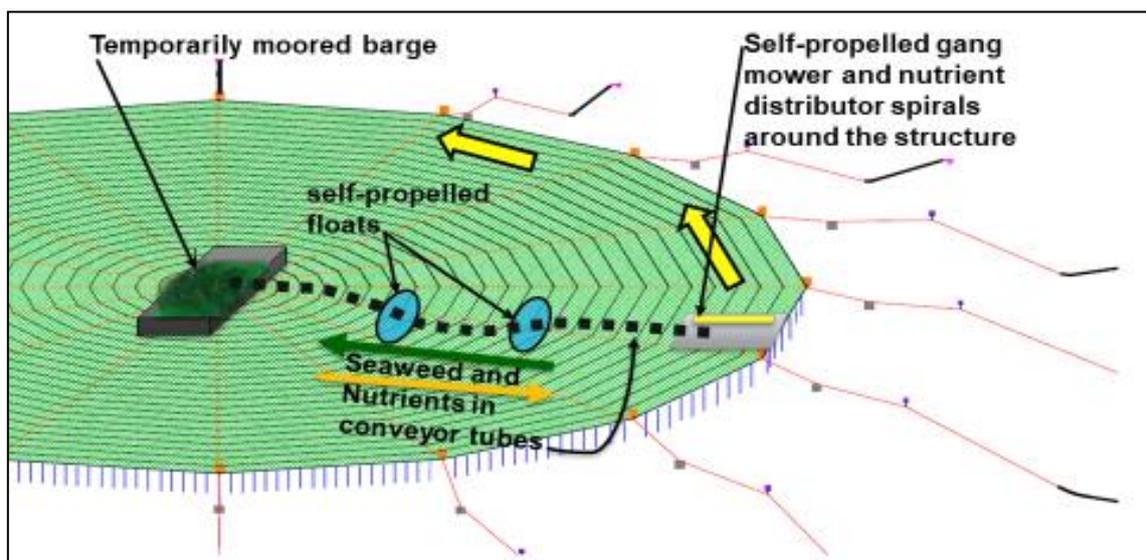
Figure S6. Schematic overview of harvesting and distributing nutrients simultaneously (from Lucas et al. 2019b)

In Figure S6 (from Lucas et al. 2019b), one pass accomplishes both operations with concurrent mow-harvesting with nutrient return and distribution. Synergies of this particular combined nutrient recycle and mow-harvest technique include:

- With harvest quantity levelized to be the same every day, the interval between harvests may not be less than a month, which will need to match macroalgae nutrient internal storage time capacity.
- Each mowing[10] leaves at least 25% of full-grown plants to absorb nutrients needed to triple in mass (mow at 75% of full growth).
- Tiny incremental costs are added to the mow-harvest-transport: a small pump, a hose, and a non-sloshing flexible tank of liquid for nutrient distribution[11].
- Relatively little preparation needed of the energy by-product water, perhaps only anaerobic digestion of the short-chain fatty acids and filtering.

B. Methods to recycle the organic carbon from HTL

The HTL process leaves some organic carbon dissolved in the water in the form of short-chain fatty acids. When water with significant organic carbon is discharged into water bodies, microbes

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[10] Not all species can be harvested with year-round mowing. Some species will need to be completely harvested and replanted at least annually. An annual harvest implies storage of the seaweed-for-energy so that the same amount of feedstock can be delivered to the HTL process 365 days a year. The nutrient return might share the storage system. In this case, the actual nutrient distribution may involve additional trips.

[11] Past abuses have caused many countries to prohibit nutrient distribution. But returning the nutrients that were removed from the reef, in a manner that increases biodiversity, is essential for sustainable aquaculture. It is ironic that unsustainable and polluting distribution of nutrients in the form of fishmeal remains acceptable in many locations.

rapidly deplete dissolved oxygen while consuming the organic carbon. There are several ways to recycle the organic carbon, and a portion of the plant nutrients, at the HTL facility:

1. Convert the pasteurized organic carbon into food pellets by growing yeast and/or other microbes while mechanically supplying dissolved oxygen.[12]

2. Convert the pasteurized leftovers into food pellets by growing yeast and/or other microbes while using micro- and/or macroalgae to supply dissolved oxygen. The algae also become part of the food pellets.[13]

3. Employ anaerobic microbes to convert fatty acids into biogas, generally 60% CH_4 (methane, the primary component of natural gas) and 40% CO_2.

4. Employ hydrothermal gasification, perhaps with a catalyst (Jiao et al. 2017) that quickly converts the fatty acids into biogas at HTL temperature and pressure.

5. Employ other processes such as fermentation.

Potential issues and benefits that might be addressed when recycling nutrients from the energy conversion, e.g. HTL, process:

•   Inadequately scrubbed coal power plants air emissions have been adding mercury to the oceans. Scientists and engineers may discover a way to remove mercury [14] and perhaps other anthropomorphic toxins, from HTL, oil, ash, or water. Not removing mercury during or after the energy conversion process will leave them in the redistributed nutrients and be returned to the ocean.

•   The macroalgae harvesting and nutrient recycling systems will be operated autonomously. They might incidentally or deliberately harvest larger plastics. Most plastic converts to oil during HTL. However, thermoset plastics (14% of the total, according to the American Chemistry Council [68]) are unlikely to convert cleanly and may go into the solid residues. But that residue could potentially be gasified into raw materials for new plastics or gasified for energy [69] in Allam Cycle plants. Or it can be shredded for filling material or reinforcement material in new products.

•   Most of the plastic in the ocean is tiny, microplastic particles. Some of the particles are the right size to be captured by filter feeders (shellfish and some finfish). The filter feeders may treat the microplastics like they do silt. Mussels collect silt and excrete a mixture of mucus and silt that sinks rapidly. Mucus and microplastics might also sink. Those filter feeders that retain microplastics can be harvested as feedstock for HTL which will break down the microplastics, so they become part of the biocrude.

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[12] This is a process used in most wastewater treatment plants but limited to non-filamentous microbes that settle quickly and lacking pasteurization. The "wastewater" or "sewage" industry is becoming the sustainable "water resource recovery" industry.

[13] Some water resource recovery facilities, those with relatively more land area, can use plants in treatment wetlands or micro- or macroalgae in ponds to supply oxygen to the microbes as well as absorb nutrients directly.

[14] We have yet to see research on which HTL products contain how much of the residual mercury.

C. Mercury removal

Mercury can be inexpensively removed. "Calgon Carbon is a producer of activated carbon and manufactures it in granular, powdered, pelletized, catalytic, and impregnated forms for vapor and liquid purification solutions. They offer activated carbon solutions for mercury removal from gases, primarily focused around their Fluepac powdered products" (quote from 8 Rivers Capital proposal related to the Allam Cycle [8]).

3.5 Hydrothermal liquefaction details: start-up, eventual scale, cost, and infrastructure

Hydrothermal reactions occur on a continuum of increasing pressure and temperature from liquid water conditions into supercritical water conditions. The HTL continuum: hydrothermal carbonization to mostly solid carbon in a few hours; hydrothermal liquefactions to mostly heavy crude oil in an hour or two; supercritical water upgrading to more valuable oil with more gas in tens of minutes; catalytic supercritical water gasification to mostly gas fuel in minutes; noncatalytic supercritical water gasification to mostly gas fuel in minutes.

Watson et al. [70] review reports the current cost contributions calculated by the U.S. DOE for the 2015 state of HTL technology (SOT) and projected cost breakdown for the projected 2022 case of HTL technology. As shown in Figure S7, the feedstock is the largest fraction of the cost, "accounting for 67–81% of the selling price." Watson et al. also say, "The feedstock cost contribution could be reduced by utilizing waste feedstock (food waste, animal excreta, etc.) as opposed to cultivated algae."

The cost of sweet biocrude oil from the version of hydrothermal liquefaction (HTL) proposed by CleanCarbon Energy (CCE) [12] (shown in Figure S8) is based on engineering by CCE. CCE's cost is an order of magnitude less than others have calculated. Part of the reason for lower cost is CCE has engineered for several orders of magnitude larger capacity, at least 400 barrels/day as the minimum commercial size and 8,000 barrels/day as the maximum expected capacity. Even CCE's designed demonstration is 100 barrels of sweet biocrude oil per day (45 dry tonnes/day of recycled biomass[15]).

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[15] This design is for consistently the same material with no contaminants delivered at zero cost to the HTL facility every day, 24/hours/day, at least 330 day/yr.
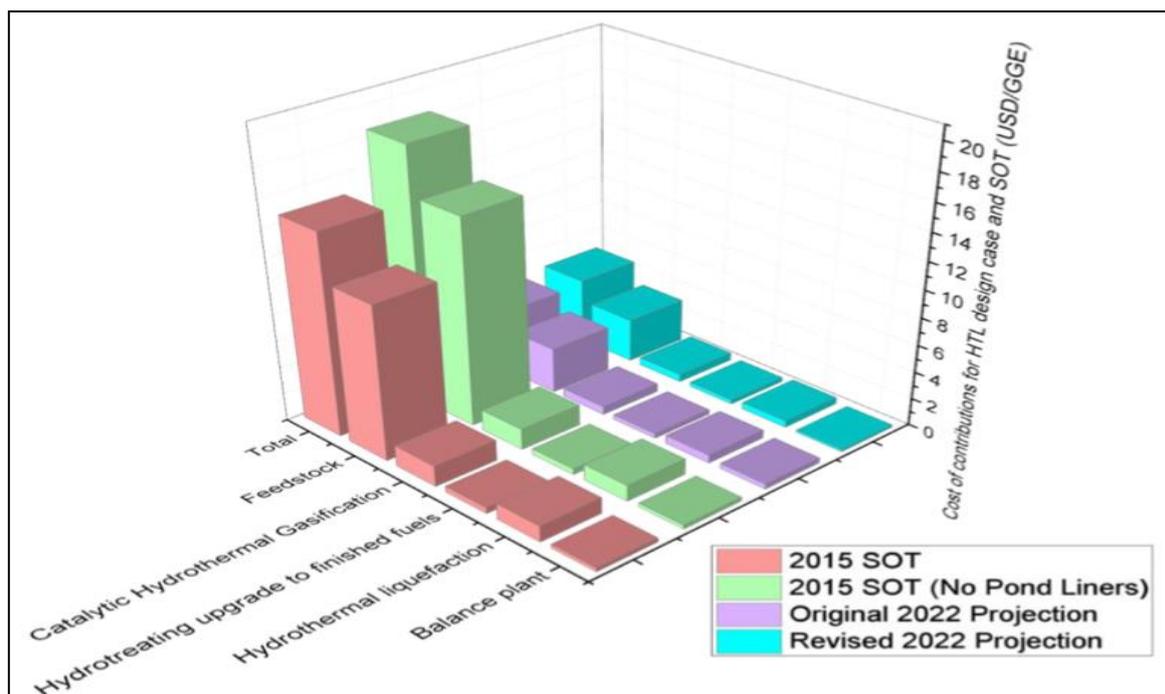
Figure S7. This is Figure 24 from Watson et al. [70], which compares the relative cost contributions to the product selling price in USD/GGE (gallons of gasoline equivalent). SOT refers to state of HTL technology in 2015. Notice their 2022 projections are about $4 per GGE, assuming the feedstock costs about $3 per GGE.

Consider the implications of Figure S8. Because communities currently pay to safely recycle and dispose of solid waste, a developed-country community could: (1) replace their landfill with an HTL facility, (2) adjust their disposal fee to $20/wet tonne, (3) transfer the biocrude to the community Allam Cycle electricity power plant for $0/GJ, (4) sequester all the CO_2, and (5) sell the electricity, including the cost for sequestering the CO_2, for $65/MWh. Developing countries might ensure complete solid waste collection by paying a modest fee, perhaps $10/wet tonne ($30/dry tonne) for solid waste and produce oil for $30/barrel.

Concepts presented in Figure S8 show how the cost of producing biocrude is related to the price paid for feedstock:

- CCE engineered their system for a consistent biomass such as micro- or macroalgae. MSW (aka trash) will be more expensive to process because the contents are not consistent. Each truckload has different carbon fraction and water fraction. The change can be mitigated with storage and blending over a few days. But storage and blending increases costs.

- The CCE initial feedstock is wood waste. The CCE cost includes pre-treating with sodium hydroxide.

- The authors are making an engineering judgement, with very little information on the additional processing cost for trash. More research is needed.

- Assuming the additional cost for processing trash is less than about US$50/barrel of biocrude, the disposal fees paid by many municipalities to landfill and/or recycle wastes can subsidize initial HTL installations. Referring to the graph in Figure S8, when the disposal fee is near $200/dry tonne (perhaps $70/wet tonne, which is normal in the East Coast USA [71]), the

biocrude oil could cost as much as $220/barrel to produce while still being sold for $70/barrel to break even.
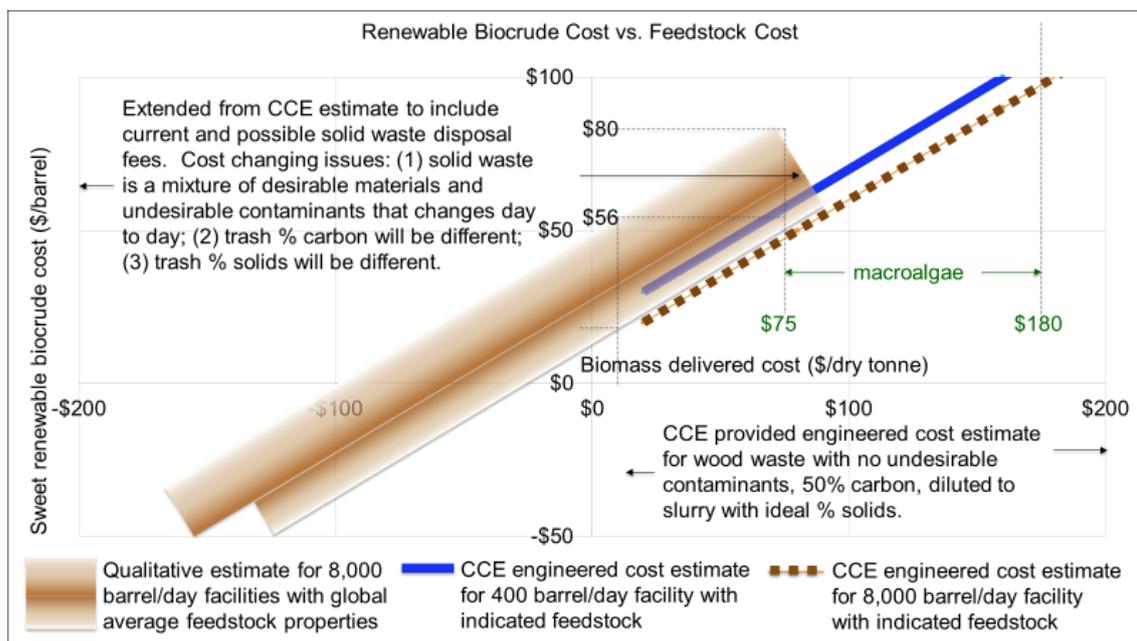

Figure S8. Interpolation and extrapolation of CCE cost projection for sweet biocrude oil from HTL as a function of the delivered biomass cost. See SMS#8 for the graph provided by CCE, which covers the range of feedstock cost from $0 to $100/dry tonne. See SMS#11 for a description of the feedstock biomass features that correspond to the CCE graph.

CCE's design and cost projections include subsystems to make sweet oil (relatively little sulfur), recover fuel gas, and recycle nutrients. Modified from graph provided by Pichach [12] (see SMS#8). For example, for macroalgae costing $75/dry tonne, the biocrude might range from $56 to $80/barrel. (Note: Scales and cost curves differ significantly between researchers and between various companies and are highly dependent on the cost and characteristics of the feedstock.)

- The World Bank (Kaza et al. 2018) projects about 6 billion dry tonnes of trash/per year appropriate for HTL in 2050, see SMS#4. Six billion tonnes of trash would produce more than 20 million barrels of biocrude/day. This size industry should be sufficient to drive improvements in the cost of the process to eventually break even when purpose-grown biomass feedstocks cost $100 to $150/dry tonne, delivered.
- The manuscript is discussing the technology situation for 30 to 100 years in the future. If CCE is underestimating the future cost of HTL, there is time for other HTL developers or an entirely new biomass-to-transportation fuel technology to fill in.

    CleanCarbon Energy believes their system addresses the issues that have prevented HTL from going commercial. Issues include:

- The produced biocrude oil often has too much oxygen, nitrogen, and sulfur to be accepted at a refinery. If the production was near 50,000 barrels/day, a refinery might adjust their system. CCE process costs include an off-the-shelf hydrotreater to reduce the concentration of non-oil

molecules such that the oil will be acceptable to most refineries, at scales as low as 100 barrels/day.

- Hydrotreaters require hydrogen. HTL produces mixed bioash and biochar byproducts. CCE includes an off-the-shelf gasifier to make syngas from the biochar (a mix of CO and H_2). Pressure swing absorption (not included) will concentrate the H_2.
- Some processes use expensive metals for the heat exchanger due to the temperature and pressure. CCE will use off-the-shelf oil industry drill pipe.
- HTL has substantial left-over water (called the aqueous) that has nutrients (but looks and smells foul). Seasoned wood is 20% water. Water-shook-off kelp is 90% water. Water must be added to dry feedstocks so that the ground-up feedstock will flow through the heat exchangers. The aqueous contains virtually all the N (nitrogen) that was in the feedstock as protein, but now in the form of ammonia and ammonium. The aqueous also contains substantial amounts of dissolved organics (mostly carbon, such as short chain fatty acids). CCE's demonstration will employ either supercritical water gasification or an off-the-shelf anaerobic digestion unit to convert the dissolved organics into biogas (60% bioCH$_4$:40% bioCO$_2$, by volume). After anaerobic digestion, the aqueous has very little carbon and perhaps 0.5 to 3% N as ammonia[16] (depending on the feedstock).
- The bioash contains the P (phosphorus in the form of phosphate) and other oxidized metals, micronutrients, and unconverted/not gasified plastics[17].
- Section 3.2 in the manuscript and these supplemental materials discuss other opportunities for recycling nutrients appropriate for large-scale macroalgae-for-HTL-feedstock.
- CCE's initial process and cost estimates do not include separating and compressing the byproduct CO_2 produced during HTL and by combustion of the biogas. These costs are much less if the HTL is co-located with an Allam Cycle plant. If not, they are estimated to be similar to the historic costs of CCS (SMS#16). The quantities of CO_2 are estimated in SMS#11, 12. The costs for capturing and sequestering byproduct CO_2 are calculated in SMS#14.

Currently, plastics are made from fossil fuels. Fuel made from plastics that were made from fossil fuel is fossil fuel. Eventually, all the plastics recycled via HTL will be made from plants, biogas, and HTL biocrude.[17] Then the HTL biofuel will be carbon neutral. If the byproduct CO_2 and fuel gas is captured and sequestered, the biofuel made from plastic will be carbon negative. Meanwhile the environment benefits when HTL feedstock includes plastics made from fossil fuels because:

- Plastics (single use gloves, bags, containers) are for safely handling medical wastes. When epidemics are spreading, everything people touch can be a medical waste for HTL feedstock.
- More plastic and trash is collected at less cost with less energy expenditure.
- When more trash and plastic is collected, less gets into the ocean.

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[16] Recovering the ammonia is critical for sustainable biomass-to-energy.

[17] Plastics manufacturers likely will quickly move to the circular economy by making plastics that perform well, but convert into biocrude oil and biogas during HTL, and are made from the biocrude and biogases made from HTL of biomass.

- When more trash is collected, more CO_2 can be captured from air and sequestered.
- Eventually, more solid waste collection and processing leads to perfect cradle-to-cradle plastics manufacturing.

CCE produced a petroleum engineering (computer model) assessment for the properties of HTL biocrude (American Petroleum Institute Gravity classification 12) that is hydrotreated to 27 API standards. See Figure S9. The higher the number, the lighter and more valuable the crude oil. Hydrotreating increases the amount of H in the oil while precipitating some carbon as ash and causing nearly all of any oxygen, nitrogen, and sulfur to offgas. Hydrotreating produces 82 tonnes of sweet 27 API biocrude from 100 tonnes of 12 API HTL biocrude. The ratio will be slightly different for different biocrude grades due to the change in density.

