1   **Restoring pre-industrial CO$_2$ levels while achieving Sustainable Development Goals**

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

5   [1]OceanForesters, Oxnard, CA, USA. [2]Pacific Centre for Environment and Sustainable
6   Development, The University of the South Pacific, Suva, Fiji. [3]Department of Food and
7   Agriculture, University of New Hampshire, Durham, NH, USA. [4]Department of Marine Science,
8   Incheon National University, Incheon, South Korea. [5]Department of Ecology and Evolutionary
9   Biology, University of Connecticut, Stamford, CT, USA. [6]Intake Works, Sacramento, CA, USA.
10   [7]Thad Cochran Marine Aquaculture Center, University of Southern Mississippi, Ocean Springs,
11   MS, USA. [8]Department of Geology, Baylor University, Waco, TX, USA. [9]Stingray Sensing,
12   Goleta, CA, USA.

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

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

15   **Key Points:**

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

18   • Sustainable development for all while reducing atmospheric CO$_2$ below 300 ppm by the
19   2100s and keeping global temperature rise below 1.5ºC

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

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23 **Abstract**

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

44 **Plain Language Summary**

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

59 **1 Introduction**

60   This paper presents nations and communities more choices for accomplishing United
61 Nations Sustainable Development Goals (SDGs) (United Nations, 2016b) while reducing CO_2
62 levels in ways consistent with integral ecology (Pope Francis, 2015; Sorondo & Ramanathan,
63 2016) and the UN Agenda for Humanity (United Nations, 2016a). The 2015 Paris Agreement
64 recommends that "rapid reductions" of greenhouse gases be achieved "on the basis of equity, and
65 in the context of sustainable development and efforts to eradicate poverty" (IPCC, 2014).

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

67 • "Climate-related risks to health, livelihoods, food security, water supply, human security,
68 and economic growth are projected to increase with global warming to 1.5°C and
69 increase further with 2°C." This implies that paths for addressing climate change will be
70 more easily started and sustained if they improve health, livelihoods, food security, water
71 supply, human security, and economic growth.

72 • "All pathways that limit global warming to 1.5°C with limited or no overshoot project
73 the use of carbon dioxide removal (CDR) on the order of $100-1000$ GtCO$_2$ over the 21st
74 century." This means that it would be wise to achieve net zero emissions with significant
75 CDR that can be sustained over decades to decrease atmospheric CO$_2$ concentrations.
76 Simply eliminating fossil fuel use will not keep warming below 1.5°C.

77 • "CDR deployment of several hundreds of GtCO$_2$ [billion tonnes] is subject to multiple
78 feasibility and sustainability constraints (*high confidence*)." This implies that CDR totals
79 of several thousand billion tonnes of CO$_2$ require multiple technologies to ensure
80 feasibility and nutrient recycling to ensure sustainability.

81 The UN Environment Programme Emissions Gap Report (UNEP, 2019) "warns that
82 unless global greenhouse gas emissions fall by 7.6 per cent each year between 2020 and 2030,
83 the world will miss the opportunity to get on track towards the 1.5°C temperature goal of the
84 Paris Agreement."

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

90 A big challenge is identifying feasible paths with rapid emission reductions, suffcent
91 CO$_2$ drawdown, and sustainable at scale for centuries, while also supporting UN Sustainable
92 Development Goals. None of those review publications included three emerging technologies:
93 total ecosystem aquaculture (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019,
94 2020a, 2020b, 2020c; Chambers, 2013; Lucas et al., 2019a, 2019b; Knowler et al., 2020); Allam
95 Cycle electricity production (8 Rivers Capital, 2020; Allam et al. 2017; Fernandes et al. 2019;
96 McMahon, 2019); and hydrothermal liquefaction (Jiang et al. 2019; Jiao et al. 2017; Pichach
97 2019).

98 Zero carbon electricity such as wind and solar stabilize, but do not reduce CO$_2$ levels.
99 This paper focuses on reducing CO$_2$ to pre-industrial levels with emerging carbon negative
100 technologies converting biomass to energy.

101 **2 Methods: Bracketing the choice between bioelectricity and biofuel**

102 The approach of this paper is to solve the climate crisis coincident with achieving SDGs.
103 That is, to solve environmental problems with respect for indigenous cultures (Rockström et al.,
104 2017), all persons, and wildlife while acting to alleviate poverty and prevent armed conflicts
105 (Pope Francis, 2015).

106 This paper presents two paths both of which embody the above goals. The two paths,
107 shown in Fig. 1 as P_{fuel} and $P_{electric}$, represent extremes of either mostly biofuel or mostly

108   electricity. Two paths are provided so that each community and nation can develop their
109   individual blend of technology and infrastructure to best fit their unique culture, people, natural
110   resources, and needs.

