The Economics of Climate Change – Likely Carbon Sequestration Costs
Bruce Parker
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Abstract

While the World has concentrated its efforts and planning on the meeting the IPCC's 2°C warming target and trying to figure out how to cost effectively reduce CO2 emissions to zero to keep greenhouse gas emissions within the IPCC's 1000 GTC carbon budget, what has been overlooked are both the serious implications of the Arctic amplification that is already underway and the expected high costs of carbon dioxide removal (CDR). A close analysis of the magnitudes of the various global warming feedbacks indicates that a significant reduction is needed to the IPCC carbon budget, and since it is also very likely that future anthropogenic emissions will exceed the existing IPCC carbon budget, we will certainly "overshoot" any realistic carbon budget that aims to prevent disruptive climate change. Our only option then becomes removing a significant quantity of CO2 from the atmosphere. But the costs for carbon dioxide removal for the "overshoot" are almost certainly more that we will be willing to pay. As a consequence, the only way to keep the temperature from increasing to the point where climate change becomes disruptive is to use some sort of albedo modification. Unfortunately, it is very unlikely that CDR costs will ever get to the point where CDR will be used to reduce the atmospheric CO2 back to necessary levels. As consequence, if albedo modification is ever started, it will have to continue indefinitely.

Summary

It is well known among climate scientists that the models that the IPCC used to determine a reasonable carbon budget did not take into account the likely magnitude of many of the known positive feedbacks from a warming world (lower albedo from the melting of the summer-time Arctic Ocean, greenhouse gas emissions from a thawing permafrost, etc.).

"It [(permafrost melt)] was first proposed in 2005. And the first estimates came out in 2011." Indeed, the problem is so new that it has not yet made its way into major climate projections, Schaefer says." …"None of the climate projections in the last IPCC report account for permafrost," says Schaefer. "So all of them underestimate, or are biased low." … "It's certainly not much of a stretch of the imagination to think that over the coming decades, we could lose a couple of gigatons per year from thawing permafrost," says Holmes…. But by 2100, the "mean" estimate for total emissions from permafrost right now is 120 gigatons, say Schaefer. http://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet/

And what is not appreciated by the public is that the "2°C pathway" requires significant carbon sequestration (from one to three GTC/year, partly through bioenergy carbon capture and sequestration - BECCS):

"Mitigation scenarios reaching about 450 ppm CO2eq in 2100 typically involve temporary overshoot of atmospheric concentrations … Depending on the level of the overshoot, overshoot scenarios typically rely on the availability and widespread deployment of BECCS and afforestation in the second half of the century." "Many models could not achieve atmospheric concentration levels of about 450 ppm CO2eq by 2100 if additional mitigation is considerably delayed or under limited availability of key technologies, such as bioenergy, CCS, and their combination" (IPCC AR5 Summary for Policy Makers).

Because of significant costs associated with BECCS (perhaps $60-$250 per ton of CO2 or $200-$1000/ton of carbon – see National Academy of Sciences - http://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration), the quantity of CO2 that needs to be removed, and the uncertainty of the development and deployment of BECCS technology, there are serious doubts that a realistic carbon budget[+] can be met.

This document examines the likely *sequestration* costs of meeting a realistic carbon budget – the costs of mitigation (which will likely be quite large) are not included. In order to do a "cost benefit analysis" of the needed sequestration costs, additional background information is first provided.

+In this document, a "realistic carbon budget" refers to maximum amount of anthropogenic greenhouse gases that can be emitted in order to keep the Earth's temperature from rising past the point where disruptive weather-related climate change becomes inevitable (certainly less than 2°C), and NOT the anthropogenic CO_2 emissions that can realistically be expected to be emitted by reasonable mitigation scenarios.