			Batch Distillation Temp (degC)	Yield (wt%)	API gravity 15C	Viscosity (cSt)
			Renewable Drop in Crude	FEED	27	3.88
Density @ 40C (g/mL)	0.79		20-150 (Naphtha/Gasoline)	20	55.82	0.55
Viscosity, cSt	2.7		150-250 (Jet)	25	35.5	1.48
C, wt%	85.6					
H, wt%	14.6		250-350 (Diesel)	35	19.11	11.36
N, wt%	<0.05					
O, wt%	< 1		>350 (Low S Bunker / Resid Oils / Asphalt / Pitch)	20	5.25	5839
S, ppm (ASTM D5453)	7-10					
H/C Atomic Ratio	1.58					
CleanCarbon Energy, January 2020						

Figure S9. CCE petroleum engineer assessment of the sweet biocrude produced when HTL biocrude is hydrotreated
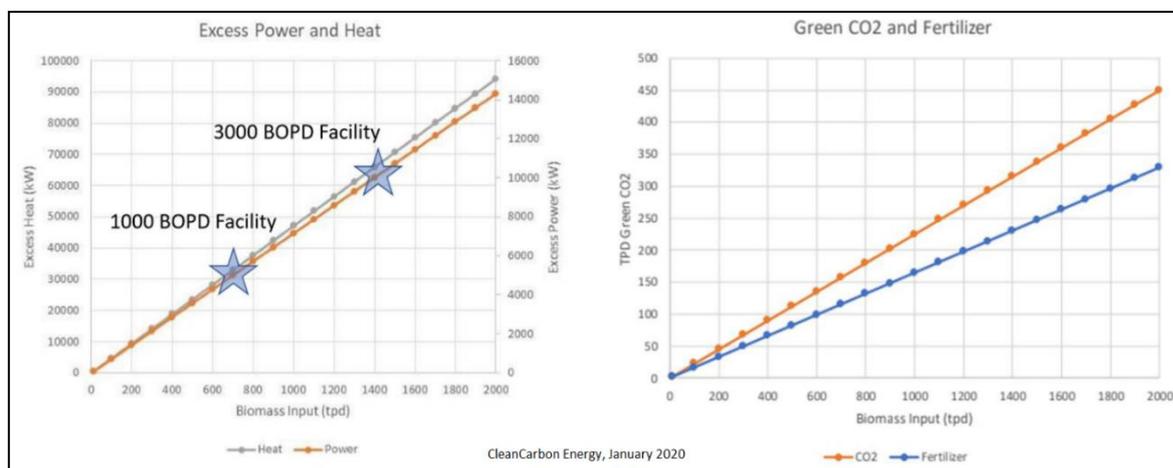

Figure S10. CCE petroleum engineer calculation of byproduct Power, Heat, bio-CO_2, and Fertilizer

Figure S10 is a graph showing the relationship between other product quantities and biomass input. Figure S11 graphs the cost as function of oil production capacity.
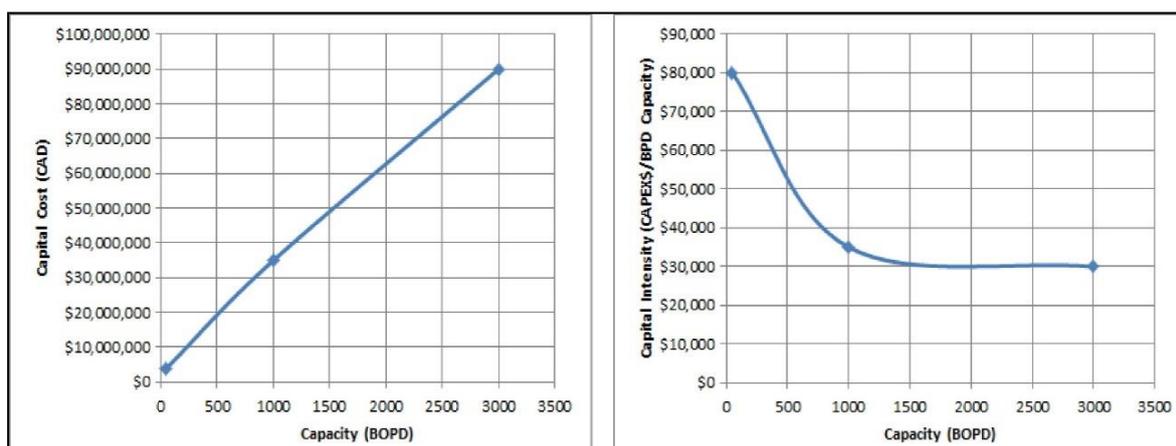
Figure S11. CCE petroleum engineer calculation of capital and capital intensity

The projected costs for delivering purpose-grown macroalgae biomass (SMS#4) range from $75 to $180/dry tonne delivered to HTL facility[18]. When applied to the speculative HTL cost curves in Figure S8, biocrude oil production costs range from $56 to $150/barrel. Meanwhile, oil prices regularly vary a few $/barrel during a month and tens of $/barrel over ten years [72] (and are increasing in the EU [73] and in California [74] because of carbon emission fees). Because HTL from waste will significantly increase supply, prices are likely to drop.

3.6 Allam Cycle details: start-up, eventual scale, cost, and infrastructure

We realize that proposing that all new electricity power plants be Allam Cycle, Figure S12, (or similar technologies), initially burning fossil fuels (coal and natural gas) may seem counter-intuitive. However, the fact is that many countries, such as China, India and Korea among many others, are currently building and planning many more fossil fueled power plants. If all these plants were Allam Cycle with full carbon sequestration, they would be carbon neutral and thus equivalent to building solar and wind power plants.

Another advantage is that the Allam Cycle plants can easily transition to consuming biomass and biocrude and thus become carbon negative, removing carbon dioxide from the atmosphere and oceans. In addition, Quirion et al. [75] found that using CCS with fossil fuels produced faster reduction in emissions with a lower carbon price because CCS does not reduce the demand for fossil fuels, hence does not reduce international fossil fuel prices. Sepulveda et al. [76] calculate "availability of firm low-carbon technologies, including nuclear, natural gas with carbon capture and sequestration, and bioenergy, reduces electricity costs by 10%– 62% across fully decarbonized cases."

Jacobson [77,78] and others argue that there should be no carbon removal until all global energy is sourced from "Wind-Water-Solar and Storage." Allam Cycle electricity makes this an unnecessary constraint for achieving net zero emissions. Further, waiting on CDR until fossil fuels are replaced means a few decades delay in scaling biomass production and replacing aging carbon neutral Wind-Water-Solar and Storage systems with carbon negative BECCS Allam Cycle. The IPCC 1.5ºC report [5] requires a quick start and ramp-up of CDR to remove the almost 2 trillion tonnes of fossil-CO_2 in

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[18] These are projected at-scale macroalgae costs after global demand for food is satisfied.

the atmosphere and oceans. A slower start on CDR means higher peak warming and higher peak ocean acidification. Jacobson ([77] also raises the issue of the health costs of continuing to burn coal and natural gas. The HTL and Allam Cycle plants referenced in the manuscript have no emissions and thus have no health impacts, while they capture CO_2 for sequestration.

Figure S12. NET Power's 50 MW$_{thermal}$ Demonstration Plant in La Porte, Texas (PRNewsfoto/NET Power, LLC)

There are variety of biofuels that could be used for Allam Cycle plants (anything easily gasified): wood, ethanol, HTL post-refinery asphalt, HTL post-refinery diesel fuel, hydrotreated HTL biocrude, HTL biocrude without hydrotreating, and more.

The cost of electricity ($/MWh) will vary as a function of the cost and quality of the biofuel. The Allam Cycle plant operator could give the pressurized CO_2 to the sequestration agent at no-cost at the edge of the plant property line. The sequestration agent pays the capital and operating cost for moving the CO_2 from the property line to the sequestration location.

The following information on the Allam Cycle is extracted from the technology owner's publicly-available proposal and reports to the U.S. Department of Energy's Coal FIRST (Flexible, Innovative, Resilient, Small, Transformative) program [8,79]. It is informed by 8 Rivers experience operating the 50-MW demonstration unit for over a year [80]. While the proposal emphasizes U.S. coal economics, it mentions natural gas and global markets.

Early adopters of Allam Cycle power plants can sell gases to decrease the cost of electricity. The gases include argon (Ar) and nitrogen (N$_2$) made while separating oxygen (O$_2$) from air. CO_2 is by far the largest volume gas. Currently, the largest volume demand for CO_2 is for enhanced oil recovery (EOR). 8 Rivers Capital [8] indicates the global demand for EOR will support US$15/tonne of CO_2 up to about 6,000 of their 300-MW units.

EOR is mostly useful when the world is procrastinating on seriously addressing climate change. It allows investors to see immediate returns for carbon-neutral technology that eventually becomes carbon-negative. Should the world become serious, they would still enjoy returns, perhaps larger returns, for their foresight. Some considerations when using CO_2 for EOR:

- Expect over 90% of EOR CO_2 to stay in the ground [81].

- Some analyses [82] show EOR-produced oil to emit 37% less CO_2 than conventional oil. Accounting gets controversial. Would the same amount of oil be produced in some other country, if it had not been produced by EOR? If not, double counting is avoided by counting all the fossil-CO_2 sold for EOR as "emitted to the atmosphere" and giving all the emission reduction credit to the oil. If the Section 3.8 Table S1 carbon fee system existed, the coal fueling Allam Cycle would pay the total fee. The Allam Cycle can elect either to take the payment for sequestering CO_2 (for the amount permanently sequestered) or sell the CO_2 for EOR (not both). Rules will be needed to define how much of the carbon fee is paid by the produced oil.

- A biomass-fueled Allan Cycle is already carbon-neutral (and becomes carbon-negative when the CO_2 is sequestered. Obviously, the biomass does not pay the fossil carbon fee. Accounting for who gets how much payment for sequestering CO_2 remains controversial.

A normal steam-electric power plant's exhaust gas to the air is 80% nitrogen and 20% CO_2 (for coal) or 91% nitrogen with water vapor and 9% CO_2 (for natural gas). Purifying, compressing, and cooling the CO_2 for sequestration requires substantial energy and capital investment. The exhaust also contains other pollutants including mercury, particulates, oxides of nitrogen (NO_x), oxides of sulfur (SO_x), etc.

All these issues can be solved by replacing steam and gas turbine plants with Allam Cycle plants. They produce inexpensive electricity with near zero emissions (below detection of NO_x, 0.4 tonne/yr of SO_x, 1 gram/yr of mercury) plus pressurized liquid CO_2 ready for storage [8].

Allam Cycle projected cost of electricity with sequestration-ready CO_2 is only $74/MWh. James et al. [83] prepared a standard baseline report for a supercritical pulverized coal (SC-PC) power plant as $64/MWh without CCS or $108/MWh with 90% carbon capture. (James is assuming similar fuel cost as 8 Rivers at $19/MWh = $1.8/MMBtu. We added $3/MWh to compress from James' 15 bar to Allam Cycles' 100 bar.) See Section 3.8 for a discussion of costs in terms of $/tonne of CO_2 sequestered.

At first, the CO_2 can be sold for EOR or conversion into plastics and other products [84]. Selling CO_2 for EOR lowers Allam Cycle electricity costs to as little as $55/MWh for coal-fired plants near markets for argon, nitrogen, and CO_2. The inherently low emissions of Allam Cycle allow substituting zero or negative cost dry paper and plastic wastes for coal to further reduce the cost of electricity.
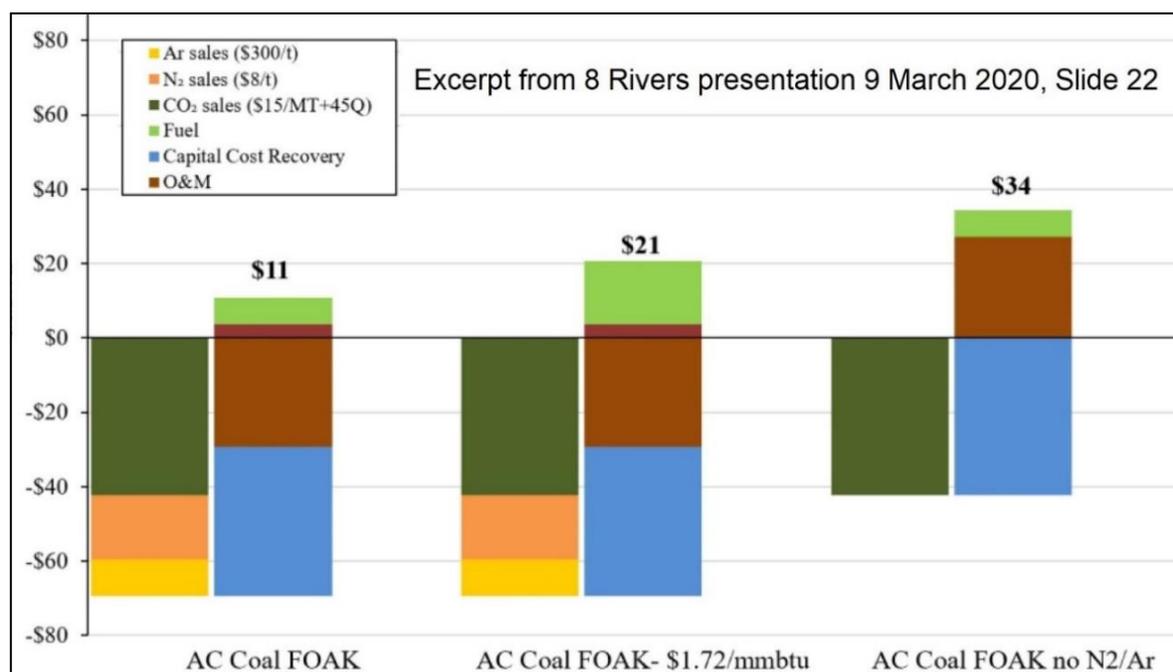
Figure S13. Allam Cycle electricity cost (US$/MWh). Note that the negative $/MWh indicate revenue from Argon (Ar), Nitrogen (N_2) and CO_2 sales plus capital cost subsidies of $18/MWh from 45Q could lower the cost to as little as $11/MWh. Graph from slide 22 of 8 Rivers Project Execution Plan Presentation [85].

Figure S13 shows the economics in the U.S. due to tax credits plus sales of many byproducts from coal-fired Allam Cycle electricity to drop the cost of electricity below that of other coal-fired plants and even below that of the most advanced natural gas power plants.

Acronyms in Figure S13 include:

EOR – enhanced oil recovery.

45Q – Section 45Q of the US tax code provides a performance-based tax credit for carbon capture projects. CO_2 can be injected into old oil wells to recover more oil, a process called enhanced oil recovery (EOR). Most of the injected CO_2 remains geologically sequestered. (See the section on CO_2 storage for an explanation of geologic sequestration.)

O&M – Operation and maintenance costs other than fuel, such as salaries, chemicals, etc.

mmbtu – million British thermal units (also MMBTU = 1.05 GJ), a measure of energy. Coal is sold as $/mass and natural gas is sold by as $/volume. The costs are more easily compared when both are converted to $/unit of energy provided by the mass or volume of fuel, $/mmbtu.

AC Coal – An Allam Cycle electricity power plant fueled with coal.

FOAK – First of a kind plant, without 48a, but with 45Q tax credits and differing values for argon and nitrogen gas sales. Illinois coal heat value and price differs from PRB coal.

By selling gas by-products, the first few thousand Allam Cycle power plants provide reliable electricity at lower cost than any other system for natural gas prices above $5/mmbtu, as little as US$62/MWh (US$0.062/kWh) (without EOR revenue). 8 Rivers estimates the demand for CO_2 for enhanced oil recovery in Asia, Middle East, Africa, and South America would require nearly 4,000 of its 300 MW power plants. Even after byproduct gas markets are saturated, coal-, natural gas-, and

biofuel-fueled Allam Cycle electricity with sequestration might remain less expensive than either coal- or natural gas-fueled steam electricity without sequestration for fuel importing countries.

The following information on the Allam Cycle is extracted from the technology owner's (8 Rivers Capital) successful funding proposal and initial reports to the U.S. Department of Energy's Coal FIRST program [8]. It is informed by 8 Rivers' experience operating the 50-MW demonstration unit on natural gas since mid-2018 [80]. While the proposal emphasizes U.S. coal economics, it mentions natural gas and global markets. Key points are as follows:

- NET Power (a subsidiary of 8 Rivers) targets commercial deployment of 300-MW natural gas Allam Cycle power plants in 2022, beginning in the U.S. because of government incentive payments for capturing CO_2, then expanding into developing countries, especially where EOR pricing is available [86].
- Coal-fired Allam Cycle requires demonstration of coal gasification with the Allam Cycle process, proposed for a Wyoming coal mine with a commercial operation date in 2026 [8]. (Dry solid waste and dry biomass could be gasified like coal, they could be demonstrated by mixing small and gradually increasing amounts with coal.)
- Emissions are nearly zero, much less than other fossil-, biomass-, or waste-fueled power plant. Expected emissions from a 300-MW coal-fired Allam Cycle plant include: below detection of NO_x, 0.4 tonne/yr of SO_x, 1 gram/yr of mercury.
- The Allam plant reduces the need for battery backup of other renewable energy because its ramping rate is faster than a combined-cycle natural gas power plant and it can increase its output by 70 MW beyond its 300 MW rating for up to four hours (by turning off the air-separation unit and running on the reserve oxygen tank).
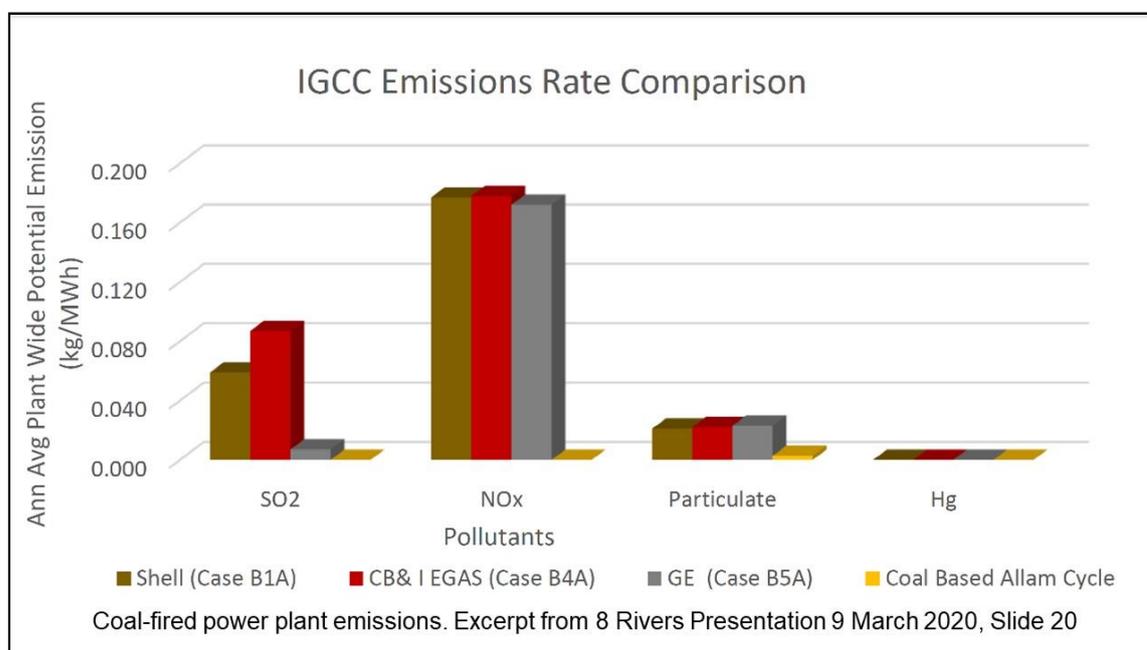

Figure S14. Emissions comparison of Allam Cycle compared to other coal plants from slide 20 of 8 Rivers Project Execution Plan Presentation [85].

Allam Cycle electricity is well suited to replace landfills or incinerators for dry organic waste and plastic. Figure S14 shows relative emissions for other coal plants compared with coal-fired Allam Cycle, which requires gasification. The same gasification process could be employed on dry waste. Because the gas from waste (like the gas from coal) is used as fuel for combustion with pure oxygen in a supercritical fluid, the emissions from waste will be similarly miniscule.

3.7 CO_2 sequestration details: start-up, eventual scale, cost, and infrastructure

A. Geologic Storage

Estimates of leakage from sedimentary basins vary, since each basin is slightly different. Kelemen et al. [87] has an extensive discussion, concluding "Probabilistic modeling of risks associated with leakage suggest that 98% of the CO_2 will be retained in 10,000 years (based on Choi et al. [88]; Alcalde et al. [89]; Rogelj et al. [2])."