111   Both paths have reasonable costs, support sustainable development, get to net zero near
112   2050, and then sequester legacy CO_2 faster than IPCC pathway P4. This added carbon-removal
113   capability can overcome potential additional CO_2 releases from land and ocean as the
114   atmospheric concentrations drop (Keller et al. 2018).
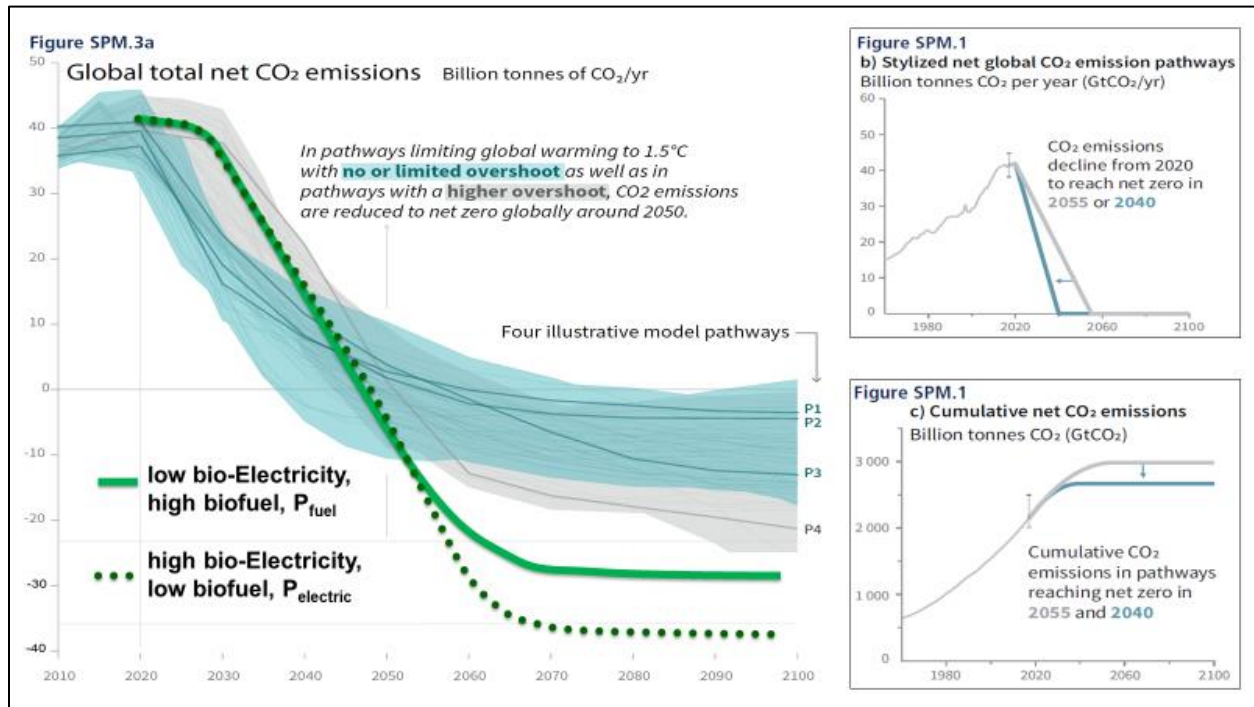
115
116   Fig. 1. The two paths, P_{fuel} and $P_{electric}$, superimposed on the four pathways of the IPCC
117   1.5ºC target (IPCC, 2018) reflect annual emissions projections (Figs. SPM.3a and SPM.1b) plus
118   IPCC cumulative projections (SPM.1c). (Note: Both trajectories between 2020 and 2070 are
119   based on calculations (SS tabs 1, 2, 10) that connect 2020 emissions with projected post-2070 (or
120   so) emissions using the technologies presented in this paper.

121   The Supplemental Materials spreadsheet (SS) provides a basis for communities to enter
122   their own values and calculate scales and costs of food production, energy production, and CO_2
123   removal from the atmosphere for their path. One pre-calculated path favors dry biomass for
124   electricity production, the other wet biomass for biofuel production. The proposed technologies
125   are sufficiently developed to allow accurate estimates of the quantities of products and
126   byproducts, but less accurate estimates of the costs. One proposed technology (Allam Cycle) will
127   gasify coal or dry biomass to produce electricity while the other, hydrothermal liquefaction
128   (HTL), will convert wet biomass into biofuel. Total ecosystem aquaculture (TEA) initially
129   produces high-value seafood and then scales to produce wet biomass (macroalgae and seagrass).
130   Calculations are based on Allam Cycle electricity production (8 Rivers Capital, 2020) (SS tabs 9,
131   12), HTL (Pichach, 2019) (SS tabs 7, 8, 11, 12), and TEA (Capron, 2019; Capron & Piper, 2019;
132   Capron et al., 2018, 2019, 2020a, 2020b, 2020c; Chambers, 2013; Lucas et al., 2019a, 2019b;
133   Knowler et al., 2020) (SS tabs 4, 5, 6, 18).
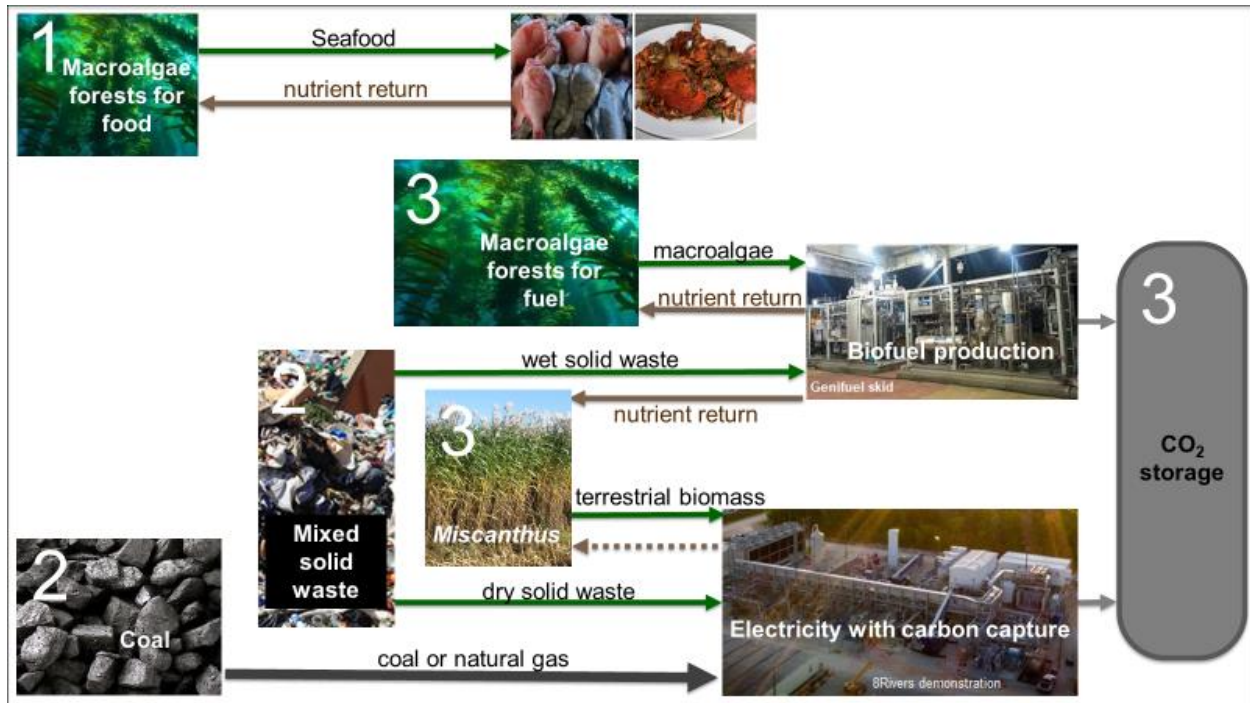
134
135   Fig. 2 – Initial technologies to achieve Sustainable Development Goals while restoring
136   300 ppm CO_2. The gray arrows represent liquid CO_2. Nutrient return from electricity production
137   is dashed because high temperature processes such as gasification, incineration, and pyrolysis,
138   can return some nutrients from the ash, but convert most of the organic nitrogen into nitrogen gas
139   and nitrogen oxides during combustion.

