The use of negative emission credits to hold global warming to 1.6°C: Needs, technologies, minimum-cost implementation, and a possible funding path

Submitted in response to: United Nations Climate Change Talanoa dialogue Question #2 - Where do we want to go?

The specific Question 2 template questions concerning "Where do we want to go?" are answered first, followed by a more detailed description of our proposed approach

Template for non-Party stakeholders' inputs for the Talanoa Dialogue

Vision of the future for your organization and/or sector in terms of its possible role in achieving the 1.5/2 degrees' goal and a net-zero emission world by this mid-century [Maximum 300 words]

The total negative emissions (790 PgC) that are required to hold global warming to 1.6°C (year 2100) in the face of current-policy positive emissions are calculated from recent work by Hansen et al. Current estimates of the total annual capabilities (10.9 PgC/year at best) and unit costs of well-known negative emissions technologies are identified from recent work by Smith et al.; these "Plan A" capabilities are insufficient to meet the requirements, and the unit costs are quite high. Our organization has developed the relatively new **OTECISATR** approach (**OTEC** **I**nducing a **S**urface **A**tmospheric **T**emperature **R**eduction) which if successfully implemented can potentially achieve a direct reduction in the Earth's Average Surface Atmospheric Temperature (SAT) of over 1°C by itself by drawing on natural climate forces, as well as generating 2.75 TW of CO_2-free power wherever needed. Its capabilities and much lower unit costs are added to the Plan A mix to get "Plan B", which does have sufficient capability (22.5 PgCeq/year) to hold global warming to 1.6°C. A year-by-year resource deployment analysis is constructed to examine the cost of the implementation. The total annual cost of the required negative emissions equivalent using Plan B is on the order of 16% of the total income that would be generated if the carbon fee rate schedule proposed by Citizens Climate Lobby is collected on the world's total projected positive emissions. This opens up the possibility of using a modest fraction of the revenue collected from carbon fees on positive emissions to totally cover the cost of the negative emission credits required to hold global warming to 1.6°C.

Possible and potential new commitments and pledges of to achieve the 1.5/2 degrees' goal and a net-zero emission world by this mid-century [Maximum 300 words]

Use a modest fraction of the revenue collected from carbon fees assessed on positive emissions to totally cover the cost of the negative emission credits required to hold global warming to 1.6°C.

Foreseen positive impact of these commitments once they are realized, including contributions to the sustainable development agenda [Maximum 300 words]

Hold global warming to 1.6C in year 2100 without requiring massive expenditure of government funds.

The use of negative emission credits to hold global warming to 1.6°C: Needs, technologies, minimum-cost implementation, and a possible funding path

Dr. Alan K. Miller, former Stanford Professor and retired Lockheed Martin alternative-energy specialist
https://www.linkedin.com/in/alan-k-miller-67a2712b/

Executive summary

The total negative emissions that are required to hold global warming to 1.6°C (year 2100) in the face of current-policy positive emissions are calculated from recent work by Hansen et al. Current estimates of the capabilities and unit costs of well-known negative emissions technologies are identified from recent work by Smith et al.; these "Plan A" capabilities are insufficient to meet the requirement. The additional capabilities and much lower unit costs of the relatively new OTECISATR (OTEC Inducing a Surface Atmospheric Temperature Reduction) approach (which if successfully implemented can potentially achieve a direct reduction in the Earth's Average Surface Atmospheric Temperature (SAT) of over 1°C by itself) are added to the mix to get "Plan B", which has sufficient capability. A year-by-year resource deployment analysis is constructed to examine the cost of the implementation. The total cost of the required negative emissions using Plan B is on the order of 16% of the total income that would be generated if the CCL-proposed carbon fee rate were collected on the world's total projected positive emissions. This opens up the possibility of using a modest fraction of the revenue collected from carbon fees on positive emissions to totally cover the cost of the negative emission credits required to hold global warming to 1.6°C.

Introduction with key results

When carbon fees are implemented worldwide, they will be a major step forward encouraging the use of renewable energy sources instead of fossil fuels, thereby making important progress in slowing the rate global warming.

But technologists and policymakers are starting to realize that just replacing fossil fuels with renewables is not enough. While there is agreement that global warming must be held to about 1.5°C in year 2100 to avoid the most serious environmental consequences, even if all the nations of the world fulfill their "INDC" policy commitments made in Paris in 2015 (a 56% reduction in CO_2 emission reductions), global warming will still rise to greater than 3°C[1]. Current projections for the "current policies" scenario point to 3.4°C[2].

To hold global warming to 1.5°C using only renewable energy in the form of wind and solar (the currently dominant CO_2-free energy technologies) requires a 100% replacement of fossil energy, with 0% emission of CO_2 beyond that point [3]. Given the realities of today's world and its ongoing policies, a 100% reduction in fossil fuel usage is not realistic.

Accordingly, those who are concerned about holding global warming to 1.5°C in year 2100 are starting to seriously consider additional measures, in particular the need to utilize "negative emissions" (greenhouse gas removal from the atmosphere, or its functional equivalent). For example, according to The Economist, "Of the 116 models the Intergovernmental Panel on Climate Change (IPCC) looks at to chart the economically optimal paths to the Paris goal [2°C], 101 assume 'negative emissions.' No scenarios are at all likely to keep warming under 1.5°C without greenhouse-gas removal." [4]

Much has been written on these subjects. In this brief, the leading sources of information are used as the basis for a new quantitative analysis of negative emissions. The current trajectory of post-Paris 2015 positive emissions is identified using Climate Action Tracker's "current policies" projections for 2017, and the implications for the 2050 emissions level and annual rate of change in positive emissions are calculated. The total negative emissions that are required through year 2100 to hold global warming to 1.6°C in the face of this level of positive emissions is calculated, based on recent work by James Hansen and colleagues. Current estimates of the capabilities and unit costs of well-known negative emissions technologies are identified from the work of Pete Smith et al. The capabilities and unit costs of the relatively new OTECISATR (OTEC Inducing a Surface Atmospheric Temperature Reduction) approach (which if successfully implemented can potentially achieve a direct reduction in the Earth's Average Surface Temperature (SAT) of over 1°C, the equivalent of negative emissions of thousands of gigatons of atmospheric carbon dioxide) are identified from recent work on that subject, and are added to the mix. A year-by-year resource deployment analysis is constructed to examine the implementation of negative emissions using two alternative approaches: "Plan A" employing only the currently well-known negative emissions technologies, and "Plan B" also including the OTECISATR approach. Within each approach, the lowest-cost technology is deployed first (up to its maximum capability) as would occur with a market-based solution, and the resulting curves of annual cost vs. year (through year 2100) are calculated.

To examine a possible method for funding such solutions, the total annual income stream that would be generated using the current Citizens' Climate Lobby (CCL) proposed carbon fee schedule (applying it to the entire world's future positive CO_2 emissions) is calculated and is compared against the total annual cost stream for the lowest-cost plan.

Key results from this preliminary analysis include the following findings:

- The sum total capability of the Plan A approach, based only on currently well-known negative emissions technologies, is insufficient to hold global warming to 1.6°C.
- In addition, over its operable extent, the total cost per unit negative emissions for Plan A would be much higher than for Plan B.
- Plan B has sufficient total capability to hold global warming to 1.6°C in year 2100.
- The total cost of the negative emissions under Plan B is on the order of 16% of the total income that would be generated if the CCL carbon fee rate were collected on the world's total projected positive emissions.
- Therefore, the Plan B approach is one that could fully fund holding global warming to 1.6°C in year 2100. This opens up the possibility of using a modest fraction of the revenue collected from carbon fees on positive emissions to totally cover the cost of the negative emissions required to avoid catastrophic global warming.

1. The current trajectory of post-Paris 2015 positive emissions is identified

Climate Action Tracker[5] has considered both the pledges made in Paris 2015 and the current policies of all the countries of the world. Their most recent (2017) projections show (Figure 1) that with current policies, emissions will be 53 $GtCO_2e$/year (14.4 PgC/yr) in 2100, and global warming will reach 3.4°C in that year.