Hang Deng, et al. [90]"Leakage risks of geologic CO_2 storage and the impacts on the global energy system and climate change mitigation" concludes the global onshore GCS capacity totals 5800 Gt CO_2 in four grades with varying costs. Deng also stated in a private communication that the off-shore GCS capacity is almost unlimited. However, Turner, et al. [27]paper titled "The global overlap of bioenergy and carbon sequestration potential" limits study to storage in highly prospective basins. They conclude that the transport via pipelines of CO_2 from BECCS is too expensive and look at the feasibility of harvesting sustainable biofuel crops for BECCS only over highly prospective basins. After deleting most land as either unprofitably unproductive, needed for food, or in forests needed for sequestration, they conclude that ~1 Gt CO_2 y^{-1} (about 0.5 billion tonnes of biomass) is sustainably feasible from terrestrial biomass.

Deng et al. [90] looked at the monetized cost of the leakage based on a case study of the Michigan basin. Based on a worst-case scenario, i.e. high permeability of leakage pathways and CO_2 in secondary traps that eventually gets back to the atmosphere, they projected maximum leakage back to the atmosphere over 50 years as < 0.2% of the total amount injected. They also estimated the monetized leakage cost is <\$ 5/tCO_2 for a majority (~75%) of the storage capacity. They projected cost of geologic storage rises above \$20/tCO_2 as the 'good' storage sites are filled and the secondary sites start to be used.

However, Alcade et al. [89]project much lower rates of leakage:

"We calculate that realistically well-regulated storage in regions with moderate well densities has a 50% probability that leakage remains below 0.0008% per year, with over 98% of the injected CO_2 retained in the subsurface over 10,000 years. An unrealistic scenario, where CO_2 storage is inadequately regulated, estimates that more than 78% will be retained over 10,000 years. Our modelling results suggest that geological storage of CO_2 can be a secure climate change mitigation option, but we note that long-term behaviour of CO_2 in the subsurface remains a key uncertainty."

Deng (private communication) says the injection rate has large uncertainty, as it depends on availability of CO_2, the configuration of the injection well(s) and the properties of the wells. As

reported in the IPCC special report [5], current pilot sites typically have injection rates of up to ~1000 tonnes of CO_2/day[19].[91]

For the purposes of this paper we ignore storage in industrial and municipal wastes because they are projected as expensive ($60 - $400/t) and limited in scope (<0.2 Gt/yr) (MSW and CDW in Figure S15 below).

B. Mineralization

On land storage in basalt (ISOB and ISOP in Figure S15) looks promising without problematic environmental impacts. Keleman, et al. [87] report that pilot-scale experiments in Iceland (Gunnarsson, et al. [92]; Snæbjörnsdóttir et al. [93]) and Wallula, WA (USA) (McGrail, et al. 2017) "have shown that *in-situ* carbon mineralization for storage in basalt formations is feasible and safe." The Iceland project found that over 95% of the CO_2 injected into the CarbFix site was mineralized to carbonate minerals in less than 2 years (Matter et al. [94]), after which there can be no leakage.

National Academies of Sciences Engineering Medicine (NASEM) [95] projected the cost of subsurface storage of supercritical CO_2 as a gas in saline aquafers at ~$10-20/t CO_2. They indicate *in situ* (underground) on land peridotite rock could sequester more than 10 Gt CO_2 per year at a cost comparable to saline aquifers. NASEM declines to conclude how many tons should be projected, because "the size, injectivity, permeability, geomechanics, and microstructure of key subsurface reservoirs for *in situ* mineral capture and storage remain almost entirely unexplored."

The analysis by Keleman, et al. [87] is shown in Figure S15:
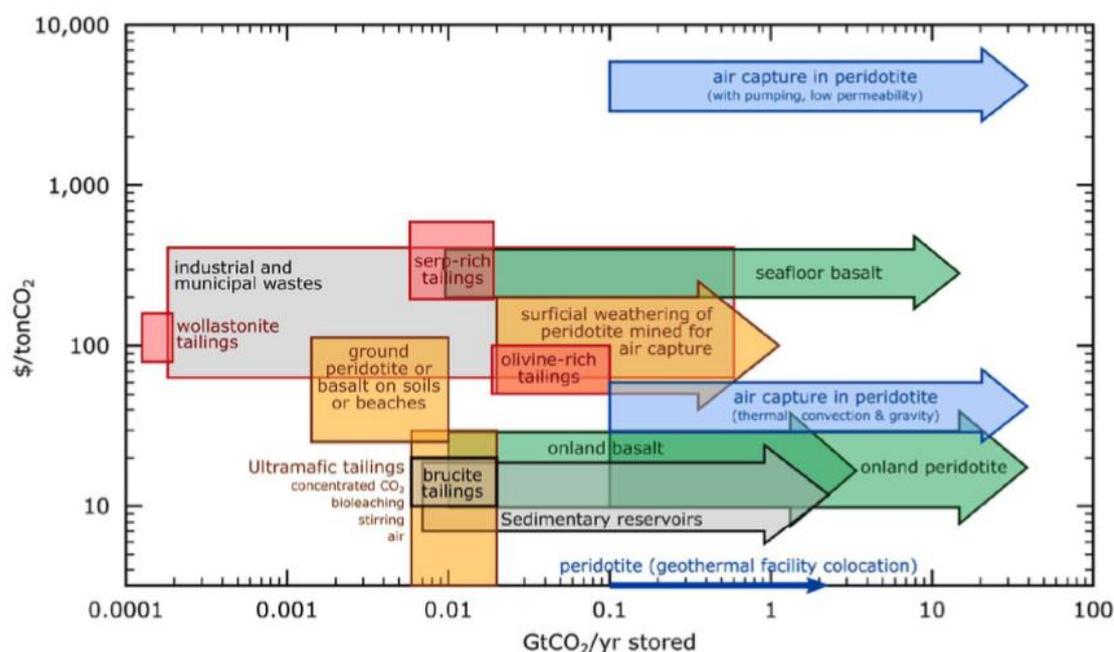

Figure S15: This figure and caption are from Kelemen et al. [87]: FIGURE 4: Summary of the cost of CO_2

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[19] About 400,000 t/yr per site would potentially require over 30,000 injection sites to sequester 13 billion tonnes/yr. The high bio-electricity path is based on 30,000 of the 300-MW Allam Cycle electricity power plants.

stored (US$/tCO₂) vs. storage potential of CO₂ per year (GtCO₂/yr). Red boxes illustrate costs and rates for *ex-situ* CO₂ mineralization using heat and concentrated CO₂. Yellow boxes are for surficial CO₂ mineralization of mine tailings, of ground peridotite added to soils or beaches, and of peridotite mined and ground for the purpose of CO₂ removal from air with solid storage. Green arrows are for *in-situ* carbon storage by injection of CO₂-enriched fluids into mafic and ultramafic formations (e.g., CarbFix). Blue arrows are for *in-situ* carbon sequestration by circulating water saturated in air into peridotite formations, and for CO₂ removal from air with solid storage. Gray arrow is for *in-situ* carbon sequestration by injecting supercritical CO₂ into subsurface sedimentary formations. Figure modified by Kelemen et al. from NASEM [95], Figure 6.19, with data from Tables 6.1 and 6.2 and references therein.

An important cost factor for CO₂ sequestration is distance to suitable storage sites. NASEM Appendix F shows a calculation of energy requirements and costs for compressing captured carbon dioxide (CO₂), transporting in a ten mile-long pipe to the sequestration site, and injecting it into a deep sedimentary formation as a levelized cost of $8.60 to $20/t CO₂/yr.

The map below from Keleman, et al. [87] (based on the references in the caption) shows the distribution of the three types of inexpensive (<$30/t CO₂) geological formations: sedimentary (including saline) basins, basaltic formations and ultramafic formations.
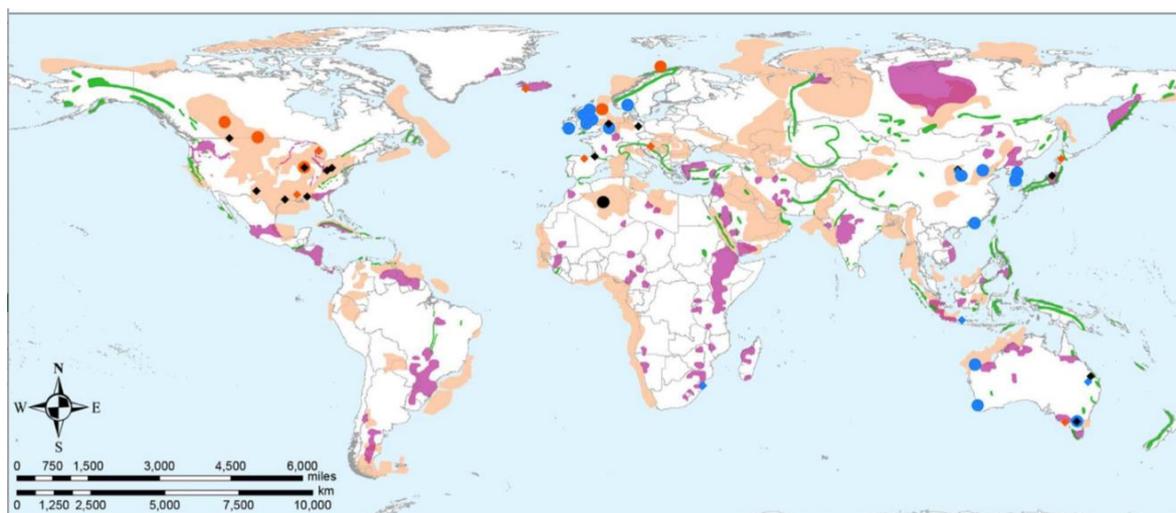
Figure S16: This map and caption from Kelemen et al. [87] FIGURE 5: Map of CO₂ land sequestration facilities, pilot projects, and long-term storage potential in geologic formations.

However, Figure S16 does not indicate the ubiquitous presence of basaltic formations underlying most of the ocean, which was projected by Kelemen et al. to be able to store billions of Gt of CO₂/year for $200 - $400/t. Snæbjörnsdóttir et al. [93] estimate the theoretical storage capacity of the ocean ridges is on the order of 100,000–250,000 GtCO₂ as shown in Figure S17.
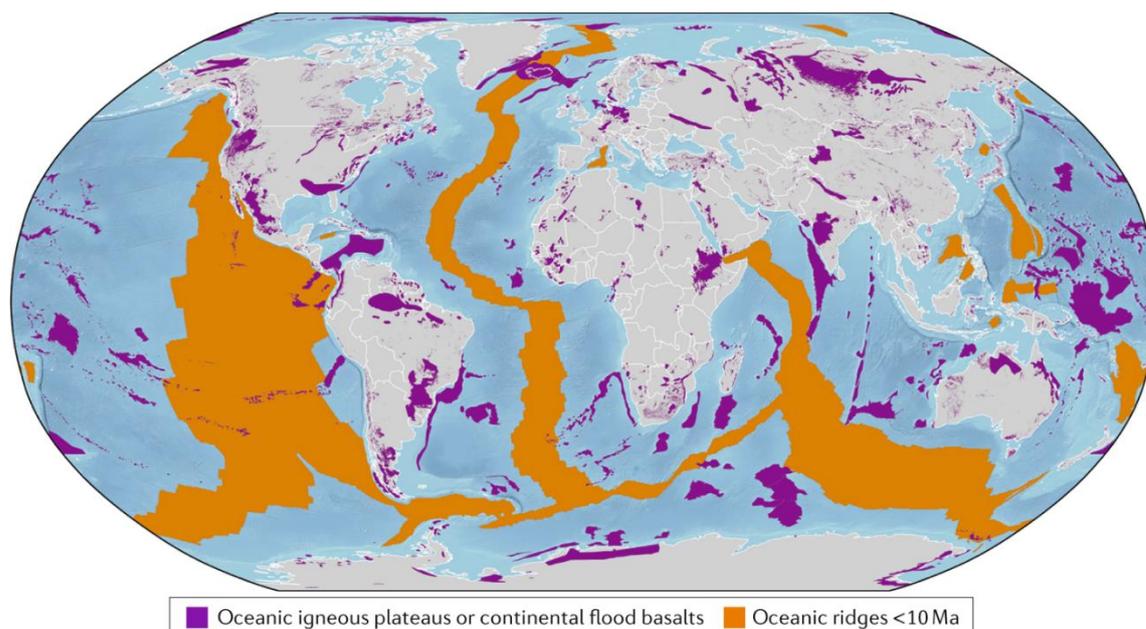
Figure S17. This figure is from Snæbjörnsdóttir et al. [93] Figure 2: Locations of feasible ocean geological formations for in situ mineral carbonation. Map showing the potential onshore and offshore targets for in situ mineral storage of CO_2. Oceanic ridges younger than 10 Ma are shown in orange, and oceanic igneous plateaus and continental flood basalts are shown in purple.

A demonstration of injecting pure CO_2 into undersea basalt is currently underway in Canada by Kate Moran et al. [96].

In conclusion, the cost of CO_2 sequestration is highly dependent on the closeness of the CO_2 source to inexpensive waste sources and appropriate geological formations. If one is in Iceland (or near other areas with basaltic fast-reacting rocks as shown in the maps in Figures S16 and S17), one can sequester many $GtCO_2$ for \$10-\$30/t CO_2. If one is over a highly prospective sedimentary reservoir (beige in Figure S16), many $GtCO_2$ can be sequestered for \$0.70-\$20/t CO_2.

Other forms of mineralization are being considered. One example, olivine beach sand promoted by Project Vesta [97]. All ways to permanently capture and sequester CO_2 should be eligible to compete for the payments described in Section 3.8 and Table S1.

C. Contained liquid CO₂ storage

Caserini et al. [98] analyzed permanently storing liquid CO_2 in glass capsules at depths between 1000 and 3000 m and less than 200 km from the shore and found essentially unlimited capacity (35 Gt in the Black Sea and 14 Gt in the Tyrrhenian Sea, etc.).

D. Contained hydrate storage

Excerpts from Capron, et al. [99]:

"Below about 1,000 m depth, ocean pressure and temperature is reliably such that liquid CO_2 will combine with water to form a hydrate. The minimum depth for stable hydrates is about 500 m. Additional depth provides faster hydrate formation and a

factor of safety considering future warming. The hydrate looks and acts structurally like ice but is slightly denser than is seawater that is saturated with dissolved CO_2.[20] The hydrate must be contained because it will (slowly) disintegrate when in contact with seawater that is not fully saturated with CO_2. Thus, an impermeable container must be maintained around the hydrate to prevent unsaturated water from contacting the hydrate. However, should the container be breached the disintegration will be slow, allowing a few months to patch the breach before significant CO_2 loss."

Brewer [100–102] (see Figure S18) shows the quick formation of a stable CO_2-hydrate skin, with negligible leakage. Thus, there is no rush to repair any damage to the geosynthetic membrane container.

Barring an easily-repaired mechanical leak caused by seismic activity, turbidity currents, biologic activity or the like, Capron, et al. [99] describes multi-layer geosynthetic membranes with CO_2 leakage rate less than 0.06% per thousand years. The Capron team proposed structures can also be constantly monitored for any damage that could cause CO_2 leakage, with a remotely operated underwater vehicle dispatched to patch leaks.

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[20] CO_2-hydrate is denser than seawater, so is stable on the seafloor. Methane-hydrate is less dense than seawater, causing concern for it erupting from the seafloor when it warms or the ooze overburden is disturbed.

Figure 5. A large Pacific Grenadier fish (Coryphaenoides acrolepsis) inspects a blob of liquid CO_2 on the ocean floor at a depth of 3627m. The existence of a thin transparent skin of the hydrate [$CO_2 \cdot 6H_2O$] forms a very strong barrier to CO_2 escape, and the animal apparently does not sense any chemical gradient.
P.G. Brewer, 1999, "Contemplating Action: Storing Carbon Dioxide in the Ocean"

Figure S18. This figure is from Brewer [102] showing the CO_2-hydrate skin is instantly formed preventing escape of liquid CO_2 as it all gradually turns to hydrate.

E. Costs of storage

The Allam Cycle generates liquid CO_2 at 100 bar pressure so almost no extra cost is required for compression. Only 5 to 30 bar is consumed in friction losses and static head[21] when pumping the liquid CO_2 to the storage depth. The remaining pressure can be used to mix the container for faster hydrate formation.

Caserini et al. [98] projected capsule storage costs between $12 and $30/tonne, with $17/t as most likely. In 2013 Capron, et al. [99] estimated costs at $16/t of CO_2. That price included compressing the CO_2, the hydrate containers, (mixing) energy converting liquid CO_2 and seawater to hydrate, monitoring sensors, and associated electronics. However, SMS#13, 17 indicates our revised (2020) cost range of only $5 to $10 per tonne of CO_2. The changes that decreased unit costs include:

- Larger containers, up to 6 million tonnes, of CO_2 per container (16 million m³ including the seawater).

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[21] The liquid or supercritical CO_2 is lower density than the seawater and must be forced below the ocean surface.

- The containers are more structurally efficient and robust with costs interpolated from off-the-shelf AquaDams[22].

F. Complementary Options

The approaches to liquid or supercritical CO_2 storage complement each other as follows:

Geographically – Geologic storage is limited to certain locations on land and continental shelves. Hydrate storage is limited to the deeper ocean beyond the continental shelves. Inexpensive mineralization is available only in certain locations on land, but more expensive mineralization locations are plentiful offshore. Land transportation of wet biomass is expensive so the HTL facilities need to be located as close as possible to their wet biomass source. Piping CO_2 from the Allam Cycle power plant is also a significant cost so the storage should be near the HTL facilities and Allam Cycle plants. All these tradeoffs must be considered for each location.

Biomass origin – In general, BECCS with geologic storage would probably use terrestrial biomass (including dry solid waste) replacing coal and natural gas. In general, HTL biocrude with byproduct CO_2 capture and sequestration would probably use wet solid waste and oceanic biomass with hydrate or subseafloor basalt storage. An exception would be the U.S. Gulf Coast where existing oil industry infrastructure, appropriate geology, and appropriate oceanography may favor geologic storage from BECCS and HTL using marine biomass. Mineralization can be done wherever there is access to appropriate rocks (see Figure S16 map from Kelemen et al. [87]).

Design and permitting – Although each geologic storage site is unique, there are existing geologic storage operations at reliable inexpensive sites. On land, mineralization has been successfully demonstrated in Iceland (Gunnarsson et al. [92]; Snæbjörnsdóttir, et al. [93]; and Wallula, WA (USA) (McGrail, et al. [91]).

G. Discussion of alternative Carbon Dioxide Removal (CDR) methods

The manuscript calculations assume CO_2 capture and sequestration by all current methods (soil sequestration, tree planting, wetlands restoration, biochar, etc.) will continue at approximately their current rates.

However, as stated by the IPCC in 2018 [5], many more billions of tons of CO_2 need to be removed each year than are done with current sequestration methods. Many authors have looked at the variety of CDR methods (also called negative emissions technologies (NETs)). For example, the U.S. National Academies of Sciences, Engineering, and Medicine (NASEM) [95] analyzed the following six categories: Coastal Blue Carbon, Terrestrial Carbon Removal and Sequestration, Bioenergy with Carbon Capture and Sequestration, Direct Air Capture, Carbon Mineralization of CO_2, and Sequestration of Supercritical CO_2 in Deep Sedimentary Geological Formations. They did not include macroalgae, although they said in Appendix C that "maximum potential global area for macroalgae may be as high as 570 million hectares. The ocean processes that affect algal transport and storage are not well understood and [with more research] could provide more accurate

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[22] AquaDams [103] include a strong fabric tube surrounding two impermeable water-filled tubes. This construction technique prevents the tube from rolling when it is used as a dam or levee.

assessment of natural carbon sequestration." They do report Krause-Jensen and Duarte [52] "estimate that [wild] macroalgae may be [naturally] sequestering 173 TgC/y," (which is about 11% of the net carbon captured by its primary productivity).

NASEM introduces mineralization options by listing the following three methods:

1. *ex situ* carbon mineralization—solid reactants are transported to a site of CO_2 capture, then reacted with fluid or gas rich in CO_2,
2. *surficial* carbon mineralization— CO_2-bearing fluid or gas is reacted with mine tailings, alkaline industrial wastes, or sedimentary formations rich in reactive rock fragments, all with a high proportion of reactive surface area, and
3. *in situ* carbon mineralization— CO_2 -bearing fluids are circulated through suitable rock formations at depth.