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

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

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

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

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

5

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

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

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

179   Table 1: Two paths of energy demand and supply a few years after net CO_2 emissions
180   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

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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**

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

191   Table 2: Balancing fossil fuel use, biomass-for-energy production, and bio-CO_2
192   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**

193   Tables 1 and 2 quantify the steps in Fig. 3 to demonstrate how net-zero emissions are
194 technically feasible by 2050. Every component of Fig. 3 can scale quickly using existing demand
195 and supply chains.
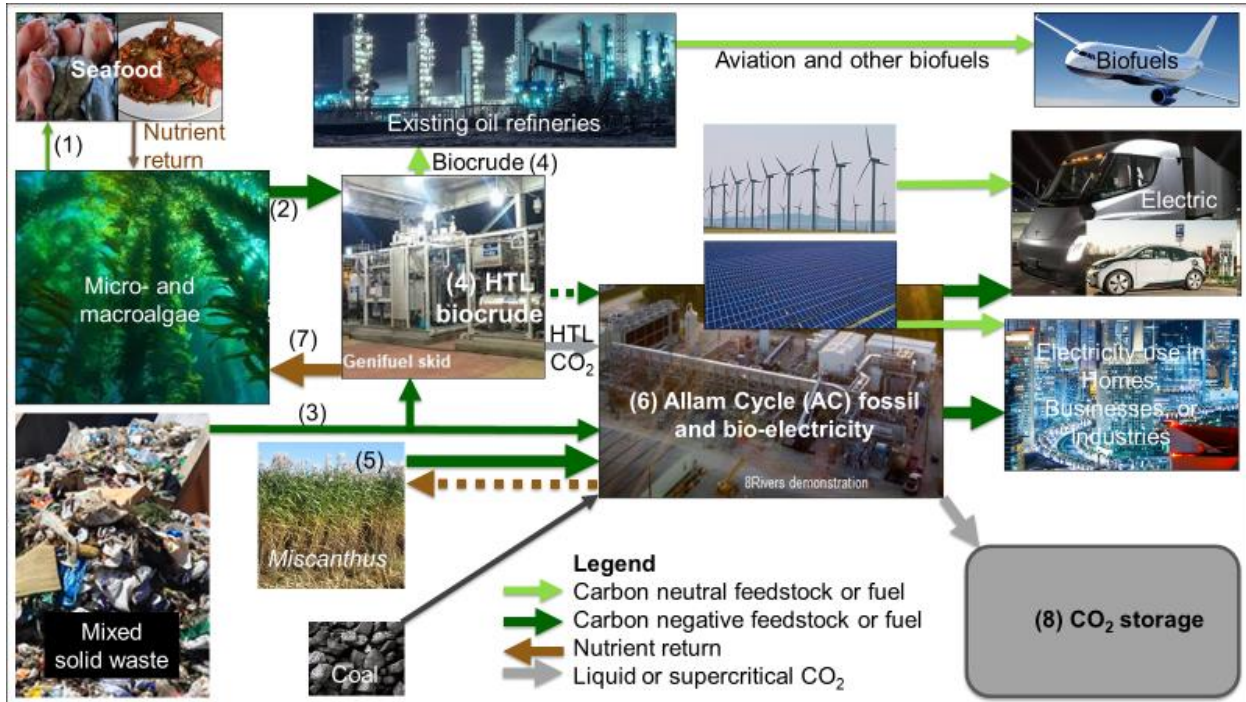
196
197   Fig. 3. Process overview for mature (2070 and beyond) production of food, energy, and
198 CO_2 sequestration. It is a simplified representation of the future global energy system with future
199 oceanic integrated food and energy systems. It does not show terrestrial food systems. Each
200 country and community will determine how much of each component is appropriate depending
201 on local economics. (Note: *Miscanthus* represents all terrestrial biomass including wood waste,
202 agricultural residues, etc. that might be gasified directly at the Allam Cycle electricity facility or
203 fed to HTL. Solid waste represents organic sludges, food waste, paper, and plastics that are not
204 recycled some other way. Micro- and macroalgae represent all watery biomass including
205 seagrass and freshwater plants. The darker green and thicker arrows are paths to more bio-CO_2
206 storage (CO_2 removed from the environment, i.e. negative emissions). The lighter green and
207 thinner arrows lead to carbon-neutral emissions, including bio-CO_2 emissions from combustion
208 by airplanes, or wind and solar.