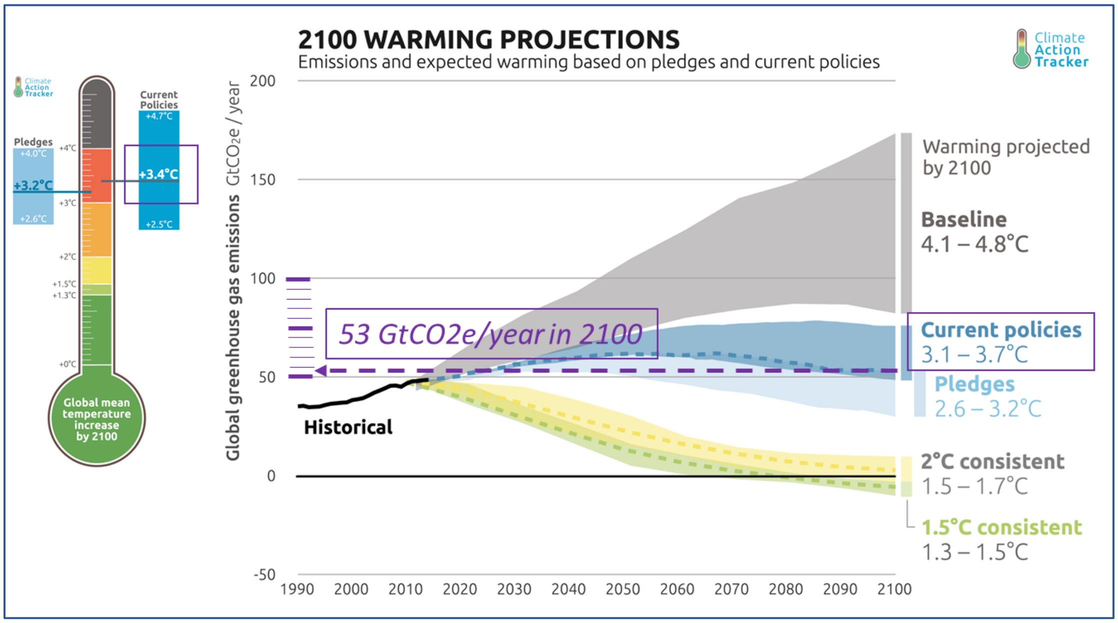
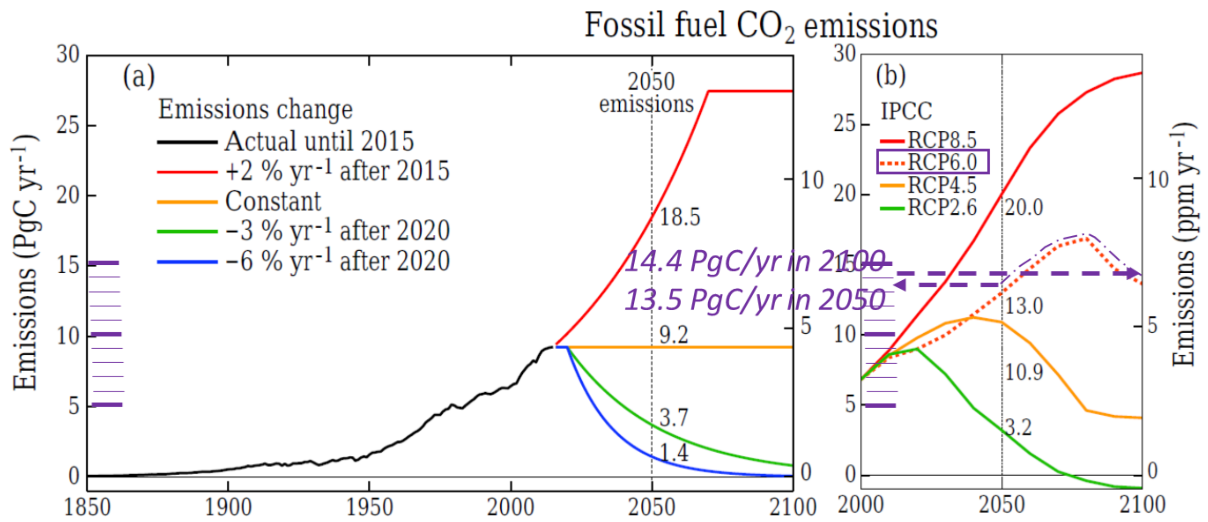


FIGURE 1 – CLIMATE ACTION TRACKER 2017 PROJECTIONS OF YEAR 2100 GLOBAL WARMING AND CO_2 EMISSIONS. THE GLOBAL WARMING PROJECTION OF 3.4°C UNDER CURRENT POLICIES IMPLIES EMISSIONS OF 53 $GTCO_2$/YR = 14.4 PGC/YR.

2. Implications for 2050 emissions levels and annual change in emissions

James Hansen et al. have summarized[6] expected carbon emissions vs. year under various scenarios, showing (Figure 2) emissions in terms of both carbon (PgC/year) and atmospheric CO_2 concentration (ppm/year) and including the various UN IPCC Representative Concentration Pathways (RCP's). A year 2100 emissions level of 14.4 PgC/yr (corresponding to the Climate Action Tracker current policies analysis) is close to the UN IPCC scenario RPC 6.0. Using the general profile shape for this pathway, the year 2050 emissions level would be about 13.5 PgC/yr.



James Hansen et al. Figure 9. Fossil fuel emission scenarios. (a) Scenarios with simple specified rates of emission increase or decrease. (b) IPCC (2013) RCP scenarios. Note: 1 ppm atmospheric CO2 is approximately 2.12 GtC

FIGURE 2 - AN EMISSIONS LEVEL OF 14.4 PGC/YR IN 2100 IS CLOSE TO THE RCP 6.0 IPCC SCENARIO AND IMPLIES AN EMISSIONS LEVEL OF ABOUT 13.5 PGC/YR IN 2050. ORIGINAL GRAPH BY HANSEN ET AL.

Cross-plotting the Hansen et al. data on % per year increase in emissions vs. the year 2050 emissions level, the annual increase in emissions associated with the Climate Action Tracker "current policies" scenario can be determined to be 1.08% per year (Figure 3).

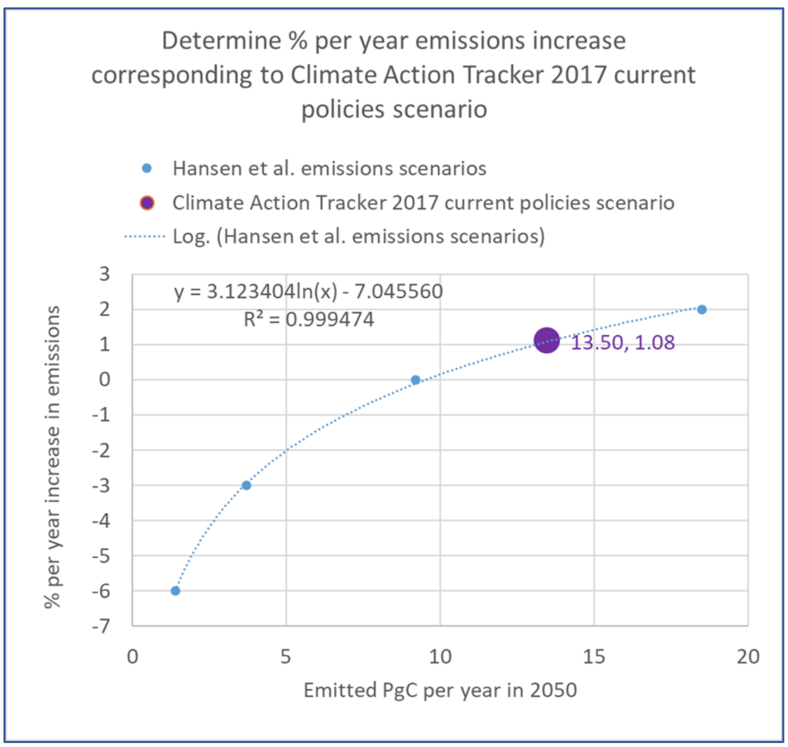
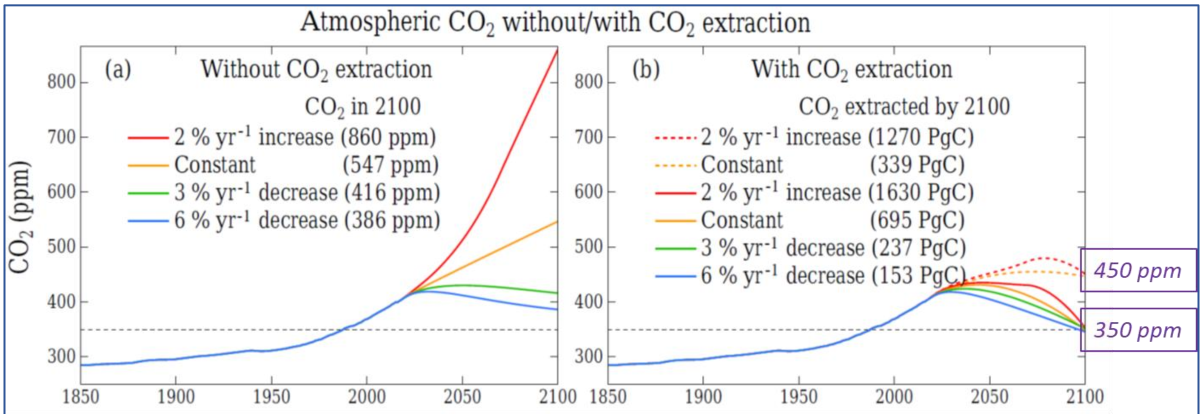


FIGURE 3 - CROSS-PLOT OF HANSEN ET AL. DATA FROM FIGURE 2. EMISSIONS OF 13.5 PGC/YR IN 2050 REPRESENTS AN ANNUAL INCREASE OF 1.08%.