NASEM goes on to say these three methods can be used either for storing CO_2 in carbonate minerals (referred to as *solid storage*), which is discussed above in 3.7 B, or both removing CO_2 from air and storing it in carbonate minerals (referred to as *combined mineral capture and storage*).

The costs and the rates of the reactions for combined mineral capture and storage are dependent on many variables, including the concentration of the CO_2 in the fluid, the temperature, the pH, the size of the rock particles, and the type of rock. NASEM Table 6.1 shows capture and storage costs of \$10-\$30/t only for the case where one drills in basaltic lava to a depth where temp >25°C and injects CO_2-rich fluid at $P(CO_2)$ > 60 bars (as demonstrated by McGrail et al. [91]). NASEM Appendix E (p. 485) calculates a levelized cost of \$866/tCO_2/yr for a general ex situ mineral carbonation process including extraction, reactant transport, pre-processing, chemical conversion, post-processing, product transport, and disposal or reuse.

Another analysis of 27 proposed "marine geoengineering techniques" was recently done by a large team (GESAMP [49]). Their summary Table 6.1 highlights only three CDR approaches: ocean fertilization, macroalgae cultivation, and enhancing ocean alkalinity with minerals. For the purposes of this paper, we will ignore the controversial ocean fertilization. We also ignore many geoengineering solutions they mention such as artificial cloud cover, reflective shields, and albedo enhancement, which may reduce temperatures but do not remove CO_2, and therefore are not CDR.

GESAMP mentions nine methods of storing carbon while enhancing ocean alkalinity:

o   Adding lime directly to the ocean
o   Adding carbonate minerals to the ocean
o   Accelerated weathering of limestone to produce alkalinity
o   Electrochemical enhancement of carbonate and silicate mineral weathering
o   Brine Thermal Decomposition of desalination reject brine
o   Open ocean dissolution of olivine
o   Coastal spreading of olivine
o   Enhanced weathering of mine waste
o   Amending soils of managed croplands with crushed reactive silicates

However, GESAMP does not provide details on projected costs for any of the above nine methods. They mention co-benefits such as "countering ocean acidification and its effects on

calcifiers," but note the risk that "Trace elements in the minerals will have biological and chemical consequences." They conclude that "Insufficient research and testing has been done on these topics to allow informed decision-making on large-scale deployment."

Many authors have pointed out that land based systems cannot scale up to meet the need for removal of 2-3 trillion tonnes."[23] For example, McLaren [104] analyzed 30 prospective negative emissions technologies (NETs), of which 14 of the most promising ones (at that time) are shown in Figure S19, with the size of the circle representing anticipated number of tonnes that could be removed for the indicated cost per tonne. The vertical scale represents the technical readiness levels, which range from TRL 2 (technology conceptualized) to TRL 7 (pilot systems demonstrated).
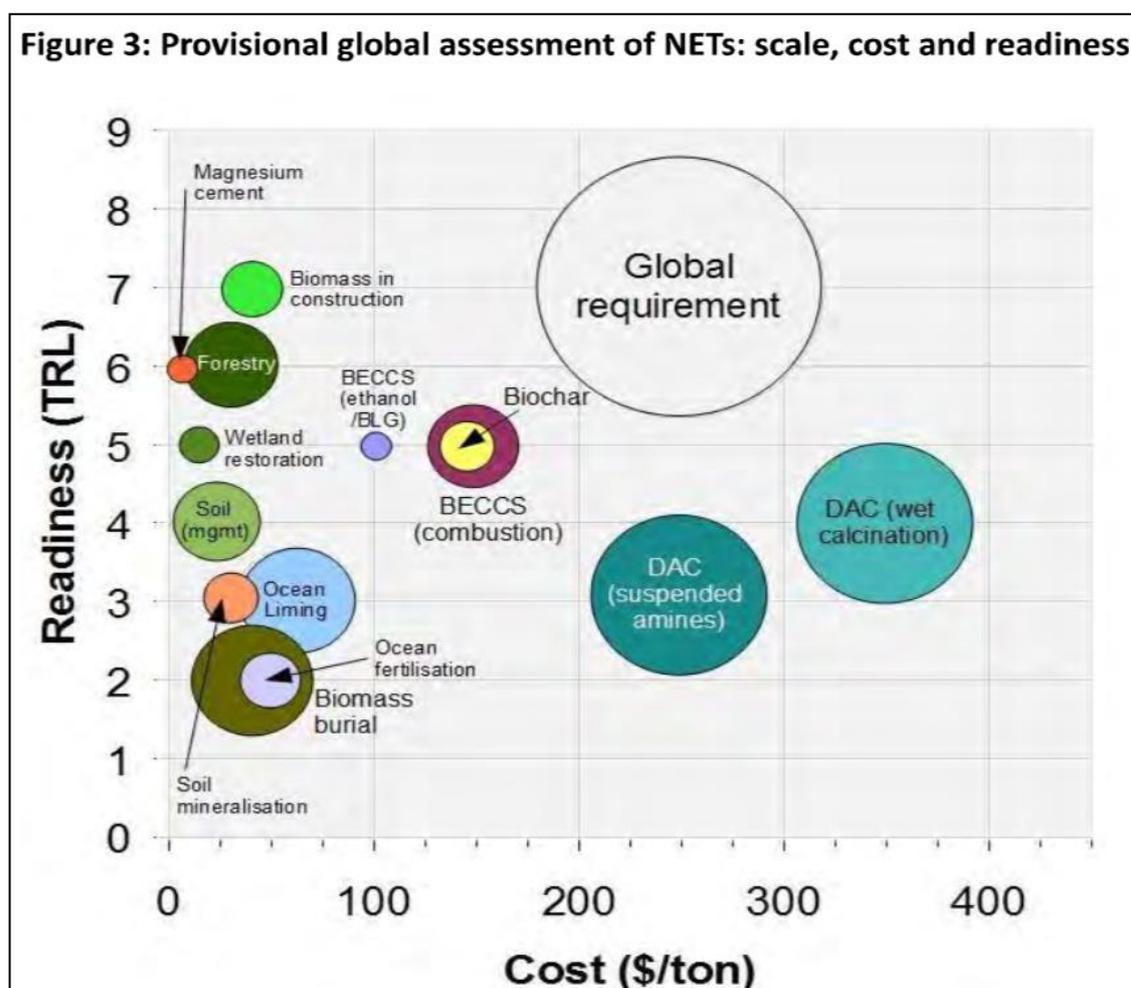
Figure S19. This figure is Figure 3 from McLaren [104].

Smith et al. [105] projected 12 Gt/yr removal by BECCS. Minx et al. [106], Fuss et al. [107]and Nemet et al. [108] have done a massive literature review of NETs. The Royal Society and Royal Academy of Engineering [109] have also done a comprehensive analysis.

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[23] Note that this paper deals only with CO_2 removal, not with the warming caused by other GHGs. Thus it may be necessary to remove more CO_2 to return the temperature to pre-industrial levels.

We recognize that the quantities and costs presented by the above review papers differ from the manuscript proposal, but as discussed above in 3.7 G, we believe that our calculations involving technological innovations with HTL and Allam Cycle plus the use of waste fuels and macroalgae can reduce the costs and increase the sustainable quantities for BECCS.

H. Additional natural CO₂ sequestration from macroalgae

The massive expansion of cultivated macroalgae for biofuels (up to 39 dry Gt/yr on the P_{fuel} path) recommended by this paper could also produce an additional amount of seaweed detritus that could be sequestered for hundreds of years or more in the deep ocean. How much detritus is lost to the deep ocean will vary widely depending on the seaweed species and methods of cultivation and harvest. A reasonable range would be from 2% to the 11% estimated by Krause-Jensen and Duarte [52] for wild macroalgae. A mid-value of 6.5% implies 1.5 dry Gt/yr of seaweed or 1.4 Gt CO_2/year, using an average carbon content of 24.8% of seaweed dry weight (Duarte [110]). If this sequestration is verified, and if the loss of nutrients is sustainable, it could reduce the amount of BECCS that is needed to achieve the needed CDR or it could slightly speed up the rate of removal so that the goal of 300 ppm CO_2 is achieved sooner. We look forward to more research quantifying detritus sequestration and associated nutrient loss as these macroalgae cultivation structures are deployed in many locations.

3.8. Costs of CDR: Paying for removing and storing legacy CO₂

A.   Process cost explained

Unlike many CDR methods, the manuscript proposes revenue from energy production will cover almost all the cost of making pure CO_2 with two sustainable biomass-to-energy processes. Essentially all the carbon input to the Allam Cycle becomes pure sequestration-ready liquid or supercritical CO_2 at 100 bar pressure using 23 kWh/tonne for energy and $3/tonne total cost. If the HTL facility's byproduct carbon, a mix of 1 atm CO_2 and fuel gas, is combusted in the Allam Cycle, all the carbon becomes pure sequestration-ready liquid or supercritical CO_2 at 100-bar pressure for only $3/tonne. If the HTL byproduct fuel gas is combusted with air, it becomes a mix of N_2 and CO_2 at 1-bar requiring 120 kWh/tonne and a cost near $65/tonne to purify and compress (SMS#14).

Section 3.8 of the manuscript explains the additional cost of capturing and sequestering CO_2 in $/MWh. Table 5 explains the additional cost in $/tonne of CO_2 sequestered. In either units, the "Process cost" of Table 5 is a component cost for how much more people need to pay for capturing and sequestering CO_2 than they are paying for electricity (directly) when not capturing and sequestering CO_2. With Allam Cycle coal-fired electricity the process cost component is the difference in cost for electricity produced at a supercritical pulverized coal (SC-PC) power plant or the Allam cycle power plant when neither practice carbon capture and storage. 8 Rivers' [8] mentions both units in ways that establish the conversion as about $15/tonne of CO_2 is equivalent to $11/MWh. A similar conversion can be made calculating using the carbon and energy density of the fuel with the efficiency of the plant.

Table 5 is based on coal-fired Allam Cycle (not natural gas-fired) because:

- Dry biomass (or dry waste) will require gasification, similar to coal. If the Allam Cycle is initially fired with natural gas, it will need a gasifier to supplement or switch to dry waste or biomass. (Note that byproduct fuel gas of HTL could supplement natural gas, regardless of the feedstock for HTL.)

- The process cost for natural gas-fired Allam Cycle varies with the cost of natural gas, which varies globally more than does coal. This means that including natural gas Allam Cycle in Table 5 would increase complexity without helping decision makers. For example, the Allam Cycle <u>additional</u> process cost relative to combined cycle gas turbine (CCGT, natural gas) ranges from $0/tonne of CO_2 for $8/MMBTU (7.6/GJ) liquefied natural gas (LNG) to $30/tonne for $2.90/MMBTU ($2.7/GJ) gas.

B. Putting the cost of sequestering CO_2 in perspective

The cost numbers below are discussed in Section 3.8 of the manuscript. These are the direct costs of capturing and storing CO_2. The $730 billion/yr achieves net zero CO_2 emissions (equivalent to net decarbonization). The $1,400 billion/yr removes enough CO_2 to return pre-industrial CO_2 levels over about 100 years (CDR in addition to net decarbonization). These are costs to society at large but could be thought of as increasing the cost of energy. The most important perspective in this direct cost is much less than historic estimates of direct cost and much less than the costs to society with business-as-usual. (SMS#16.)

- $1,400 billion/yr is 33% of recent annual fossil-fuel revenue. (The total global annual revenue of companies and governments for oil, gas, and coal exploration and production is about $4 trillion. Oil and gas revenues in 2019 were about $3.3 trillion [111]. Coal company revenues in 2019 were about $900 billion [112].)

- $1,400 billion is only 1.6% of the total global 2019 gross domestic product of $87 trillion [113].

- $1,400 billion/yr appears to be much less than a potential $50 trillion/yr future cost of inaction in 2100 (based on projecting the 10% direct damage to U.S. economy estimated by the U.S. Fourth National Climate Assessment [114] under the high-emissions scenario (in Figure S29.3, p. 1360 of that report) applied to a global projection of $500 trillion/yr GDP by 2100 [115]. But differing discount factors accounting for the time value of money, improved technology, and other factors affect comparing $1,400 billion/yr in 2020 dollars with $50,000 billion/yr in 2100 dollars.)

- Economists are fine-tuning models to determine the future damage inflicted by emitting a tonne of CO_2. Metcalf [116][24] indicates U.S. damage models value a tonne of CO_2 at $40 to $47 in 2020 (assuming a 3 percent discount rate). Damage-based CO_2 values less than about $74/tonne of CO_2 are less than the breakeven economic penalty for capturing and sequestering CO_2 using super critical pulverized coal plants (SC-PC) for making electricity (James et al., 2019). But even the low-end damage model prediction of $40/tonne of CO_2 is significantly higher than Allam Cycle's $22/tonne of CO_2 breakeven economic penalty (relative to SC-PC electricity) (SMS#14).

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[24] Metcalf confirmed by email that every mention of $/ton in his article means $/tonne of CO_2, not $/tonne of C.

- One concern about carbon fees is that globally higher energy costs make food, water, and most everything more expensive. The first sustainable development, total ecosystem aquaculture, mentioned in Section 2, is to produce up to a billion wet tonnes of seafood. The new seafood may reduce the cost of high-protein food globally, offsetting increased energy costs.

C. Lower costs for early adopters

The cost of geologic storage ranges from –\$40 to \$56/tonne of CO_2. The negative numbers are for locations where (and when) oil companies will pay for CO_2 for enhanced oil recovery (EOR). Even without EOR sales, geologic storage sites range in cost. Early adopters will fill the least expensive sites first.

Allam Cycle electricity power plants produce gases. Nitrogen (N_2) and argon (Ar) are produced in the oxygen-producing air separation unit, plus pure CO_2 at 100-bar pressure as a byproduct of combustion. 8 Rivers [8] estimates the first owners of 300-MW power plants can offset the cost of electricity as shown in Figure S13:

- Plants commencing construction in the US before 31 December 2023 can receive 45Q tax credits worth about \$20/MWh when CO_2 is sold for enhanced oil recovery (EOR).
- Perhaps 30 plants located near markets for argon can sell argon worth \$8/MWh before the price for argon drops. (Argon is currently worth over \$300/tonne, but air is less than 1% argon.)
- An unknown number of power plants can be located near a demand for nitrogen. The sale of nitrogen can net near \$20/MWh. Nitrogen is 78% of air and is currently worth \$8/tonne when close to markets.
- As many as 6,000 of the 300 MW power plants globally can expect to sell CO_2 for EOR at \$15/tonne of CO_2 (before demand is saturated), netting a \$11/MWh drop in electricity cost.

These electricity prices are additive, so a coal-fired power plant selling Ar, N_2, and CO_2 could decrease its electricity cost from about \$74/MWh by \$39/MWh to \$35/MWh. There are many local variables that will change these numbers: the price of fuel for the power plant, location near markets for these gases, and their sale prices.

D. Allocating costs for removing legacy CO_2

Discussing cost allocation has several purposes: (1) quantify the cost of removing legacy CO_2; (2) quantify how delaying attainment of net zero emission increases uncertainty in fossil fuel investments; and (3) introduce a mechanism for continuing fossil fuel use after net zero emissions. The mechanism works as an example to accomplish the other purposes.

Ceasing the use of fossil fuels will not be sufficient. Humanity needs to remove legacy CO_2 (CO_2 emitted prior to net zero emissions). The simple approach is for people to start by paying higher energy prices to fund storage of all fossil-CO_2. As fossil fuel use decreases, people may have to pay higher energy prices to store bio-CO_2. Because most energy has been from fossil fuel, "energy" is closely tied to CO_2. Because most everyone uses energy, or buys food and water delivered by using energy, everyone's budget is affected when energy costs more.

One example of a pricing mechanism is outlined in Table S1. People using fossil fuel would pay a range $40 to $71/tonne of CO_2 produced when the fossil fuel is consumed. See Table S1 (plus SMS#10, 15, 16). People would also be paid up to $26/tonne of CO_2 to sequester CO_2, from any source (Table 5 in the manuscript, plus SMS#14). The fee and both payments might need adjusting every few years. The fee could become higher with continued business-as-usual and more CO_2 needing sequestration. The payments may become lower with new technology. The fee and both payments likely need adjusting every few years.

The highest initial fee stockpiles money from 2020 to 2050 to pay for sequestering bio-CO_2 after fossil fuel use ceases. The intermediate and lowest initial fees presume decades of continued fossil fuel use for Allam Cycle electricity generation (always with CO_2 sequestration). This long-term fossil-fuel use would be carbon neutral when carbon-neutral biofuel or carbon-neutral electricity is used to mine and transport the fossil fuel. Table 2 shows significant fossil fuel use when overall CO_2 emissions are at net zero (Table 2 is on SMS#2. Table S1 below is on SMS#15).

Table S1: Setting the fee on fossil fuel to pay for continuing bio-CO_2 sequestration.

Metric	units	Highest initial fee	Intermediate fee on fossil-CO_2	Lowest initial fee
Time of continued (all sequestered) fossil fuel use for electricity after net zero emissions	years	0	50	100
Average mass/yr of fossil fuel use after net zero emissions (all with offsetting fossil-CO_2 sequestration)	billion tonnes of CO_2/yr	0	10	20
Payment to companies for sequestering fossil-CO_2	$/tonne of CO_2	$26	$26	$26
Payment for sequestering bio-CO_2		$26	$26	$26
Total fee (cost) collected from fossil fuel producers to capture sufficient reserve funds		**$71**	**$63**	**$40**

The bottom row in Table S1 is more than the amount paid for sequestration so the fossil fuel use can pay for removing past CO_2 emissions. For comparison on prices, the current California market price on CO_2 of $18/tonne in 2020 (California Air Resources Board, 2020) is projected to rise to $50/tonne by 2030 [117]. California's current Low Carbon Fuel Standard has an effective price of $200/tonne [74].

Economists can select the amount of the carbon tax to equal future damage from fossil fuel CO_2. Eventually the damage estimate could become so high that fossil fuel use almost stops. The manuscript paths involve continued fossil fuel use (with capture and sequestration). The revenue

from a carbon tax has many potential uses, including retraining people, funding clean energy, paying off national debts, dividends to every citizen, etc. The approach shown in Table S1 could work with an international fund collecting all the fees, investing the fees, and making actual-cost payments for capturing and sequestering CO_2. Note that the lowest fee on fossil fuel ($40/tonne of CO_2) is the same as lowest damage-based value on emitted CO_2 mentioned in Metcalf [116]. However, in our proposal the fee and the payments for sequestering CO_2 accomplish much more by actually reducing legacy CO_2.

E.   Examples of fossil-CO_2 fees and sequestration payments

Any coal-fired power plant sells CO_2 for EOR:

➢ The power plant pays for coal delivered plus the US$40/tonne of CO_2 fee (the power plant passes on the fee to its customers in the cost of electricity). This fee (which is paid to the international fund) effectively adds about US$3.8/MMBtu ($3.6/GJ to the cost of coal) (see conversions on SMS#14, 15).

➢ The oil company buys all the CO_2 captured by the power plant. 8 Rivers expects the average global sales price will be $15/tonne of CO_2 when sold for EOR. The power plant can apply the $15/tonne to lower the cost of electricity as if the power plant were paying a net fee of $40 minus $15 equals $25/tonne of CO_2 ($2.4/MMBtu, $2.3/GJ). (Early adopters can also lower the cost of electricity with sales of argon and nitrogen.)

➢ The oil company receives US$0 to $26/tonne for permanently sequestered CO_2. Melzer [81] found that about 90% of the CO_2 used for EOR is permanently sequestered. The international fund might use a competitive process to select projects to receive sequestration payments. As demand for CO_2 to conduct EOR drops off over decades and as inexpensive geologic storage sites fill-up, the payment for capture, compression, transportation, and sequestration may increase, but should remain below $26/tonne.

➢ The oil company pays the $40/tonne of CO_2 fee for all the oil they extract, which increases the cost of oil to customers by $17/barrel or about US$0.11/liter, $0.40/gallon.

A coal-fired power plant without gas sales:

➢ The power plant pays for coal delivered plus the US$40/tonne CO_2 fee (the power plant passes on the fee to its customers in higher cost of electricity). This fee (which is paid to the international fund) effectively adds about US$3.8/MMBtu ($3.6/GJ to the cost of coal) (see conversions on SMS#14, 15).