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

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

219   (2) Ocean (aquatic) plants produce wet biomass feedstock for food and energy (subsection
220   3.1, SS tabs 4 and 6).

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

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

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

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

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

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

235 **3 Calculations, results, and discussion for each component**

236   3.1 Biomass start-up, eventual scale, cost, and infrastructure

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

241   Wet biomass production starts with seafood grown in total-ecosystem aquaculture (TEA).
242 The macroalgae biomass grown on flexible floating reef ecosystems (Capron, 2019; Capron &
243 Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b; Chambers, 2013; Lucas et al., 2019a,
244 2019b) and other systems (Buschmann et al., 2017; Kim et al., 2017a, 2017b; Knowler et al.,
245 2020; Park et al., 2018; Radulovich et al. 2015; Shi et al., 2018) provides food and oxygen for
246 traditional seafoods (i.e. finfish, crabs, oysters, and the like). Gentry et al. (2017), Froehlich et al.
247 (2019), and Theuerkauf et al. (2019) provide global overviews of potential locations. The SD
248 explains TEA adaptation research is needed to ensure seafood and biomass productivity with
249 biodiversity in warming tropical waters. Fish are currently migrating toward Earth's poles to
250 escape marine heat waves (Hastings et al., 2020).

251   While harvesting seafood, macroalgal biomass-for-energy production would be
252 demonstrated and improved. Fish and shellfish production should cost less than $2/kg on
253 average. Domestic sales might be $1 - $2/kg while exports earn $4/kg or more at the dock. At
254 $2/kg, a billion wet shell-on tonnes of seafood would be worth $2 trillion/yr. When demand for
255 biomass-for-biofuel rises, aquaculture ecosystems can be managed to simultaneously produce
256 both a billion wet tonnes of seafood and 7 billion wet tonnes (0.7 billion dry tonnes) of

257   macroalgae for energy. At \$100/dry tonne (Lucas et al. 2019a), this start-up macroalgae-for-
258   energy would be worth \$70 billion/yr.

259   The P_{fuel} path presumes increasing ocean net primary productivity by 40% or about 40
260   billion dry tonnes/yr. The $P_{electric}$ path projects increasing terrestrial net primary productivity by
261   15% or about 17 billion dry tonnes/yr. Currently, the world's net primary productivity is near
262   210 billion tonnes/yr of biomass (Field et al., 1998). Total land productivity is about 110 billion
263   tonnes on an area of 150 million km^2. Ocean productivity is about 96 billion tonnes on 360
264   million km^2. This implies oceans are under-producing relative to land, which could be remedied
265   by nutrient recycling and structures supporting macroalgae or seagrass in the photic zone. See
266   SD Section 3.1 for a discussion of how macroalgae-for-fuel can support biodiversity better than
267   traditional marine protected areas.

268   Primary conclusions from Table 3 include:

269   •   There is more-than-sufficient potential additional biomass, between 60 and 100 billion
270   dry tonnes/yr, much more than the 30−40 billion dry tonnes/yr needed in these
271   projections. Thus, there is no need to use wood from forests, which is often regarded as
272   unsustainable (Hudiburg, et al., 2013). More discussion in SD.

273   •   There is more than enough solid waste (Kaza et al. 2018) for 22 million barrels/day (by
274   2050) of sweet biocrude oil (SS tabs 4, 7, 11, 12).

275   •   Every kind of biomass or waste (wet or dry) can contribute, which means every country
276   can participate in some form of biomass production.

277   •   While there are obvious differences in maximum scale and cost, most every type of
278   biomass is significant and is, or will become, a viable industry.

279   •   These numbers are speculative in that the macroalgae projections are based on theoretical
280   studies, not physical demonstration projects.

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

Metric	Estimated global scale at indicated cost[1]	Estimated cost delivered to energy process	Estimated energy-return ratio[2]
	billions of dry tonnes/yr	\$/dry tonne	E_{out}/E_{in}
Organic waste including mixed biosolids, paper, plastic, food waste, etc.[3]	5 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)

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

287   The availability of large quantities of ocean biomass relieves pressure on terrestrial
288   sources of biomass, which are increasingly limited by demands for food as well as climate
289   impacts. TEA could grow 1 billion tonnes/yr of seafood on less than 10% of the suitable

290 continental shelf less than 200-m seafloor depth (identified by Gentry et al., 2017). That would
291 be about 0.3% of the world's oceans (SS tabs 6 and 18). TEA could grow 39 billion dry tonnes
292 of oceanic biomass-for-energy on 7% of the world's oceans, including some deep ocean (SD 3.1
293 and SS tab 6). The remaining 93% of ocean area would not be needed for food or bioenergy
294 production.