3. <u>Negative emissions required to hold global warming to acceptable levels</u>

Hansen et al. have also calculated[7] how much negative emissions (CO_2 extraction) is required in order to hold the year 2100 atmospheric CO_2 concentration to specific levels, for various levels of continued positive emissions (Figure 4). Using data from the Intergovernmental Panel on Climate Change, Working Group III[8], their 450 ppm corresponds to a global warming of 1.6°C which is close to the 1.5°C overall goal.



James Hansen et al. Figure 10. (a) Atmospheric CO2 for Fig. 9a emission scenarios. (b) Atmospheric CO2 including effect of CO2 extraction that increases linearly after 2020 (after 2015 in +2% yr-1 case).

FIGURE 4 - HANSEN ET. AL HAVE CALCULATED THE NEGATIVE EMISSIONS REQUIRED TO HOLD CO2 CONCENTRATIONS TO CERTAIN LEVELS. 450 PPM CO2 CORRESPONDS TO 1.6C GLOBAL WARMING.

The Hansen et al. data can be cross-plotted (Figure 5) to calculate the required total negative emissions vs. the positive emissions increase rate. For an emissions increase rate of 1.08% per year (corresponding to current policy commitments) and a year 2100 CO_2 level of 450ppm the required cumulative total carbon removal level is 790 PgC.

Figure 6 adds the apparent required negative emissions of 790 PgC (by year 2100) to the Hansen et al. framework.

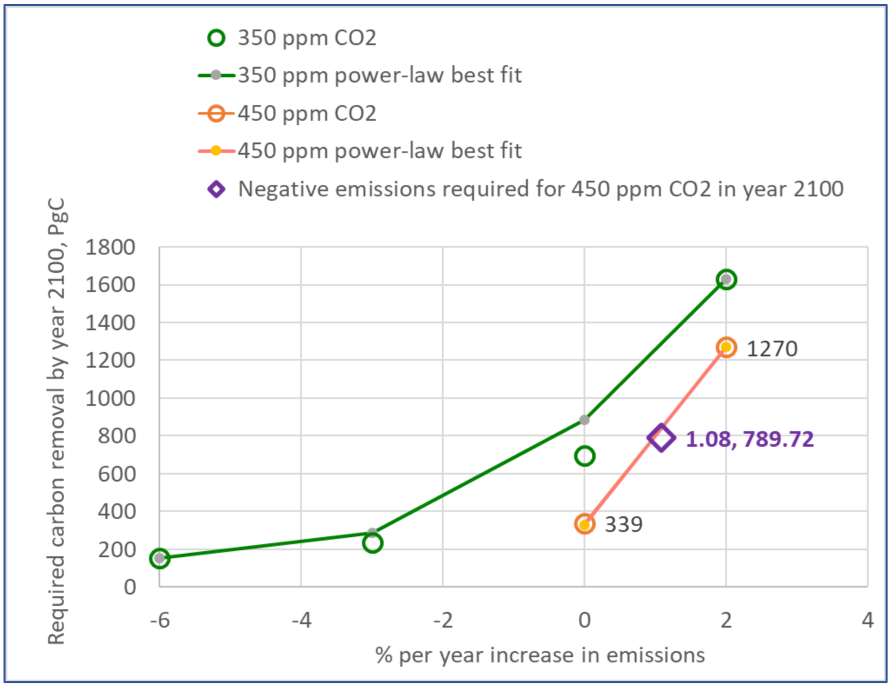
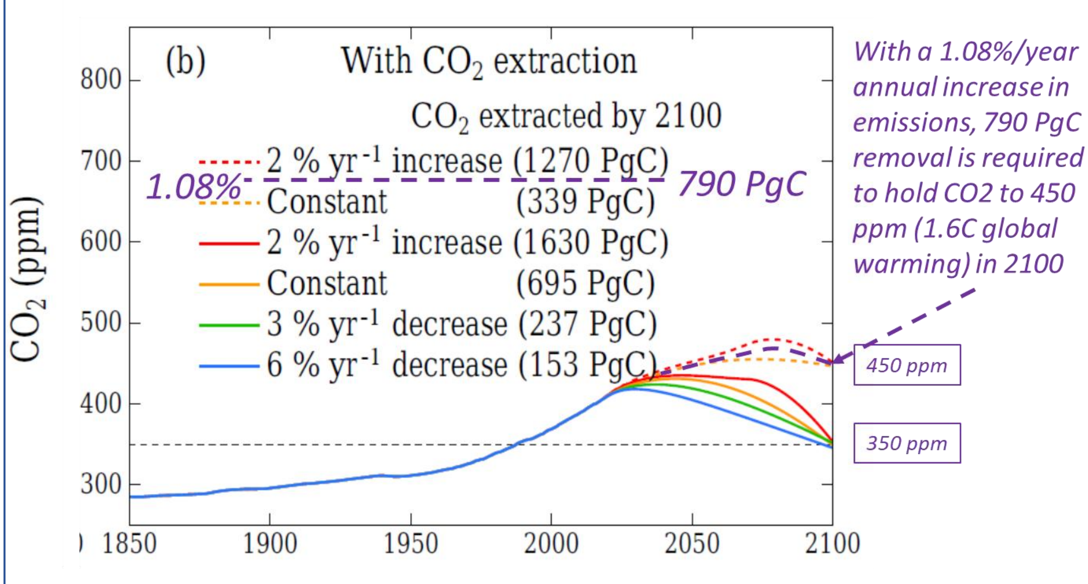


FIGURE 5 - CROSS-PLOT OF HANSEN ET AL. DATA FROM FIGURE 4 RIGHT. FOR A 1.08% ANNUAL INCREASE IN EMISSIONS, TO HOLD CO_2 CONCENTRATION TO 450PPM IN 2100 (1.6C GLOBAL WARMING), A TOTAL OF 790 PG OF CARBON MUST BE REMOVED FROM THE ATMOSPHERE BY 2100.



James Hansen Figure 10. (b) Atmospheric CO2 including effect of CO2 extraction that increases linearly after 2020 (after 2015 in +2% yr^{-1} case).

FIGURE 6 – ADDING NEGATIVE EMISSIONS REQUIRED TO HOLD GLOBAL WARMING TO 1.6C (450 PPM CO_2) UNDER THE CURRENT POLICIES SCENARIO TO THE HANSEN ET AL. DATA FROM FIGURE 4 RIGHT. TO HOLD GLOBAL WARMING TO 1.6C IN 2100, A TOTAL OF 790 PGC MUST BE REMOVED FROM THE ATMOSPHERE BY 2100.