➢ A combined power plant and sequestration company receives up to $26/tonne for permanently sequestered CO_2. With Allam Cycle, up to about $11/tonne will be spent on compression, transportation and storage. At least $15/tonne can be available to reduce the cost of electricity, as in the EOR example.

Any dry biomass-fired power plant sells bio-CO_2 for EOR:

✓ The power plant pays for biomass delivery. Biomass in the US would be competitive with coal at $3/MMBtu plus $3.8/MMBtu carbon fee. $6.8/MMBtu equates to about $130/dry tonne of

biomass delivered (SMS#4). (This is far more than the $60/dry tonne for purpose-grown biomass estimated by the U.S. Department of Energy in its *Billion-Ton Report* [16].) (Note that transporting and handling waste and other dry biomass may be more expensive per tonne than handling coal, reducing its relative value.)

✓ The oil company buys all the bio-CO_2 captured by the power plant. Price will be determined by complex market conditions. (Early adopters can also lower the cost of electricity with sales of argon and nitrogen.)

✓ The biomass producer, the power plant and the oil company receive and share up to $26/tonne for permanently sequestered CO_2. Biomass growth, harvest, and transport capture carbon from air. An Allam Cycle power plant would purify and compress the CO_2. The oil company transports and sequesters the CO_2. This would be an example of the international fund selecting carbon-negative bio-CO_2 to offset emissions from the fossil-oil.

✓ The oil company pays the $40/tonne of CO_2 fee for all the oil they extract, plus about $15/tonne for the CO_2 for EOR. These costs are offset by their portion of up to $26/tonne they receive for the ~90% of the CO_2 which is permanently sequestered.

A process converting wet biomass (or wet wastes) to bio-oil, such as HTL:

✓ The biofuel process avoids the $40/tonne of CO_2 fossil carbon fee, allowing it to sell for $17/barrel less than fossil-oil.

✓ If co-located with an Allam Cycle power plant, the HTL biofuel production could contribute carbon neutral fuel gas and share in the $26/tonne capture, compress, transport, and sequester payment. (More analysis is needed to quantify how the costs of biofuel, electricity, and sequestration might change when HTL is integrated with Allam Cycle.)

A process capturing and sequestering CO_2 from air, such as olivine sand beaches:

✓ The international fund might fund appropriate size demonstrations for processes which might scale with avoided costs near $26/tonne or appropriate component costs. For example, an appropriate component cost is near $8/tonne for sequestration. Other components include: transportation, compression, capture, biomass, and conversion process.

✓ The international fund would contract with the best value processes (cost, rate, permanence, other environmental factors), paying not more than $26/tonne (full avoided cost) for permanently sequestered CO_2.

✓ Ideally, the processes use carbon-negative electric equipment and carbon negative biofuels, materials, and equipment (made from biomass) in their operations.

F. Carbon fee or regulation options

There are many approaches to supporting sustainable development goals while achieving net-zero CO_2 emissions and then quickly decreasing CO_2 levels including:

• Regulations – Emitting CO_2 without sequestration becomes illegal in some situations. People pay for the sequestration by increased energy costs, plus a little extra for paperwork and enforcement. This method is currently working in many countries and many US states in so-

called renewable energy portfolio standards (RPS) which mandate certain percentages of renewable energy be included in electricity delivered to consumers. There may be less cost transparency and perhaps less opportunity for innovation to reduce costs in this approach.

- Cap and trade – Fossil fuel companies buy permits to emit CO_2, the cost of which increases as the cap decreases. People pay by increased energy costs, plus a little extra for paperwork and enforcement. Most of the permit fees in California's system are used to fund a variety of mitigation and sequestration measures, although those related to electrical generation are rebated to consumers. Such distribution to consumers leaves less funds for sequestering legacy CO_2.

- Carbon fee, tax, dividends – Fossil-fuel companies pay a fee at the mine or well or refinery and again people pay by increased energy costs, plus a little extra for paperwork and enforcement. The income can be distributed to individuals, applied to government general fund expenditures, and/or used for mitigation and sequestration. The increased cost of fossil fuels encourages people to switch to carbon-neutral energy. But distribution to consumers or governments leaves no (or much less) funds for sequestering legacy CO_2.

- Carbon fees to fund sequestration – Fossil-fuel companies pay a fee at the mine or well. The fees pay for fossil-CO_2 and bio-CO_2 capture and sequestration. The fees may be accumulated into a fund to keep paying for bio-CO_2 sequestration after ceasing fossil fuel use.

Instead of a carbon fee, Tvinnereim and Mehling [118] suggest a blend of policies involving regulations, financial incentives, and public and private investment that would support the rapid comprehensive implementation of co-located biofuel and bioelectricity production with CO_2 sequestration. Tabara et al. [119] recommend, "multiple interlinked actions — or interlinked systems of transformative solutions — which eventually push a system towards a new desired configuration."

The approach can change over the decades. Countries and international agreements can start with whatever approach most quickly achieves net-zero. Then transition to the approach that can pay for the most bio-CO_2 capture and sequestration per year for a century or so.

3.9. SDGs details: Achieving Sustainable Development Goals

United Nations Sustainable Development Goals [120] directly addressed by total ecosystem aquaculture reefs include:

- **SDG #1. No Poverty:** Ocean farming reefs are sustainable environmental community enterprises that create jobs especially for underserved communities. The jobs range from reef construction and maintenance to planting and harvesting to seafood processing and marketing to manufacturing fertilizers, pharmaceuticals, chemicals and other products, plus producing bio-energy.

- **SDG #2. Zero Hunger:** Ocean farming rapidly grows a variety of sustainable and protein-rich food sources. Seaweed requires neither fresh water, pesticides nor land input to grow. As one of the fastest growing plants in the world, from seed to harvest varies from only 6 to 30 weeks, depending on the species. Ocean forests can also grow large amounts of shellfish such as mussels, oysters, clams, etc., as well as invertebrates, including profitable sea cucumbers and sponges. In addition, many species of finfish eat seaweed, others lay eggs in seaweed and others

are attracted to the ocean forest, expanding fish populations and increasing catches. Seaweed is also an excellent fertilizer for terrestrial crops.

- **SDG #3. Good Health and Well Being:** Fish and shellfish provide the healthiest source of protein, complete with micronutrients often lacking in terrestrial crops from depleted soils. In addition, seaweed contains high amounts of iodine, potassium, magnesium, calcium and iron, as well as vitamins, antioxidants, phytonutrients, amino acids, omega-3 fats and fiber.

- **SDG #5. Gender Equality:** Ocean farming enterprises can focus on training and advancing women as an economic development tool that serves the immediate family and ripples out to the community and nation. In some developing countries, seaweed cultivation is a prime source of income for women.

- **SDG #6. Clean Water and Sanitation:** In some developing countries, coastal waters are polluted by runoff from overloaded sewage systems, malfunctioning septic tanks, and even raw sewage discharges. Ocean forests can clean up these issues, restoring a clean healthy ocean environment, plus reducing disease for coastal residents. In addition, OceanForesters will work with local authorities to establish new human and animal waste collection systems that will pasteurize wastes and use them to fertilize seaweed forests.

- **SDG #7. Affordable and Clean Energy:** Seaweed farming sustainably grows seaweed suitable for conversion to bio-energy, including cooking gas, electricity, and biodiesel fuel.

- **SDG #8. Decent Work and Economic Growth:** By creating ocean farming jobs for dislocated workers and underserved populations and growing healthy local food, we cultivate a foundation for a new blue-green economy. The goal is to operate seaweed farm enterprises to support stable market channels. Ocean farms result in diverse income streams including: fish, shellfish, edible seaweed, sea cucumbers, fertilizers, pharmaceuticals, chemicals, health supplements, bio-energy, and more. In addition, after ocean forests clean up polluted waters, tourism opportunities can be expanded.

- **SDG #10. Reduced Inequalities:** Ocean farming jobs with good year-round incomes reduce economic inequality. Sustainable jobs that are not damaged by climate change support coastal communities affected by rising sea levels and storms and reduce the number of climate refugees.

- **SDG #11. Sustainable Cities and Communities:** Ocean forests can help restore coral reefs and barrier islands to protect coastal cities against storms. Inexpensive biofuels help make cities sustainable and reduce pollution from energy sources such as coal.

- **SDG #13. Climate Action:** Removing carbon is essential to reduce global warming, desertification and ocean acidification. Removing and sequestering several trillion tonnes of CO_2 will require massive sequestration by photosynthesis. The $P_{electric}$ path needs 17 billion dry tonnes/year of terrestrial biomass and 13 billion dry tonnes/year of macroalgae to remove 38 billion tonnes/yr of CO_2. The P_{fuel} path needs 4 billion dry tonnes/year of terrestrial biomass and 39 billion dry tonnes/year of macroalgae to remove 28 billion tonnes/yr of CO_2.

- **SDG #14. Life Below Water:** Carbon emissions are not just causing increased temperatures resulting in changes to global weather patterns, these emissions are also increasing ocean acidity and reducing ocean oxygen levels beneath those necessary for sea life and the ecological and biological processes for sustainable life on our planet. While most climate programs aim to

reduce carbon emissions and a few to capture and sequester carbon dioxide, restorative ocean reefs make profits from food sales while also capturing carbon in seaweed. Ocean waters around seaweed farms have measurably lower acidity, which helps crustaceans and sea life of all kinds.

- **SDG #15. Life on Land:** Major drivers of deforestation and desertification are lack of food and fuel for cooking and heating. Ocean forests provide abundant, inexpensive, healthy, sustainable seafood and biofuels, reducing the need for cutting wood, clearing forests, farming marginal lands, or overdrawing aquifers.

- **Other SDGs:** While directly addressing the above twelve SDGs, ocean forests indirectly support the other five Goals by creating sound economic and social foundations so that everyone can participate in and gain from (4) Quality Education, (9) Industry, Innovation and Infrastructure, (12) Responsible Consumption and Production, (16) Peace, Justice and Strong Institutions, and (17) Partnerships for the Goals.

3.9.1 Food Systems

The global wild seafood catch is declining due to overfishing of many species. Yet, seafood protein provides up to 50% of the protein need in some developing countries. It also contains essential micronutrients which cannot easily be substituted by other food commodities [121,122]. In addition, many developing countries (even coastal ones) have a seafood shortage. For example, "According to WorldFish Nigeria Strategy 2018-2022, Nigeria produces one million metric tonnes of fish annually, leaving a deficit of about 800,000 metric tonnes; which is imported" [123].

Terrestrial crops in the tropics are decreasing yields, and in some places in Central America and Africa failing completely, causing many to migrate within countries and beyond (Jones 2020). As Tirado [121] says: "The current global food system is leaving 795 million people hungry, [and] two billion micronutrient deficient." "Many of the world's food systems are exceeding or approaching planetary limits and are compromising the capacity of the planet to produce food in the future."

As the tropical temperatures soar above the capacity for humans to survive in the open, locations close to the ocean will still be cooler and thus survivable, and they will require food and jobs. All the above needs can be addressed by our proposed TEA seafood reefs.

As discussed in the paper and shown on SMS#24, combined meat and seafood production in 2019 was about 500 million tonnes per year. The FAO [124] 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 [125,126] SMS#24. Seafood GHG impact is about three tonnes of CO_{2eq} per tonne of seafood (including both wild-caught and aquaculture) [127,128]. 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 SMS#24).

Since food supplies are especially decreasing in the tropics, and the nutritional needs are often higher there, priority should be given to placing the TEA seafood reefs in developing countries in the tropics.

Parker et al. [127] report a wide variation from pelagic fish <30 cm at 0.2 to crustaceans at 7.9 kg CO_{2eq} per kg of landed animal seafood. This variation is principally caused by lower tonnage of harvests of crustaceans per tonne of fuel used. They calculate average GHG emissions of 2.2 tonnes CO_{2eq} per tonne landed (which is comparable to live weight).

MacLeod et al. [127] similarly report a wide variation in average emissions for aquaculture from 1.1 for bivalves to 6.6 kg CO_{2eq} per kg for shrimps, with a global average of 3.3 tonnes CO_{2eq}/tonnes live weight.

In SMS#24 we calculate a weighted average of 2.7 tonnes CO_{2eq}/tonnes live weight for all animal seafood, which we use to compare with the weighted average of 17.3 tonnes CO_{2eq}/tonnes live weight for all terrestrial meat.

Expected GHG emissions from TEA reefs are likely close to average animal seafood emissions, since TEA reefs are normally positioned close to shore, the boat fuel per tonne harvested will likely be less than that for wild fisheries. However, a large GHG component for the TEA reefs is the carbon equivalent embodied in the structure, but much of that is expected to be amortized over at least a decade and hopefully much longer.

3.9.9 Sustainability criteria: In 2012 N'Yeurt et al. [10] discussed growing macroalgae forests to reverse climate change. The technologies have evolved, and the economics have improved, now offering even more sustainability in all the ways listed by N'Yeurt et al.:

1) Environmental sustainability at local and global scales implies addressing issues beyond carbon capture such as species biodiversity, ocean acidification, food, water, and energy.

2) Climate sustainability implies the need for robust and distributed processes that are neither impacted by nor cause droughts, floods, heat, cold, changing wind patterns, and ocean acidification. Total-ecosystem aquaculture must be designed to deal with some fish populations moving toward the poles as the tropical oceans become too warm (Morley et al., 2018).

3) Political sustainability requires improving populations' quality of life and global opportunities particularly in developing countries.

4) Social sustainability means countering the water, food, jobs, health, sanitation, and natural disaster stresses of climate change while minimizing negative side effects. Flexible, floating fishing reefs provide the income needed to adapt to sea-level rise. Some coastal communities could welcome sea-level-rise refugees to help work their new reefs [41][46].

5) Energy sustainability implies that significantly more carbon is permanently stored than is required to generate the energy to capture and sequester the carbon (EROI for macroalgae was projected to be over 20:1 by Lucas et al. [36]).

6) Economic sustainability with current low carbon prices requires multiple products from the process to make the overall system profitable (See Fig. S20).
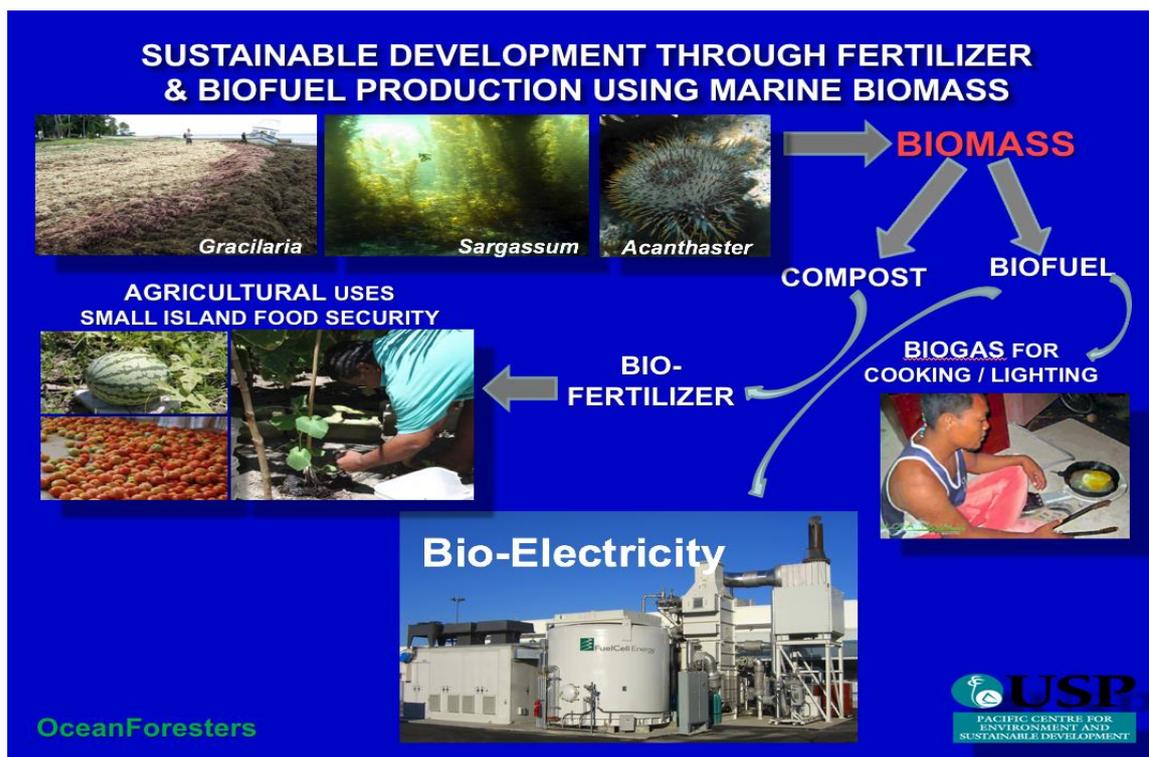
Figure S20. Diagram of a Fiji proposal for energy and food independence with biofuels from macroalgae that support SDGs.

Conclusions and Recommendations

4.1 Summary

Quantified benefits of the recommended approach:

- Total ecosystem aquaculture (TEA) with nutrient recycling can increase seafood yields (improve global food security) from the current 0.2 billion wet shell-on tonnes/yr to more than 0.7 billion tonnes/yr to meet the FAO projections for an additional 0.5 billion tonnes/yr by 2050 [124]. This is equivalent to an additional 250 g (half pound) per person per day for 8 billion people (SMS#18).
- TEA might grow up to 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. [43]). That would be about 0.3% of the world's oceans (see SMS#6, 18). Growing more food in less ocean allows increasing marine protected areas.
- The cost to capture, compress, transport, and sequester one tonne of CO_2 drops
  from more than:
  - $150/tonne for direct air capture (in 2019 USD) [129];
  - $74/tonne for capture from flue gas after producing electricity, if biomass fuel costs the same as coal [83];

  to less than:

- o $21/tonne of CO_2 ($0.015/kWh using the James et al. [83] formula in SMS#16 or $26/tonne ($0.02/kWh) from the sum of components in SMS#14 with coal or natural gas or biomass for CCS through Allam Cycle power generation;
  - o $3/tonne (or even negative) for the first few thousand Allam Cycle power plants that sell liquid CO_2 combustion product for EOR plus byproduct gases.
- Biocrude oil produced by HTL is carbon negative for less than $3 to $26/tonne of CO_2 when HTL byproduct carbon fuel gas is used to power carbon-sequestering Allam Cycle plants selling produced liquid CO_2 for EOR (see manuscript 3.8 and Tables 4 and 5).
- Global solid waste projections based on Kaza et al. [15] could yield 13 million barrels/day now and 22 million barrels/day (3 million tonnes/day) of biocrude oil by 2050 (SS tabs 4, 7, 11, and 12).
- Net-zero emissions can be achieved by both paths (P_{fuel} and $P_{electric}$) while using as much as 27 to 80 million barrels per day of fossil oil and 0 to 30 million barrels per day of carbon negative biofuel, producing 15 to 56 billion MWh/yr of carbon-neutral electricity from traditional renewables (solar, wind, etc.) and CO_2-sequestered fossil-carbon-neutral electricity plus 14 to 25 billion MWh/yr of carbon negative electricity (see Table 2). (This approach to sustainable development substantially increases global electricity supply over and above 2018's 23 billion MWh/yr.)
- If net-zero emissions are achieved by 2050 and negative emissions reach 28 tonnes of CO_2/yr by 2070, 2 trillion tonnes of CO_2 will be removed from the environment by 2130 on the P_{fuel} path or by 2110 at 38 billion tonnes/yr on the $P_{electric}$ path (SS tabs 1 and 2).
- Some fossil fuel use with the appropriate carbon fee from Table 6 is desirable so that fossil fuel use pays for removing the legacy fossil-CO_2.

    Unquantified benefits:

- Each country or community determining the path that best fits their resources to achieve SDGs.
- Quick transition to carbon neutral electricity (by CCS) using existing fossil fuel supply chains followed by straightforward conversion to carbon-negative biomass electricity (BECCS).
- Reduced marine plastic pollution.
- Support for community adaptations to climate change.
- Quick reductions in local ocean acidity by the macroalgae production followed by global return to preindustrial ocean pH levels.
- Substantially reduced pollution from electric power plants and wood stove indoor cooking.
- Reducing deforestation and freshwater use because land-based foods and biofuels will be replaced by ocean-based foods and biofuels.