295   3.2 Nutrient recycling start-up, eventual scale, cost, and infrastructure

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

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

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

310 • Buying ammonia would add $24/tonne to the cost of oceanic biomass, (i.e. add US$22/barrel
311   to the cost of biocrude oil produced by HTL) based on values used by Jiang et al. (2019).
312   There are additional costs for other nutrients, such as phosphates.

313 • 2018 global artificial nitrogen production of 176 million tonnes of N, production of which
314   emitted 505 million tonnes of CO_2. Between 75 and 90% of manufactured ammonia is used
315   for agriculture. Artificial nitrogen fertilizer production already produces ~1% of global CO_2
316   emissions (Brown, 2016).

317 • If nutrients were not recycled, waste-treatment costs for conventional "wastewater" biologic
318   nutrient removal processes would increase the cost of bio-oil by $60/barrel.

319 • 1.2 billion tonnes of inorganic nitrogen is available in 2−3 million km^3 of deep ocean water.
320   Removing the inorganic nitrogen (and other nutrients) from a few million km^3 of deep ocean
321   water each year is not sustainable. Temporarily using a smaller amount of deep ocean water
322   to start and expand primary production may be acceptable.

323 • Upwelling deep ocean water for nutrient supply brings up CO_2, drops surface water pH
324   (ocean acidification), and might increase the amount of CO_2 in the air (Chan et al., 2008;
325   Chen, 2018; Feely et al., 2008; Köhn et al. 2017; Ries, 2010).

326 • Several processes (in addition to HTL, such as anaerobic digestion) convert macroalgae to
327   energy with good efficiency while separating most of the carbon from the nutrients. These
328   separated nutrients can be returned to the macroalgae ecosystem during harvesting without
329   significant cost.

330   3.3 HTL start-up, eventual scale, cost, and infrastructure

331   Recent innovations and cost reductions with HTL (Genifuel, 2019; Jiang et al., 2019; Jiao
332   et al., 2017; Pichach, 2019; ReNew ELP, 2019; Steeper Energy, 2019; Watson et al., 2019) make
333   it practical to scale up as a solid waste-collection system that pays for itself. HTL converts any
334   blend of wet plants, paper, wax, and most plastics to bio-oil – expired juice in plastic bottles,
335   newspaper, expired packages of meat, seaweed, microalgae, switch grass, feces, biohazard
336   wastes in plastic – all chopped and blended together. The process is similar to the way algae
337   became oil when buried deep in the Earth. By using a combination of high temperature (350ºC,
338   660ºF) and pressure (200 atmospheres, 3,000 psi) the conversion to oil is complete in about
339   30 min. Because the reaction temperature is less than 400ºC, all plant nutrients can be recovered
340   and used to grow more plants (see SD 3.3).

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

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

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

365   3.4 Allam Cycle start-up, eventual scale, cost, and infrastructure

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

372 ready CO_2. Its pressure, 100 to 150-bar (10 to 15 MPa, 1450 to 2,175 psi), will push it through a
373 pipeline for direct injection into underground or underwater sequestration.

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

380 There are more designs for electricity with carbon capture and storage than just Allam
381 Cycle. Several, including Allam Cycle, have detailed technical and cost analyses presented at the
382 website for the U.S. Department of Energy's Coal FIRST program (2020). Allam Cycle is used
383 throughout this paper because its projected cost of electricity from coal, with sequestration-ready
384 CO_2 at 100-bar pressure is $74/MWh, using typical US coal costs. The other six Coal FIRST
385 program projects captured a lower fraction of produced CO_2 at 1-bar pressure. Adding $12/MWh
386 for compression of CO_2 from 1 to 100-bar (SS tabs 14 and 15), their projected costs ranged from
387 $118 to $243/MWh. (Fuel costs and byproduct sales differ, which complicates this comparison.)

388 James et al. (2019) prepared a standard baseline report for several power plant processes
389 with CCS. The process with the least avoided cost, supercritical pulverized coal (SC-PC),
390 levelized cost of electricity is $64/MWh without CCS or $109/MWh with 90% carbon capture.
391 These are James' figures without transport and sequestration (T&S) costs with an added
392 $3/MWh to compress from James' 15-bar to Allam Cycles' 100-bar. Irlam (2017) reports similar
393 values to James. Allam Cycle with CCS in a comparable situation has electricity cost at
394 $74/MWh (8 Rivers Capital, 2020). See Section 3.6 for a discussion of costs in terms of $/tonne
395 of CO_2 sequestered.

396 8 Rivers Capital (2020) explains that early adopters can sell gas products argon (Ar),
397 nitrogen (N_2), and CO_2 and use the income to decrease the price of electricity to $55/MWh ($54
398 less than SC-PC coal with CCS).

399 NET Power (a subsidiary of 8 Rivers) targets commercial deployment of 300-MW
400 natural gas Allam Cycle power plants in 2022 (McMahon, 2019). 8 Rivers has proposed a
401 demonstration of a 300-MW Allam Cycle with coal gasification at a Wyoming coal mine
402 including selling all the argon and CO_2. The commercial operation date would be 2026 (8 Rivers
403 Capital, 2020). Allam Cycle power plants are almost zero emissions and have operating
404 flexibility that reduces the need for battery backup of solar and wind energy (8 Rivers Capital,
405 2020). They also provide "firm" power which has been calculated by Sepulveda et al. (2018) to
406 reduce overall electricity costs in decarbonized scenarios. See discussion in SD Section 3.4.

