Restoring pre-industrial CO_2 levels while achieving Sustainable Development Goals

M. E. Capron[1*†], J. R. Stewart[1†], A. d. R. N'Yeurt[2†], M. D. Chambers[3†], J. K. Kim[4], C. Yarish[5†], A. T. Jones[6†], R. B. Blaylock[7†], S. C. James[8†], R. Fuhrman[9†], M. T. Sherman[1†], D. Piper[1], G. Harris[1], M. A. Hasan[1]

[1]OceanForesters, Oxnard, CA, USA. [2]Pacific Centre for Environment and Sustainable Development, The University of the South Pacific, Suva, Fiji. [3]Department of Food and Agriculture, University of New Hampshire, Durham, NH, USA. [4]Department of Marine Science, Incheon National University, Incheon, South Korea. [5]Department of Ecology and Evolutionary Biology, University of Connecticut, Stamford, CT, USA. [6]Intake Works, Sacramento, CA, USA. [7]Thad Cochran Marine Aquaculture Center, University of Southern Mississippi, Ocean Springs, MS, USA. [8]Department of Geology, Baylor University, Waco, TX, USA. [9]Stingray Sensing, Goleta, CA, USA.

*Corresponding author: Mark E. Capron (markcapron@oceanforesters.com)

†Part of a MARINER (US Department of Energy ARPA-E) team.

Key Points:

- Feeding the world with sustainable seafood from artificial reefs that also restore ocean biodiversity and support marine protected areas
- Sustainable development for all while reducing atmospheric CO_2 below 300 ppm by the 2100s and keeping global temperature rise below 1.5ºC
- Quadrupling global electricity production, all carbon-neutral or carbon-negative, while replacing oil with carbon-negative biofuel

Abstract

A framework is presented with examples of technologies capable of achieving carbon neutrality while sequestering sufficient CO_2 to ensure global temperature rise less than 1.5°C (after a small overshoot), then continuing to reduce CO_2 levels to 300 ppm within a century. Two paths bracket the continuum of opportunities including dry, sustainable, terrestrial biomass (such as *Miscanthus*, paper, and plastic) and wet biomass (such as macroalgae, food, and green waste). Suggested paths are adaptable, consistent with concepts of integral ecology, and include holistic, environmentally friendly technologies. Each path addresses food security, marine plastic waste, social justice, and UN Sustainable Development Goals. Moreover, oceanic biomass-to-biofuel production with byproduct CO_2 sequestration simultaneously increases ocean health and biodiversity. Both paths can accomplish net-zero fossil-CO_2 emissions by 2050. Both paths include: (1) producing a billion tonnes/yr of seafood; (2) collecting six billion dry tonnes of solid waste (any mix of organic waste, paper, and plastic) to produce twenty million barrels/day of biocrude; and (3) installing a million megawatts of CO_2-sequestering (Allam Cycle) electric power plants initially running on fossil fuels. Resulting food production, solid waste-to-energy, and fossil-fueled Allam Cycle infrastructure will strengthen the economies in developing countries. Next steps are (4) sequestering four billion tonnes of byproduct CO_2/yr from solid waste-to-biofuel by hydrothermal liquefaction; (5) increasing macroalgae-for-biofuel production; (6) replacing fossil fuel with terrestrial biomass for Allam Cycle power plants; (7) recycling nutrients for sustainability; and (8) eventually sequestering a total of 28 to 38 billion tonnes/yr of bio-CO_2 for about $26/tonne, avoided cost.

Plain Language Summary

Pope Francis, "The urgent challenge to protect our common home includes a concern to bring the whole human family together to seek a sustainable and integral development…" People can do this with new ways to grow food from healthy oceans, collect and reuse wastes, make fuel and electricity, store carbon dioxide, and heal climate change. First, grow more food than needed in less well-off states, selling some food to better-off states. Second, build ways to reuse the nutrients and energy in sewage and trash to produce more food and energy. Third, using the income from food sold to better-off states, install new ways to make energy that address climate change while making all states better-off. The new energy can start using coal, natural gas, waste (paper, plastic, food waste), and crop residues, then move to sustainable crops such as switchgrass, seaweed, and seagrass. The CO_2 normally emitted when making energy is captured and stored. Growing food and biomass for energy, storing CO_2, and improving ocean biodiversity and health need to displace the current fossil-fuel industry. These new industries can work in harmony with all life on Earth for many generations while healing climate change (i.e., removing CO_2 from the air).

1 Introduction

This paper presents nations and communities more choices for accomplishing United Nations Sustainable Development Goals (SDGs) (United Nations, 2016b) while reducing CO_2 levels in ways consistent with integral ecology (Pope Francis, 2015; Sorondo & Ramanathan, 2016) and the UN Agenda for Humanity (United Nations, 2016a). The 2015 Paris Agreement recommends that "rapid reductions" of greenhouse gases be achieved "on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty" (IPCC, 2014).

The 2018 IPCC 1.5ºC report (IPCC, 2018) findings include:

- "Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming to 1.5°C and increase further with 2°C." This implies that paths for addressing climate change will be more easily started and sustained if they improve health, livelihoods, food security, water supply, human security, and economic growth.
- "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." This means that it would be wise to achieve net zero emissions with significant CDR that can be sustained over decades to decrease atmospheric CO_2 concentrations. Simply eliminating fossil fuel use will not keep warming below 1.5°C.
- "CDR deployment of several hundreds of $GtCO_2$ [billion tonnes] is subject to multiple feasibility and sustainability constraints (*high confidence*)." This implies that CDR totals of several thousand billion tonnes of CO_2 require multiple technologies to ensure feasibility and nutrient recycling to ensure sustainability.

The UN Environment Programme Emissions Gap Report (UNEP, 2019) "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."

Many authors have looked at a variety of CDR methods (also called negative emissions technologies (NETs)). For example, the U.S. National Academies of Sciences, Engineering, and Medicine (2019) plus the massive literature reviews by Minx et al. (2018), Fuss et al. (2018) and Nemet et al. (2018), as well as Tim Flannery's books (2015, 2017) and the recent Project Drawdown Review (2020).

A big challenge is identifying feasible paths with rapid emission reductions, sufficent CO_2 drawdown, and sustainable at scale for centuries, while also supporting UN Sustainable Development Goals. None of those review publications included three emerging technologies: total ecosystem aquaculture (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b, 2020c; Chambers, 2013; Lucas et al., 2019a, 2019b; Knowler et al., 2020); Allam Cycle electricity production (8 Rivers Capital, 2020; Allam et al. 2017; Fernandes et al. 2019; McMahon, 2019); and hydrothermal liquefaction (Jiang et al. 2019; Jiao et al. 2017; Pichach 2019).

Zero carbon electricity such as wind and solar stabilize, but do not reduce CO_2 levels. This paper focuses on reducing CO_2 to pre-industrial levels with emerging carbon negative technologies converting biomass to energy.

2 Methods: Bracketing the choice between bioelectricity and biofuel

The approach of this paper is to solve the climate crisis coincident with achieving SDGs. That is, to solve environmental problems with respect for indigenous cultures (Rockström et al., 2017), all persons, and wildlife while acting to alleviate poverty and prevent armed conflicts (Pope Francis, 2015).

This paper presents two paths both of which embody the above goals. The two paths, shown in Fig. 1 as P_{fuel} and $P_{electric}$, represent extremes of either mostly biofuel or mostly electricity. Two paths are provided so that each community and nation can develop their individual blend of technology and infrastructure to best fit their unique culture, people, natural resources, and needs.

Both paths have reasonable costs, support sustainable development, get to net zero near 2050, and then sequester legacy CO_2 faster than IPCC pathway P4. This added carbon-removal capability can overcome potential additional CO_2 releases from land and ocean as the atmospheric concentrations drop (Keller et al. 2018).

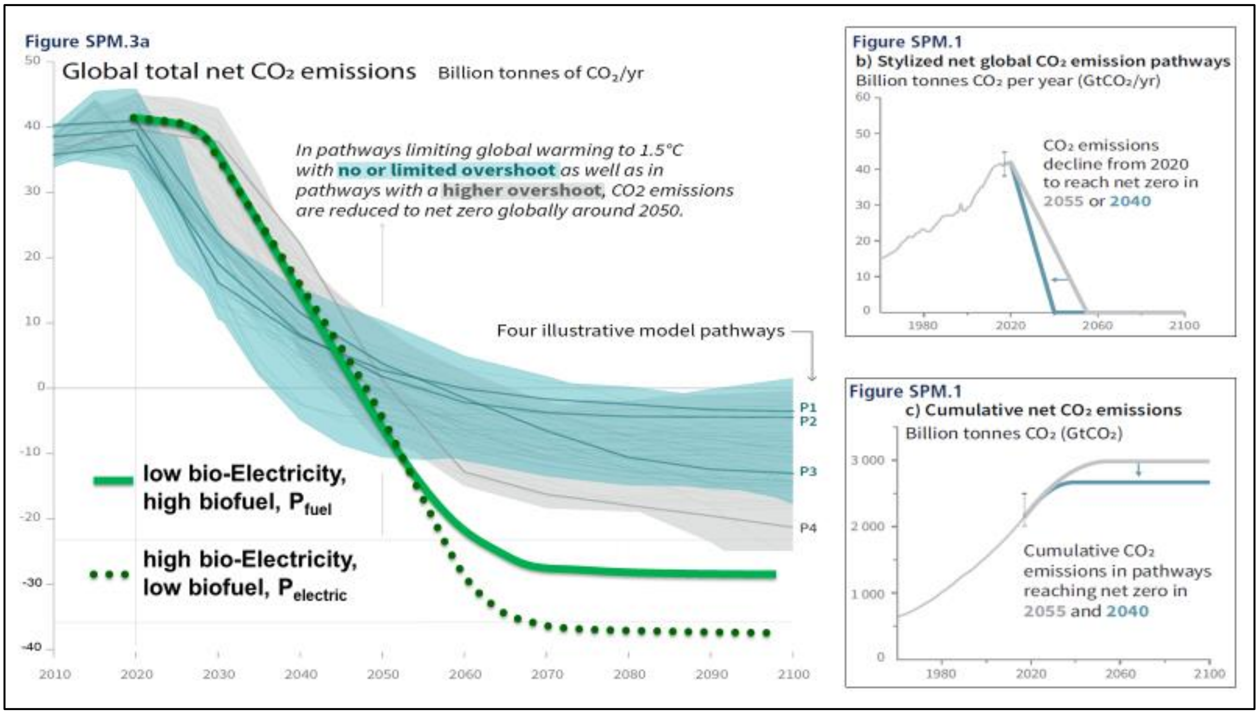

Fig. 1. The two paths, P_{fuel} and $P_{electric}$, superimposed on the four pathways of the IPCC 1.5ºC target (IPCC, 2018) reflect annual emissions projections (Figs. SPM.3a and SPM.1b) plus IPCC cumulative projections (SPM.1c). (Note: Both trajectories between 2020 and 2070 are based on calculations (SS tabs 1, 2, 10) that connect 2020 emissions with projected post-2070 (or so) emissions using the technologies presented in this paper.

The Supplemental Materials spreadsheet (SS) provides a basis for communities to enter their own values and calculate scales and costs of food production, energy production, and CO_2 removal from the atmosphere for their path. One pre-calculated path favors dry biomass for electricity production, the other wet biomass for biofuel production. The proposed technologies are sufficiently developed to allow accurate estimates of the quantities of products and byproducts, but less accurate estimates of the costs. One proposed technology (Allam Cycle) will gasify coal or dry biomass to produce electricity while the other, hydrothermal liquefaction (HTL), will convert wet biomass into biofuel. Total ecosystem aquaculture (TEA) initially produces high-value seafood and then scales to produce wet biomass (macroalgae and seagrass). Calculations are based on Allam Cycle electricity production (8 Rivers Capital, 2020) (SS tabs 9, 12), HTL (Pichach, 2019) (SS tabs 7, 8, 11, 12), and TEA (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b, 2020c; Chambers, 2013; Lucas et al., 2019a, 2019b; Knowler et al., 2020) (SS tabs 4, 5, 6, 18).