Major Points

1. Catastrophic sea level rise cannot be prevented
2. Catastrophic ocean acidification is almost certain
3. If we have not already past the "tipping point" for the eventual release of significant quantities of greenhouse gas emission from global warming feedbacks, we are not far from it
4. The 1000 GTC budget (based on 2°C IPCC target) is too high, so a lower target is needed
5. We will certainly overshoot the target by a very large amount, so we will need to remove significant quantities CO_2 to meet a realistic carbon budget
6. Bio-energy carbon capture and storage (BECCS) is the least expensive carbon dioxide removal (CDR) technique, but will likely play a minimal role in removing excess CO_2 from the atmosphere.
7. Other CDR options are likely more expensive the BECCS at the scale that is needed
8. Greenhouse gas emissions need to be brought under control BEFORE global warming feedbacks start contributing significantly to the Earth's temperature, as an additional equivalent amount of CO_2 wound then need be sequestered, driving the costs even higher.
9. If we want to prevent disruptive climate change, we can't wait for technologic advances to significantly reduce the costs of CDR before employing it aggressively.
10. Removing CO_2 at the rate needed will cost roughly a trillion dollars a year (and likely much more)
11. CDR provides no useful economic benefit in and of itself
12. There is no "return on investment" so there will be no private funding
13. Costs avoided this century will be much less than CDR costs (for this century, the "cost of inaction" is significantly less than the "cost of action")
14. Society can barely afford 0.1% of what is needed
15. There a maximum amount that society could be realistically expected to be willing to pay for CDR
16. That maximum amount is almost certainly less than expected costs of the CDR expenditures that would be needed
17. No politician will ever recommend spending significant dollars "today" on CDR, so costs will always be passed on to future generations
18. It is very unlikely that, through realistic mitigation and CDR expenditures alone, it will be possible to prevent disruptive climate change that will be in addition to the expected catastrophic sea level rise

For emissions 2015-2100 (">>" = much greater than):

(Total Realistic Emissions – Realistic Carbon Budget) * CDR Costs >> Realistically Willing to Pay
((E-B)*C >> WP)

This implies that we will almost certainly pass the "Arctic temperature tipping point" that leads to disruptive climate change that is in addition to that caused by catastrophic sea level rise.

There are only four variables (the value for the "Arctic temperature tipping point" is part of the "Realistic Carbon Budget") and reasonable values for the lower/upper bounds are all known with enough accuracy to know that the above formula is correct.

Short Version

(1) Catastrophic sea level rise cannot be prevented (expect an "equilibrium" rise of 10-20 meters/°C, so at least 10 meters is unavoidable)
(2) "Permafrost melt was first proposed in 2005. And the first estimates came out in 2011." …"None of the climate projections in the last IPCC report account for permafrost melt" (Permafrost thawing will release greenhouse gases)
(3) There is an "Arctic temperature tipping point" which, when reached, will cause a "feedback loop" of greenhouse gas emissions and albedo changes that will drive the temperature increase to well over 4°C with disastrous consequences for our civilization
(4) This "Arctic temperature tipping point" is correlated to the atmospheric concentration of CO2, so there is also an "Arctic atmospheric CO2 level tipping point" (although it will take years for the "Arctic temperature tipping point" to be reached after the "Arctic atmospheric CO2 level tipping point" is reached)
(5) It is possible that the "Arctic atmospheric CO2 level tipping point" is at or below 400PPM (where we are now), but it is almost certainly less than 425 PPM (where we will in about ten years)
(6) Once the "Arctic atmospheric CO2 level tipping point" is reached any additional CO2 which is added to the atmosphere will have to be removed
(7) The IPCC 2°C scenario envisions a maximum atmospheric concentration of CO2 of about 450 PPM. Since almost no one expects this target to be met, a reasonable "minimum overshoot" is 460 PPM (and will likely be very much more)
(8) It is very unlikely that the "overshoot" will be less than 35 PPM, which represents about 640 gigatons of CO2 (about 15 years of emissions)
(9) Sequestration costs for carbon dioxide removal (CDR) are expected to be about $60-$250 per ton of CO2, with average costs toward the high end of the range expected to be more likely because of the large amount that needs to be removed
(10) At $100/ton, total CDR costs will almost certainly be over $64 trillion - much more that we will be willing to spend

Really short version

- The amount of CO2 that the Earth's atmosphere can hold if we are to avoid disruptive climate change is significantly less than what the IPCC estimated in their last report
- Based on realistic projections of future greenhouse gas emissions, the warming that will eventually occur will almost certainly cause disruptive climate change
- The costs to remove enough CO2 to sufficiently reduce the future warming are likely to exceed $1 Trillion dollars per year – much more than our society would be willing to pay