407 3.5 CO_2 sequestration start-up, eventual scale, cost, and infrastructure

408 There are many options for liquid CO_2 sequestration start-up using the current 13 billion
409 tonnes/yr of fossil-fueled CO_2 emissions from electricity generation. There are many more
410 carbon and CO_2 storage techniques appropriate for situations other than low-cost liquid CO_2 not
411 discussed in this paper. The options shown in Table 4 can retain acceptable costs while scaling
412 for the safe sequestration of trillions of tonnes of liquid CO_2 produced by the HTL and Allam
413 Cycle power plants. They include geologic carbon sequestration in depleted oil and gas wells and
414 brine aquifers (Turner et al., 2018; Deng et al., 2017; Alcalde et al., 2018), basalt and other rocks

14

415   on land and sub-seafloor (National Academies of Sciences, Engineering, Medicine, 2018;
416   Kelemen et al., 2019; Snæbjörnsdóttir et al., 2020, Moran et al. 2020), and contained CO_2-
417   hydrate storage on the seafloor (Brewer, 2000; Capron et al., 2013).

418   SD includes more discussion of the concepts and results in Table 4, including how the
419   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.

420   3.6 Paying for removing and storing legacy CO_2

421   Legacy CO_2 is commonly thought of as CO_2 from emissions already in the atmosphere
422 and ocean (Friedlingstein et al., 2019; Knutti & Rogelj, 2015). Our calculation includes future
423 fossil-fuel CO_2 uncaptured emissions in the total legacy CO_2 to be removed from the air and
424 oceans. The total cost is a cost to society in the form of higher energy costs. The cost calculation
425 below is an apples-to-apples comparison with:
426   o $150/tonne for direct air capture (in 2019 USD) (Baker et al., 2020);
427   o $74/tonne ($52/MWh) (James et al., (2019) breakeven emissions penalty (aka
428   "avoided") cost when adding CCS to a SC-PC coal power plant, the lowest cost
429   option in James' Exhibit ES-4). Costs may be slightly higher when biomass replaces
430   coal (BECCS).

431   3.6.1 Capture

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

436   3.6.2 Compression

437   The second added cost and energy component is for compressing the pure CO_2 to a liquid
438 or supercritical state for permanent sequestration, which varies for the following different
439 situations:
440   • CO_2 capture from Allam Cycle – Each 300-MW coal- (and likely biomass)-fired power
441   plant compresses 4,600 tonnes/hr of CO_2 from 30 to 150 bar. Most of the CO_2 is
442   recirculated working fluid. About 230 tonnes/hour is produced from coal for sale or
443   sequestration. The energy required to compress CO_2 from a gas at 30 bar to a
444   supercritical fluid at 100 to 150 bar is small, about 9 kWh/tonne (8 Rivers Capital, 2020).
445   The combined energy plus other operating and capital costs are near $1/tonne of CO_2 for
446   coal or $2/tonne for natural gas. This is based on data from Fernandes et al. (2019), Atlas
447   Copco CO_2 compressors (2020), Allam et al. (2017), and 8 Rivers Capital (2020) (SS tab
448   14).

- 449 • CO$_2$ capture from HTL – HTL produces bio-crude plus fuel gas that could be combusted
- 450   with air such that it produces gas with a high fraction of CO$_2$ (10 to 20%) at 1 bar.
- 451   Capturing >95% of the CO$_2$ costs about $40/tonne of CO$_2$. Compressing CO$_2$ from 1 to
- 452   100 bar requires about 130 kWh/tonne of CO$_2$. The combined capture, energy plus other
- 453   operating, and capital costs are near $65/tonne of CO$_2$. Most of the cost is for capture and
- 454   compressing energy, which varies significantly by location, by technology, and over
- 455   time, as indicated in Table 5.
- 456 • Hybrid of HTL co-located with Allam Cycle – HTL's byproduct fuel gas and CO$_2$ at 1
- 457   bar would be blended and provided as fuel (low-grade fuel gas) to the Allam Cycle. Its
- 458   value as fuel should cover the cost of compressing it to the required fuel pressure. This
- 459   situation's capture and compression cost should be similar to the $1 or $2/tonne of CO$_2$
- 460   for the Allam Cycle situation (SS tab 14).

461   3.6.3 Transportation

462   The third added cost component (relatively little energy needed because the CO$_2$ is a
463 supercritical fluid with very little friction) is the capital cost for transportation, which has been
464 projected by National Academies of Sciences, Engineering, Medicine (2019) as $2/tonne for a
465 100 km pipeline.

466   3.6.4 Storage

467   The fourth added cost is sequestration of the pure, compressed CO$_2$. Table 5 (SS tabs 13
468 and 14) values are based on transportation and storage costs of $10/tonne of CO$_2$. (We note that
469 James et al. (2019) and Rubin (2015) used $9/MWh in SC-PC avoided cost calculations ($12 per
470 tonne of CO$_2$) for transportation and storage.) This paper used $8/tonne of CO$_2$ as an average
471 cost of sequestering liquid or supercritical CO$_2$ because Turner et al. (2018), Deng et al. (2017)
472 and others project costs for many saline aquifers as $1 - $8/tonne. In addition, Table 4 shows
473 negative costs (a credit) for those able to sell CO$_2$ for EOR (see more discussion in SD).

474   3.6.5 Input fuel cost

475   A fifth cost component is the varying cost of fuels plus economics of the new and old
476 technologies for converting fuel into liquid fuel and/or electricity and process heat. For example,
477 if the new fuel source is less expensive (such as solid waste) than the old fuel (such as liquified
478 natural gas), capturing and sequestering CO$_2$ might have negative additional cost (Table 5, first
479 two rows). Similarly, if the new fuel source costs $11/GJ (such as HTL biocrude from
480 macroalgae) instead of $2.5/GJ (U.S. coal), the additional cost might be $180/tonne of CO$_2$
481 (Table 5, bottom row).