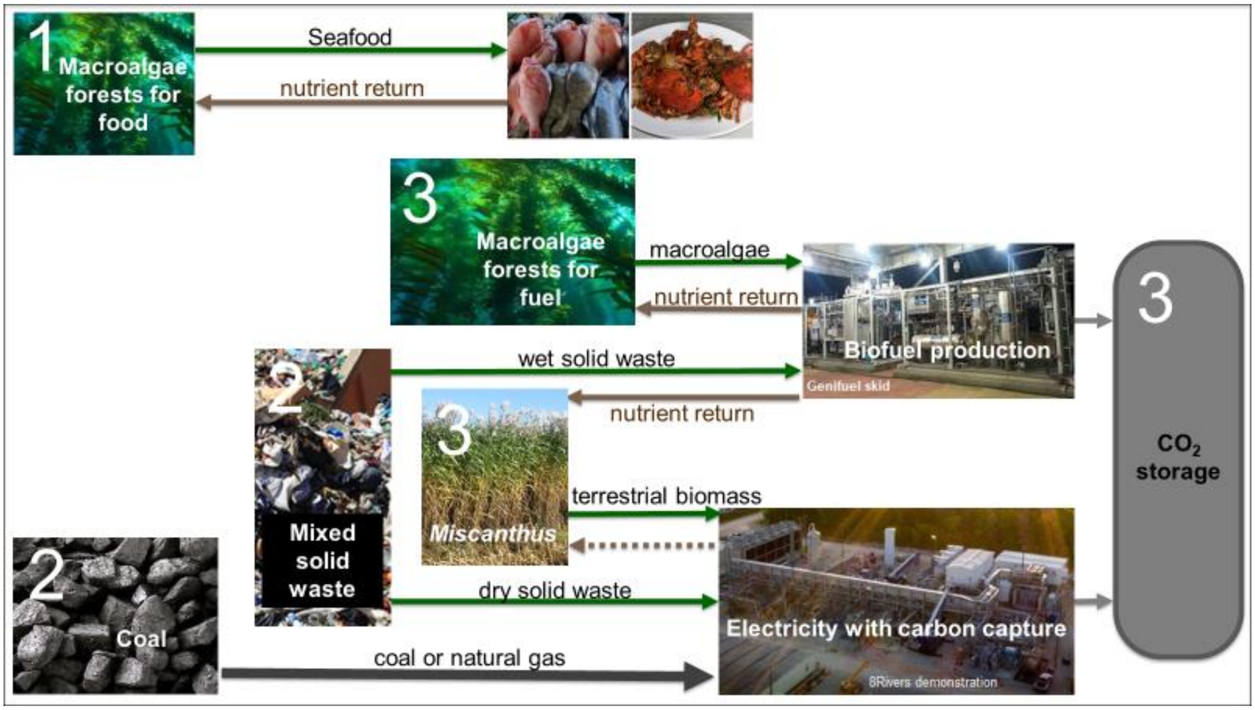

Fig. 2 – Initial technologies to achieve Sustainable Development Goals while restoring 300 ppm CO_2. The gray arrows represent liquid CO_2. Nutrient return from electricity production is dashed because high temperature processes such as gasification, incineration, and pyrolysis, can return some nutrients from the ash, but convert most of the organic nitrogen into nitrogen gas and nitrogen oxides during combustion.

Both paths achieve SDGs in the sequence shown in Fig. 2, then use the same infrastructure to reduce CO_2 levels (see later sections for details):

(1) Install total ecosystem aquaculture (TEA) on floating, flexible, fishing reefs with macroalgae forests to produce seafood while returning nutrients for sustainability (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b, 2020c; Chambers, 2013; Lucas et al., 2019a, 2019b; Knowler et al., 2020).

(2) Install solid waste-collection systems that pay for themselves by producing bioenergy. Simultaneously install electrical power plants that capture and compress CO_2 normally emitted from coal and natural gas. Switch to capture and compress CO_2 from biomass combustion as rapidly as possible, starting with wastes.

(3) Sequester the captured fossil- and bio-CO_2. Increase the amount of biomass (such as macroalgae, *Miscanthus*, and other sustainable biomass crops) to make carbon negative liquid fossil fuels (using the HTL process which captures some CO_2). Gradually increase the ratio of biomass-fueled electricity to fossil-fueled. Up to 7% of the ocean might be needed for macroalgae (seaweed) to make biofuel on the P_{fuel} path. The rest of the ocean can be marine protected area managed in coordination with indigenous people.

Developed countries might skip the first step while importing high-value seafood from developing countries. Ideally, developed countries lead the second and third steps to more quickly optimize the sustainability and economics of all processes.

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

These two bracketing paths are offered so that each nation and community can plan for paths within the brackets with the kinds of biomass that fit their resources and needs. Globally, one path and/or technology is no better than any other; however, at the community level, some paths and technologies are better than others. At both global and community levels, all paths satisfy global food demand before significant production of biomass for energy.

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

Table 1: Two paths of energy demand and supply a few years after net CO_2 emissions drop to zero (~2070) (SS tab 1).

Metric	**Units**	**P_{fuel}: low bioelectricity, high biofuel**	**$P_{electric}$: high bioelectricity, low biofuel**
Global population	Billion	10	10
Projected global average electricity generation in 2070 (2018 world average: 3.5 MWh/capita, China: 5.0, US: 13.6, Japan: 8.3 (BP, 2019))	MWh/yr/person	4	7
Global electricity generation (26 billion MWh/yr in 2018 (BP, 2019))	Billion MWh/yr	40	70
Fraction of global electricity production projected to be BECCS with the remainder nuclear or renewable: solar PV, solar thermal, wind, hydro, wave, geothermal, etc.	%	28%	67%
Global non-electric HTL-produced biofuel use (transportation, industry, heating) (global oil demand of 100 million barrels/day (14 million tonnes/day) or 37 billion barrels/yr in 2018 (U.S. Energy Information Administration, 2020))	Billion barrels/yr	40	10

Global biomass production for Allam Cycle electricity BECCS	Billion dry tonnes/yr	4	17
Global biomass production for non-electric biofuel		35	9
Global biomass production for HTL bio-construction materials (asphalt, plastic, carbon fiber, textiles, etc.)		4	4
Total global biomass production (well past net zero, perhaps 2080)		**43**	**30**
Mass of bio-CO_2 captured and stored (well past net zero, perhaps 2080)	**Billion tonnes of CO_2/yr**	**28**	**38**
Year when 2 trillion tonnes of CO_2 are removed from atmosphere and ocean and permanently sequestered	**Year**	**2130**	**2110**

Table 2 (SS tab 2) outlines possible approaches to achieve net-zero emissions with some fossil fuel in 2050 by: (1) capturing and storing all CO_2 emitted by fossil-fuel electricity generation to make such electricity production carbon neutral, (2) capturing and storing some CO_2 from biofueled electricity production to offset some non-captured fossil fuel use, (3) capturing and storing most of the byproduct CO_2 produced when biomass is converted to biofuel to offset other fossil fuel emissions, and (4) carbon-negative biofuels and electricity replacing fossil-fueled transportation. Negative emissions from the captured and stored bio-CO_2 offset the use of fossil fuels (mainly natural gas) for heating and industry. After net zero CO_2 emissions, increasing biomass-fueled energy production with carbon capture removes CO_2 from the atmosphere at the rates indicated in Table 1.

Table 2: Balancing fossil fuel use, biomass-for-energy production, and bio-CO_2 sequestration for net zero emissions about 2050 (SS tab 2)

Metric	**units**	**Low bio-electricity, high biofuel**	**High bio-electricity, low biofuel**
Global fossil oil and natural gas use without sequestering the CO_2.	Billion barrels /yr (energy equiv.)	29	10
Global negative emissions biofuel production for non-electric use (transportation, industry, heating)		11	0
Global carbon neutral electricity (solar, wind, nuclear, fossil fuel with emissions capture, etc.)	Billion MWh/yr	15	56
Global carbon negative electricity (biomass with carbon capture and sequestration)		25	14
Biomass production **at net zero** (mix of waste, *Miscanthus* and similar, and macroalgae)	billion dry tonnes/yr	14	3
Resulting approximation of fossil- and bio-CO_2	billion	28	28

sequestration **(at net zero)**	tonnes/yr		
Computed net CO_2 emissions	**billion tonnes/yr**	**0.0**	**0.0**

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

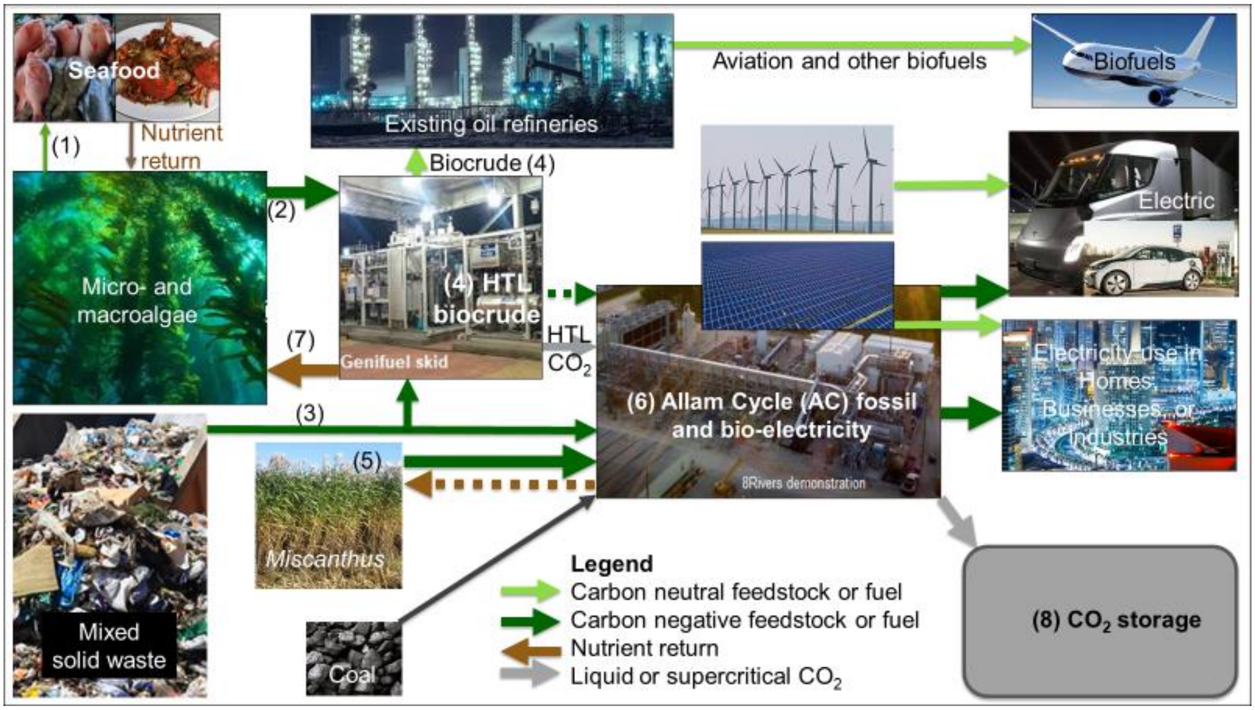

Fig. 3. Process overview for mature (2070 and beyond) production of food, energy, and CO_2 sequestration. It is a simplified representation of the future global energy system with future oceanic integrated food and energy systems. It does not show terrestrial food systems. Each country and community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

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

(1) Increasing seafood production can start now with excess and artificial nutrients (subsection 3.1, SS tab 18).

(2) Ocean (aquatic) plants produce wet biomass feedstock for food and energy (subsection 3.1, SS tabs 4 and 6).

(3) Wet solid waste is the initial feedstock for HTL biofuel. Dry solid waste can be the initial biomass feedstock for Allam Cycle electricity.

(4) About 60% of the carbon in biomass or plastic becomes biocrude oil during HTL (subsection 3.3). Biocrude can be refined at existing refineries. About 40% of the carbon can be recovered as a mixture of fuel gas and CO_2 for Allam Cycle (or other) electricity and heat co-generation or the CO_2 can be separated and sequestered.

(5) Dry terrestrial biomass can be gasified for Allam Cycle electricity production with carbon capture and sequestration.

(6) The Allam Cycle (subsection 3.4) produces electricity from gasified coal, gasified biomass, or natural gas at 40−60% efficiency while also producing pure CO_2 compressed to 100-bar ready for sequestration.

(7) Nutrient recycling is essential for sustained production of seafood and energy. (subsection 3.2).

(8) There are many ways to permanently sequester CO_2 (subsection 3.5).