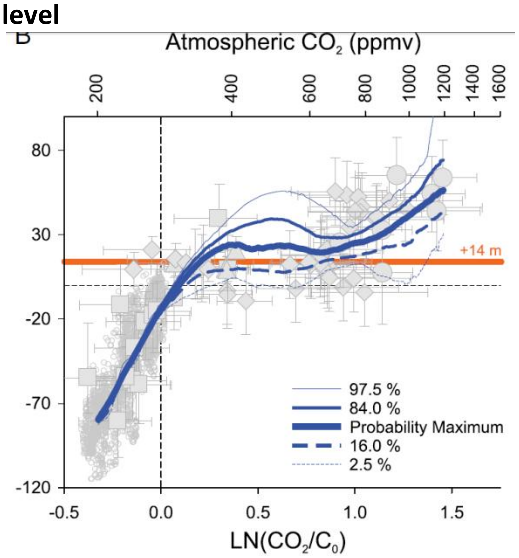
Sea Level Rise

The sea level is rising for two reasons: as the ocean warm the water expands; and as the Earth's average atmospheric temperature rises land ice melts. Since 1993, global sea level has risen at an accelerating rate of around 3.5 mm/year. More recently the sea level rise has been 4.5 mm/year

Based on paleoclimatic data we can expect an equilibrium sea level rise of about 10-20 meters per degree C of temperature increase (see Figures SLR1 and SLR2)

Sea level rise will almost certainly be catastrophic no matter how aggressively CO2 emissions can be reduced, since we should plan on at least 10 meters (30 feet) of sea level rise for the amount of CO2 already in the atmosphere. This will not likely happen before 2100 (expectations are 1-2 meters), but a sea level rise of about a foot per decade can be expected after that.

Cross-plot of estimates of atmospheric CO2 and coinciding sea level

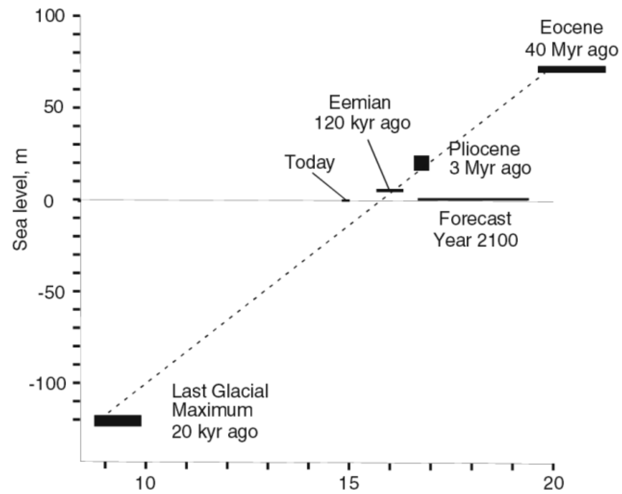


Cross-plot of estimates of atmospheric CO2 and coinciding sea level… (B) Results from our probabilistic analysis of the data that fully accounts for uncertainty in both X and Y parameters … dotted lines denote the preindustrial conditions of 0 m and 280 ppm CO2. The horizontal orange line shows +14 m, which is the sea-level rise associated with the total melting of WAIS and GrIS (31). (WAIS= West Antarctic Ice Sheet, GrIS=Greenland Ice Sheet) Source: "Relationship between sea level and climate forcing by CO2 on geological timescales", Gavin L. Foster and Eelco J. Rohling, Sept 2012 – *(Vertical axis is meters of sea level rise)*

http://www.pnas.org/content/110/4/1209.figures-only

Figure SLR1

The relationship between sea level and temperature on geologic time scales. Data from (Alley et al. 2005)



There is a clear and strong correlation between long-term global average temperature and sea level in the geologic record. Sea level has the potential to change much more than is forecast for the coming century, and it has done so in the past. The slope of covariation from the geologic record has been 10–20 m/°C. (*Horizontal axis is atmospheric temperture in degrees C)*

https://geosci.uchicago.edu/~archer/reprints/archer.2008.tail_implications.pdf

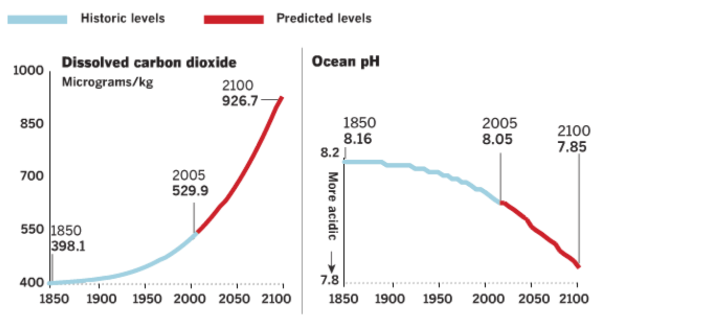
Figure SLR2

Ocean Acidification

As CO_2 dissolves in the oceans, it leads to a drop in pH. This change in sea water chemistry adversely affects corals, shellfish and other marine organisms whose shells or skeletons are made from calcium carbonate. The ocean pH has dropped about .1 pH from preindustrial times. (See Figure AA1)