4. <u>Negative emissions technologies (NET) total capabilities and unit costs</u>

a. Well-known NET's for which details are in the literature

Smith et al.[9] have reviewed and analyzed the most well-known negative emissions technologies. The unit costs and other requirements are shown on Figure 7, which also adds data for the OTECISATR approach (see next section). A short non-technical description of each technology recently appeared in an overview article in the NY Times and these are quoted here. The technologies analyzed by Smith et al. include:

- Bioenergy with carbon capture and storage (BECCS)[10] (Crop, Forest): **"**In this high-tech approach, called bioenergy with carbon capture and storage, or BECCS, vegetation would be used to naturally remove carbon dioxide. The vegetation would then be burned in a power plant and the carbon dioxide in the exhaust gases would be captured and stored. So far there are only a handful of working BECCS projects; others have been canceled. Among the many questions about the technology is whether emissions are really negative if the carbon cost of growing and harvesting the vegetation is taken into account."[11]

- Direct air capture of CO2 from ambient air by engineered chemical reactions (DAC)[12]: **"**There has been a significant amount of research into "direct air capture." Much of the technology is similar to what is used in carbon capture projects at power plants: chemicals bind with carbon dioxide molecules and then are heated or otherwise treated to release them for capture. Several companies, including Carbon Engineering and Climeworks, have developed machines to do this. But carbon capture at a fossil-fuel plant, where carbon dioxide can make up perhaps 5 to 10 percent of the exhaust gases, is one thing. Doing it from the air is another. For all the rightful concern about rising carbon dioxide levels, the gas still makes up only about 0.04 percent of the atmosphere. Removing a significant amount of it would involve moving huge volumes of air through thousands upon thousands of capture machines, and powering the machines for decades."[13]

- Afforestation and reforestation (AR)[14]: **"**Trees remove carbon dioxide naturally, incorporating it into their tissues as they grow. Worldwide, forests store about one billion to two billion tons of carbon annually, offsetting a chunk of the roughly 10 billion tons emitted by human activity. Reforestation and afforestation, properly managed, could remove a lot more and keep it out of the atmosphere. But planting forests is slow work — as Icelanders know well — and requires a lot of land. The world is currently much better at cutting down forests than planting new ones."[15]

- Enhanced weathering of minerals (EW)[16]: **"**This technique is … based on the fact that some types of rock weather by naturally combining with carbon dioxide in the air or water. One suggested approach would use the mineral olivine, which is plentiful, crushing it into fine sand and spreading it on land, perhaps along coastlines. But mining, crushing and transporting the billions of tons needed would be expensive and energy intensive. And the carbon removal would still be exceedingly slow."[17]

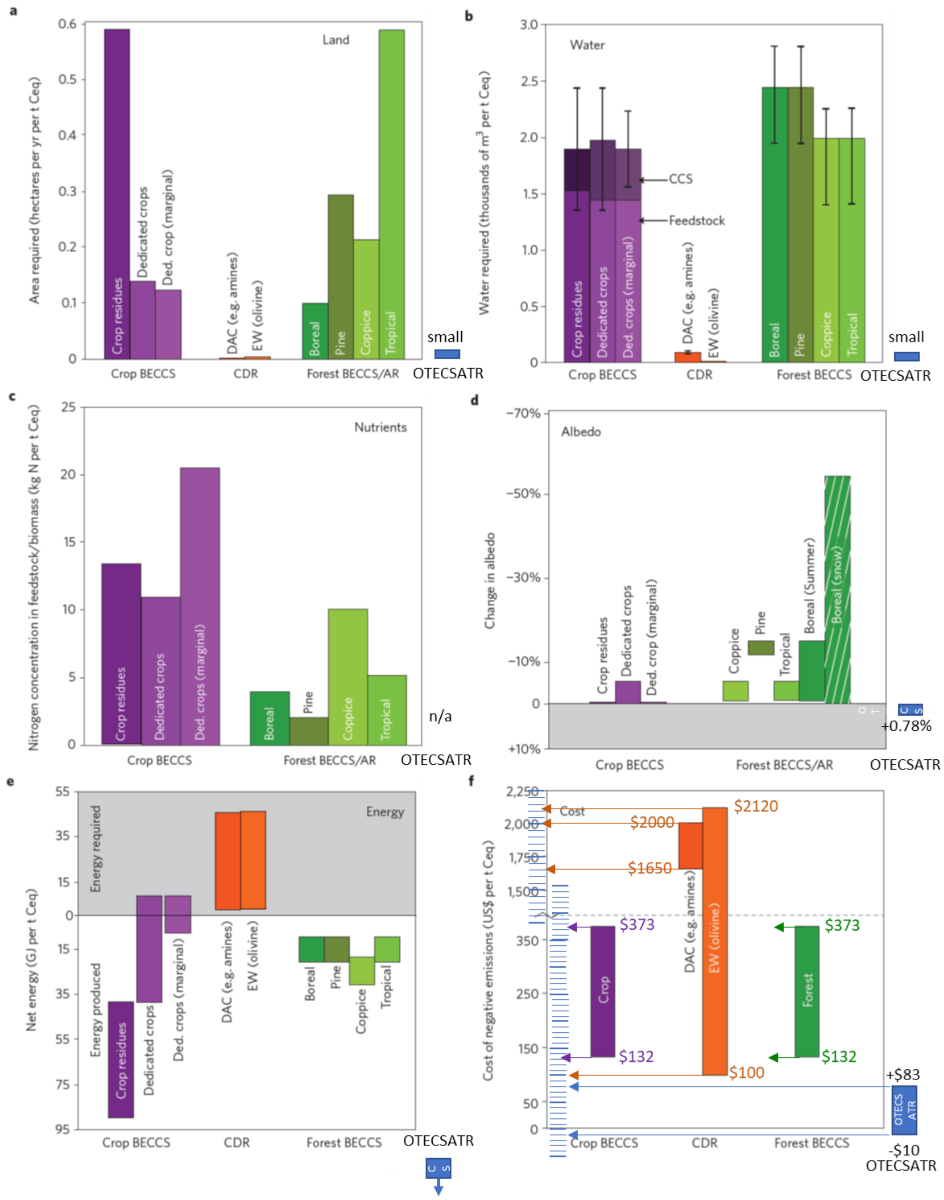


Figure 7 (Smith et al. Figure 3) The different requirements and impacts of NETs. **a**–**f**, Negative emissions technologies have different land (**a**), water (**b**) and nutrient (**c**) requirements, different geophysical impacts on climate (for example, albedo; **d**), generate or require different amounts of energy (**e**), and entail different capital and operating costs (**f**). For example, carbon dioxide removal (CDR) technologies such as DAC and EW of silicate rock tend to require much less land and water than strategies that depend on photosynthesis to reduce atmospheric carbon (**a**,**b**), but the CDR technologies demand substantial energy and economic investment per unit of negative emissions (**e**,**f**). Among BECCS options, forest feedstocks tend to require less nitrogen than purpose-grown crops (**c**), but present greater risk of unwanted changes in albedo (**d**), and generate less energy (**e**). AR has been omitted from **b**,**e**,**f** to avoid confusion with forest BECCS (where the CCS component is included). *Requirements and impacts for OTECISATR have been added on the same axes.*

Figure 8 summarizes the capabilities for the negative emission technologies analyzed by Smith et al.

If we look at Figure 8, first two columns, we see that the maximum annual capabilities (PgC/year) of the well-known carbon removal technologies (NET's) in year 2100 are 3.3 for BECCS, 3.3 for DAC, and (at very large scale) 1.0 for EW and 3.3 for AR. These add up to a total capability of 10.9 PgC/year at best.

Table 1 | Global impacts of NETs for the average needed global C removals per year in 2100 in 2 °C-consistent scenarios (430–480 ppm scenario category; Supplementary Table 3).

NET	Global C removal (Gt Ceq yr^{-1} in 2100)	Mean (max.) land requirement (Mha in 2100)	Estimated energy requirement (EJ yr^{-1} in 2100)	Mean (max.) water requirement (km^3 yr^{-1} in 2100)	Nutrient impact (kt N yr^{-1} in 2100)	Albedo impact in 2100	Investment needs (BECCS for electricity/ biofuel; US$ yr^{-1} in 2050)
BECCS	3.3	380–700	−170	720	Variable	Variable	138 billion/123 billion
DAC	3.3	Very low (unless solar PV is used for energy)	156	10–300	None	None	>>BECCS
EW*	0.2 (1.0)	2 (10)	46	0.3 (1.5)	None	None	>BECCS
AR*	1.1 (3.3)	320 (970)	Very low	370 (1,040)	2.2 (16.8)	Negative, or reduced GHG benefit where not negative	<<BECCS

10.9 GtCeq/year: Annual total capability in year 2100 including very large-scale deployment of EW and AR

*NETs with lower maximum potential than the BECCS emission requirement of 3.3 Gt Ceq per year in 2100; their mean (and maximum) potential is given along with their impacts (see Supplementary Methods). Wide ranges exist for most impacts, but for simplicity and to allow comparison between NETs (sign and order of magnitude), mean values are presented. See main text and Supplementary Methods for full details. PV, photovoltaic.