3 Calculations, results, and discussion for each component

3.1 Biomass start-up, eventual scale, cost, and infrastructure

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

Wet biomass production starts with seafood grown in total-ecosystem aquaculture (TEA). The macroalgae biomass grown on flexible floating reef ecosystems (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b; Chambers, 2013; Lucas et al., 2019a, 2019b) and other systems (Buschmann et al., 2017; Kim et al., 2017a, 2017b; Knowler et al., 2020; Park et al., 2018; Radulovich et al. 2015; Shi et al., 2018) provides food and oxygen for traditional seafoods (i.e. finfish, crabs, oysters, and the like). Gentry et al. (2017), Froehlich et al. (2019), and Theuerkauf et al. (2019) provide global overviews of potential locations. The SD explains TEA adaptation research is needed to ensure seafood and biomass productivity with biodiversity in warming tropical waters. Fish are currently migrating toward Earth's poles to escape marine heat waves (Hastings et al., 2020).

While harvesting seafood, macroalgal biomass-for-energy production would be demonstrated and improved. Fish and shellfish production should cost less than $2/kg on average. Domestic sales might be $1 - $2/kg while exports earn $4/kg or more at the dock. At $2/kg, a billion wet shell-on tonnes of seafood would be worth $2 trillion/yr. When demand for biomass-for-biofuel rises, aquaculture ecosystems can be managed to simultaneously produce both a billion wet tonnes of seafood and 7 billion wet tonnes (0.7 billion dry tonnes) of macroalgae for energy. At $100/dry tonne (Lucas et al. 2019a), this start-up macroalgae-for-energy would be worth $70 billion/yr.

The P_{fuel} path presumes increasing ocean net primary productivity by 40% or about 40 billion dry tonnes/yr. The $P_{electric}$ path projects increasing terrestrial net primary productivity by 15% or about 17 billion dry tonnes/yr. Currently, the world's net primary productivity is near 210 billion tonnes/yr of biomass (Field et al., 1998). Total land productivity is about 110 billion tonnes on an area of 150 million km^2. Ocean productivity is about 96 billion tonnes on 360 million km^2. This implies oceans are under-producing relative to land, which could be remedied by nutrient recycling and structures supporting macroalgae or seagrass in the photic zone. See SD Section 3.1 for a discussion of how macroalgae-for-fuel can support biodiversity better than traditional marine protected areas.

Primary conclusions from Table 3 include:

- There is more-than-sufficient potential additional biomass, between 60 and 100 billion dry tonnes/yr, much more than the 30−40 billion dry tonnes/yr needed in these projections. Thus, there is no need to use wood from forests, which is often regarded as unsustainable (Hudiburg, et al., 2013). More discussion in SD.
- There is more than enough solid waste (Kaza et al. 2018) for 22 million barrels/day (by 2050) of sweet biocrude oil (SS tabs 4, 7, 11, 12).
- Every kind of biomass or waste (wet or dry) can contribute, which means every country can participate in some form of biomass production.
- While there are obvious differences in maximum scale and cost, most every type of biomass is significant and is, or will become, a viable industry.
- These numbers are speculative in that the macroalgae projections are based on theoretical studies, not physical demonstration projects.

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

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

[1] Terrestrial material scale and cost is from references in SS tab 4. Macroalgae scale and cost are interpolated from techno-economic analyses anticipating technologies and systems (SS tab 6). The analyses were funded by the U.S. Department of Energy's Advanced Research Projects-Energy MARINER Program (2017b).
[2] Terrestrial material energy-return ratios are from references in SS tab 4. Macroalgae energy-return rations were defined in the MARINER Program as the lower heating value of macroalgae for the energy out (E_{out}) and the non-ambient energy required for planting, growing, harvesting, and transporting to the energy processor for energy in (E_{in}) (ignoring the energy embedded in the structure, ships, etc.). The embedded energy was represented in the capital for ambient energy (wind, wave, solar) in the $/dry tonne.
[3] Solid waste pays a disposal fee as if the HTL unit was a landfill. Landfill fees in the U.S. range from $30−$100/wet ton ($120−$400/dry tonne) (Environmental Research & Education Foundation, 2019). Negative values (because solid waste pays a disposal fee) could produce oil for $0/barrel. E_{in} is the difference between the energy expended now to collect and transport solid waste to landfills compared to the energy expended to collect, transport, and process it at HTL facilities. (Quantity from Kaza et al., 2018).
[4] Based on data from Kaza et al., 2018; Turner et al. 2018; REN21, 2019; U.S. Department of Energy, 2018; Eisentraut, 2010; Daly &Halbleib, 2014; Das et al. 2019; Pandur et al., 2015. (SS tab 4). Significant dry biomass could be delivered to the electricity process (Allam Cycle) for $50/tonne about the same price as US coal at $2.5/GJ ($2.6/MMBTU) (SS tab 4).
[5] The scale of high-protein products paying for the structure (so that the cost of biomass-for-energy can be as low as $40/DMT) is limited by humanity's demand for high-protein seafood (Capron & Piper, 2019; Capron et al., 2019, 2020a, 2020b)
[6] U.S. Department of Energy (2018) and Jiang et al. (2019) projected a range of $400−$2,000 per dry ash-free tonne of microalgae in their techno-economic uncertainty analysis. Energy return on investment (EROI) from Zaimes & Khanna (2013).
[7] The area available for anchored macroalgae systems assumes seafloor depths from 0 to 200-m, generally on relatively flat continental shelves (Lucas et al., 2019a). There are moored systems appropriate for deeper seafloors and steep slopes (Sims et al., 2019). Fig. 11 in SD suggests that wet biomass delivered to the biofuel process (HTL) for less than about $120/dry tonne would produce biocrude oil for less than about $70/barrel.
[8] Free-floating deep-ocean systems access large open-ocean areas by floating in currents, eddies, and gyres with minor steering inputs. Individually free-floating plants include *Sargassum* (*S. fluitan*s and *S. natans*) (Sherman et al., 2018). Attached growth plants on free-floating structures (Huesemann et al., 2017) include *Saccharina japonica, Saccharina latissima, Undaria pinnatifida, Nereocystis luetkeana, Gracilaria tikvahiae, Gracilaria edulis, Gracilariopsis lemaneiformis* and *Sargassum polycystum*. (SS tabs 4 and 6)

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

The availability of large quantities of ocean biomass relieves pressure on terrestrial sources of biomass, which are increasingly limited by demands for food as well as climate impacts. TEA could grow 1 billion tonnes/yr of seafood on less than 10% of the suitable continental shelf less than 200-m seafloor depth (identified by Gentry et al., 2017). That would be about 0.3% of the world's oceans (SS tabs 6 and 18). TEA could grow 39 billion dry tonnes of oceanic biomass-for-energy on 7% of the world's oceans, including some deep ocean (SD 3.1 and SS tab 6). The remaining 93% of ocean area would not be needed for food or bioenergy production.

3.2 Nutrient recycling start-up, eventual scale, cost, and infrastructure

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

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

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

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

3.3 HTL start-up, eventual scale, cost, and infrastructure

Recent innovations and cost reductions with HTL (Genifuel, 2019; Jiang et al., 2019; Jiao et al., 2017; Pichach, 2019; ReNew ELP, 2019; Steeper Energy, 2019; Watson et al., 2019) make it practical to scale up as a solid waste-collection system that pays for itself. HTL converts any blend of wet plants, paper, wax, and most plastics to bio-oil – expired juice in plastic bottles, newspaper, expired packages of meat, seaweed, microalgae, switch grass, feces, biohazard wastes in plastic – all chopped and blended together. The process is similar to the way algae became oil when buried deep in the Earth. By using a combination of high temperature (350ºC, 660ºF) and pressure (200 atmospheres, 3,000 psi) the conversion to oil is complete in about 30 min. Because the reaction temperature is less than 400ºC, all plant nutrients can be recovered and used to grow more plants (see SD 3.3).

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

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

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

3.4 Allam Cycle start-up, eventual scale, cost, and infrastructure

The Allam Cycle (8 Rivers Capital, 2020; Allam et al. 2017; Fernandes et al. 2019; McMahon, 2019) first makes pure oxygen separated from air. The left-over nitrogen and argon from air separation can be sold. Inside the Allam Cycle combustion chamber, pure O_2, gasified coal, gasified biomass or plastic, or natural gas, and CO_2 (for cooling the combustion chamber) mix. After spinning the turbine, all the CO_2 is compressed and cooled. Most is recirculated. A little, 3 to 5%, depending on the type of fuel, is available as liquid or supercritical sequestration-ready CO_2. Its pressure, 100 to 150-bar (10 to 15 MPa, 1450 to 2,175 psi), will push it through a pipeline for direct injection into underground or underwater sequestration.

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

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

James et al. (2019) prepared a standard baseline report for several power plant processes with CCS. The process with the least avoided cost, supercritical pulverized coal (SC-PC), levelized cost of electricity is \$64/MWh without CCS or \$109/MWh with 90% carbon capture. These are James' figures without transport and sequestration (T&S) costs with an added \$3/MWh to compress from James' 15-bar to Allam Cycles' 100-bar. Irlam (2017) reports similar values to James. Allam Cycle with CCS in a comparable situation has electricity cost at \$74/MWh (8 Rivers Capital, 2020). See Section 3.6 for a discussion of costs in terms of \$/tonne of CO_2 sequestered.

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

NET Power (a subsidiary of 8 Rivers) targets commercial deployment of 300-MW natural gas Allam Cycle power plants in 2022 (McMahon, 2019). 8 Rivers has proposed a demonstration of a 300-MW Allam Cycle with coal gasification at a Wyoming coal mine including selling all the argon and CO_2. The commercial operation date would be 2026 (8 Rivers Capital, 2020). Allam Cycle power plants are almost zero emissions and have operating flexibility that reduces the need for battery backup of solar and wind energy (8 Rivers Capital, 2020). They also provide "firm" power which has been calculated by Sepulveda et al. (2018) to reduce overall electricity costs in decarbonized scenarios. See discussion in SD Section 3.4.

3.5 CO_2 sequestration start-up, eventual scale, cost, and infrastructure

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

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

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

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

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

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

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

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

[5] Different fuels have different \$/MWh (with the same \$/tonne of CO_2) due to differences in their electrical efficiency and their carbon:hydrogen ratio. This column shows the \$/MWh using gasified coal into Allam Cycle plant. The Supplemental spreadsheet shows it for other fuels. Note that US\$10/MWh corresponds to 1 cent/kWh
[6] With geologic or mineralization storage, the injection rate of CO_2 should not exceed that which causes earthquakes or leaks due to high pressure in the ground near the injection point (Deng et al., 2017).
[7] The actual mineralization rate depends on the characteristics of the local rocks (McGrail et al., 2017; Snæbjörnsdóttir et al., 2020). See SD for maps and discussion of different types of rocks with more references (Gunnarsson et al., 2018; Kelemen et al., 2019; Moran et al., 2020).
[8] Contained ocean hydrate storage scale and injection rate is essentially unlimited. It may be the least expensive option for coastal communities with small continental shelves. From Capron et al. (2013) but updated in SS tab 17.

3.6 Paying for removing and storing legacy CO_2

Legacy CO_2 is commonly thought of as CO_2 from emissions already in the atmosphere and ocean (Friedlingstein et al., 2019; Knutti & Rogelj, 2015). Our calculation includes future fossil-fuel CO_2 uncaptured emissions in the total legacy CO_2 to be removed from the air and oceans. The total cost is a cost to society in the form of higher energy costs. The cost calculation below is an apples-to-apples comparison with:

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

3.6.1 Capture

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

3.6.2 Compression

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

- <u>CO_2 capture from Allam Cycle</u> – Each 300-MW coal- (and likely biomass)-fired power plant compresses 4,600 tonnes/hr of CO_2 from 30 to 150 bar. Most of the CO_2 is recirculated working fluid. About 230 tonnes/hour is produced from coal for sale or sequestration. The energy required to compress CO_2 from a gas at 30 bar to a supercritical fluid at 100 to 150 bar is small, about 9 kWh/tonne (8 Rivers Capital, 2020). The combined energy plus other operating and capital costs are near $1/tonne of CO_2 for coal or $2/tonne for natural gas. This is based on data from Fernandes et al. (2019), Atlas Copco CO_2 compressors (2020), Allam et al. (2017), and 8 Rivers Capital (2020) (SS tab 14).