If CO_2 emissions continue at the current rate the ocean pH will likely drop another 0.3 to 0.4 pH units by2100, which would kill off most corals and shell fish. For the Southern Ocean, the acidification tipping point is about 450-ppm atmospheric CO_2 (http://www.pnas.org/content/105/48/18860.long) , which will be reached in about 25 years at the current rate of increase (2.11PPM/Year). Ocean Acidification will almost certainly be catastrophic (or at least very bad) based on any reasonable CO_2 emissions mitigation scenario.

Here's more info on ocean acidification, from the Royal Society's seminal study:



Note: 100 micrograms represents a 10,000th of one gram for each thousand grams of seawater.

Ocean acidification due to atmospheric carbon dioxode, Altered Oceans: A Chemical Imbalance

Good source for new research:
Ocean Acidification blog

Figure AA1

Arctic Amplification

The Arctic region is currently warming about three times as fast as the Earth as a whole (.42 degrees/decade for the Arctic (see Figure AA1) vs .15 degrees/decade for the Earth as a whole), primarily due to the melting of summer-time sea ice (which is happening much more quickly than the IPCC models expected - see Figure AA2).

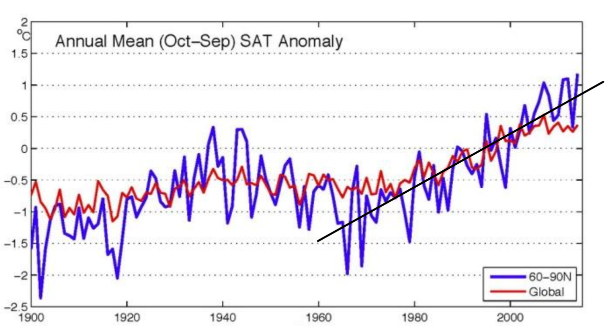
> "Although northern peatlands are currently a net carbon sink, … they are a net source of CH_4 [methane, emitting an] equivalent [of] 6–12% of annual fossil fuel emissions of CO2" (about .67-1.33 GTC or 2.4-4.8 GTCO2) http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4000816/ (April 2014)

> "As climate change thaws Arctic permafrost and releases large amounts of methane into the atmosphere, it is creating a feedback loop that is "certain to trigger additional warming," according to the lead scientist of a new study investigating Arctic methane emissions." (May 2014) http://www.climatecentral.org/news/arctic-methane-emissions-certain-to-trigger-warming-17374

> "Since the year 2000, the rate of absorbed solar radiation in the Arctic in June, July and August has increased by five percent. … When averaged over the entire Arctic Ocean, the increase in the rate of absorbed solar radiation is about 10 Watts per square meter." (Dec 2014) http://www.nasa.gov/press/goddard/2014/december/nasa-satellites-measure-increase-of-sun-s-energy-absorbed-in-the-arctic
>
> Since the Arctic Ocean covers about 2.8% of the Earth's surface, this is equivalent to about .3 W/M^2 for the entire Earth. With an increase of about .77 degrees C for each w/m^2 increase in "radiative forcing" (http://www.realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/), this represents about .2°C of warming, or about 100 GTC (based on 800 GTC raising the temperature 1.6°C)