**4.2 Recommendations and Needed Research**
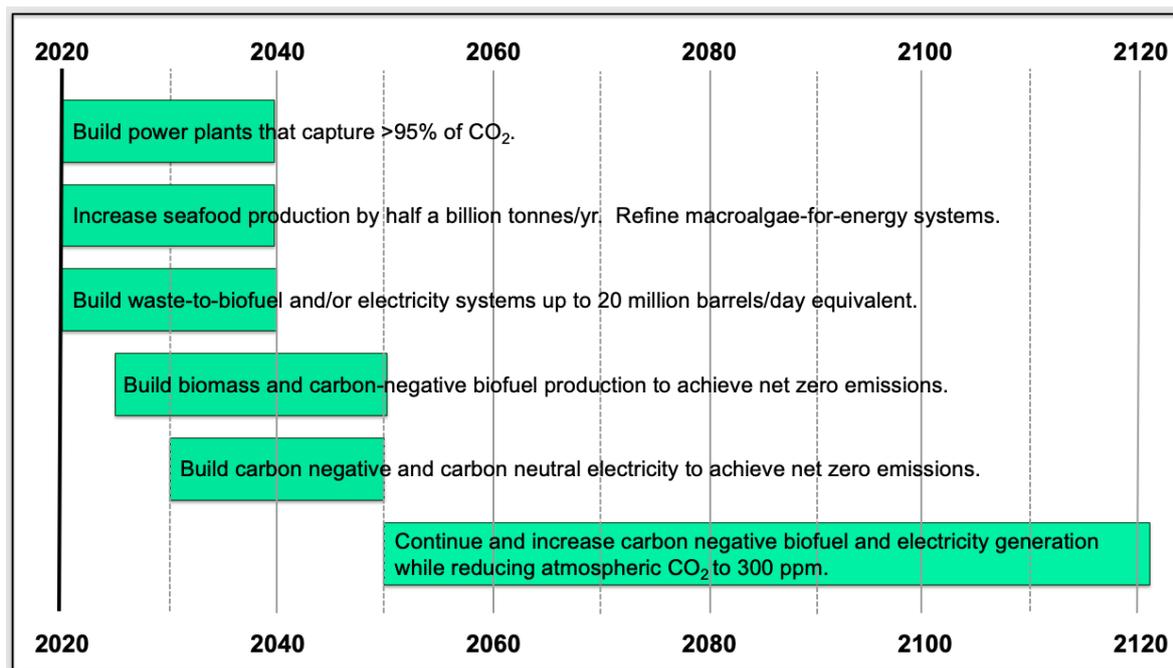
Figure S21. Potential global timeline to reduce CO_2 levels to near 300 ppm near 2100

Figure S21 shows some actions for implementing either of the paths (or a combination) with more details below:

2020 to 2040 – Build total ecosystem aquaculture production, mostly in developing countries, up to a billion tonnes (water-shook-off, shell-on weight) to satisfy global demand for high-protein foods and restore ocean biodiversity. Refine growing, harvesting, and nutrient recycling macroalgae-for-energy systems with seafood production paying for infrastructure.

2020 to 2040 – Build solid waste-to-biofuel and/or electricity systems such that the products can pay for collecting the waste. Paying for waste means much less plastic entering the oceans. Design the collection and distribution system to:

- Safely handle medical and other hazardous waste.
- Recycle mixed plastics, paper, and organics into energy and inorganic plant nutrients.
- Distribute the nutrients to grow healthy food.
- Can easily add sequestering byproduct CO_2.
- Support refining biomass-for-energy nutrient recycling, growing, harvesting, and transporting systems.

2020 to 2040 – Stop building (even if construction has started) power plants or incinerators that do not capture >95% of CO_2. Instead, build fossil- and bio-fueled CO_2-sequestering electrical power plants (such as Allam Cycle) that produce liquid CO_2 except where economics favor other renewables such as hydro, wind, or solar electricity.

2025 to 2050 – Build biomass and carbon-negative biofuel production (such as HTL) to completely replace fossil transportation fuels. Some countries also might replace most liquid

transportation fuels with battery-electric vehicles. Coordinate with carbon-capturing electricity generation to achieve net-zero emissions by 2050.

2030 to 2050 – Decrease fossil-electricity generation while increasing biofuel-electricity generation with CCS. Coordinate with biofuel production to achieve net-zero emissions by 2050.

Through 2150 – Continue producing enough biomass to satisfy transportation and electricity demand while sequestering CO_2 to return atmospheric CO_2 levels to 300 ppm.

Examples of Needed Research for Implementation

The process of building, operating, and maintaining the needed commercial-scale infrastructure will involve needed technology refinements. Potential research topics include the following:

- Life-cycle costs, planetary boundaries (Algunaibet et al. [130]), 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. [131], Mehlmann et al. [132] 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. [133]; Sumaila et al. [134]).

- Economics and governance – Economists and political leaders need to devise equitable ways to pay 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 [135,136]. Can these benefits be achieved faster by regulations than by a tax on fossil carbon?

- The United Nations Decade of Ocean Science for Sustainable Development [137] could use the above framework to focus on supporting sustainable management of the oceans to achieve the UN SDGs.

- Biofuel for electricity – What product of HTL is acceptable for the lowest \$/GJ as biofuel for Allam Cycle plants? Oil at \$70/barrel costs \$11/GJ, more expensive than global liquified natural gas at \$7.6/GJ or U.S. prices near \$2.8/GJ for delivered coal and natural gas.

- Other synergies – Can HTL of marine biomass remove microplastics and mercury from the ocean?

- Micro- and macro-plastic removal – Can HTL of marine biomass and/or biofueled Allam cycle plants remove microplastics from the ocean? People can capture the larger pieces of plastic.
  o What size range is filtered by animals (filter feeding shellfish and finfish)?
  o Can these animals be raised in restorative aquaculture ecosystems to filter microplastics out of the ocean? They could then be used as feedstock for HTL.

- Mercury removal – Can HTL of marine biomass and/or biofueled Allam cycle plants remove mercury and other metals from the ocean? Macroalgae (like most plants and animals) will accumulate mercury.
  o How much of the mercury is in the biocrude oil made from algae?
  o How much in the ash?

- o   How much in the leftover water (the water that was in the plants)?
- o   Wherever it goes, can the mercury, and other metals, be recovered separately from the essential nutrients that must be recycled to feed the plants?
- Recycling toxics – What other toxic chemicals, pharmaceuticals, sunscreens, chemicals, biocides, pesticides, and herbicides are degraded to harmlessness when converted to energy by either HTL or biofueled-Allam Cycle?
- o   Life cycle cost, planetary boundaries[25], energy, circular economy, and emissions analysis – The economics of reducing atmospheric CO_2 concentrations on either path appear acceptable. But what are their complete life cycle costs and energy return?
- o   How do life cycle metrics change as biomass replaces coal, oil, and natural gas?
- o   How do life cycle metrics change as biomass-to-energy use increases?
- o   Does either path exceed or increase[26] planetary boundaries?
- o   Is the service life of components actually as long as expected?
- o   How are the climate change impacts, improved biodiversity, and many other benefits factored into the life cycle analyses?
- How can the economically viable scale of HTL, Allam Cycle electricity, and carbon sequestration be reduced for small island states and support SDGs? Perhaps as a hybrid with other technologies, such as anaerobic digestion (Fig. S21)?
- Circular economy for plastics –
- o   Which plastics transform cleanly into oil and fuel gas without residue in the byproduct water?
- o   Which plastics remain in the solid residue?
- o   What plastics can be manufactured from biofuel, fuel gas byproducts, or CO_2 byproduct?

- Location-specific studies of differing local infrastructures – Variations include:
- o   For optimal economics – How much of the dry biomass should be feedstock for Allam Cycle power and how much of the dry biomass (blended with wet biomass) should be feedstock for HTL? Allam Cycle biomass all becomes bio-CO_2 removed from air, perhaps worth the local cost of coal. HTL biomass becomes mostly carbon-neutral biofuel with some bio-CO_2 removed from air, but worth the local cost of sweet crude oil.
- o   Should a community use the income from biocrude oil sales to pay people to deliver trash to an HTL process? Paying people is one way to reduce plastic and other trash polluting

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[25] Algunaibet, et. al. [130], "Planetary boundaries are global limits on environmental flows that should never be transgressed to prevent the occurrence of catastrophic nonlinear events challenging the Earth's ecological capacity." Nine planetary boundaries include: stratospheric ozone depletion; biodiversity loss and extinctions; chemical pollution and the release of novel entities; climate change; ocean acidification; freshwater consumption and the global hydrological cycle; land system change; nitrogen and phosphorus flows to the biosphere and oceans; and atmospheric aerosol loading.

[26] For example, building reef structures increases the area available for fixed primary productivity. The increased area of fixed plant growth can accommodate higher (global basis) flows of nitrogen and phosphorous while maintaining biodiversity. That is, the boundary is increased.

the ocean. Or should municipalities adjust fees and payments throughout their water resource recovery, human resource recovery, solid resource recovery, energy, and CO_2 sequestration systems to balance all societal goals?

o How much carbon-neutral or carbon negative H_2 should be produced for transportation or to fill natural gas distribution systems? This as opposed to replacing natural gas use with electricity. H_2 production is carbon neutral when the electricity is carbon neutral or the carbon from CH_4 is captured and sequestered. H_2 produced from biomass-fired Allam Cycle with CO_2 sequestration would be carbon negative.

- Sheltered ecosystem aquaculture – Each region of the world needs a total ecosystem aquaculture research and training center for sheltered and/or polluted water. These may be like the research and training center Dr. Prasad proposed for Oceania at the 2020 Ocean Sciences Meeting [38].

  o Total ecosystem aquaculture and associated science questions are explained in Appendix A – Concepts for the UN Decade of Ocean Sciences for Sustainable Development and this entry in the Rockefeller Food Systems Vision Prize [39].

  o Particularly in the tropics, research and training centers are needed to discover adaptations to maintain (or improve) tropical seafood production as climate changes.

  o Open ocean ecosystem aquaculture – Each region of the world needs a total ecosystem aquaculture research and training center for open ocean floating flexible reefs.

  o Open ocean reefs are described in a presentation by Capron et al. [41] at the International Symposium on Stock Enhancement & Sea Ranching. (The nature of the structures, the storms, and the animals interacting with the structures varies.)

  o Many of the eighteen projects funded by the U.S. Department of Energy, Advanced Research Project Agency-Energy's MARINER program [42] will be publishing results. AdjustaDepth project deliverables are available at [35,36].
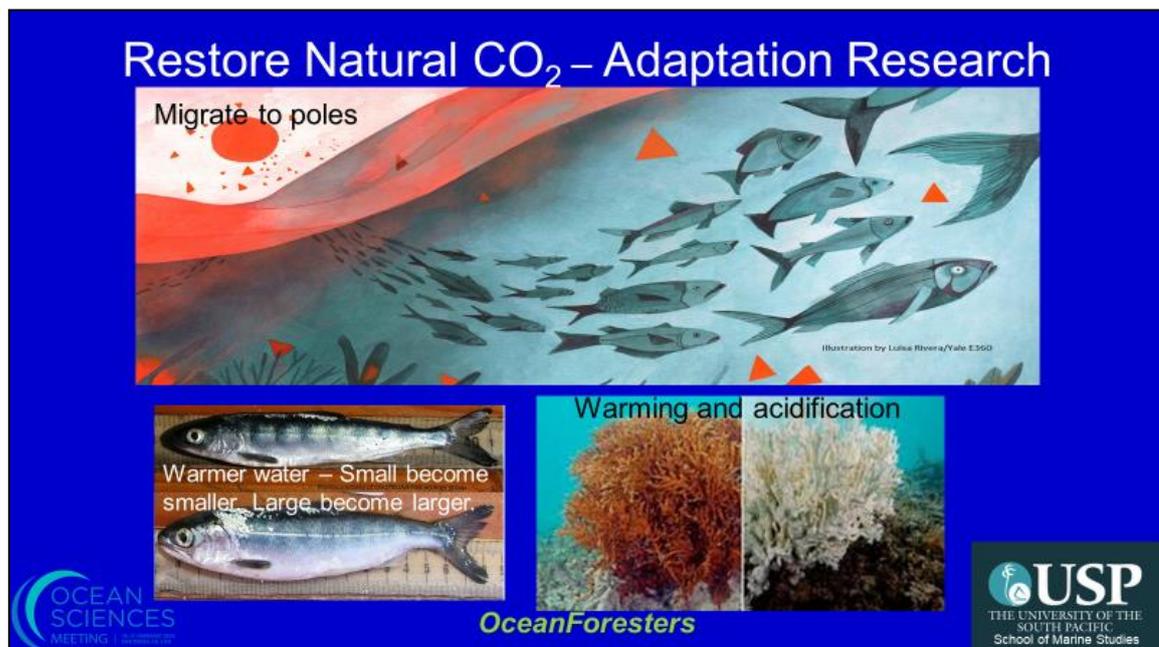

Figure S22. Climate impacts on ocean life.

o   Tropical fisheries (wild, penned finfish, seaweed and/or shellfish, and total ecosystem aquaculture) need adaptations for climate change. See Figs. S22 and S23. Every reef is also an opportunity for intense data gathering with simultaneous measurements of environmental DNA in water samples and creature stomachs, automated flow cytometry, autonomous image recognition from stationary and mobile cameras, autonomous signal processing for active and passive sonar, and assorted chemistry and physical properties sensors. Much of this science data pays for itself through increased seafood production. For example, the graph at upper right in the picture below shows that dissolved oxygen concentrations drop and fish need more oxygen as waters warm. Adequate sensors may allow accurate maintenance of macroalgal oxygen production for abundant fish production even as waters warm.
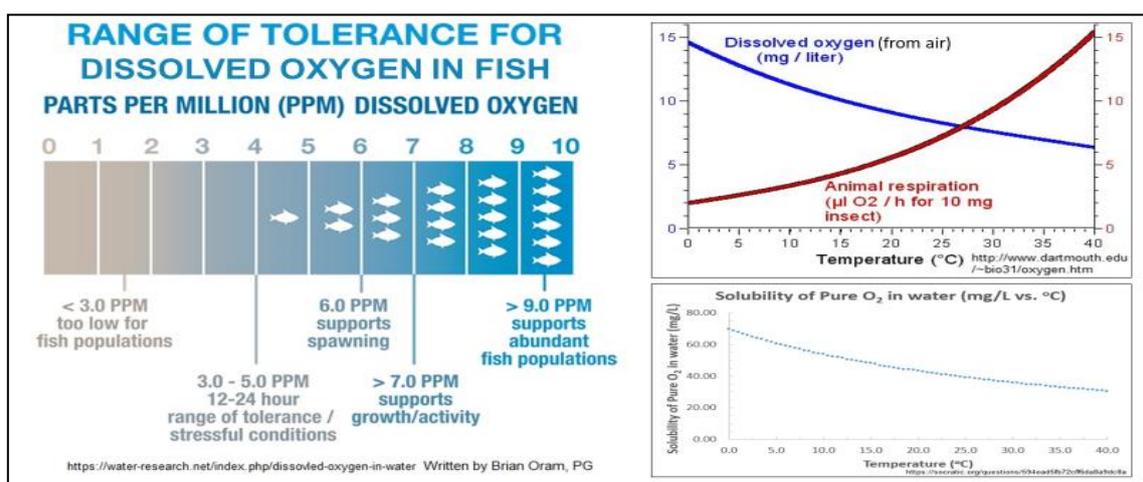

Figure S23. Impacts of reduced dissolved oxygen.

o   Refine nutrient recycling while developing and calibrating ecosystem computer models so that reef operators can preemptively adapt to marine heat waves, disease in a species, and other changes to reef conditions. The simplified diagram in Figure S24 hints at the complexity of total ecosystem aquaculture. Each coastal community will need a computer model with information output like shown in the picture at the right to manage their ecosystem. The model should include at least the product species plus dozens of the other species important to ecosystem health, even including bacteria.
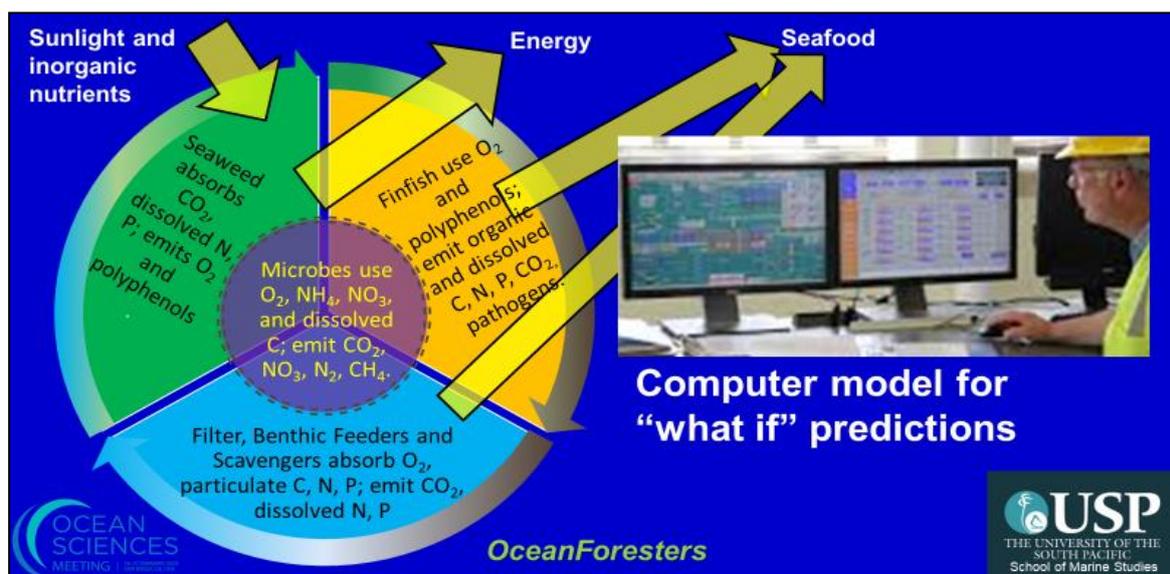
Figure S24. Computer model research needed.

o   Fear of ecosystem crashes will motivate a global organization of Ecosystem Operating Communities to fund better and better computer models. The computer models would allow "what if" for actions when anticipating events. For example: 90% of Northern California's kelp forests disappeared when sea stars died-off and sea urchin populations exploded. Kelp and abalone populations both crashed.

o   The computer helps predict the possible situation and allows trying many options, on the computer, months in advance. Do you harvest the sea urchins for sale to Japan or throw them into mangrove forests to feed mud crabs? Or do you find another community with an abundance of lobsters that you buy and stock to eat the sea urchins?

- Biofuel for electricity – What product of HTL (or hydrothermal carbonization, HTC) is acceptable at the least $/mmbtu as biofuel for the Allam Cycle plants? Oil at $70/barrel costs $12/mmbtu, much more expensive than global liquified natural gas at $8/mmbtu, or U.S. prices near $3/mmbtu for delivered coal or natural gas.