- <u>CO_2 capture from HTL</u> – HTL produces bio-crude plus fuel gas that could be combusted with air such that it produces gas with a high fraction of CO_2 (10 to 20%) at 1 bar. Capturing >95% of the CO_2 costs about $40/tonne of CO_2. Compressing CO_2 from 1 to 100 bar requires about 130 kWh/tonne of CO_2. The combined capture, energy plus other operating, and capital costs are near $65/tonne of CO_2. Most of the cost is for capture and compressing energy, which varies significantly by location, by technology, and over time, as indicated in Table 5.
- <u>Hybrid of HTL co-located with Allam Cycle</u> – HTL's byproduct fuel gas and CO_2 at 1 bar would be blended and provided as fuel (low-grade fuel gas) to the Allam Cycle. Its value as fuel should cover the cost of compressing it to the required fuel pressure. This situation's capture and compression cost should be similar to the $1 or $2/tonne of CO_2 for the Allam Cycle situation (SS tab 14).

3.6.3 Transportation

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

3.6.4 Storage

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

3.6.5 Input fuel cost

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

3.6.6 Process cost

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

3.6.7 Total cost

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

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

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

SS tab 16 includes a traditional calculation of "avoided" or "breakeven emissions penalty" costs. With $SC\text{-}PC_{ref}$ and Allam $Cycle_{CCS}$ the avoided cost is $22/tonne of CO_2. This compares well with the slightly more conservative $26/tonne of CO_2 shown in Table 5.

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

Metric	Additional $/tonne of CO_2	Comment
Allam Cycle power plant gasifying $0/GJ	**-$250**	Lower electricity fuel cost

($0/MMBTU) dry waste in place of $7.6/GJ ($8/MMBTU) LNG, including income from sales of argon and nitrogen plus CO_2 for EOR		possible when retaining solid waste disposal fees to offset Allam capital and operating costs.
Allam Cycle power plant gasifying $0/GJ ($0/MMBTU) dry waste in place of $2.5/GJ Illinois coal delivered in US, including income from gas sales	**-$34**	
Allam Cycle power plant burning terrestrial biomass delivered for the same $2.5/GJ as for US coal, no gas sales	**$26**	When fuel costs the same, all the additional cost is process change ($15/tonne), compressing ($1/tonne), transporting, and sequestering liquid CO_2 ($10/tonne).
Allam Cycle power plant burning $11/GJ HTL biocrude instead of fossil oil for the same $11/GJ, no gas sales	**$26**	
Hybrid co-located HTL and fossil-fired (some HTL biogas) Allam Cycle capturing and compressing CO_2 from both processes. Same $/GJ for biomass or fossil fuel, no gas sales	**$26**	
Standalone HTL facility using by-product biogas internally with internal capture and compression of by-product CO_2, no gas sales	**$75**	Using historic capture and compression average cost of $65/tonne plus the same $10/tonne for sequestration.
Allam Cycle power plant burning $11/GJ HTL biocrude in place of $7.6/GJ LNG (approximate), no gas sales	**$90**	Higher fuel cost increasing electricity price is most of the added expense.
Allam Cycle power plant burning $11/GJ HTL biocrude in place of $2.5/GJ coal (approximate), no gas sales	**$180**	

Table 2 shows about 28 billion tonnes/yr of fossil- and bio-CO_2 being sequestered on either path at net zero emissions. With mostly co-located HTL and Allam Cycle facilities, the global cost is 28 billion tonnes/yr times $26/tonne, which rounds to $730 billion/yr.

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

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

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

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

3.7 SDGs path

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

3.7.1 Food systems

Total ecosystem aquaculture systems are built-reef ecosystems with nutrient recycling that can provide abundant, inexpensive multi-species seafood. Distributed globally, seafood reefs (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b; Chambers, 2013; Lucas et al., 2019a, 2019b) can sustainably and economically produce a billion tonnes/yr of seafood, 300 grams/person/day for 8 billion people. (The FAO (2018) estimates current seafood production (including aquaculture and wild-caught) near 170 million tonnes/yr.) Developing countries might earn income from developed countries initially by exporting seafood. Developing countries might earn income from developed countries by accommodating refugees and migrants as temporary or permanent guest workers on their built-reef ecosystems. Aquatic-based organic fertilizers can replace chemical fertilizers. Scaling built-reef total ecosystem aquaculture allows more marine protected areas.

3.7.2 Human waste resource recovery systems

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

3.7.3 Solid waste resource recovery systems

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

3.7.4 Sustainable energy systems

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

3.7.5 Sustainable ocean biomass-for-energy

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

3.7.6 CO_2 sequestration systems

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

3.7.7 Floating land systems

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

3.7.8 Other public health systems

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

3.7.9 All systems must be sustainable

In 2012 N'Yeurt et al. discussed sustainability criteria for 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.: environmental, climate, political, social, energy, and economic. (See SD for more discussion on how ocean forest reefs directly support twelve of the SDGs.)

4 Conclusions and Recommendations

4.1 Summary

Each country or community can pick the sustainable developments and associated technologies that best fit their resources and goals. Every sustainable development listed in Section 3.7 can start now and grow while achieving SDGs with excellent economic efficiency. These technologies can deploy to significant scale while earning profits producing seafood plus energy and nutrients from mixed plastics and organic solid waste. This is consistent with Otto et al. (2020) in that major climate efforts must be "explicitly compatible with the Sustainable Development Goals, in the sense of positive social tipping dynamics." The health co-benefits of zero emissions energy and waste recovery strongly support this approach by generating local support, especially as these benefits are primarily local and near-term (West et al., 2013).

Food, jobs, adaptations for tropical oceans, and ocean SDGs are addressed while oceanic-biomass-for-energy production slowly improves. Global seafood production can increase to a billion tonnes/yr. This is nearly 6 times current seafood production (FAO, 2018) and double the combined current total meat and seafood production. (Global meat production in 2018 was 327 million tonnes (Shahbandeh, 2019), with an average climate impact per kg four times that of seafood (Poore & Nemecek, 2018).)

The increased seafood production is supported by improved ways to ensure the nutrients people eat are recycled to land and ocean. In the ocean, recycled nutrients are distributed to macroalgae or seagrass grown on floating flexible fishing reefs positioned in the photic zone independent of seafloor depth. The fishing reefs form highly productive ecosystems supported by nutrients optimized for seasonal productivity and natural variations in nutrients and dissolved oxygen supply. Calculations suggest a billion tonnes of seafood can be grown on less than 10% of the suitable continental shelf less than 200-m seafloor depth (identified by Gentry et al., 2017). That would be about 0.3% of the world's oceans (see SS tabs 6 and 18). By growing more food in less ocean, the marine protected areas could be increased.

Allam Cycle power plants reduce the avoided cost (the economic penalty) to capture, compress, transport, and sequester one tonne of CO_2 from current over $60/tonne for CCS to less than $0/tonne for early adopters (SS tabs 14 and 16). (As "waste" sources become valuable and gases produced during Allam Cycle electricity production exceed commercial demand, the avoided cost could rise to $26/tonne.) This significant cost drop for CCS, combined with developing country needs for new reliable electricity, provides an opportunity for developing countries to lead in healing climate change.

All countries can enjoy safe handling of biohazard wastes and mixed solid wastes in general with low, even negative, disposal fees using hydrothermal liquefaction (HTL) to produce 22 million barrels/day (3 million tonnes/day) of biocrude oil from wastes by 2050. Additional benefits include less plastic trash reaches the ocean, less methane emissions from landfills, and profitably cleaning excess *Sargassum* off beaches.

4.2 Recommendations

The following recommendations should be implemented as soon as is feasible:

- Pause (even in the middle of construction) electricity power plant construction to check local feasibility of Allam Cycle plants. The design of Allam Cycle plants facilitates mass production. Funding agencies could purchase blocks of a thousand factory-built 300 MW power plants at a time. In addition to lower costs from mass production, this action will increase budget certainty for developing countries as they switch to Allam Cycle power. Fast start-up is encouraged while the oil industry is still buying CO_2 for enhanced oil recovery. Income from selling CO_2 for EOR will decrease the cost of electricity. (8 Rivers Capital (2020) estimated in early 2020 that the global demand for CO_2 used for EOR is equivalent to nearly 6,000 of the 300 MW Allam Cycle power plants or 1,800 GW.)
- Quickly build seafood-production infrastructure in developing countries.
- Convert solid waste to biocrude oil in developed and developing countries.
- Co-locate the HTL and Allam Cycle facilities to maintain the cost for capturing, compressing, and sequestering CO_2 near $26/tonne as opposed to the $75/tonne expense

for a stand-alone facility. Co-locate with other businesses and waste handling to maximize a circular economy and overall energy efficiency (e.g., pasteurizing human and medical wastes with "waste" heat and manufacturing high-performance plastics that more easily convert to biocrude or electricity).

- Take advantage of the immediate benefits from food, jobs, waste handling, and sales of liquid CO_2 byproduct to achieve SDGs. Start-up actions are further described in the SD and by Capron et al. (2020a, 2020d).
- Increase marine protected areas in proportion to the area converted to total ecosystem aquaculture.
- Establish a Legacy Carbon Fund (each country could have its own fund but with global accounting). The fund would collect more-than-the-cost of sequestering fossil-CO_2 from fossil fuel producers/users. The more-than costs are used to pay for sequestering bio-CO_2.

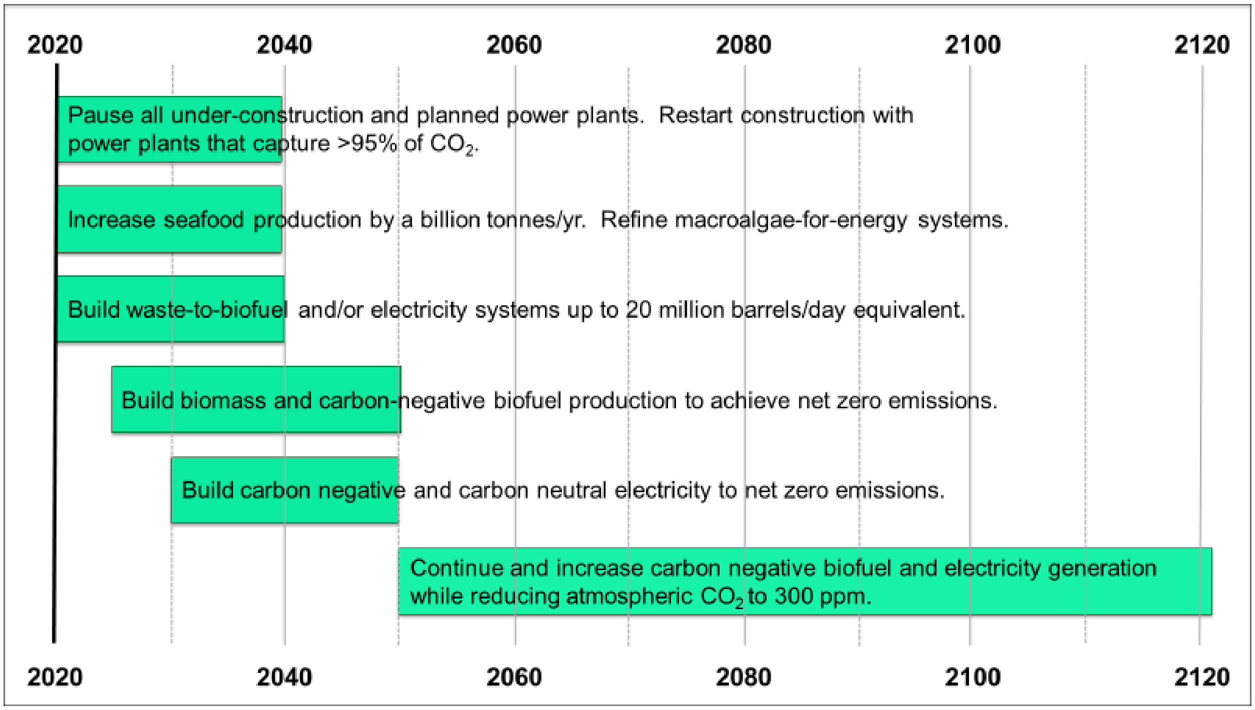

Fig. 4. Global timeline to achieve SDGs and reduce atmospheric CO_2 by 2 trillion tonnes around 2100 (details in SD)

4.3 Further Research

Our recommendation is to conduct research while building, operating, and maintaining commercial-scale infrastructure. The urgent needs for SDGs, addressing climate change, and assessing the effectiveness of each technology are best addressed at commercial scale. Examples of research needs include the following (see SD for additional examples):

- Life-cycle cost, planetary boundaries (Algunaibet et al., 2019) energy, and emissions analyses – The economics of reducing atmospheric CO_2 concentrations on either path appear feasible. But what are their complete life-cycle costs? Does either path exceed or increase planetary boundaries?