FIGURE 8 – TOTAL CARBON REMOVAL CAPABILITIES OF THE MOST WELL-KNOWN NEGATIVE EMISSIONS TECHNOLOGIES. IF ALL METHODS WERE DEPLOYED AT THEIR MAXIMUM CAPABILITIES, THE TOTAL COULD BE 10.9 GTCEQ/YEAR IN 2100

b. Emerging, less well-known, but promising NET's

- *OTEC Inducing a Surface Atmospheric Temperature Reduction (OTECISATR)*

This is a relatively new and not yet well-known approach. However its capabilities and costs appear to be quite attractive as an addition to well-known NET technologies. Therefore a bit more background information is given here than for the others. Full details and references are available elsewhere [18].

The OTECISATR approach is based on the 2015 discovery that the overall cold water upwelling rate from an environmentally-acceptable level (7 TW) of Ocean Thermal Energy Conversion (OTEC) (Figure 9a) is similar to the overall "artificial upwelling" rate which has been shown by Earth Systems Climate Modeling to directly decrease the Earth's Surface Atmospheric Temperature (SAT) by 1.08°C (Figure 9b). At 8.75 TW of OTEC, the upwelling rates are identical (Figure 9c - compare rows 1 and 4). The artificial upwelling study showed that the atmosphere-cooling effects of the cold water upwelling were felt far away from the actual locations of the upwelling (for example at the interiors of the Asian, African, and South American continents) and also as increased sea-ice coverage and albedo in the Arctic and Antarctic regions. In other words, the climate effects of the cold water upwelling spread globally. Therefore it is expected that at the same upwelling rate, the OTEC-induced upwelling (implemented between 30° north latitude and 30° south in the zone most favorable for OTEC) would be felt over a similarly broad worldwide area and with the same effects. This is an assumption until further climate modelling with the upwelling specifically in the OTEC zone can be conducted to examine it, but it appears to be a reasonable assumption.

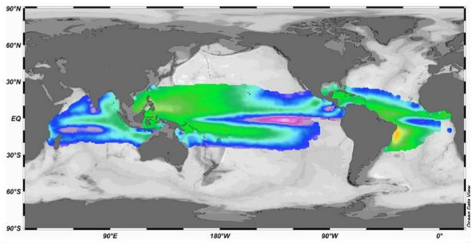
Assuming for now that the effects of OTEC-induced upwelling will be felt far away, it can be calculated (Figure 9d) that an SAT decrease of 1.08°C is equivalent to removing 2,261 $GtCO_2$ (616 PgC) from the atmosphere, which is about 78% of the total negative emissions (790 PgC) required to hold global warming to 1.6°C in year 2100 at the "current policies" emission levels of CO_2. The fact that it is accomplished by triggering large-scale natural forces is what keeps the cost low, compared to other methods of negative emissions.

Within the above assumptions, the SAT reduction produced by this approach should be just as effective for air temperature reduction as that produced by direct CO_2-removal methods (and therefore just as beneficial for the mitigation of sea-level rise and terrestrial manifestations of global warming). However its benefit in terms of mitigating ocean acidification will not be as large as an equivalent solution based solely on reducing positive emissions. A current estimate[19] is that (combined with sufficient wind, wave, and solar energy (WWS) to hold global warming to 1.5°C) it mitigates about 40% of the 0.27 "business-as-usual" decrease in pH expected between 2017 and 2100, whereas a 100% WWS solution holding global warming to 1.5C mitigates about 69% of the expected BAU decrease in pH.

The OTEC-induced reduction in surface air temperature requires the upwelled, discharged, and initially dense cold water to be diluted, maintained near the surface, and spread out over a wide area. Recent work has designed and analytically validated a method for doing so. Further details on this recent engineering element in the development of this technology can be found elsewhere.[20]

Using liquid ammonia as the storable hydrogen energy carrier, the approach can also supply roughly 2.8 TW of uninterruptible, dispatchable, CO_2-free electricity wherever needed on land, which importantly generates revenue that helps offset the costs of the negative emissions. Including the electricity revenue (at the same delivered-to-the-load rate of $0.1137/KwH as used in an analysis of WWS (wind, wave, and solar) powering the entire US[21]) and expressing the overall cost as a Net Present Value, the unit cost of negative emissions for the OTECSATR approach ranges from -$10/tCeq to +$83/tCeq (depending on the cost basis for the type of OTEC plant being referenced). This is considerably lower than any of the other negative emission technologies now being considered (Figure 7f). In addition, it produces more energy (172GJ/tCeq) than any of the other methods and its requirements for land and water resources are negligible.

Nihous et al. determined the extent to which OTEC can be deployed stably (in the tropical oceans)



K. Rajagopalan and G. Nihous, "An Assessment of Global Ocean Thermal Energy Conversion Resources With a High-Resolution Ocean General Circulation Model," Journal of Energy Resources Technology December 2013, Vol. 135, http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2010/01/Global-OTEC-Resources_2013.pdf

MIT GCM model calculations

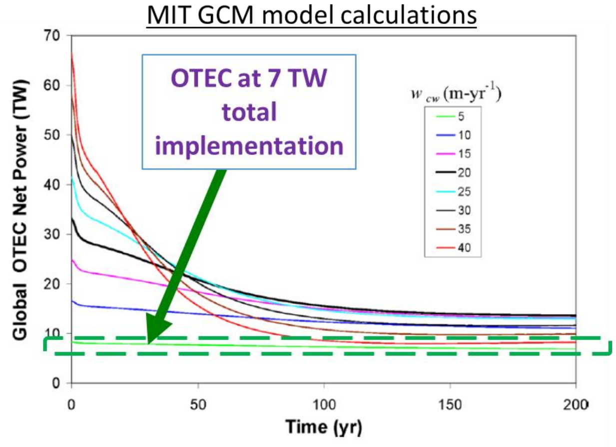


Fig. 3 Yearly averaged global OTEC power as a function of time for different OTEC flow intensities w_{cw} (m yr^{-1})

OTEC grazing plants operating at a total upwelling rate W_{cw} of 5 m/yr (1.4 cm/day) can produce net power on the order of 7 TW, forever.

- *The cold water resource is not consumed; it is regenerated in the polar regions and flows to tropical regions by means of the Earth's thermohaline circulation.*
- *When converted to ammonia and then burned on land wherever needed in power plants, this can generate 2.6 TW of storable, dispatchable, non-interruptible electric power.*[14]

FIGURE 9A – A SUMMARY OF RAJAGOPALAN AND NIHOUS MODEL PREDICTIONS FOR OTEC AT 7 TW TOTAL IMPLEMENTATION OVER THE AREA SHOWN