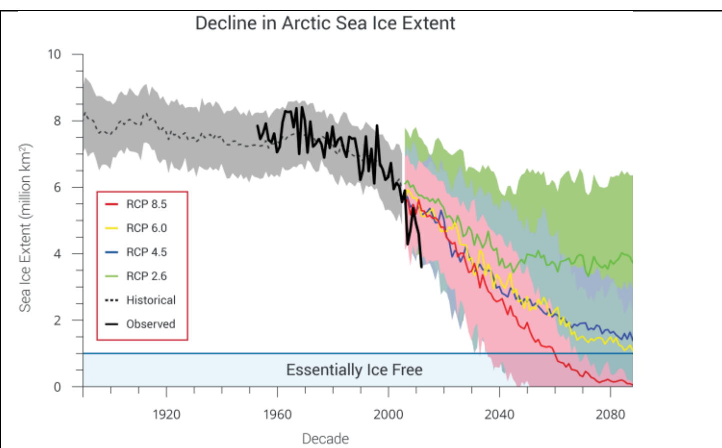
The Arctic amplification will very likely hasten arrival of the Arctic's temperature "tipping point" - that temperature at which the albedo changes and emissions from a thawing permafrost (see Table AA1) will provide a strong enough feedback so that significant greenhouse gas emissions from the thawing permafrost becomes unstoppable. When this tipping point is reached, the resulting equilibrium temperature increase will be over 4°C.

Although determining this tipping point exactly is impossible (and we may have already passed it), it is sufficient to pick a point (either atmospheric CO2 or temperature, as they are closely correlated) above which we are confident that the tipping point (i.e., self reinforcing positive feedbacks) will occur and see if this point is below that which is likely to be reached by future anthropogenic emissions (i.e., the tipping point likely to be below the minimum expected temperature increase from expected anthropogenic greenhouse gas emissions).



Arctic and global mean annual surface air temperature (SAT) anomalies (in °C) for the period 1900-2014 relative to the 1981-2010 mean value. The Arctic data are for land stations north of 60°N (The line shows an increase of about .42°C /decade) http://www.arctic.noaa.gov/reportcard/air_temperature.html

Figure AA1



http://data.globalchange.gov/file/6c06e9fb-29ea-41c1-acf5-c81ed0cbd831

Figure AA2

Feedback/Factor	Carbon Store Size	Range of Likely Emission Values/Temperature Changes
Albedo Changes		
Arctic Ocean	Already .27 W/M^2, with pollution reducing the amount[7]	
		.3-1.3 w/m[8,9]
Retreating snowline		1.3 w/m[8,9]
Tundra greening		
Land use changes		
Other?		
CO2 Emissions		
Permafrost	1,600	.4-.6°F by 2100[1] 190 GTC by 2200[2] 250 GTC[3] by 2100
Peat Bogs	270 to 370[4]	100-220[5]
Methane Hydrates	5,000 to 20,000[3,6]	
Other Soils		
Tropical Forests	86 GTC (Amazon)	
Temperate Forests		
Other?		
Atmosphere	820 GTC	
Anthropogenic Emissions	525 GTC	(through 2011)
Fossil Fuel Reserves	760 GTC	1.6°C if all reserves burned
1. http://nca2014.globalchange.gov/report/our-changing-climate/melting-ice .4-.6°F		
2. http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt264.pdf		
3. http://whatweknow.aaas.org/wp-content/uploads/2014/07/whatweknow_website.pdf		
4. globalcarbonproject.org/global/pdf/pep/Limpens.2008.Peatlands& Carbon.BiogeosciencesDiscus.pdf		
5. http://thinkprogress.org/climate/2015/01/13/3610618/peat-wetlands-global-warming/		
6. http://www.killerinourmidst.com/methane and MHs2.html		
7. http://www.nasa.gov/press/goddard/2014/december/nasa-satellites-measure-increase-of-sun-s-energy-absorbed-in-the-arctic		
8. http://www.esrl.noaa.gov/gmd/co2conference/posters_pdf/jones1_poster.pdf		
9. http://arctic-news.blogspot.com/2012/07/albedo-change-in-arctic.html		

Table AA1 – Feedback Factors

Other links of note:
http://www.sciencedaily.com/releases/2013/06/130619101521.htm
http://www.motherjones.com/blue-marble/2013/03/were-getting-scarily-close-permafrost-tipping-point
http://www.colorado.edu/geography/class_homepages/geog_4271_f11/lectures/Schaefer_Permafrost.pdf
http://www.climatecentral.org/news/nearing-a-tipping-point-on-melting-permafrost-15636

"In Antarctica, sea ice grows quite extensively during winter but nearly completely melts away during the summer (Figure 1). That is where the important difference between Antarctic and Arctic sea ice exists as much of the Arctic's sea ice lasts all the year round. During the winter months it increases and before decreasing during the summer months, but an ice cover does in fact remain in the North which includes quite a bit of ice from previous years (Figure 1). Essentially Arctic sea ice is more important for the earth's energy balance because when it increasingly melts, more sunlight is absorbed by the oceans whereas Antarctic sea ice normally melts each summer leaving the earth's energy balance largely unchanged."(http://www.skepticalscience.com/antarctica-gaining-ice.htm)

Has the Arctic Ocean always had ice in summer?