Appendix A

Planning Concrete Deliverables for the UN Decade of Ocean Science
for Sustainable Development
Sustainable Development that supports Ocean Science
Ocean Science that supports Sustainable Development
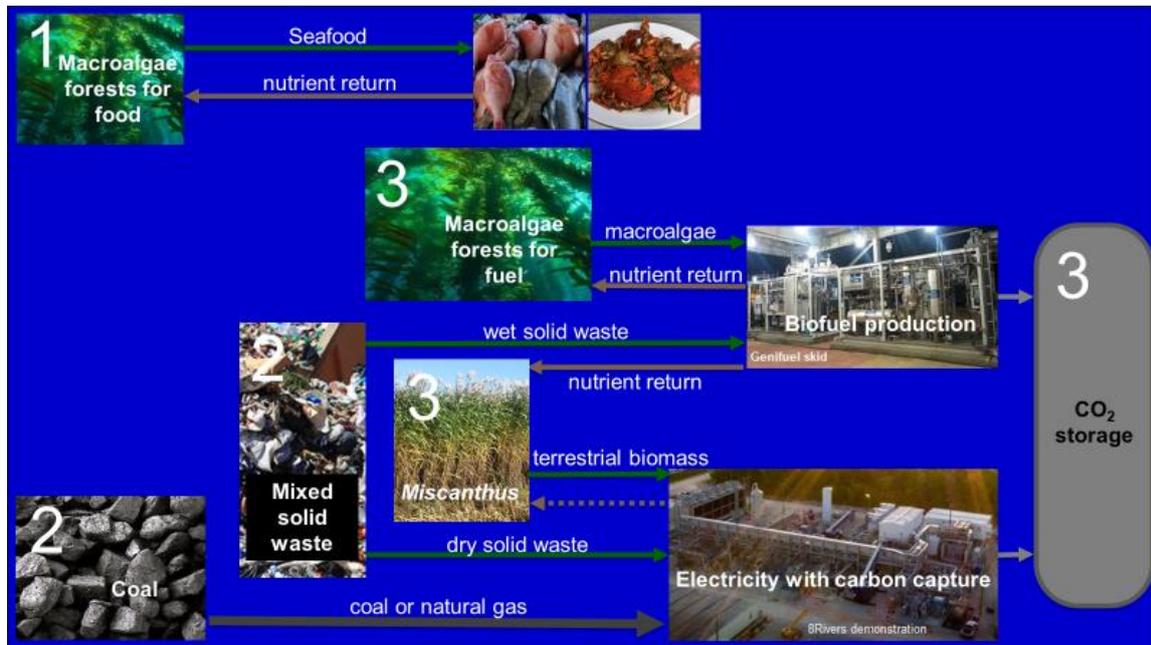
Resource published on UNESCO Ocean Decade website [137] **at**:

https://www.oceandecade.org/resource/103/OceanForesters-Draft-Document-Planning-Concrete-Deliverables-for-the-UN-Decade-of-Ocean-Sciences-for-Sustainable-Development-2021-2030

Back to Contents

Appendix B

Example work program to design-test-improve a seaweed biofuel system

System Performance: There is need for at-sea testing to demonstrate/test/calibrate:

- low-energy system to submerge and re-surface with improved tension management, load distribution, and structural forces;

- biologic growth model;

- the effective service life;

-retention of seaweed and other biomass during storms;

- interactions of mammals and turtles with the grow-substrate and structure;

- a full year of yield with ambient nutrients;

- effect of continued mowing of seaweed plants;

- yield as a function of shellfish and other reef creature nutrient conversions;

non-seaweed harvestable biomass; and

- potential contributions of non-plant species for nutrient distribution and as potential food products that could be harvested for profit.

Continuous measurements: The following parameters need to be monitored and logged continuously with SeaBird sensors: Temperature, Salinity, pH, Dissolved Oxygen, Nitrate, Phosphate, and Photosynthetically Active Radiation (PAR). Nutrient inputs need to be controlled by the nitrate and phosphate *in-situ* sensors.

Discrete measurements: Daily AM and PM spot checks of the following parameters need to be measured with a sensor: Temperature, Salinity, pH, Dissolved Oxygen. Light intensity should be measured daily with an Apogee PAR sensor. Water samples should be taken and analyzed on a weekly basis to verify inorganic nitrate and phosphate concentrations. Biomass can be measured as wet weight to calculate % growth by weighing water-shook-off frames with plants attached twice a week. These photographs would allow us to calibrate "weigh-by-picture." Then at sea, each seaweed plant becomes an inexpensive sensor of nutrient availability, calibrated with occasional water samples. Biomass measurements need to be made prior to mowing events. The harvested biomass needs to be measured to determine growth rate and yield, including both wet and dry weights. Samples of biomass must also be taken to measure particulate organic carbon and particulate organic nitrogen.

Growth Model – These results need be applied to calibrate the growth model and predict the expected yield during the at-sea structure demonstrations. Biomass measurements can be applied to determine the energy per area per time throughout the entire experimental run. That is MWh/ha/yr (Mega Watt-hour per hectare per year) at N^{th} scale interpolated from $kWh/m^2/day$ for tank tests.

It is important to pulse nutrient concentrations as suggested by Lapointe [138]. Perhaps half the time with 1) nitrate concentration at annual average of at-sea ambient, some intermediate level, and half with 2) higher nitrate concentration expected with full scale organic-to-inorganic conversions. Be aware of possible seaweed internal biologic timers. For example, perhaps identical nutrients, light, temperature, and salinity in March and October do not give identical growth rates.

Haploid/diploid Impacts: There are subtle, but fundamental differences between diplontic (e.g., animals and seed plants) and haplodiplontic life cycles (e.g., algae like *Gracilaria tikvahiae*; see Krueger-Hadfield and Hoban [139]). *G. tikvahiae* must pass through a propagule, germling, juvenile, and adult stage before the life cycle can be completed. As a consequence of multiple free-living stages that undergo significant development, we must understand what differences may exist between them in order to effectively farm and cultivate populations of *Gracilaria tikvahiae* or other seaweed species.

Growth Variables that should be measured:

- Growth rate compared to ambient nutrient concentrations
- Growth rate compared to temperature
- Growth rate compared to total light available at the growing depth (sunlight diminished by water absorption)
- Growth rate depending on frequency of mowing
- Growth rate depending on how much remains (height/density of remaining plant(s) after mowing)
- Growth rate with and without proximate shellfish
- Fish, turtles, and mammals types and density measurements
- Number, size, and species of fish (every kind of non-plant) measured over the year to determine the overall reef productivity over time
- Some seaweed panels left undisturbed for observation
- Turtle, and mammal interactions and behavior around structure observed

References:

1.   UNEP. Emissions Gap Report 2019. Available online: https://www.unenvironment.org/resources/emissions-gap-report-2019 (accessed on Sep 9, 2020).

2.   Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. Mitigation pathways compatible with 1.5°C in the context of sustainable development. In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*; Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Ed.; 2018; pp. 1–82.

3.   UNFCCC. What is the Paris Agreement? 2015. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement (accessed on Apr 14, 2020).

4.   IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [R.K. Pachauri and L.A. Meyer (eds.)].*; 2014;

5.   IPCC. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.*; 2018;

6.   Friedlingstein, P.; Jones, M.W.; O'Sullivan, M.; Andrew, R.M.; Hauck, J.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; Le Quéré, C.; et al. Global Carbon Budget 2019. *Earth Syst. Sci. Data* **2019**, *11*, 1783–1838, doi:10.5194/essd-11-1783-2019.

7.   Allam, R.; Martin, S.; Forrest, B.; Fetvedt, J.; Lu, X.; Freed, D.; Brown, G.W.; Sasaki, T.; Itoh, M.; Manning, J. Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture. *Energy Procedia* **2017**, *114*, 5948–5966, doi:10.1016/j.egypro.2017.03.1731.

8.   8 Rivers Capital. Direct Supercritical Carbon Dioxide Power Plant System. 2020. Available online: https://www.netl.doe.gov/coal/tpg/coalfirst/DirectSupercriticalCo2 (accessed on Sep 9, 2020).

9.   Patel, S. Inside NET Power: Gas Power Goes Supercritical. 2019. Available online: https://www.powermag.com/inside-net-power-gas-power-goes-supcritical/ (accessed on Sep 9, 2020).

10.   N'Yeurt, A. de R.; Chynoweth, D.P.; Capron, M.E.; Stewart, J.R.; Hasan, M.A. Negative carbon via Ocean Afforestation. *Process Saf. Environ. Prot.* **2012**, *90*, 467–474, doi:10.1016/J.PSEP.2012.10.008.

11.   Jiang, Y.; Jones, S.B.; Zhu, Y.; Snowden-Swan, L.; Schmidt, A.J.; Billing, J.M.; Anderson, D. Techno-economic uncertainty quantification of algal-derived biocrude via hydrothermal liquefaction. *Algal Res.* **2019**, *39*, 101450, doi:10.1016/J.ALGAL.2019.101450.

12.   Pichach, C. CleanCarbon Energy: Carbon Balanced Renewable Energy, plus private communication. Available online: https://www.f6s.com/cleancarbonenergy (accessed on Apr 10, 2020).

13.   Shrestha, P. UK first: Hydrogen injected into gas grid as landmark trial gets underway. Available online: https://www.energylivenews.com/2020/01/06/uk-first-hydrogen-injected-into-gas-grid-as-landmark-trial-gets-underway (accessed on Sep 9, 2020).

14.   The Royal Society. Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store. Available online: https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia (accessed on Sep 9, 2020).

15.   Kaza, S, Yao, L, Bhada-Tata, P, and Van Woerden, F. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.*; The World Bank, 2018; ISBN 978-1-4648-1329-0.

16.   U.S. Department of Energy. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. **2018**, doi:10.2172/1271651.

17.   Jolly, R. Dutch Industrial waste continues to decrease. 2004. Available online: https://www.cbs.nl/en-gb/news/2004/42/industrial-waste-continues-to-decrease .

18.   CalRecycle. Disposal-Facility-Based Characterization of Solid Waste in California. 2015. Available online: https://www2.calrecycle.ca.gov/Publications/Details/1546.

19.   Smil, V. Crop Residues: Agriculture's Largest Harvest: Crop residues incorporate more than half of the world's agricultural phytomass. *BioScience* **1999**, *49*, 299–308, doi:10.2307/1313613.

20.   Devi, S.; Gupta, C.; Jat, S.L.; Parmar, M.S. Crop residue recycling for economic and environmental sustainability: The case of India. *Open Agric. 2*, 486–494, doi:https://doi.org/10.1515/opag-2017-0053.

21.   Kumar, P.; Kumar, S.; Joshi, L. Socioeconomic and Environmental Implications of Stubble Burning in Punjab. *Springer Briefs Environ. Sci.* **2015**, 156, doi:10.1007/978-81-322-2014-5.

22.   Ravindra, K.; Singh, T.; Mor, S. Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions. *J. Clean. Prod.* **2019**, *208*, 261–273, doi:https://doi.org/10.1016/j.jclepro.2018.10.031.

23.   Saini, J.K.; Saini, R.; Tewari, L. Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production: concepts and recent developments. *3 Biotech* **2015**, *5*, 337–353, doi:10.1007/s13205-014-0246-5.

24. Deng, Y.Y.; Koper, M.; Haigh, M.; Dornburg, V. Country-level assessment of long-term global bioenergy potential. *Biomass Bioenergy* **2015**, *74*, 253–267, doi:https://doi.org/10.1016/j.biombioe.2014.12.003.

25. Daioglou, V, Stehfest, E, Wicke, B, Faaij, A. Projections of the availability and cost of residues from agriculture and forestry. *Bioenergy* **2016**, *8*, 456–470, doi:10.1111/gcbb.12285.

26. REN21. Renewables 2019 Global Status Report. Available online: https://www.ren21.net/gsr-2019/ (accessed on Apr 11, 2020).

27. Turner, P.A.; Mach, K.J.; Lobell, D.B.; Benson, S.M.; Baik, E.; Sanchez, D.L.; Field, C.B. The global overlap of bioenergy and carbon sequestration potential. *Clim. Change* **2018**, *148*, 1–10, doi:10.1007/s10584-018-2189-z.

28. Hudiburg, T.W.; Luyssaert, S.; Thornton, P.E.; Law, B.E. Interactive Effects of Environmental Change and Management Strategies on Regional Forest Carbon Emissions. *Environ. Sci. Technol.* **2013**, *47*, 13132–13140, doi:10.1021/es402903u.

29. Das, PK, Das, BP, Dash, P. Role of Energy Crops to Meet the Rural Energy Needs: An Overview. *Biomass Valorization Bioenergy* **2019**, doi:10.1007/978-981-15-0410-5_2.

30. Eisentraut, A. Sustainable production of second-generation biofuels: potential and perspectives in major economies and developing countries. *IEA Energy Pap. No 201001 OECD Publ. Paris* **2010**, doi:10.1787/5kmh3njpt6r0-en.

31. Hoogwijk, M.; Faaij, A.; de Vries, B.; Turkenburg, W. Exploration of regional and global cost–supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass Bioenergy* **2009**, *33*, 26–43, doi:https://doi.org/10.1016/j.biombioe.2008.04.005.

32. Smeets, E.M.W.; Faaij, A.P.C.; Lewandowski, I.M.; Turkenburg, W.C. A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog. Energy Combust. Sci.* **2007**, *33*, 56–106, doi:https://doi.org/10.1016/j.pecs.2006.08.001.

33. Faaij, A. Contribution of Bioenergy to the World's Future Energy. 2007. Available online: https://www.ieabioenergy.com/publications/potential-contribution-of-bioenergy-to-the-worlds-future-energy-demand (accessed on Sep 9, 2020).

34. Advanced Research Projects Agency - Energy (ARPA-E) - U.S. Department of Energy. MacroAlgae Research Inspiring Novel Energy Resources (MARINER) Program Overview. Available online: https://arpa-e.energy.gov/sites/default/files/documents/files/MARINER_ProgramOverview_FINAL.pdf (accessed on Apr 10, 2020).

35. Capron, M.E., Lucas, K., Stewart, J.R., Blaylock, R., Howden, S., Chambers, M.D., James, S.C., Brooks, M.T., Lapointe, B., N'Yeurt, A.d.R., et al. AdjustaDepth TechnoEconomic Analysis for ARPA-E Phase 1 Contract DE-AR0000916. Available online: https://www.researchgate.net/publication/343697255_AdjustaDepth_TechnoEconomic_Analysis_for_ARPA-E_Phase_1_Contract_DE-AR0000916 (accessed on Sep 9, 2020).

36. Lucas, K., Capron, M.E., Blaylock, R., Chambers, M.D., Stewart, J.R., DiMarco, S.F., Whilden, K., Kim, MH, Moscicki, Z., Sullivan, C., et al. AdjustaDepth Phase 1 Final Report to ARPA-E, DE-AR0000916. 2019. Available online:

https://www.researchgate.net/publication/341997484_AdjustaDepth_Phase_1_Final_Report_DE-AR0000916_Feed_the_world_on_the_way_to_abundant_biofuels (accessed on Sep 9, 2020).

37.   Capron, M.E., Blaylock, R., Lucas, K., Chambers, M.D. Stewart, J.R., DiMarco, S.F., Whilden, K., Wang, B., Kim, M.H., Moscicki, Z., et al., Ocean Forests: Breakthrough Yields for Macroalgae. In Proceedings of the OCEANS 2018 MTS/IEEE Charleston; 2018; pp. 1–6. doi:10.1109/OCEANS.2018.8604586.

38.   Capron, M.E.; Prasad, R.; N'Yeurt, A. de R.; Hopkins, K.; Stewart, J.R.; Harris, G.; Hasan, M.A.; Piper, D. Increasing South Pacific aquaculture with complete ecosystems. *Ocean Sciences Meeting Presentation SI12A-05*. 2020. Available online: https://agu.confex.com/agu/osm20/meetingapp.cgi/Paper/649244 (accessed on Sep 9, 2020).

39.   Capron, M.E.; Prasad, R.; N'Yeurt, A.d.R.; Hewavitharane, C.; Stewart, J.R. Total Ecosystem Aquaculture - Sustainable Seafood Production for Fiji, the Pacific, and then the World. 2020. Available online: https://challenges.openideo.com/challenge/food-system-vision-prize/open-submission/restorative-aquaculture-sustainable-seafood-production-for-the-world (accessed on Mar 9, 2020).

40.   Lucas, K.; Capron, M.E.; Blaylock, R.; Chambers, M.D.; Stewart, J.R.; DiMarco, S.F.; Whilden, K.; Wang, B.; Kim, M.H.; Moscicki, Z.; et al. Ocean Forests: Feeding the World with Floating Artificial Reefs. In Proceedings of the World Aquaculture Society, #666; New Orleans, 2019. Available online: https://wasblobstorage.blob.core.windows.net/meeting-abstracts/AQ2019AbstractBook.pdf.   (accessed on Sep 9, 2020).

41.   Capron, M.E.; Lucas, K.; Chambers, M.D.; Lapointe, B.; N'Yeurt, A.d.R.; Krueger-Hadfield, S.A.; James, S.C.; Blaylock, R.; Stewart, J.R.; Piper, D.; et al. Building New Fishery Ecosystems: The Science of Flexible Floating Fishing Reefs. In Proceedings of the International Symposium on Stock Enhancement & Sea Ranching; 2019. Available online: https://mote.org/media/uploads/contact/ISSESR-Wednesday-1150-Piper.pdf (accessed on Sep 9, 2020).

42.   U.S. Department of Energy Advanced Research Projects Agency-Energy. MacroAlgae Research Inspiring Novel Energy Resources (MARINER) Project Listing. 2017. Available online: https://arpa-e.energy.gov/?q=arpa-e-programs/mariner (accessed on Oct 4, 2020).

43.   Gentry, R.R.; Froehlich, H.E.; Grimm, D.; Kareiva, P.; Parke, M.; Rust, M.; Gaines, S.D.; Halpern, B.S. Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.* **2017**, *1*, 1317–1324, doi:10.1038/s41559-017-0257-9.

44.   Sherman, M.T.; Lucas, K.; Stewart, J.R. SeaweedPaddock : Initial Modeling and Design for a Sargassum Ranch. In Proceedings of the OCEANS 2018 MTS/IEEE Charleston; 2018; pp. 1–6.

45.   Huesemann, M. Nautical Offshore Macroalgal Autonomous Device. 2017. Available online: https://arpa-e.energy.gov/?q=slick-sheet-project/nautical-offshore-macroalgal-autonomous-device (accessed on Sep 9, 2020).

46.   Capron, M.E. Centuries of food and job security for coastal peoples. 2019. Available online: https://challenges.openideo.com/challenge/2019-bridgebuilder-challenge/ideas/centuries-of-food-and-job-security-for-coastal-peoples.

47.   Chambers, M.D. Integrated Multi-Trophic Aquaculture of Steelhead, Blue Mussels and Sugar Kelp., PhD dissertation, University of New Hampshire, Durham, NH, 2013.

48. Radulovich, R.; Umanzor, S.; Cabrera, R.; Mata, R. Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. *Aquaculture* **2015**, *436*, 40–46, doi:10.1016/J.AQUACULTURE.2014.10.032.

49. GESAMP. (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/ UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) *High level review of a wide range of proposed marine geoengineering techniques.*; Boyd, P.W. and Vivian, C.M.G.,   eds, Ed.; GESAMP No. 98, 2019;

50. Aldridge, J., van der Molen, J., & Forster, R. Wider ecological implications of macroalgae cultivation. The Crown Estate, Marine Estate Research Report. **2012**. Available online: https://www.researchgate.net/publication/285680370_Wider_ecological_impli-%20cations_of_Macroalgae_cultivation%0A. (accessed on Sep 9, 2020).

51. Cottier-Cook, E.J.; Nagabhatla, N.; Badis, Y.; Campbell, M.L.; Chopin, T.; Fang, J.; He, P.; Hewitt, C.L.; Kim, G.H.; Huo, Y.; et al. Global Seaweed Aquaculture Industry 2016. Available online: https://inweh.unu.edu/safeguarding-the-future-of-the-global-seaweed-aquaculture-industry/ (accessed on Sep 9, 2020).

52. Krause-Jensen, D.; Lavery, P.; Serrano, O.; Marba, N.; Masque, P.; Duarte, C.M. Sequestration of macroalgal carbon: The elephant in the Blue Carbon room. *Biol. Lett.* **2018**, *14*, doi:10.1098/rsbl.2018.0236.

53. Zaimes, G.G.; Khanna, V. Microalgal biomass production pathways: evaluation of life cycle environmental impacts. *Biotechnol. Biofuels* **2013**, *6*, 88, doi:10.1186/1754-6834-6-88.

54. D'Angelo, C. Historic California Kelp Harvest, 1916–2009. National Marine Fisheries Service Report. Available online: https://drive.google.com/file/d/1hVQXdt2TrdVB2LRpnWp1SGvs7XqDE3re/view?usp=sharing (accessed on Sep 9, 2020).

55. Gough, C. Terrestrial Primary Production: Fuel for Life. Available online: https://www.nature.com/scitable/knowledge/library/terrestrial-primary-production-fuel-for-life-17567411/ (accessed on Apr 12, 2020).

56. Boyd, P.W., Sundby, S., and Pörtner, H.-O. Cross-chapter box on Net Primary Production in the Ocean. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea,   and L.L.W., Ed.; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2014; pp. 133–136.

57. Huesemann, M, Mumford, T, Wood, G, Quinn, J, Wang, T, Yang, Z. Nautical Offshore Macroalgal Autonomous Device (NOMAD). Available online: https://arpa-e.energy.gov/?q=slick-sheet-project/nautical-offshore-macroalgal-autonomous-device (accessed on Apr 4, 2020).

58. Meyers, A. Ocean Energy from Macroalgae. Available online: https://arpa-e.energy.gov/?q=slick-sheet-project/ocean-energy-macroalgae (accessed on Sep 9, 2020).