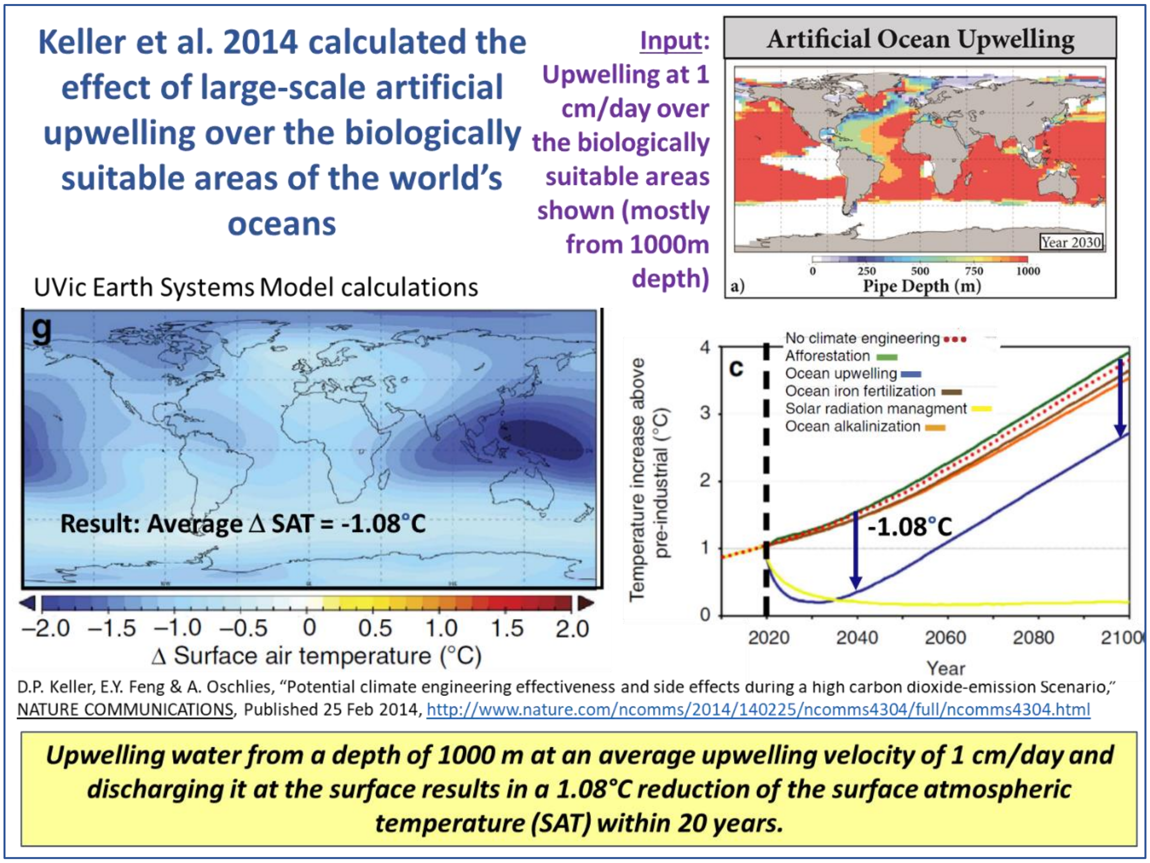


FIGURE 9B – A SUMMARY OF KELLER ET AL. MODEL PREDICTIONS FOR ARTIFICIAL OCEAN UPWELLING AT 1 CM/DAY UPWELLING VELOCITY OVER THE AREA SHOWN

1 Sv (Sverdrup) = 1.00E+06

Process	Net OTEC-generated electrical power, TW	Ratio of cold water flow to warm water flow	Net output of each OTEC plant	Number of OTEC plants per cluster	Number of OTEC plant clusters	Pipe diameter	Cross-sectional area	Average upwelling rate			Total cold water volumetric flow	Area of upwelling for all OTEC plants
			MW			m	m^2	cm/day	m/year	m/sec	Sv	m^2
Artificial upwelling of deep ocean water at an average velocity of 1 cm/day (3.65 m/yr) over the biologically-suitable area used by Keller et al						1	0.79	1	3.653	1.16E-07	26.4	2.28E+14
OTEC at 7 TW net generation using CW/WW flow ratio from Rajagopalan and Nihous	7	0.667							5.00	1.58E-07		1.14E+14
7 TW of OTEC using CW/WW flow ratio from report "OTEC Life Cycle Cost Assessment"	7	0.775	100	1	70,000	10	78.5			3.84		1.14E+14
100 MW grazing OTEC plants producing the same total upwelling as Keller et al	8.75	0.775	100	1	87,508	10	78.5			3.84		1.14E+14
Same as preceding but using 400 MW OTEC plants	8.75	0.775	400	1	21,877	20	314			3.84		1.14E+14
Same as preceding but using clusters of 10 OTEC plants	8.75	0.775	400	10	2,188	20	314			3.84		1.14E+14
Same as preceding but adding in discharged warm water	8.75	0.775	400	10	2,188	20	314			3.84		1.14E+14
Same as preceding but diluting the discharged warm water by 51.6	8.75	0.775	400	10	2,188	20	314			3.84		1.14E+14

m^3/sec

Type of discharge	Additional dilution	cold water mass flow Per OTEC plant or cluster	water density	Cold water volumetric flow per OTEC plant or cluster	Total volumetric flow	% of Keller et al upwelling flow rate	Delta T between surface and water being delivered	Total rate of coldness being delivered to surface	Change in Earth's surface air temperature (SAT)	Ocean area per OTEC plant cluster	Spacing of OTEC plants
		kg/sec	kg/m^3	m^3/sec	m^3/sec		C	C- m^3/sec	Degrees C	m^2	km
Cold water					2.64E+07	100%	-21.2	-5.60E+08	-1.08		
Cold water					1.81E+07	68%					
Cold water		3.10E+05	1027.56	302	2.11E+07	80%	-21.2	-4.48E+08	-0.86		
Cold water		3.10E+05	1027.56	302	2.64E+07	100%	-21.2	-5.60E+08	-1.08		
Cold water		1.24E+06	1027.56	1,207	2.64E+07	100%	-21.2	-5.60E+08	-1.08		
Cold water		1.24E+07	1027.56	12,067	2.64E+07	100%	-21.2	-5.60E+08	-1.08	5.21E+10	228
Mixed cold/warm	2.290	2.84E+07	1027.56	27,634	6.05E+07	229%	-9.3	-5.60E+08	-1.08	5.21E+10	228
Diluted mixed cold/warm	51.6	1.47E+09	1027.56	1,425,933	3.12E+09	11816%	-0.179	-5.60E+08	-1.08	5.21E+10	228

FIGURE 9C – COMPARISON OF THE TOTAL UPWELLING RATES FOR THE OTEC PREDICTIONS AND FOR THE ARTIFICIAL OCEAN UPWELLING PREDICTIONS. 8.75 TW OF OTEC HAS THE SAME TOTAL UPWELLING RATE AS THE CONDITIONS THAT RESULT IN A 1.08 C DECREASE IN THE EARTH'S SURFACE ATMOSPHERIC TEMPERATURE.

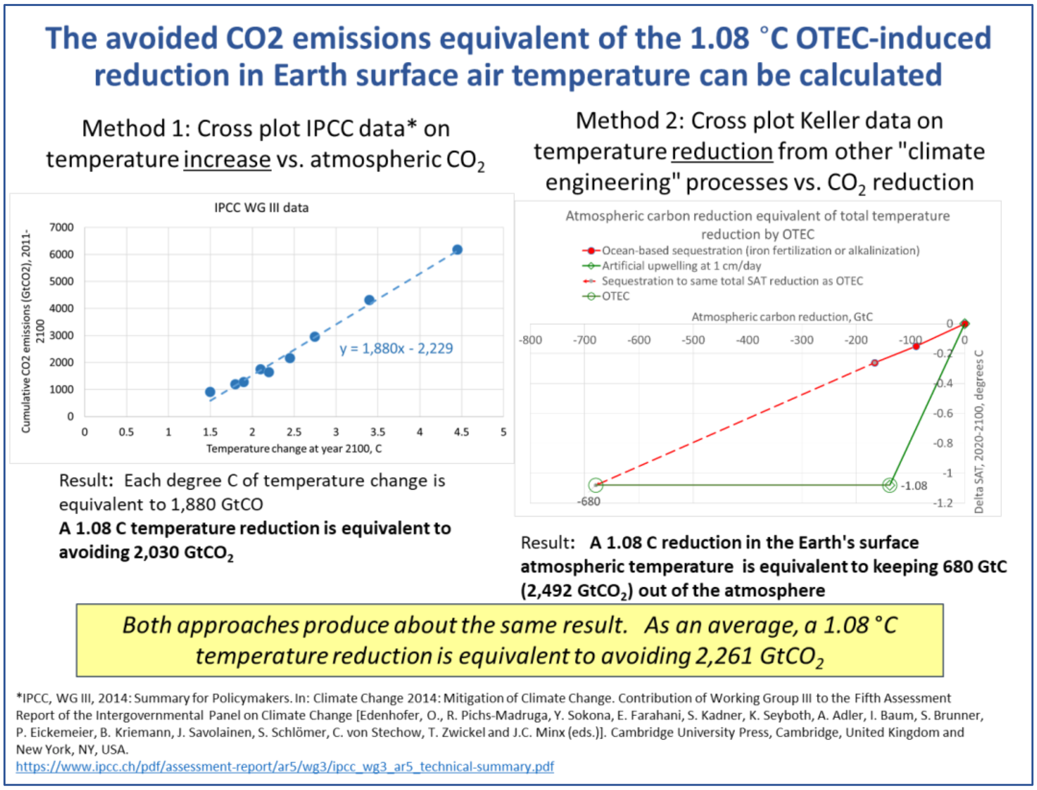


FIGURE 9D – *A 1.08 °C TEMPERATURE REDUCTION IS EQUIVALENT TO AVOIDING 2,261 $GtCO_2$*

5. <u>Total capabilities and total costs for various negative emissions technologies</u>

Figure 10 summarizes the annual capabilities, unit costs, and total annual costs (at max capability) for the negative emissions technologies analyzed by Smith et al. as "Plan A." "Plan B" in Figure 10 adds OTECISATR to this mix. Within each plan, the individual technologies are given in order of increasing average unit cost, so that they can be deployed with the most efficient technology first as a market response in the presence of finite available funds. For OTECISATR, its maximum estimated cost is used instead of an average of maximum and minimum data, for conservatism with a relatively new system-level concept. Note that for Plan A the maximum annual capability is 10.9 PgCeq/year, whereas for Plan B it is much larger, at 22.5 PgCeq/year and with a much lower unit cost for much of this capability.