- Total-ecosystem aquaculture must be designed for continued biodiversity and seafood production even with some fish species moving toward the poles as the tropical oceans become too warm (Morley et al., 2018; Sumaila et al., 2019).
- Economics and governance – Who pays how much for achieving net-zero CO_2 emissions? Who pays how much for removing legacy CO_2 emissions from the atmosphere for a century or so after achieving net-zero CO_2 emissions?

Acknowledgments, Samples, and Data

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

Funding: This research was not directly funded by agencies in the public, commercial, or not-for-profit sectors. However, the authors appreciate funding by the U.S. Department of Energy's Advanced Research Projects Agency - Energy (ARPA-E) MacroAlgae Research Inspiring Novel Energy Resources (MARINER) Program, which helped assemble teams and facilitated work on ocean macroalgae-for-energy cultivation under the following Department of Energy contracts: DE-AR0000911, DE-AR0000912, DE-AR0000915, DE-AR0000916, DE-AR0000919, DE-AR0000923, DE-AR0000925.

Acknowledgements:

Dr. Marc von Keitz for establishing and leading the U.S. Department of Energy Advanced Research Projects Agency-Energy's MARINER Program.

Dr. Michael Huesemann and his team for providing cost and global-scale information from the Pacific Northwest National Laboratory's MARINER team – Nautical Offshore Macroalgal Autonomous Device (NOMAD).

Dr. Michael Stekoll and his team for providing cost and global-scale information from the University of Alaska, Fairbanks' MARINER team – Scalable Coastal and Offshore Macroalgal Farming.

Dr. Kelly Lucas, University of Southern Mississippi, for leading the Thad Cochran Marine Aquaculture Center to propose and execute two MARINER projects: AdjustaDepth and SeaweedPaddock.

Dr. Michael Rust of the U.S. National Oceanic and Atmospheric Administration for suggesting teaming with the Thad Cochran Marine Aquaculture Center and insights concerning total ecosystem aquaculture.

Matthew Wennerholm of AquaDam for contributing construction insights and cost data informing the design, performance, and cost of containers for CO_2-hydrate storage.

James R. Oyler of Genifuel, Matt Atwood of Algae Systems, Craig Pichach of CleanCarbon Energy, Jeffrey Moeller and Aaron Fisher of the Water Research Foundation's Leaders Innovation Forum for Technology, and Greg Yamamoto of FreshMining for insights into hydrothermal liquefaction, biocrude upgrading, and potential nutrient-recycling processes.

Rodney J. Allam, 8 Rivers, Toshiba, the U.S Department of Energy, and others associated with inventing and developing Allam Cycle electrical power plants.

Jade Chongsathapornpong for his pro-bono illustrations of an AdjustaDepth floating flexible reef structure with total ecosystem aquaculture while a student at Oxnard High School and edits/comments as a freshman at the Massachusetts Institute of Technology.

Supplemental Document and Supplemental Spreadsheet available online.

References

8 Rivers Capital. (2020). *Allam Cycle Zero Emission Coal Power*. Retrieved from https://www.netl.doe.gov/coal/tpg/coalfirst/DirectSupercriticalCo2

Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., Scott, V., Gilfillan, S. M. V, Ogaya, X., & Haszeldine, R. S. (2018). Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications*, *9*(1), 2201. https://doi.org/10.1038/s41467-018-04423-1

Aldridge, J., van der Molen, J., & Forster, R. (2012). *Wider ecological implications of macroalgae cultivation. The Crown Estate, Marine Estate Research Report*. https://www.researchgate.net/publication/285680370_Wider_ecological_impli-cations_of_Macroalgae_cultivation

Algunaibet, I. M., Pozo, C., Galán-Martín, Á., Huijbregts, M. A. J., Mac Dowell, N., & Guillén-Gosálbez, G. (2019). Powering sustainable development within planetary boundaries. *Energy & Environmental Science*, *12*(6), 1890–1900. https://doi.org/10.1039/C8EE03423K

Allam, R., Martin, S., Forrest, B., Fetvedt, J., Lu, X., Freed, D., Brown, G. W., Sasaki, T., Itoh, M., & Manning, J. (2017). 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*, *114*(November 2016), 5948–5966. https://doi.org/10.1016/j.egypro.2017.03.1731

Atlas-Copco. (2020). *CO_2 Compressors*. Retrieved from https://www.atlascopco.com/en-us/compressors/products/gas-compressors/co2-compressor

Baker, S. E., Stolaroff, J. K., Peridas, G., Pang, S. H., Goldstein, H. M., Lucci, F. R., et al. (2020). *Getting to Neutral: Options for Negative Carbon Emissions in California*. The ASHA Leader. Retrieved from https://www.llnl.gov/news/new-lab-report-outlines-ways-california-could-reach-goal-becoming-carbon-neutral-2045

Boerner, L. K. (2019). Industrial ammonia production emits more CO_2 than any other chemical-making reaction. Chemists want to change that. Chemical & Engineering News, 97 (24). https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-production-emits-CO2/97/i24

Boyd, P.W., Sundby, S., and Pörtner, H.-O. (2014). Cross-chapter box on Net Primary Production in the Ocean. In 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 (Ed.), *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* (pp. 133–136). Cambridge University Press. Retrieved from https://www.ipcc.ch/report/ar5/wg2/

BP. (2019). *BP Statistical Review of World Energy*. Retrieved from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Bradshaw, J., & Dance, T. (2005). Mapping geological storage prospectivity of CO_2 for the world's sedimentary basins and regional source to sink matching. *Greenhouse Gas Control Technologies*, *August*, 583–591. https://doi.org/10.1016/B978-008044704-9/50059-8

Brewer, P. G. (2000). Roger Revelle commemorative lecture contemplating action: Storing carbon dioxide in the ocean. *Oceanography*, *13*(SPL.ISS. 2), 84–92. https://doi.org/10.5670/oceanog.2000.38

Brown, T. (2016). *Ammonia production causes 1% of total global GHG emissions.* Retrieved from https://ammoniaindustry.com/ammonia-production-causes-1-percent-of-total-global-ghg-emissions/

Bruun, J. (2019). *Revolutionizing the way we manage waste*. Retrieved from https://eng.au.dk/en/news-and-events/news/show/artikel/revolutionising-the-way-we-manage-waste-a-danish-researcher-is-developing-a-pioneering-new-technolo-1/

Buschmann, A. H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M. C., Pereda, S. V, Gomez-Pinchetti, J. L., Golberg, A., Tadmor-Shalev, N., & Critchley, A. T. (2017). Seaweed production: overview of the global state of exploitation, farming and emerging research activity. *European Journal of Phycology*, *52*(4), 391–406. https://doi.org/10.1080/09670262.2017.1365175

California Air Resources Board. (2020). *California-Quebec Joint Auction Settlement Prices*. Retrieved from https://ww3.arb.ca.gov/cc/capandtrade/auction/results_summary.pdf

CalRecycle. (2014). *Disposal-Facility-Based Characterization of Solid Waste in California. Publication # DRRR-2015-1546*. Retrieved from https://www2.calrecycle.ca.gov/Publications/Details/1546

Capo, T. R., Jaramillo, J. C., Boyd, A. E., Lapointe, B. E., & Serafy, J. E. (1999). Sustained high yields of *Gracilaria* (Rhodophyta) grown in intensive large-scale culture, *Journal of Applied Phycology*, *11*(2), 143. https://doi.org/10.1023/A:1008077722769

Capron, M. E. (2019). *Centuries of food and job security for coastal peoples*. Contest Entry in BridgeBuilder™ 2019 Challenge: People on the Move. Retrieved from https://challenges.openideo.com/challenge/2019-bridgebuilder-challenge/ideas/centuries-of-food-and-job-security-for-coastal-peoples

Capron, M. E., & Piper, D. (2019). *Abundant Food and Export Income with Total ecosystem Aquaculture*. Contest Entry in Reshaping Development Pathways in LDCs. Retrieved from https://www.climatecolab.org/contests/2019/reshapingdevelopmentpathwaysinLDCs/c/proposal/1334620

Capron, M. E., Lucas, K, Chambers, MD, Lapointe, B, N'Yeurt, A. de R., Krueger-Hadfield, SA, et al. (2019). Building New Fishery Ecosystems: The Science of Flexible Floating Fishing Reefs. *International Symposium on Stock Enhancement & Sea Ranching*. Retrieved from https://mote.org/media/uploads/contact/ISSESR-Wednesday-1150-Piper.pdf

Capron, M. E., Lucas, K., Chambers, M. D., & Stewart, J. R. (2018). Ocean Forests : Breakthrough Yields for Macroalgae. *OCEANS 2018 MTS/IEEE Charleston*, 1–6. https://doi.org/10.1109/OCEANS.2018.8604586

Capron, M. E., N'Yeurt, A. de R., Kim, J. K., Pichach, C., Chambers, M. D., Fuhrman, R., et al. (2020a). Reversing Climate Change within 100 years: The scale to restore natural CO_2 levels. *Ocean Sciences Meeting Presentation SI41A-02*. Retrieved from https://agu.confex.com/agu/osm20/meetingapp.cgi/Paper/648119

Capron, M. E., Prasad, R., N'Yeurt, A. de R., Hewavitharane, C., & Stewart, J. R. (2020b). *Total Ecosystem Aquaculture - Sustainable Seafood Production for Fiji, the Pacific, and then the World*. Contest Entry in Rockefeller Foundation Food System Vision Prize. Retrieved from https://challenges.openideo.com/challenge/food-system-vision-prize/open-submission/restorative-aquaculture-sustainable-seafood-production-for-the-world

Capron, M. E., Prasad, R., N'Yeurt, A. de R., Hopkins, K., Stewart, J. R., Hasan, M. A., et al. (2020c). Increasing South Pacific aquaculture with complete ecosystems. *Ocean Sciences Meeting Presentation SI12A-05*. Retrieved from https://agu.confex.com/agu/osm20/meetingapp.cgi/Paper/649244

Capron, M. E., Stewart, J. R., & Rowe, R. (2013). Secure Seafloor Container CO_2 Storage. *OCEANS'13 MTS/IEEE San Diego Technical Program #130503-115*. https://doi.org/10.23919/OCEANS.2013.6741182

Capron, M. E., Stewart, J. R., N'Yeurt, A. de R., Prasad, R., Hewavitharane, C., Hasan, M. A., et al. (2020d). *Sustainable Development that supports Ocean Science. Ocean Science that supports Sustainable Development. Concepts for the UN Decade of Ocean Science for Sustainable Development*. Retrieved from https://oceandecade.org/resource/102/Planning-Concrete-Deliverables-for-the-UN-Decade-of-Ocean-Sciences-for-Sustainable-Development-2021-2030

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

Chan, F., Barth, J. A., Blanchette, C. A., Byrne, R. H., Chavez, F., Cheriton, O., Feely, R. A., Friederich, G., Gaylord, B., Gouhier, T., Hacker, S., Hill, T., Hofmann, G., McManus, M. A., Menge, B. A., Nielsen, K. J., Russell, A., Sanford, E., Sevadjian, J., & Washburn, L. (2017). Persistent spatial structuring of coastal ocean acidification in the California Current System. *Scientific Reports*, *7*(1), 2526. https://doi.org/10.1038/s41598-017-02777-y

Chen, S. (2018). *The development of sea surface carbonate chemistry in the coastal upwelling area off Peru following a simulated OMZ upwelling event*. Thesis submitted to Kiel University, Kiel, Germany.