We know for sure that at least in the distant past, the Arctic was ice-free. Fossils from the age of the dinosaurs, 65 million years ago, indicate a temperate climate with ferns and other lush vegetation.

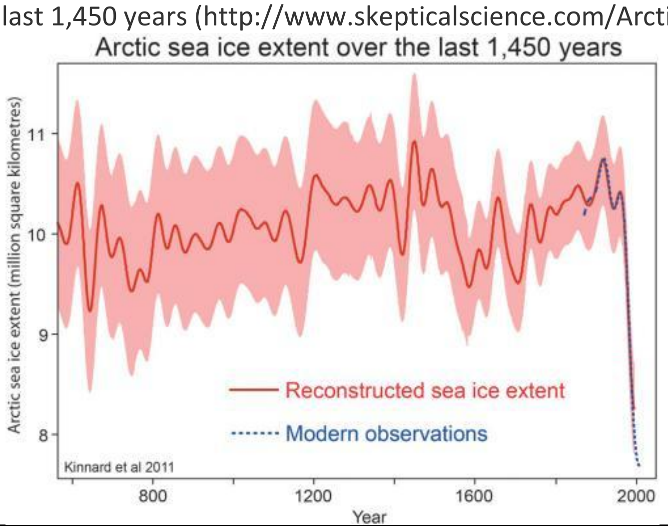
Based on the paleoclimate record from ice and ocean cores, the last warm period in the Arctic peaked about 8,000 years ago, during the so-called Holocene Thermal Maximum. Some studies suggest that as recent as 5,500 years ago, the Arctic had less summertime sea ice than today. However, it is not clear that the Arctic was completely free of summertime sea ice during this time.

The next earliest era when the Arctic was quite possibly free of summertime ice was 125,000 years ago, during the height of the last major interglacial period, known as the Eemian. Temperatures in the Arctic were higher than now and sea level was also 4 to 6 meters (13 to 20 feet) higher than it is today because the Greenland and Antarctic ice sheets had partly melted. Because of the burning of fossil fuels, global averaged temperatures today are getting close to the maximum warmth seen during the Eemian. Carbon dioxide levels now are far above the highest levels during the Eemian, indicating there is still warming to come.

According to analyses at NASA and NOAA, the past decade has been the warmest in the observational record dating back to the 19th century and the Arctic has been substantially higher than the global average.

http://nsidc.org/arcticseaicenews/faq/

A recent scientific paper, (Kinnard [2011]) shows that the present rate of melt in the Arctic summer is unprecedented in the last 1,450 years (http://www.skepticalscience.com/Arctic-sea-ice-hockey-stick-melt-unprecedented-in-last-1450-years.html



Daily Arctic temperatures can be seen at http://ocean.dmi.dk/arctic/meant80n.uk.php

IPCC Carbon Budget

In order to provide policy makers with a guideline for limiting future greenhouse gas emissions, the Intergovernmental Panel on Climate Change (IPCC) first recommended a goal of limiting the Earth's temperature increase in the year 2100 to 2°C above that in pre- industrial times. Then based on computer models of our climate system, they estimated that in order to have a 66% chance of not exceeding the 2°C target, a total of 1,000 gigatons of carbon (GTC) can be emitted from 1870 through 2100. As a part of their analysis the IPCC expects that about .4°C of the warming will come from non-CO2 sources (e.g., methane, ozone, soot, albedo changes, etc.). This means that, since the temperature increase from CO2 alone must be kept to 1.6°C, total emissions from CO2 from 1870 to 2100 must be limited to 800 GTC. Since about 545 GCT were emitted from 1870 to 2014, the remaining ("post 2014") IPCC carbon budget is about 255 GTC.