Costs for negative emission technologies		"Market-based approach" (Deploy lowest-unit-cost technologies first)				
These costs are taken from Smith et al Figure 3. They differ from some of the numbers mentioned in the Smith et al text						
Technology	Annual capability in year 2100 after ramp-up	Unit cost (minimum)	Unit cost (average)	Unit cost (maximum)	Total annual capability with lowest unit cost process deployed first	Total annual cost at each step in total annual capability
	PgCeq/year	$/tCeq	$/tCeq	$/tCeq	PgCeq/year	(based on average costs)
Plan A: Use only well-known negative emissions technologies (from Smith et al)						
Forest BECCS/AR	3.3	$132	$253	$373	3.3	$833,250,000,000
Crop BECCS	3.3	$132	$253	$373	6.6	$1,666,500,000,000
EW	1.00	$100	$1,110	$2,120	7.6	$2,776,500,000,000
DAC	3.3	$1,650	$1,825	$2,000	10.9	$8,799,000,000,000
Total or average	10.9		$807.25			
Plan B: Use all negative emissions technologies including OTECSATR						
OTECSATR (average over built-out)	11.6		$82.61	$82.61	11.6	$960,297,140,204
Forest BECCS/AR	3.3	$132	$253	$373	14.9	$1,793,547,140,204.03
Crop BECCS	3.3	$132	$253	$373	18.2	$2,626,797,140,204
EW	1.00	$100	$1,110	$2,120	19.2	$3,736,797,140,204
DAC	3.3	$1,650	$1,825	$2,000	22.5	$9,759,297,140,204.03
Total or average	22.5		$433.28			

FIGURE 10 – ANNUAL CAPABILITIES, UNIT COSTS, AND TOTAL ANNUAL COSTS (AT MAX CAPABILITY) FOR TWO SETS OF NEGATIVE EMISSIONS TECHNOLOGIES. PLAN A INCLUDES ONLY THE WELL-KNOWN NEGATIVE EMISSIONS TECHNOLOGIES REVIEWED BY SMITH ET AL., WHEREAS PLAN B ADDS OTECSATR TO THAT MIX.

In modeling the deployment of negative emissions, Hansen et al. assumed an implementation starting in 2010 with a linear increase in annual capability thereafter. With this assumption, Figure 11 (orange line) shows the annual negative emission level that is required to reach the total negative emissions of 790 PgC, which was determined in Figure 5 to be needed to hold global warming to 1.6°C in the presence of current policy positive emissions (dashed black line). We see that the total annual capability of the well-known negative emissions methods (Plan A) is insufficient to meet this requirement, but if OTECISATR is added per Plan B, the total is more than sufficient to meet the negative emissions requirement through 2100.

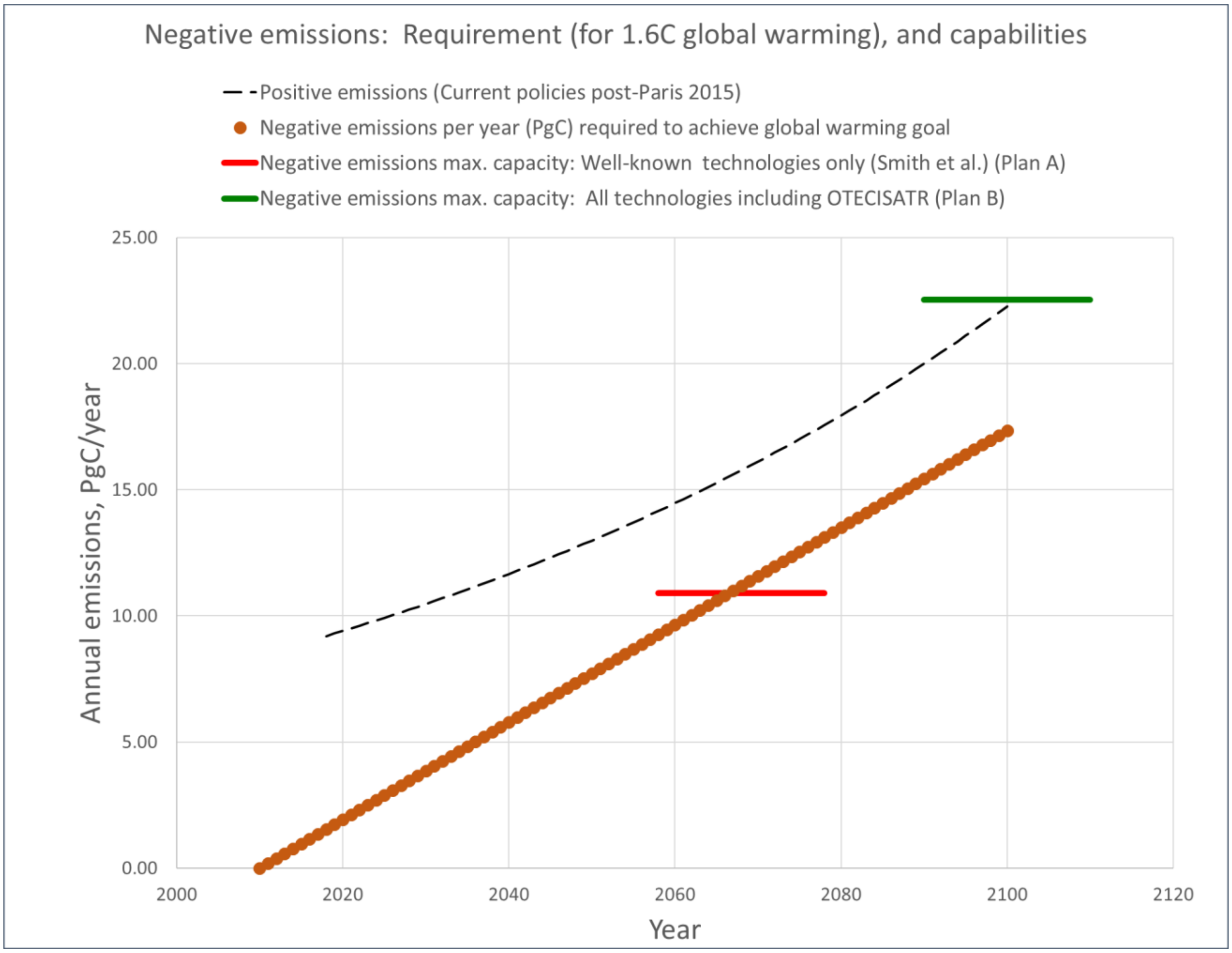


FIGURE 11 – REQUIRED ANNUAL NEGATIVE EMISSIONS TO KEEP GLOBAL WARMING BELOW 1.6C IN YEAR 2100 IN THE PRESENCE OF CURRENT-POLICY POSITIVE EMISSIONS. THE WELL-KNOWN NEGATIVE EMISSIONS TECHNOLOGIES (PLAN A) HAVE INSUFFICIENT CAPABILITY TO MEET THE NEED, BUT IF OTECSATR IS ADDED TO THEM (PLAN B), THERE IS SUFFICIENT CAPABILITY

6. Year-by-year resource deployment analysis comparing the costs of various negative emissions technologies against one potential source of funding

Figure 12 shows the annual costs for "Plan A" and "Plan B" negative emissions technologies, deployed in order of increasing cost to meet the calculated increasing annual demand. As described above, Plan A is insufficient in capability (Figure 11) and is also considerably more expensive at any level of negative emissions than Plan B. For comparison against the Plan B costs, the carbon fee rate proposed by Citizens' Climate Lobby is also shown, along with the carbon fee income that would be available if that rate were collected on the entire world's positive emissions of CO_2 (black dashed line in Figure 11). The total negative emissions cost is on the order of 16% of the carbon fee collected. This finding opens up the possibility of using a modest fraction of the revenue collected from carbon fees on positive emissions as a negative emissions credit to totally cover the cost of the negative emissions required to avoid catastrophic global warming