Choi, Y.-S., Young, D., Nešić, S., & Gray, L. G. S. (2013). Wellbore integrity and corrosion of carbon steel in CO_2 geologic storage environments: A literature review. *International Journal of Greenhouse Gas Control*, *16*, S70–S77. https://doi.org/10.1016/J.IJGGC.2012.12.028

Chung, I. K., Oak, J. H., Lee, J. A., Shin, J. A., Kim, J. G., & Park, K.-S. (2013). adaptation against global warming : Korean Project Overview. *ICES Journal of Marine Science*, *68*(November), 66–74. https://doi.org/10.1093/icesjms/fss206

Clarke, S. & Preto, F. (2011). Biomass Burn Characteristics. Ministry of Agriculture, Food and Rural Affairs, Ontario, Canada. Retrieved from http://www.omafra.gov.on.ca/english/engineer/facts/11-033.pdf

Cottier-Cook, E. J., Nagabhushan, N., Badis, Y., Campbell, M. L., Chopin, T., Fang, J., ... Jiang, Z. (2016). Safeguarding the future of the global seaweed aquaculture industry. United Nations University (INWEH) and Scottish Association for Marine Science Policy Brief. ISBN 978-92-808-6080-1. Retrieved from http://inweh.unu.edu/safeguarding-the-future- of-the-global-seaweed-aquaculture-industry-policy-brief/

D'Angelo, C. (2010). Historic California Kelp Harvest, 1916 – 2009. National Marine Fisheries Service report. Retrieved from https://drive.google.com/file/d/1hVQXdt2TrdVB2LRpnWp1SGvs7XqDE3re/view?usp=sharing

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

Daly, C. and Halbleib, M. (2014). *Potential Yield Mapping of Dedicated Energy Crops*. Retrieved from http://energy.gov/sites/prod/files/2014/11/f19/daly_biomass_2014.pdf

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

Deng, H., Bielicki, J. M., Oppenheimer, M., Fitts, J. P., & Peters, C. A. (2017). Leakage risks of geologic CO_2 storage and the impacts on the global energy system and climate change mitigation. *Climatic Change*, *144*(2), 151–163. https://doi.org/10.1007/s10584-017-2035-8

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

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

Duarte, C. M. (1992). Nutrient concentration of aquatic plants: Patterns across species. *Limnology and Oceanography*, *37*(4), 882–889. https://doi.org/10.4319/lo.1992.37.4.0882

Eisentraut, A. (2010). *Sustainable production of second-generation biofuels: potential and perspectives in major economies and developing countries*. https://doi.org/10.1787/5kmh3njpt6r0-en

Enerdata. (2019). *Global Energy Statistical Yearbook*. Retrieved from https://yearbook.enerdata.net/electricity/electricity-domestic-consumption-data.html

Environmental Research & Education Foundation. (2019). *Analysis of MSW Tipping Fees*. Retrieved from http://www.erefdn.org

Eriksson, O. & Finnveden, G. (2009). Plastic waste as a fuel – CO_2-neutral or not? *Energy and Environmental Science*, 2, 907–914. DOI: 10.1039/b908135f

Faaij, A. (Lead Author) (2007). Potential Contribution of Bioenergy to the World's Future Energy Demand, IEA Bioenergy Strategic Position Paper, IEA Bioenergy:ExCo:2007:02. Retrieved from https://www.ieabioenergy.com/publications/potential-contribution-of-bioenergy-to-the-worlds-future-energy-demand

FAO. (2018). *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals*. Retrieved from http://www.fao.org/documents/card/en/c/I9540EN/

FAO. (2015). *World fertilizer trends and outlook to 2018*. ISBN 978-92-5-108692-6. Retrieved from http://www.fao.org/3/a-i4324e.pdf

Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D., & Hales, B. (2008). Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf. *Science*, *320*(5882), 1490–1492. https://doi.org/10.1126/science.1155676

Fernandes, D., Wang, S., Xu, Q., Buss, R., & Chen, D. (2019). Process and Carbon Footprint Analyses of the Allam Cycle Power Plant Integrated with an Air Separation Unit. *Clean Technologies*, *1*(1), 325–340. https://doi.org/10.3390/cleantechnol1010022

Field, C. B., Behrenfeld, M. J., Randerson, J. T., & Falkowski, P. (1998). Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components. *Science*, *281*(5374), 237 LP – 240. https://doi.org/10.1126/science.281.5374.237

Fischer, G. & Schrattenholzer, L. (2001), "Global Bioenergy Potentials Through 2050," Biomass and Bioenergy, Vol. 20, pp. 151-159. https://doi.org/10.1016/S0961-9534(00)00074-X

Flannery, T. (2015). *Atmosphere of Hope: Searching for Solutions to the Climate Crisis*. Boston: Atlantic Monthly Press.

Flannery, T. (2017). *Sunlight and Seaweed, an Argument for How to Feed, Power and Clean Up the World*. Melbourne, Australia: The Text Publishing Company.

Frank, A. B., Berdahl, J. D., Hanson, J. D., Liebig, M. A., & Johnson, H. A. (2004). Biomass and Carbon Partitioning in Switchgrass. *Crop Science*, *44*, 1391–1396. https://doi.org/10.2135/cropsci2004.1391

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., et al. (2019). Global Carbon Budget 2019. *Earth System Science Data*, *11*(4), 1783–1838. https://doi.org/10.5194/essd-11-1783-2019

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6). https://doi.org/10.1088/1748-9326/aabf9f

Future Timeline. (2018). World GDP per capita, 1950-2100. Retrieved from https://www.futuretimeline.net/data-trends/8.htm

Genifuel. (2019). *Clean Conversion of Wet Waste to Fuel*. Retrieved from https://www.genifuel.com/

Gentry, R. R., Froehlich, H. E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S. D., & Halpern, B. S. (2017). Mapping the global potential for marine aquaculture. *Nature Ecology & Evolution*, *1*(9), 1317–1324. https://doi.org/10.1038/s41559-017-0257-9

GESAMP. (2019). High level review of a wide range of proposed marine geoengineering techniques. Boyd, P.W. and Vivian, C.M.G. eds. (IMO/FAO/UNESCO-

IOC/UNIDO/WMO/IAEA/UN/UN Environment/ UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). GESAMP Report No. 98. Retrieved from http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques

Gíslason, S. R., Sigurdardóttir, H., Aradóttir, E. S., & Oelkers, E. H. (2018). A brief history of CarbFix: Challenges and victories of the project's pilot phase. *Energy Procedia*, *146*, 103–114. https://doi.org/10.1016/j.egypro.2018.07.014

Global CCS Institute. (2019). *CO_2RE Database*. Retrieved from https://co2re. co

Gough, C. (2011). *Terrestrial Primary Production: Fuel for Life*. Retrieved from https://www.nature.com/scitable/knowledge/library/terrestrial-primary-production-fuel-for-life-17567411/

Guarino, B. (2019). As seas rise, the U.N. explores a bold plan: Floating cities. *Washington Post*. Retrieved from https://www.washingtonpost.com/science/2019/04/05/seas-rise-un-explores-bold-plan-floating-cities/

Gunnarsson, I., Aradóttir, E. S., Oelkers, E. H., Clark, D. E., Arnarson, M. Þ., Sigfússon, B., et al. (2018). The rapid and cost-effective capture and subsurface mineral storage of carbon and sulfur at the CarbFix2 site. *International Journal of Greenhouse Gas Control*, *79*, 117–126. https://doi.org/10.1016/J.IJGGC.2018.08.014

Hall, C. A. S., Dale, B. E., & Pimentel, D. (2011). Seeking to understand the reasons for different energy return on investment (EROI) estimates for biofuels. *Sustainability*, *3*(12), 2413–2432. https://doi.org/10.3390/su3122413

Hartmann, J. & Moosdorf, N. (2012). The new global lithological map database GLiM: a representation of rock properties at the Earth surface. *Geochem. Geophys. Geosyst.* **13**, Q12004. https://doi.org/10.1029/2012GC004370

Hastings, R. A., Rutterford, L. A., Freer, J. J., Collins, R. A., Simpson, S. D., & Genner, M. J. (2020). Climate Change Drives Poleward Increases and Equatorward Declines in Marine Species. *Current Biology*, *30*(8), 1572-1577.e2. https://doi.org/https://doi.org/10.1016/j.cub.2020.02.043

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., et al. (2019). The technological and economic prospects for CO_2 utilization and removal. *Nature*, *575*(7781), 87–97. https://doi.org/10.1038/s41586-019-1681-6

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

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

Hudiburg, T. W., Luyssaert, S., Thornton, P. E., & Law, B. E. (2013). Interactive Effects of Environmental Change and Management Strategies on Regional Forest Carbon Emissions.

Environmental Science & Technology, *47*(22), 13132–13140. https://doi.org/10.1021/es402903u

Huesemann, M., Mumford, T., Wood, G., Quinn, J., Wang, T., Yang, Z. (2017). *Nautical Offshore Macroalgal Autonomous Device (NOMAD)*. Retrieved from https://arpa-e.energy.gov/?q=slick-sheet-project/nautical-offshore-macroalgal-autonomous-device

Ibisworld. (2019). *Global Coal Mining Industry - Market Research Report*. Retrieved from https://www.ibisworld.com/global/market-research-reports/global-coal-mining-industry

IEA. (2018). *World Energy Outlook 2018.* Retrieved from https://www.iea.org/reports/world-energy-outlook-2018

Investopedia. (2020). *What percentage of the global economy consists of the oil and gas drilling sector?* Retrieved from https://www.investopedia.com/ask/answers/030915/what-percentage-global-economy-comprised-oil-gas-drilling-sector.asp

Ioelovich, M. (2015). Recent Findings and the Energetic Potential of Plant Biomass as a Renewable Source of Biofuels – A Review. *BioResources, 10*(1), 1879-1914. Retrieved from https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes_10_1_Ioelovich_Review_Plant_Biomass_Renewable_Source_Biofuels

IPCC. (2014). *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.)]*. Retrieved from https://www.ipcc.ch/report/ar5/syr/

IPCC. (2018). *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, sustainable development, and efforts to eradicate poverty*. Retrieved from https://www.ipcc.ch/sr15/download/

Irlam, L. (2017). Global costs of carbon capture and storage. Report for the Global CCS Institute. Retrieved from https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf

Jacobson, M. Z. (2019). The Health and Climate Impacts of Carbon Capture and Direct Air Capture, *Energy & Environmental Science.* https://doi.org/10.1039/C9EE02709B

Jacobson, M. Z. (2020). 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. In *100% Clean, Renewable Energy and Storage for Everything,* Textbook in press, *Cambridge University Press*. Retrieved from https://web.stanford.edu/group/efmh/jacobson/WWSBook/WWSBook.html

James, R., Kearins, D., Turner, M., Woods, M., Kuehn, N., Zoelle, A. (2019). Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. Report prepared by MESA for the U.S. DOE NETL. DOI: 10.2172/1569246

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

Jiao, J. P., Wang, F., Duan, P. G., Xu, Y. P., Yan, W. H. (2017). Catalytic hydrothermal gasification of microalgae for producing hydrogen and methane-rich gas Energy Sources, Part A: Recovery, Utilization, and Environmental Effects Volume 39, 2017 – Issue 9. https://doi.org/10.1080/15567036.2016.1270375

Johansson, L., Zahirovic, S. & Müller, R. D. (2018). The interplay between the eruption and weathering of Large Igneous Provinces and the deep-time carbon cycle. *Geophys. Res. Lett.* **45**, 5380–5389. https://doi.org/10.1029/2017GL076691

Jolly, R. (2004). Dutch Industrial waste continues to decrease. Retrieved from https://www.cbs.nl/en-gb/news/2004/42/industrial-waste-continues-to-decrease

Kaza, S., Yao, L., Bhada-Tata, P., and Van Woerden, F. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. The World Bank. https://doi.org/doi:10.1596/978-1-4648-1329-0

Kelemen, P. (1998). Melt extraction from the mantle beneath mid-ocean ridges. *Oceanus*, *41*, 23–28. Retrieved from https://www.whoi.edu/oceanus/feature/melt-extraction-from-the-mantle-beneath-mid-ocean-ridges/

Kelemen, P., Benson, S. M., Pilorgé, H., Psarras, P., & Wilcox, J. (2019). An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. *Frontiers in Climate*, *1*, 9. https://doi.org/10.3389/fclim.2019.00009

Keller, D. P., Lenton, A., Littleton, E. W., Oschlies, A., Scott, V., & Vaughan, N. E. (2018). The Effects of Carbon Dioxide Removal on the Carbon Cycle. *Current Climate Change Reports*, *4*(3), 250–265. https://doi.org/10.1007/s40641-018-0104-3

Kim, J. K., Yarish, C., Hwang, E. K., Park, M., & Kim, Y. (2017). Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. *ALGAE*, *32*(1), 1–13. https://doi.org/10.4490/algae.2017.32.3.3

Kim, J. K., Wu, H., Shin, S. K., Park, M. S., Kim, Y. D., Do, Y. H., Kim, N. G., Han, T. (2017). An effective integrated multi-trophic aquaculture system for Korean waters. In *The 2nd International Integrated Multi-Trophic Aquaculture Symposium Book of Abstracts* (pp. 17–32).