59. Roberson, L. Techniques for Tropical Seaweed Cultivation. Available online: https://arpa-e.energy.gov/?q=slick-sheet-project/techniques-tropical-seaweed-cultivation (accessed on Sep 9, 2020).

60.   Sims, NA, Vollbrecht, L, Bullock, M, Martin, K. Ocean Era Blue Fields Offshore Macroalgae Demonstration Project. 2019. Available online: http://ocean-era.com/projects (accessed on Apr 4, 2020).

61.   Zotter, B. Continuous, High-Yield Kelp Production Available online: https://arpa-e.energy.gov/?q=slick-sheet-project/continuous-high-yield-kelp-production (accessed on Sep 9, 2020).

62.   Stekoll, M. Scalable Coastal and Offshore Macroalgal Farming (SCOMF). 2017. Available online: https://arpa-e.energy.gov/?q=slick-sheet-project/scalable-coastal-and-offshore-macroalgal-farming (accessed on Sep 9, 2020).

63.   Cruver, P. Design of Large Scale Macroalgae Systems. Available online: https://arpa-e.energy.gov/?q=slick-sheet-project/design-large-scale-macroalgae-systems (accessed on Sep 9, 2020).

64.   Pauly, D. Micronutrient richness of global fish catches. *Nature* **2019**, *574*, 41–42, doi:d41586-019-02810-2.

65.   Hicks, C.C.; Cohen, P.J.; Graham, N.A.J.; Nash, K.L.; Allison, E.H.; D'Lima, C.; Mills, D.J.; Roscher, M.; Thilsted, S.H.; Thorne-Lyman, A.L.; et al. Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* **2019**, *574*, 95–98, doi:10.1038/s41586-019-1592-6.

66.   Kunzig, R. Is a world without trash possible? *Natl. Geogr.* March 2020. Available online: https://www.nationalgeographic.com/magazine/2020/03/ (accessed on Sep 9, 2020).

67.   Brown, T. Ammonia production causes 1% of total global GHG emissions. 2016. Available online: https://ammoniaindustry.com/ammonia-production-causes-1-percent-of-total-global-ghg-emissions/ (accessed on Apr 4, 2020).

68.   American Chemistry Council. U.S. Resin Production & Sales 2018 vs. 2017.

69.   Ongen, A. Methane-rich syngas production by gasification of thermoset waste plastics. *Clean Technol. Environ. Policy* **2016**, *18*, 915–924, doi:10.1007/s10098-015-1071-1.

70.   Watson, J.; Wang, T.; Si, B.; Chen, W.T.; Aierzhati, A.; Zhang, Y. Valorization of hydrothermal liquefaction aqueous phase: pathways towards commercial viability. *Prog. Energy Combust. Sci.* **2020**, *77*, doi:10.1016/j.pecs.2019.100819.

71.   Environmental Research & Education Foundation. Analysis of MSW Tipping Fees. 2019. Available online: http://www.erefdn.org (accessed on Apr 4, 2020).

72.   Markets Insider. Oil Price of WTI Crude (West Texas Intermediate) History from 2006 to 2020. Available online: https://markets.businessinsider.com/commodities/oil-price?type=wti (accessed on Sep 9, 2020).

73.   BusinessInsider. CO2 European Emission Allowances. Available online: https://markets.businessinsider.com/commodities/co2-european-emission-allowances (accessed on Sep 9, 2020).

74.   California Air Resources Board California-Quebec Joint Auction Settlement Prices. Available online: https://ww3.arb.ca.gov/cc/capandtrade/auction/results_summary.pdf (accessed on Apr 11, 2020).

75.   Quirion, P, Rozenberg, J, Sassi, O, Vogt-Schilb, A. How CO2 Capture and Storage Can Mitigate Carbon Leakage. *SSRN Electron. J.* **2012**, doi:10.2139/ssrn.1763165.

76.   Sepulveda, N.A.; Jenkins, J.D.; de Sisternes, F.J.; Lester, R.K. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule* **2018**, *2*, 2403–2420, doi:10.1016/j.joule.2018.08.006.

77.   Jacobson, M.Z. The health and climate impacts of carbon capture and direct air capture. *Energy Environ. Sci.* **2019**, *12*, 3567–3574, doi:10.1039/C9EE02709B.

78.   Jacobson, M.Z. Why Not Synthetic Direct Air Carbon Capture and Storage (SDACCS) as Part of a 100% Wind-Water-Solar (WWS) and Storage Solution to Global Warming, Air Pollution, and Energy Security? *Camb. Univ. Press Camb. UK* **2019**.

79.   8 Rivers Capital. Allam Cycle Zero Emission Coal Power Plant DOE Grant Proposal 89243319CFE000015. 2020. Available online: https://www.netl.doe.gov/coal/tpg/coalfirst/concept-reports (accessed on Apr 10, 2020).

80.   Flin, D. First fire for La Porte carbon capture demo. Gas Turbine World. Available online: https://gasturbineworld.com/first-fire-for-la-porte-carbon-capture-demo/ (accessed on Apr 10, 2020).

81.   Melzer, L.S. Carbon Dioxide Enhanced Oil Recovery (CO2 EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery. 2012. Available online: https://carboncapturecoalition.org/wp-content/uploads/2018/01/Melzer_CO2EOR_CCUS_Feb2012.pdf (accessed on Apr 4, 2020).

82.   Nagabhushan, D.; Thompson, J. Carbon Capture & Storage in the United States Power Sector. Available online: https://www.catf.us/resource/45q-ccs-analysis (accessed on Sep 9, 2020).

83.   James, R.E.; Kearins, D.; Turner, M.; Woods, M.; Kuehn, N.; Zoelle, A. *Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity.*; United States, 2019. doi:10.2172/1569246.

84.   Hepburn, C.; Adlen, E.; Beddington, J.; Carter, E.A.; Fuss, S.; Mac Dowell, N.; Minx, J.C.; Smith, P.; Williams, C.K. The technological and economic prospects for CO2 utilization and removal. *Nature* **2019**, *575*, 87–97, doi:10.1038/s41586-019-1681-6.

85.   8 Rivers Capital. Project Execution Plan Presentation. 2020. Available online: https://netl.doe.gov/sites/default/files/netl-file/DOE-Coal-FIRST-Project-Execution-Plan-Presentation-3-9-2020-Public-Version.pdf (accessed on Sep 9, 2020).

86.   McMahon, J. Multiple Zero-Carbon Natural-Gas Plants Planned At Lower Cost Than Conventional Plants. *Forbes Mag.* 2019.

87.   Kelemen, P.; Benson, S.M.; Pilorgé, H.; Psarras, P.; Wilcox, J. An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations. *Front. Clim.* **2019**, *1*, 9, doi:10.3389/fclim.2019.00009.

88.   Choi, Y.-S.; Young, D.; Nešić, S.; Gray, L.G.S. Wellbore integrity and corrosion of carbon steel in CO2 geologic storage environments: A literature review. *Int. J. Greenh. Gas Control* **2013**, *16*, S70–S77, doi:10.1016/J.IJGGC.2012.12.028.

89.   Alcalde, J.; Flude, S.; Wilkinson, M.; Johnson, G.; Edlmann, K.; Bond, C.E.; Scott, V.; Gilfillan, S.M. V; Ogaya, X.; Haszeldine, R.S. Estimating geological CO2 storage security to deliver on climate mitigation. *Nat. Commun.* **2018**, *9*, 2201, doi:10.1038/s41467-018-04423-1.

90.   Deng, H.; Bielicki, J.M.; Oppenheimer, M.; Fitts, J.P.; Peters, C.A. Leakage risks of geologic CO2 storage and the impacts on the global energy system and climate change mitigation. *Clim. Change* **2017**, *144*, 151–163, doi:10.1007/s10584-017-2035-8.

91.   McGrail, B.P.; Schaef, H.T.; Spane, F.A.; Horner, J.A.; Owen, A.T.; Cliff, J.B.; Qafoku, O.; Thompson, C.J.; Sullivan, E.C. Wallula Basalt Pilot Demonstration Project: Post-injection Results and Conclusions. *Energy Procedia* **2017**, *114*, 5783–5790, doi:10.1016/J.EGYPRO.2017.03.1716.

92. Gunnarsson, I.; Aradóttir, E.S.; Oelkers, E.H.; Clark, D.E.; Arnarson, M.Þ.; Sigfússon, B.; Snæbjörnsdóttir, S.Ó.; Matter, J.M.; Stute, M.; Júlíusson, B.M.; et al. The rapid and cost-effective capture and subsurface mineral storage of carbon and sulfur at the CarbFix2 site. *Int. J. Greenh. Gas Control* **2018**, *79*, 117–126, doi:10.1016/J.IJGGC.2018.08.014.

93. Snæbjörnsdóttir, S.Ó.; Sigfússon, B.; Marieni, C.; Goldberg, D.; Gislason, S.R.; Oelkers, E.H. Carbon dioxide storage through mineral carbonation. *Nat. Rev. Earth Environ.* **2020**, *1*, 90–102, doi:10.1038/s43017-019-0011-8.

94. Matter, J.M.; Stute, M.; Snæbjörnsdottir, S.Ó.; Oelkers, E.H.; Gislason, S.R.; Aradottir, E.S.; Sigfusson, B.; Gunnarsson, I.; Sigurdardottir, H.; Gunnlaugsson, E.; et al. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science* **2016**, *352*, 1312 LP – 1314, doi:10.1126/science.aad8132.

95. National Academies of Sciences, Engineering, and Medicine. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.*; The National Academies Press: Washington, DC, 2019; ISBN 978-0-309-48452-7.

96. Moran, K.; Crawford, C.; Webb, R.; Holmes, G.; Paulson, M;. Rankin, M. Solid Carbon: A Climate Mitigation Partnership Advancing Stable Negative Emissions. Available online: https://www.solidcarbon.ca/ (accessed on Apr 12, 2020).

97. Project Vesta. Available online: https://projectvesta.org/ (accessed on Sep 9, 2020).

98. Caserini, S.; Dolci, G.; Azzellino, A.; Lanfredi, C.; Rigamonti, L.; Barreto, B.; Grosso, M. Evaluation of a new technology for carbon dioxide submarine storage in glass capsules. *Int. J. Greenh. Gas Control* **2017**, *60*, 140–155, doi:https://doi.org/10.1016/j.ijggc.2017.03.007.

99. Capron, ME, Stewart, JR, and Rowe, R. Secure Seafloor Container CO2 Storage. In Proceedings of the OCEANS'13 MTS/IEEE San Diego Technical Program #130503-115; 2013.

100. Brewer, P.G.; Orr Franklin M.; Friederich, G.; Kvenvolden, K.A.; Orange, D.L. Gas Hydrate Formation in the Deep Sea: In Situ Experiments with Controlled Release of Methane, Natural Gas, and Carbon Dioxide. *Energy Fuels* **1998**, *12*, 183–188, doi:10.1021/ef970172q.

101. Brewer, P.G.; Friederich, G.; Peltzer, E.T.; Orr, F.M. Direct Experiments on the Ocean Disposal of Fossil Fuel CO2. *Science* **1999**, *284*, 943 LP – 945, doi:10.1126/science.284.5416.943.

102. Brewer, P.G. Roger Revelle commemorative lecture contemplating action: Storing carbon dioxide in the ocean. *Oceanography* **2000**, *13*, 84–92, doi:10.5670/oceanog.2000.38.

103. Wennerholm, M. AquaDam manufactures large flexible tubes for construction, flood control and other applications. Available online: https://www.aquadam.net/ (accessed on Sep 9, 2020).

104. McLaren, D. A comparative global assessment of potential negative emissions technologies. *Process Saf. Environ. Prot.* **2012**, *90*, 489–500, doi:10.1016/J.PSEP.2012.10.005.

105. Smith, P. Soil carbon sequestration and biochar as negative emission technologies. *Glob. Change Biol.* **2016**, *22*, doi:10.1111/gcb.13178.

106. Minx, J.C.; Lamb, W.F.; Callaghan, M.W.; Fuss, S.; Hilaire, J.; Creutzig, F.; Amann, T.; Beringer, T.; de Oliveira Garcia, W.; Hartmann, J.; et al. Negative emissions—Part 1: Research landscape and synthesis. *Environ. Res. Lett.* **2018**, *13*, 63001, doi:10.1088/1748-9326/aabf9b.

107. Fuss, S.; Lamb, W.F.; Callaghan, M.W.; Hilaire, J.; Creutzig, F.; Amann, T.; Beringer, T.; De Oliveira Garcia, W.; Hartmann, J.; Khanna, T.; et al. Negative emissions - Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **2018**, *13*, doi:10.1088/1748-9326/aabf9f.

108. Nemet, G.F.; Callaghan, M.W.; Creutzig, F.; Fuss, S.; Hartmann, J.; Hilaire, J.; Lamb, W.F.; Minx, J.C.; Rogers, S.; Smith, P. Negative emissions—Part 3: Innovation and upscaling. *Environ. Res. Lett.* **2018**, *13*, 63003, doi:10.1088/1748-9326/aabff4.

109. The Royal Society and Royal Academy of Engineering. Greenhouse Gas Removal. Available online: https://royalsociety.org/topics-policy/projects/greenhouse-gas-removal (accessed on Sep 9, 2020).

110. Duarte, C.M. Nutrient concentration of aquatic plants: Patterns across species. *Limnol. Oceanogr.* **1992**, *37*, 882–889, doi:10.4319/lo.1992.37.4.0882.

111. Investopedia. What percentage of the global economy consists of the oil and gas drilling sector? Available online: https://www.investopedia.com/ask/answers/030915/what-percentage-global-economy-comprised-oil-gas-drilling-sector.asp (accessed on Apr 11, 2020).

112. Ibisworld. Global Coal Mining Industry - Market Research Report. 2019. Available online: https://www.ibisworld.com/global/market-research-reports/global-coal-mining-industry (accessed on Apr 12, 2020).

113. StatisticsTimes. Gross World Product. Available online: http://statisticstimes.com/economy/gross-world-product.php (accessed on Apr 12, 2020).

114. USGCRP. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Available online: https://nca2018.globalchange.gov/ (accessed on Apr 10, 2020).

115. Future Timeline 2018 World GDP per capita, 1950-2100. Available online: https://www.futuretimeline.net/data-trends/8.htm (accessed on Apr 11, 2020).

116. Metcalf, G.E. How to Set a Price on Carbon Pollution. *Sci. Am.* 2020, 1–16.

117. Yang Y, Hagerty M, Palmarozzo A, Celebi M, Chupka M, Sheffield, H. The Future of Cap-and-Trade Program in California: Will Low GHG Prices Last Forever? Available online: https://brattlefiles.blob.core.windows.net/files/11768_the_future_of_cap-and-trade_program_in_california_final_12.4.17.pdf (accessed on Apr 11, 2020).

118. Tvinnereim, E.; Mehling, M. Carbon pricing and deep decarbonisation. *Energy Policy* **2018**, *121*, 185–189, doi:10.1016/J.ENPOL.2018.06.020.

119. Tàbara, D.; Frantzeskaki, N.; Hölscher, K.; Pedde, S.; Kok, K.; Lamperti, F.; Christensen, J.; Jäger, J.; Berry, P. Positive tipping points in a rapidly warming world. *Curr. Opin. Environ. Sustain.* **2018**, *31*, 120–129, doi:10.1016/j.cosust.2018.01.012.

120. United Nations. Sustainable Development Goals. 2016. Available online: https://sustainabledevelopment.un.org (accessed on Apr 10, 2020).

121. Tirado-von der Pahlen, C. Sustainable Diets for Healthy People and a Healthy Planet. 2017. Available online: https://www.unscn.org/uploads/web/news/document/Climate-Nutrition-Paper-EN-.pd (accessed on Aug 3, 2020).

122. FAO. *World Aquaculture 2015 : a Brief Overview.*; 2017; Vol. 1140;.

123. Bradley, B., Byrd, K.A., Atkins, M., Isa, S., Akintola, S.L., Fakoya, K.A., Ene-Obong, H., Thilsted, S. Fish in food systems in Nigeria: A review. Available online: https://hdl.handle.net/20.500.12348/4210 (accessed on Aug 1, 2020).

124. FAO. *The future of food and agriculture – Alternative pathways to 2050.*; 2018; ISBN 9789251301586.

125. Ritchie, Hannah and Roser, M. Global "Meat and Dairy Production" for 2018. Available online: https://ourworldindata.org/meat-production (accessed on Nov 8, 2020).

126. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **2018**, *360*, 987 LP – 992, doi:10.1126/science.aaq0216.

127. MacLeod, M.J.; Hasan, M.R.; Robb, D.H.F.; Mamun-Ur-Rashid, M. Quantifying greenhouse gas emissions from global aquaculture. *Sci. Rep.* **2020**, *10*, 11679, doi:10.1038/s41598-020-68231-8.

128. Parker, R.W.R.; Blanchard, J.L.; Gardner, C.; Green, B.S.; Hartmann, K.; Tyedmers, P.H.; Watson, R.A. Fuel use and greenhouse gas emissions of world fisheries. *Nat. Clim. Change* **2018**, *8*, 333–337, doi:10.1038/s41558-018-0117-x.

129. Baker, S.E.; Stolaroff, J.K.; Peridas, G.; Pang, S.H.; Goldstein, H.M.; Lucci, F.R.; Li, W.; Slesarev, E.W.; Pett-Ridge, P.; Ryerson, F.J.; et al. Getting to Neutral: Options for Negative Carbon Emissions in California., Lawrence Livermore National Laboratory, LLNL-TR-796100, 2020.

130. Algunaibet, I.M.; Pozo, C.; Galán-Martín, Á.; Huijbregts, M.A.J.; Mac Dowell, N.; Guillén-Gosálbez, G. Powering sustainable development within planetary boundaries. *Energy Environ. Sci.* **2019**, *12*, 1890–1900, doi:10.1039/C8EE03423K.

131. Stemmler, I.; Hense, I.; Quack, B. Marine sources of bromoform in the global open ocean – global patterns and emissions. *Biogeosciences* **2015**, *12*, 1967–1981, doi:10.5194/bg-12-1967-2015.

132. Mehlmann, M.; Quack, B.; Atlas, E.; Hepach, H.; Tegtmeier, S. Natural and anthropogenic sources of bromoform and dibromomethane in the oceanographic and biogeochemical regime of the subtropical North East Atlantic. *Environ. Sci. Process. Impacts* **2020**, *22*, 679–707, doi:10.1039/C9EM00599D.

133. Morley, J.W.; Selden, R.L.; Latour, R.J.; Frölicher, T.L.; Seagraves, R.J.; Pinsky, M.L. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLOS ONE* **2018**, *13*, e0196127, doi:10.1371/journal.pone.0196127.

134. Sumaila, U.R.; Tai, T.C.; Lam, V.W.Y.; Cheung, W.W.L.; Bailey, M.; Cisneros-Montemayor, A.M.; Chen, O.L.; Gulati, S.S. Benefits of the Paris Agreement to ocean life, economies, and people. *Sci. Adv.* **2019**, *5*, eaau3855, doi:10.1126/sciadv.aau3855.

135. Buck, H.J. How to Decolonize the Atmosphere. 2020. Available online: https://progressive.international/blueprint/46253391-5b3d-4e68-bd3f-d53dc54180fd-holly-jean-buck-how-to-decolonize-the-atmosphere/en (accessed on Sep 8, 2020).

136. Morrow, D.R.; Thompson, M.S.; Anderson, A.; Batres, M.; Buck, H.J.; Dooley, K.; Geden, O.; Ghosh, A.; Low, S.; Njamnshi, A.; et al. Principles for Thinking about Carbon Dioxide Removal in Just Climate Policy. *One Earth* **2020**, *3*, 150–153, doi:10.1016/j.oneear.2020.07.015.

137. Intergovernmental Oceanographic Commission. United Nations Decade of Ocean Science for Sustainable Development. 2020. Available online: https://oceandecade.org (accessed on Sep 9, 2020).

138. Lapointe, B.E. Strategies for pulsed nutrient supply to Gracilaria cultures in the Florida Keys: Interactions between concentration and frequency of nutrient pulses. *J. Exp. Mar. Biol. Ecol.* **1985**, *93*, 211–222, doi:https://doi.org/10.1016/0022-0981(85)90240-0.

139. Krueger-Hadfield, S.A.; Hoban, S.M. The importance of effective sampling for exploring the population dynamics of haploid–diploid seaweeds. *J. Phycol.* **2016**, *52*, 1–9, doi:10.1111/jpy.12366.