482   3.6.6 Process cost

483   A sixth cost component is because different processes result in different levelized
484 electricity cost ($/MWh) even with the same fuel cost ($/MMBTU). The process cost may also
485 be expressed in $/tonne of CO_2 captured and compressed. The mainstream processes competing
486 with Allam Cycle for fossil fuel or biomass electricity are supercritical pulverized coal (SC-PC)
487 and combined cycle gas turbine (CCGT using natural gas). The Allam Cycle process cost with
488 CCS appears to be $15/tonne of CO_2 higher than for SC-PC without CCS (based on statements in
489 8 Rivers Capital (2020), explained in SD, used in Table 5).

490   3.6.7 Total cost

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

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

499   1) Waste can be converted to inexpensive energy with CO_2 capture and sequestration
500   because disposal fees decrease the cost of fuel.

501   2) Terrestrial (dry) biomass (agricultural wastes and purpose-grown biomass) costs about
502   the same as coal. That might be $1.9/GJ in some countries (such as US) and $4.7/GJ in
503   other countries (such as Japan which is dependent on imported coal at about $100/tonne).

504   3) The hybrid of HTL co-located with Allam Cycle has about the same added cost for
505   sequestering CO_2 as does Allam Cycle alone (greatly reducing the sequestration cost for
506   the byproduct fuel gas and CO_2 generated during HTL).

507   4) HTL biocrude and biogas made from purpose-grown biomass are likely to cost much
508   more than coal or natural gas as shown in the bottom two rows of Table 5. Therefore, we
509   assume essentially no HTL biocrude-from-macroalgae will be fed into Allam Cycle
510   plants for electricity production; it will be used for transportation fuels.

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

524   • Process cost explained

525   • Putting the cost of sequestering CO_2 in perspective

526   • Lower costs for early adopters

527   • Allocating costs for removing legacy CO_2

528   • Examples of fossil-CO_2 fees and sequestration payments

3.7 SDGs path

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

3.7.1 Food systems

535   Total ecosystem aquaculture systems are built-reef ecosystems with nutrient recycling
536   that can provide abundant, inexpensive multi-species seafood. Distributed globally, seafood reefs
537   (Capron, 2019; Capron & Piper, 2019; Capron et al., 2018, 2019, 2020a, 2020b; Chambers,
538   2013; Lucas et al., 2019a, 2019b) can sustainably and economically produce a billion tonnes/yr
539   of seafood, 300 grams/person/day for 8 billion people. (The FAO (2018) estimates current
540   seafood production (including aquaculture and wild-caught) near 170 million tonnes/yr.)
541   Developing countries might earn income from developed countries initially by exporting
542   seafood. Developing countries might earn income from developed countries by accommodating
543   refugees and migrants as temporary or permanent guest workers on their built-reef ecosystems.
544   Aquatic-based organic fertilizers can replace chemical fertilizers. Scaling built-reef total
545   ecosystem aquaculture allows more marine protected areas.

3.7.2 Human waste resource recovery systems

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

3.7.3 Solid waste resource recovery systems

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

3.7.4 Sustainable energy systems

558   Install multi-fuel energy systems that produce sequestration-ready CO_2. The "multi-"
559   includes coal, natural gas, and biomass. Include ways to recycle nutrients from the energy
560   process to grow more food and biomass-for-energy. Developing countries might earn income
561   from developed countries by growing terrestrial biomass to fuel the developing country's

562   electricity production and sequestering the bio-CO_2 less expensively than can be done in
563   developed countries. Co-locate the human and solid waste resource recovery plants with
564   sustainable energy systems for cost and circular economy synergies.

565   3.7.5 Sustainable ocean biomass-for-energy

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

569   3.7.6 CO_2 sequestration systems

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

573   3.7.7 Floating land systems

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

576   3.7.8 Other public health systems

577   Both proposed paths help replace inefficient open-flame charcoal cooking with clean-
578   burning fuel or electric stoves. They also eliminate air pollutants from electricity generation,
579   yielding large co-benefits for air quality and human health. West et al. (2013) calculated local
580   average marginal co-benefits of avoided mortality from air pollution ranging from $50–
581   380/tonne of CO_2.

582   3.7.9 All systems must be sustainable

583   In 2012 N'Yeurt et al. discussed sustainability criteria for growing macroalgae forests to
584   reverse climate change. The technologies have evolved, and the economics have improved, now
585   offering even more sustainability in all the ways listed by N'Yeurt et al.: environmental, climate,
586   political, social, energy, and economic. (See SD for more discussion on how ocean forest reefs
587   directly support twelve of the SDGs.)

588   **4 Conclusions and Recommendations**

589   4.1 Summary

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

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

605 The increased seafood production is supported by improved ways to ensure the nutrients
606 people eat are recycled to land and ocean. In the ocean, recycled nutrients are distributed to
607 macroalgae or seagrass grown on floating flexible fishing reefs positioned in the photic zone
608 independent of seafloor depth. The fishing reefs form highly productive ecosystems supported by
609 nutrients optimized for seasonal productivity and natural variations in nutrients and dissolved
610 oxygen supply. Calculations suggest a billion tonnes of seafood can be grown on less than 10%
611 of the suitable continental shelf less than 200-m seafloor depth (identified by Gentry et al.,
612 2017). That would be about 0.3% of the world's oceans (see SS tabs 6 and 18). By growing more
613 food in less ocean, the marine protected areas could be increased.