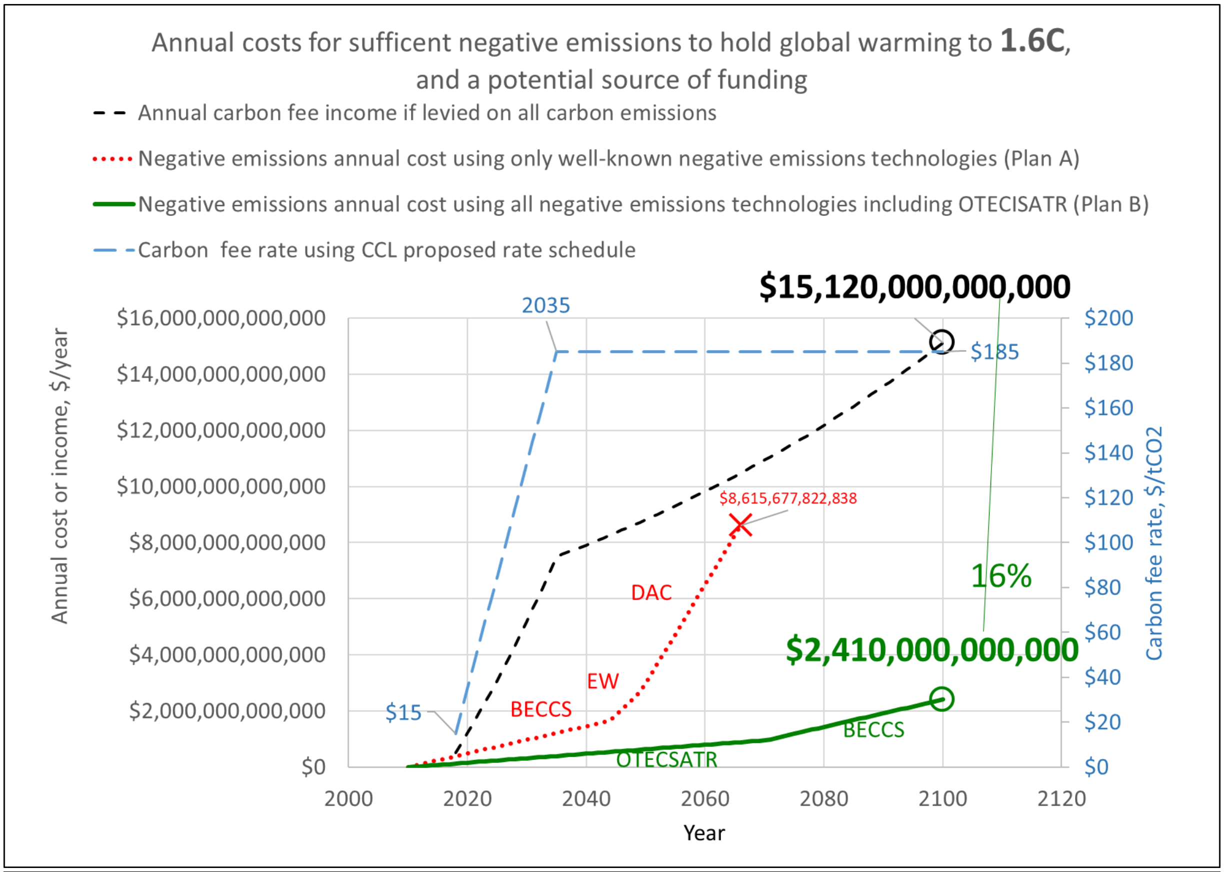


FIGURE 12 – ANNUAL COSTS FOR SUFFICIENT NEGATIVE EMISSIONS TO HOLD GLOBAL WARMING TO 1.6°C USING PLAN B. PLAN A HAS INSUFFICIENT TOTAL CAPABILITY (FIGURE 11) AND IS ALSO OF SUBSTANTIALLY HIGHER COST PER UNIT CAPABILITY. THE TECHNOLOGY BEING USED (LOWEST COST AT EACH STAGE) IS INDICATED. THE CARBON FEE INCOME THAT WOULD BE AVAILABLE IF THE CCL-PROPOSED CARBON FEE RATE WERE COLLECTED ON THE ENTIRE WORLD'S POSITIVE EMISSIONS OF CO2 IS ALSO SHOWN. THE TOTAL NEGATIVE EMISSIONS CREDIT THAT WOULD BE PAID OUT UNDER PLAN B IS ON THE ORDER OF 16% OF THE CARBON FEE THAT WOULD BE COLLECTED, WHICH MIGHT ENABLE CARBON FEES TO BE THE SOURCE OF FUNDING IMPLEMENTING THE NECESSARY NEGATIVE EMISSIONS.

7. Conclusions

- A year-by-year resource deployment analysis has been constructed to examine the implementation of negative emissions sufficient to hold global warming to 1.6°C in year 2100 with current policy levels of positive emissions.
- Two alternative approaches have been considered: "Plan A" employing only the currently well-known negative emissions technologies, and "Plan B" also including the OTECISATR approach.
- Within each approach, the lowest-cost technology is deployed first (up to its maximum capability) as would occur with market-based solutions, and the resulting curves of annual cost vs. year (through year 2100) are calculated.
- The total capability of the Plan A approach, based only on currently well-known negative emissions technologies, is insufficient to hold global warming to 1.6°C. In addition, over its operable extent, the total cost per unit negative emissions for Plan A would be much higher than for Plan B.
- Plan B has sufficient total capability to hold global warming to 1.6°C in year 2100.

- The total cost of the negative emissions under Plan B is on the order of 16% of the total income that would be generated if the CCL carbon fee rate could be collected on the world's total projected positive emissions.
- This finding opens up the possibility of using a modest fraction of the revenue collected from carbon fees on positive emissions as a negative emissions credit to totally cover the cost of the negative emissions required to avoid catastrophic global warming.

Full disclosure: The author is the originator of the OTECISATR approach described in the preceding

---

[1] Global Carbon Project, *Global Carbon Budget 2015*, 7 December 2015, Slide 8, http://www.globalcarbonproject.org/carbonbudget/archive/2015/GCP_budget_2015_v1.02.pdf

[2] Climate Action Tracker Warming Projections, Global Update 2017, http://climateactiontracker.org

[3] Joeri Rogelj et al., "Paris Agreement climate proposals need a boost to keep warming well below 2 °C", Nature, Vol. 534, June 30, 2016 http://www.nature.com/nature/journal/v534/n7609/abs/nature18307.html

[4] "Greenhouse gases must be scrubbed from the air " The Economist, Nov 16th 2017 https://www.economist.com/news/briefing/21731386-cutting-emissions-will-not-be-enough-keep-global-warming-check-greenhouse-gases-must-be

[5] Climate Action Tracker Warming Projections, op cit.

[6] James Hansen et al., Young people's burden: requirement of negative CO2 emissions, Earth Syst. Dynam., 8, 577–616, 2017, https://www.earth-syst-dynam.net/8/577/2017/esd-8-577-2017.pdf

[7] James Hansen et al., op. cit.

[8] IPCC, WG III, 2014: IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Table SPM.1. https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_technical-summary.pdf

[9] Pete Smith et al., "Biophysical and economic limits to negative CO_2 emissions", *Nature Climate Change* volume 6, pages 42–50 (2016), https://www.nature.com/articles/nclimate2870

[10] Pete Smith et al., op. cit.

[11] Claire O'Neill, "Can We Really Scrub Carbon Dioxide From the Atmosphere?", NY Times, Feb. 28, 2018 https://www.nytimes.com/2018/02/28/climate/remove-co2-from-air.html?emc=edit_clim_20180228&nl=&nlid=62937158&te=1

[12] Pete Smith et al., op. cit.

[13] Claire O'Neill, op cit.

[14] Pete Smith et al., op. cit.

[15] Claire O'Neill, op cit.

[16] Pete Smith et al., op. cit.

[17] Claire O'Neill, op cit.

[18] Alan K. Miller et al., https://www.cool-it-earth.com/

[19] Alan K. Miller, Steven Rizea, Brian von Herzen, "An approach to holding global warming to 1.5°C within the CO_2 reduction commitments from Paris 2015, using OTEC technology", 2018 manuscript available at https://www.cool-it-earth.com/

[20] Alan K. Miller, Steven Rizea, Brian von Herzen, op cit.

[21] Jacobson, M.Z.; Delucchi, M.A.; Cameron, M.; Frew, B.A., "Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes," *PNAS*, **2015**, *112*, pp. 15060-15065, Table 2, doi/10.1073/pnas.1510028112