Knowler, D., Chopin, T., Martínez-Espiñeira, R., Neori, A., Nobre, A., Noce, A., & Reid, G. (2020). The economics of Integrated Multi-Trophic Aquaculture: where are we now and where do we need to go? *Reviews in Aquaculture*. https://doi.org/10.1111/raq.12399

Knutti, R., & Rogelj, J. (2015). The legacy of our CO_2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change*, *133*(3), 361–373. https://doi.org/10.1007/s10584-015-1340-3

Köhn, E. E., Thomsen, S., Arévalo-Martinez, D. L., & Kanzow, T. (2017). Submesoscale CO_2 variability across an upwelling front off Peru. *Ocean Science, 13*(6), 1017–1033. https://doi.org/10.5194/os-13-1017-2017

Korai, M. S., Mahar, R. B., Uqaili, M. A. (2014). Assessment of Power Generation Potential from Municipal Solid Wastes: A Case Study of Hyderabad City, Sindh, Pakistan. *Pakistan Journal of Analytical and Environmental Chemistry* 15 (1) 18 – 27. https://doaj.org/article/cf1958f16a2143f2829a43b64a4540de

Kostecki, J., Greinert, A., Drab, M., Wasylewicz, R., Szafraniec, M., Stodulski, G., Wypych, M. (2014). The total content of nitrogen in leaves and wood of trees growing in the area affected by the Glogow Copper Smelter. Journal of Elementology 1:137-148. https://doi.org/10.5601/jelem.2014.19.4.401

Krause-Jensen, D., Lavery, P., Serrano, O., Marba, N., Masque, P., & Duarte, C. M. (2018). Sequestration of macroalgal carbon: The elephant in the Blue Carbon room. *Biology Letters*, *14*(6). https://doi.org/10.1098/rsbl.2018.0236

Krevor, S. C., Graves, C. R., Van Gosen, B. S., & McCafferty, A. E. (2009). Mapping the mineral resource base for mineral carbon-dioxide sequestration in the conterminous United States. In *Data Series* (Version 1). https://doi.org/10.3133/ds414

Krueger-Hadfield, S. A. & Hoban, S. M. (2015). The importance of effective sampling for exploring the population dynamics of haploid-diploid seaweeds. *Journal of Phycology* 52:1–9. https://doi.org/10.1111/jpy.12366

Kumar, P., Kumar, S., & Joshi, L. (2015). *Socioeconomic and Environmental Implications of Agricultural Residue Burning: A Case Study of Punjab, India*. Springer: New Delhi Heidelberg New York Dordrecht London.

Kunzig, R. (2020). The End of Trash. *National Geographic* March 2020. Retrieved from https://www.nationalgeographic.com/magazine/2020/03/

Lapointe, B. E. (1985), Strategies for pulsed nutrient supply to Gracilaria cultures in the Florida Keys: Interactions between concentration and frequency of nutrient pulses, *Journal of Experimental Marine Biology and Ecology, 3*, 211-222. https://doi.org/10.1016/0022-0981(85)90240-0

Lapointe, B. E., & Ryther, J. H. (1978). Some aspects of the growth and yield of *Gracilaria tikvahiae* in culture, *Aquaculture*, *15*(3), 185-193. https://doi.org/10.1016/0044-8486(78)90030-3

Lee, M.-S., Wycislo, A., Guo, J., Lee, D. K., Voight, T. (2017). Nitrogen Fertilization Effects on Biomass Production and Yield Components of *Miscanthus* × *giganteus*. *Frontiers in Plant Science* 18, 544. Retrieved from https://doi.org/10.3389/fpls.2017.00544

Lombardelli, G., Pirone, R., Ruggeri, B. (2017). LCA analysis of different MSW treatment approaches in the light of energy and sustainability perspectives, *Chemical Engineering Transactions, 57*, 469-474. https://doi.org/10.3303/CET1757079

Lucas, K., Capron, M. E., Blaylock, R., Chambers, M. D., Stewart, J. R., DiMarco, S. F., et al. (2019a). Ocean Forests: Feeding the World with Floating Artificial Reefs. *World Aquaculture Society*. Retrieved from https://www.was.org/meetings/ShowAbstract.aspx?Id=136247

Lucas, K., Capron, M. E., Blaylock, R., Stewart, J. R., Howden, S., Chambers M. D., et al. (2019b). AdjustaDepth Phase 1 Final Report to ARPA-E, DE-AR0000916. https://doi.org/10.13140/RG.2.2.29150.46405

Markets Insider. (2020). Oil Price of WTI Crude (West Texas Intermediate) History from 2006 to 2020. Retrieved from https://markets.businessinsider.com/commodities/oil-price?type=wti

Martin, A. R., Erickson, D. L., Kress, W. J., & Thomas, S. C. (2014). Wood nitrogen concentrations in tropical trees: phylogenetic patterns and ecological correlates. *New Phytologist* 204: 484–495. https://doi.org/10.1111/nph.12943

Matter, J. M., Stute, M., Snæbjörnsdottir, S. Ó., Oelkers, E. H., Gislason, S. R., Aradottir, E. S., et al. (2016). Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science* 352, 1312–1314. https://doi.org/10.1126/science.aad8132

McGlashan, N., Shah, N., Caldecott, B., & Workman, M. (2012). High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection*, *90*(6), 501–510. https://doi.org/10.1016/J.PSEP.2012.10.004

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. (2017). Wallula Basalt Pilot Demonstration Project: Post-injection Results and Conclusions. *Energy Procedia*, *114*, 5783–5790. https://doi.org/10.1016/J.EGYPRO.2017.03.1716

McLaren, D. (2012). A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection*, *90*(6), 489–500. https://doi.org/10.1016/J.PSEP.2012.10.005

McMahon, J. (2019). Multiple Zero-Carbon Natural-Gas Plants Planned At Lower Cost Than Conventional Plants. *Forbes Magazine*. Retrieved from https://www.forbes.com/sites/jeffmcmahon/2019/07/23/net-power-developing-multiple-zero-carbon-natural-gas-plants-exec-says/#5762b0a68ac2

Melzer, S. (2012). *Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery*. Report for the National Enhanced Oil Recovery Initiative, Center for Climate and Energy Solutions. Retrieved from https://carboncapturecoalition.org/wp-content/uploads/2018/01/Melzer_CO2EOR_CCUS_Feb2012.pdf

Metcalfe, G. E. (2020). What Should Carbon Cost?" *Scientific American* 322, 6, 62-69 (June 2020). doi:10.1038/scientificamerican0620-62

Milledge, J.J. & Harvey, P.J. (2016), Potential process 'hurdles' in the use of macroalgae as feedstock for biofuel production in the British Isles. Journal of Chemical Technology and Biotechnology 91: 2221-2234. https://doi.org/10.1002/jctb.5003

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 63001. https://doi.org/10.1088/1748-9326/aabf9b

Monterey Bay Aquarium Research Institute (MBARI). (2019). Ocean Data FloatViz 6.0. Retrieved from https://www.mbari.org/science/upper-ocean-systems/chemical-sensor-group/floatviz

Moran, K, Crawford, C, Webb, R, Holmes, G, Paulson, M, Rankin, M, et al. (2020). *Solid Carbon: A Climate Mitigation Partnership Advancing Stable Negative Emissions*. Retrieved from https://www.solidcarbon.ca/

Morley, J. W., Selden, R. L., Latour, R. J., Frölicher, T. L., Seagraves, R. J., & Pinsky, M. L. (2018). Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLOS ONE*, *13*(5), e0196127. https://doi.org/10.1371/journal.pone.0196127

Müller, R. D., Seton, M., Zahirovic, S., Williams, S. E., Matthews, K. J., Wright, N. M., et al. (2016). Ocean basin evolution and global-scale plate reorganization events since Pangea breakup. *Annual Reviews of Earth and Planetary Science* **44**, 107–138.

N'Yeurt, A. de R., Chynoweth, D. P., Capron, M. E., Stewart, J. R., & Hasan, M. A. (2012). Negative carbon via Ocean Afforestation. *Process Safety and Environmental Protection, 90*(6), 467–474. https://doi.org/10.1016/J.PSEP.2012.10.008

Nagabhushan, D., & Thompson, J. (2019) Carbon Capture & Storage in the United States Power Sector. Report for the Clean Air Task Force. Retrieved from https://www.catf.us/resource/45q-ccs-analysis

National Academies of Sciences, Engineering, & Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. The National Academies Press. https://doi.org/10.17226/25259

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., Lamb, W. F., Minx, J. C., Rogers, S., & Smith, P. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters, 13*(6), 63003. https://doi.org/10.1088/1748-9326/aabff4

Oelkers, E. H., Gislason, S. R., & Matter, J. (2008). Mineral Carbonation of CO_2. *Elements*, *4*(5), 333–337. https://doi.org/10.2113/gselements.4.5.333

Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W., et al. (2020). Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences*, *117*(5), 2354 LP – 2365. https://doi.org/10.1073/pnas.1900577117

Pachauri, R. K. & Meyer, L. (2014). *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* (IPCC, Geneva, Switzerland). Retrieved from https://www.ipcc.ch/report/ar5/syr/

Pan, W. L., Port, L. E., Xiao, Y., Bary, A. I., & Cogger, C. G. (2017). Soil Carbon and Nitrogen Fraction Accumulation with Long-Term Biosolids Applications. *Soil Science Society of America Journal*, *81*, 1381–1388. https://doi.org/10.2136/sssaj2017.03.0075

Pandur, Z., Šušnjar, M., Zorić, M., Nevečerel, H., and Horvat, D. (2015). Energy Return on Investment (EROI) of Different Wood Products. In M. Zlatic (Ed.), *Precious Forests - Precious Earth*. IntertechOpen. https://doi.org/10.5772/61144

Paraskova, T. (2019). Global LNG Markets Are Circling The Drain. Retrieved from https://oilprice.com/Energy/Natural-Gas/Global-LNG-Markets-Are-Circling-The-Drain.html

Park, M., Shin, S. K., Do, Y. H., Yarish, C., & Kim, J. K. (2018). Application of open water integrated multi-trophic aquaculture to intensive monoculture: A review of the current status and challenges in Korea. *Aquaculture*, *497*, 174–183. https://doi.org/10.1016/J.AQUACULTURE.2018.07.051

Pauly, D. (2019). Micronutrient richness of global fish catches. *Nature*, *574*(7776), 41–42. https://doi.org/d41586-019-02810-2

Penniman, C. A. (1983). Ecology of *Gracilaria tikvahiae* McLachlan (Gigartinales, Rhodophyta) in the Great Bay Estuary, New Hampshire. University of New Hampshire Doctoral Dissertation. Retrieved from https://scholars.unh.edu/dissertation/1405

Pichach, C. (2019). CleanCarbon Energy: Carbon Balanced Renewable Energy, plus private communication. Retrieved from https://www.f6s.com/cleancarbonenergy

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360* (6392), 987– 992. https://doi.org/10.1126/science.aaq0216

Pope Francis. (2015). *Encyclical Letter Laudato Si' of the Holy Father Francis on Care for Our Common Home*. Retrieved from http://www.vatican.va/content/francesco/en/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si.html

PRNewswire. (2018). NET Power Achieves Major Milestone for Carbon Capture with Demonstration Plant First Fire. Retrieved from https://www.prnewswire.com/news-releases/net-power-achieves-major-milestone-for-carbon-capture-with-demonstration-plant-first-fire-300656175.html

Quirion, P., Rozenberg, J., Sassi, O., Vogt-Schilb, A. (2011). How CO_2 Capture and Storage Can Mitigate Carbon Leakage. Fondazione Eni Enrico Mattei Working Paper 2011.015. Retrieved from https://www.feem.it/en/publications/feem-working-papers-note-di-lavoro-series/how-co2-capture-and-storage-can-mitigate-carbon-leakage/

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

Ravindra, K., Singh, T., & Mor, S. (2019). Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions. *Journal of Cleaner Production*, *208*, 261–273. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.031

Reinhart, D. (2004). Estimation of Energy Content of Municipal Solid Waste. Retrieved from http://msw.cecs.ucf.edu/wastecharacterization.html