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

621 All countries can enjoy safe handling of biohazard wastes and mixed solid wastes in
622 general with low, even negative, disposal fees using hydrothermal liquefaction (HTL) to produce
623 22 million barrels/day (3 million tonnes/day) of biocrude oil from wastes by 2050. Additional
624 benefits include less plastic trash reaches the ocean, less methane emissions from landfills, and
625 profitably cleaning excess *Sargassum* off beaches.

626 4.2 Recommendations

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

628 • Pause (even in the middle of construction) electricity power plant construction to check
629 local feasibility of Allam Cycle plants. The design of Allam Cycle plants facilitates mass
630 production. Funding agencies could purchase blocks of a thousand factory-built 300 MW
631 power plants at a time. In addition to lower costs from mass production, this action will
632 increase budget certainty for developing countries as they switch to Allam Cycle power.
633 Fast start-up is encouraged while the oil industry is still buying CO_2 for enhanced oil
634 recovery. Income from selling CO_2 for EOR will decrease the cost of electricity. (8
635 Rivers Capital (2020) estimated in early 2020 that the global demand for CO_2 used for
636 EOR is equivalent to nearly 6,000 of the 300 MW Allam Cycle power plants or
637 1,800 GW.)
638 • Quickly build seafood-production infrastructure in developing countries.
639 • Convert solid waste to biocrude oil in developed and developing countries.
640 • Co-locate the HTL and Allam Cycle facilities to maintain the cost for capturing,
641 compressing, and sequestering CO_2 near \$26/tonne as opposed to the \$75/tonne expense

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

646   • Take advantage of the immediate benefits from food, jobs, waste handling, and sales of
647   liquid CO_2 byproduct to achieve SDGs. Start-up actions are further described in the SD
648   and by Capron et al. (2020a, 2020d).

649   • Increase marine protected areas in proportion to the area converted to total ecosystem
650   aquaculture.

651   • Establish a Legacy Carbon Fund (each country could have its own fund but with global
652   accounting). The fund would collect more-than-the-cost of sequestering fossil-CO_2 from
653   fossil fuel producers/users. The more-than costs are used to pay for sequestering bio-CO_2.
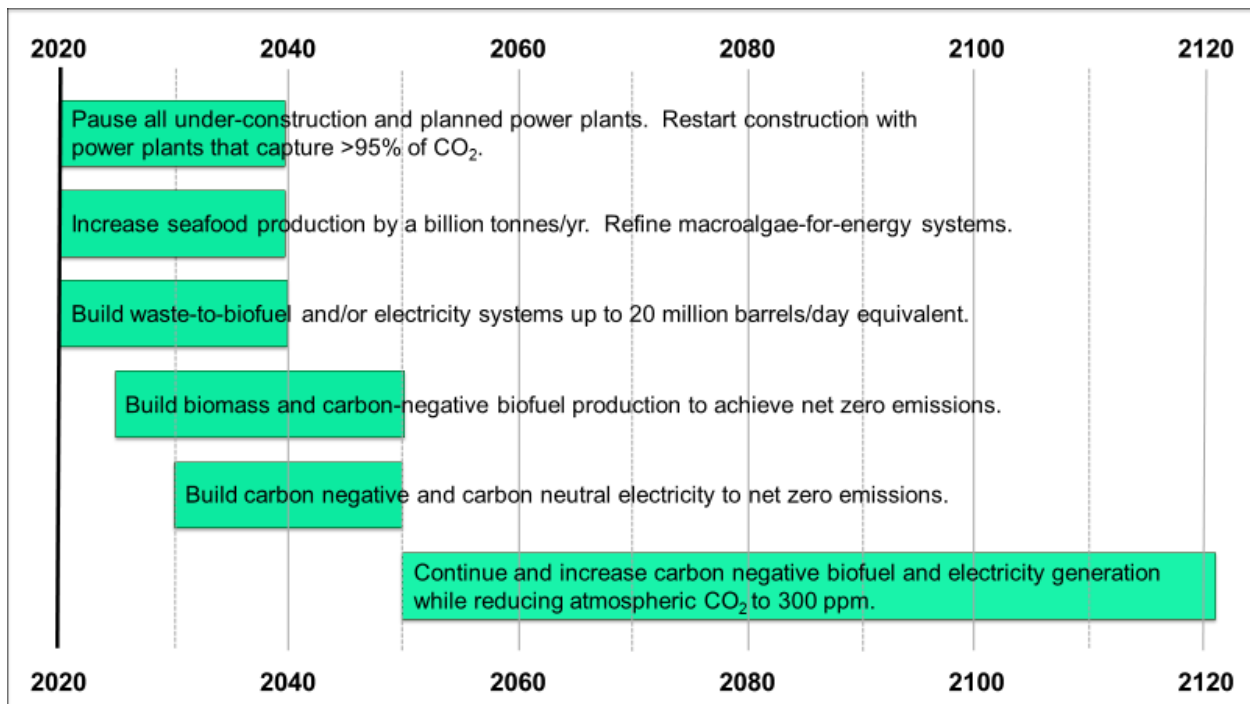
654

655   Fig. 4. Global timeline to achieve SDGs and reduce atmospheric CO_2 by 2 trillion tonnes around
656   2100 (details in SD)

657   4.3 Further Research

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

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

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

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711 **Supplemental Document and Supplemental Spreadsheet** available online.

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