REN21. (2019). *Renewables 2019 Global Status Report*. Retrieved from https://www.ren21.net/gsr-2019/

ReNew ELP. (2019). *Unlocking the Value in Plastic Waste*. Retrieved from https://renewelp.co.uk/

Ries, J. B. (2010). Review: geological and experimental evidence for secular variation in seawater Mg/Ca (calcite-aragonite seas) and its effects on marine biological calcification. *Biogeosciences*, *7*(9), 2795–2849. https://doi.org/10.5194/bg-7-2795-2010

Rivers, P. (2017). The density of corrugated cardboard. Retrieved from https://www.hunker.com/13419984/the-density-of-corrugated-cardboard

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., & Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science*, *355*(6331), 1269–1271. https://doi.org/10.1126/science.aah3443

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. (2018). Mitigation pathways compatible with 1.5ºC in the context of sustainable development. In Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., et al. (eds.), *Global Warming of 1.5ºC: An IPCC Special Report on the impacts of global warming of 1.5ºC 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, sustainable* *development, and efforts to eradicate poverty.* (pp. 1–82). Retrieved from https://report.ipcc.ch/sr15/pdf/sr15_chapter2.pdf

Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. *Critical Reviews of Environmental Science and Technology*, 2;45(17):1827-1879. https://doi.org/10.1080/10643389.2014.1000761

Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*, *40*, 378–400. https://doi.org/10.1016/J.IJGGC.2015.05.018

Saini, J. K., Saini, R., & Tewari, L. (2015). Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production: concepts and recent developments. *3 Biotech*, *5*(4), 337–353. https://doi.org/10.1007/s13205-014-0246-5

Schulz, K. G., Hartley, S., & Eyre, B. (2019). Upwelling Amplifies Ocean Acidification on the East Australian Shelf: Implications for Marine Ecosystems. In *Frontiers in Marine Science*, *6*, p. 636). https://doi.org/10.3389/fmars.2019.00636

Sepulveda, N. A., Jenkins, J. D., de Sisternes, F. J., Lester, R. K. (2018). Role of firm low-carbon electricity resources in deep decarbonization of power generation. *Joule* 2, 2403–2420. https://doi.org/10.1016/j.joule.2018.08.006

Shahbandeh, M. (2019). Global Meat Industry - Statistics & Facts. Retrieved from https://www.statista.com/topics/4880/global-meat-industry/

Sherman, M. T., Lucas, K., & Stewart, J. R. (2018). SeaweedPaddock : Initial Modeling and Design for a Sargassum Ranch. *OCEANS 2018 MTS/IEEE Charleston*, 1–6. https://doi.org/10.1109/OCEANS.2018.8604848

Shi, H., Zheng, W., Zhang, X., Zhu, M., & Ding, D. (2013). Ecological–economic assessment of monoculture and integrated multi-trophic aquaculture in Sanggou Bay of China. *Aquaculture*, *410–411*, 172–178. https://doi.org/10.1016/J.AQUACULTURE.2013.06.033

Shrestha, P. (2020). UK first: Hydrogen injected into gas grid as landmark trial gets underway. Retrieved from https://www.energylivenews.com/2020/01/06/uk-first-hydrogen-injected-into-gas-grid-as-landmark-trial-gets-underway/

Sims, N. A., Vollbrecht, L., Bullock, M., & Martin, K. (2019). *Ocean Era Blue Fields Offshore Macroalgae Demonstration Project*. Retrieved from http://ocean-era.com/projects

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M., & Turkenburg, W. C. (2007). A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, *33*(1), 56–106. https://doi.org/10.1016/j.pecs.2006.08.001

Smil, V. (1999). Crop Residues: Agriculture's Largest Harvest: Crop residues incorporate more than half of the world's agricultural phytomass. *BioScience*, *49*(4), 299–308. https://doi.org/10.2307/1313613

Snæbjörnsdóttir, S. Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S. R., & Oelkers, E. H. (2020). Carbon dioxide storage through mineral carbonation. *Nature Reviews Earth & Environment*, *1*(2), 90–102. https://doi.org/10.1038/s43017-019-0011-8

Sorondo, M. S., & Ramanathan, V. (2016). Pursuit of integral ecology. *Science*, *352*(6287), 747. https://doi.org/10.1126/science.aag0826

StatisticsTimes. (2019). *Gross World Product*. Retrieved from http://statisticstimes.com/economy/gross-world-product.php

Steeper Energy. (2019). *Hydrofaction technology*. Retrieved from https://steeperenergy.com/

Strauss, W. & Walker, S. (2018). Global pellet market outlook in 2018, Canadian Biomass Magazine, 2 February 2018. Retrieved from https://www.canadianbiomassmagazine.ca/pellets/increasing-demand-6705

Sumaila, U. R., Tai, T. C., Lam, V. W. Y., Cheung, W. W. L., Bailey, M., Cisneros-Montemayor, A. M., et al. (2019). Benefits of the Paris Agreement to ocean life, economies, and people. *Science Advances*, *5*(2), eaau3855. https://doi.org/10.1126/sciadv.aau3855

Sverdrup, H. U., Johnson, M. W., Fleming, R. H. (1942). The Oceans, Their Physics, Chemistry, and General Biology. New York: Prentice-Hall. Retrieved from http://ark.cdlib.org/ark:/13030/kt167nb66r/

Tàbara, D., Frantzeskaki, N., Hölscher, K., Pedde, S., Kok, K., Lamperti, F., Christensen, J., Jäger, J., & Berry, P. (2018). Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, *31*, 120–129. https://doi.org/10.1016/j.cosust.2018.01.012

Tang, Z., Xu, W., Zhou, G., Shu, J., Han, W., Bai, Y., et al. (2014). Patterns of plant carbon, nitrogen, and phosphorus concentration in relation to productivity in China's terrestrial ecosystems. PNAS April 17, 2018 115 (16) 4033-4038. https://doi.org/10.1073/pnas.1700295114

Tanger P, Field J L, Jahn C E, DeFoort M W, Leach J E. (2013) Biomass for thermochemical conversion: targets and challenges. Frontiers in Plant Science 4, Article 218. doi:10.3389/fpls.2013.00218

TechLink. (2019). The 9 Technology Readiness Levels of the DoD. Retrieved from https://techlinkcenter.org/technology-readiness-level-dod

Timko, M. T., Ghoniem, A. F., Green, W. H. (2015). Upgrading and desulfurization of heavy oils by supercritical water. *The Journal of Supercritical Fluids*, *96*, 114–123. https://doi.org/10.1016/j.supflu.2014.09.015

The Royal Society. 2020. Ammonia: zero-carbon fertiliser, fuel and energy store**.** February 2020 DES5711 ISBN: 978-1-78252-448-9. Retrieved from https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/

Turner, P. A., Mach, K. J., Lobell, D. B., Benson, S. M., Baik, E., Sanchez, D. L., et al. (2018). The global overlap of bioenergy and carbon sequestration potential. *Climatic Change*, *148*(1), 1–10. https://doi.org/10.1007/s10584-018-2189-z

Tvinnereim, E., & Mehling, M. (2018). Carbon pricing and deep decarbonisation. *Energy Policy*, *121*, 185–189. https://doi.org/10.1016/J.ENPOL.2018.06.020

U.S. Department of Energy Advanced Research Projects Agency-Energy. (2017a). MacroAlgae Research Inspiring Novel Energy Resources (MARINER) Project Listing. Retrieved from https://arpa-e.energy.gov/?q=arpa-e-programs/mariner

U.S. Department of Energy Advanced Research Projects Agency-Energy. (2017b). *MacroAlgae Research Inspiring Novel Energy Resources (MARINER) Program Overview*. Retrieved from https://arpa-e.energy.gov/sites/default/files/documents/files/MARINER_ProgramOverview_FINAL.pdf

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

U.S. Department of Energy. (2019). *U.S. Department of Energy Invests $7 Million for Projects to Advance Coal Power Generation under Coal FIRST Initiative*. https://www.energy.gov/fe/articles/us-department-energy-invests-7-million-projects-advance-coal-power-generation-under-coal

U.S. Department of Energy. (2020). Reports for the Coal FIRST concepts of interest. National Energy Technology Laboratory. Retrieved from https://netl.doe.gov/coal/tpg/coalfirst/concept-reports

U.S. Energy Information Administration (EIA). (2005). Average Heat Content of Selected Biomass Fuels. Renewable Energy Annual 2004. Retrieved from https://www.eia.gov/renewable/annual/

U.S. Energy Information Administration. (2019). Coal explained: Coal prices and outlook. https://www.eia.gov/energyexplained/coal/prices-and-outlook.php

U.S. Energy Information Administration. (2020). Petroleum and other liquids. https://www.eia.gov/international/data/world/petroleum-and-other-liquids/annual-petroleum-and-other-liquids-production

UNEP. (2019a). Emissions Gap Report 2019. Retrieved from https://www.unenvironment.org/resources/emissions-gap-report-2019

UNEP. (2019b). Waste-to-Energy: Considerations for Informed Decision-Making. Retrieved from http://wedocs.unep.org/bitstream/handle/20.500.11822/28413/WTEfull.pdf]

UNFCCC. 2015. What is the Paris Agreement? Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement (accessed April 14, 2020).

United Nations. (2016a). Agenda for Humanity. Retrieved from https://www.agendaforhumanity.org

United Nations. (2016b). Sustainable Development Goals. Retrieved from https://sustainabledevelopment.un.org

USGCRP. (2018). Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. (B. C. S. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock (ed.)). https://doi.org/10.7930/NCA4.2018.

Vance E. **(**2017). Baja California's recipe for saving fishing communities. *National Geographic* September 2017. Retrieved from https://www.nationalgeographic.com/magazine/2017/09/baja-mexico-marine-conservation-tourism-fish-sharks-whales/

Wallace, M., Kuuskraa, V., & DiPietro, P. (2013). CO2 Utilization from "Next Generation" CO2 Enhanced Oil Recovery Technology. Energy Procedia 37:6854-6866. https://doi.org/10.1016/j.egypro.2013.06.618

Watson, J., Wang, T., Si, B., Chen, W. T., Aierzhati, A., & Zhang, Y. (2020). Valorization of hydrothermal liquefaction aqueous phase: pathways towards commercial viability. *Progress in Energy and Combustion Science*, *77*. https://doi.org/10.1016/j.pecs.2019.100819

Wennerholm, M. (2020). AquaDam Special Project Applications. Retrieved from https://www.aquadam.net

Wesseler, S. (2019). *In King County, Washington, human waste is a climate solution*. Retrieved from https://www.yaleclimateconnections.org/2019/11/in-king-county-washington-human-waste-is-a-climate-solution/

West, J. J., Smith, S. J., Silva, R. A., Naik, V., Zhang, Y., Adelman, Z., et al. (2013). Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, *3*(10), 885–889. https://doi.org/10.1038/nclimate2009

Whittaker, JM, Alfonso JC, Masterton S, Müller D, Wessel P, Williams S, et al. (2015). Long-term interaction between mid-ocean ridges and mantle plumes. *Nat. Geosci.* **8**, 479–483. https://doi.org/10.1038/NGEO2437

Wilkinson K. 2020. The Drawdown Review 2020: Climate Solutions for a New Decade. Retrieved from https://drawdown.org/drawdown-framework/drawdown-review-2020 (accessed April 10, 2020).

Wilkinson, K. (2020). *The Drawdown Review 2020: Climate Solutions for a New Decade*. https://drawdown.org/drawdown-framework/drawdown-review-2020

Wood, D., Capuzzo, E., Kirby, D., Mooney-McAuley, K., & Kerrison, P. (2017). UK macroalgae aquaculture: What are the key environmental and licensing considerations? *Marine Policy*, *83*(August 2016), 29–39. https://doi.org/10.1016/j. marpol.2017.05.021

Yang, Y., Hagerty, M., Palmarozzo, A., Celebi, M., Chupka, M., & Sheffield, H. (2017). The Future of Cap-and-Trade Program in California: Will Low GHG Prices Last Forever? https://brattlefiles.blob.core.windows.net/files/11768_the_future_of_cap-and-trade_program_in_california_final_12.4.17.pdf

Zaimes, G. G., & Khanna, V. (2013). Microalgal biomass production pathways: evaluation of life cycle environmental impacts. *Biotechnology for Biofuels*, *6*(1), 88. https://doi.org/10.1186/1754-6834-6-88