Since many factors contribute to global warming and since different models forecast different temperature increases for the same factors, the best the IPCC can do is to make a set of assumptions and then provide a very rough likelihood that a specific quantity of greenhouse gas emissions will result in a specific temperature increase by the year 2100. For example, Table CB1 lists the probability of meeting the 2°C target for three different emission amounts. And the 2°C is somewhat arbitrary – scientists simply do not know enough about the Earth's climate system to accurately predict what will happen if the Earth warms by 1°C, 2°C, 3°C, etc. But by specifying a "carbon budget", the IPCC has converted the "temperature target" (2°C) to an "emissions target" (255 GTC from CO2 after 2014, which would result in an atmospheric concentration of 450PPM of CO2), thus providing a yard stick against which projected CO2 emissions can be measured.

Percent Chance of Staying Below 2°C	Carbon Budget for CO2 Emissions (GTC)	"Post 2014" Budget for CO2 Emissions (GTC)	"Post 2014" Budget for CO2 Emissions (GTCO2)[3]
33%	900	355	1301
50%	818	273	1000
66%	800	255	934

Table CB1 - IPCC Model-Based Probability of Staying below 2°C for different carbon dioxide emission amounts[6]

Atmospheric PPM	Temp. Increase for Climate Sensitivity of 3°C Due to CO2[1]		Temp. Increase Due to Anthropogenic CO2	Carbon Budget for CO2 Emissions (GTC)	"Post 2014" Budget for CO2 Emissions (GTC)[2]	"Post 2014" Budget for CO2 Emissions (GTCO2)[3]	Percent of 255 GTC Budget
469	2.2°C	4.0°F	1.8°C	894	349	1279	137
459	2.1°C	3.8°F	1.7°C	847	302	1107	118
450	2.0°C	3.6°F	1.6°C	800	255	934	100
441	1.9°C	3.4°F	1.5°C	753	208	762	82
431	1.8°C	3.2°F	1.4°C	706	161	590	63
422	1.7°C	3.1°F	1.3°C	659	114	418	45
412	1.6°C	2.9°F	1.2°C	612	67	245	26
403	1.5°C	2.7°F	1.1°C	565	20	73	8
394	1.4°C	2.5°F	1.0°C	518	-27	-99	
375	1.2°C	2.2°F	0.8°C	424	-121	-443	
356	1.0°C	1.8°F	0.6°C	330	-215	-788	

Table CB2 – Expected Temperature Increase (With a Probability of 66%) For Other Emission Budgets [C5]

1. From Anthropogenic Emissions (Note: 1C = 1.8F)
2. Based on the IPCC estimate of an additional 255 GTC of emissions resulting in a temperature increase of 1.6°C, other factors raising the temperature an additional .4°C, an "airborne fraction" of 42%, and a climate sensitivity of 3 for a doubling of CO2 (resulting in about 47 GTC per .1°C temperature change).
3. To covert from GTC to GTCO2, multiply by 3.664 (a molecule of CO2 weighs 3.664 times a much an atom of carbon)

Why the IPCC Carbon Budget Way is Too High

There is a growing realization that the IPCC 1000 GTC carbon budget is too big by a large margin. This is based on the following:

1. The set of assumptions that the climate models used to determine the budget are very difficult to determine and have very likely underestimated the size of many of the possible global warming feedbacks[2] (this is most likely due to the fact that the magnitude of the various feedbacks is very difficult to model, and hence were likely ignored)
2. It is very difficult to determine what the IPCC included in the .4 °C of the warming that will come from non-CO2 sources. For example, it is quite possible that methane emissions from agriculture will be much larger than they forecast.
3. "It [(permafrost melt)] was first proposed in 2005. And the first estimates came out in 2011." Indeed, the problem is so new that it has not yet made its way into major climate projections, Schaefer says." …"None of the climate projections in the last IPCC report account for permafrost," says Schaefer. "So all of them underestimate, or are biased low." … "It's certainly not much of a stretch of the imagination to think that over the coming decades, we could lose a couple of gigatons per year from thawing permafrost," says Holmes…. But by 2100, the "mean" estimate for total emissions from permafrost right now is 120 gigatons, say Schaefer. http://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet/
4. "Cumulative emissions of ~1000 GtC, sometimes associated with 2°C global warming, would spur "slow" feedbacks and eventual warming of 3–4°C with disastrous consequences. Rapid emissions reduction is required to restore Earth's energy balance and avoid ocean heat uptake that would practically guarantee irreversible effects." James Hansen http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0081648
5. If we have not already past the "Arctic temperature tipping point", which would cause the eventual release of significant quantities of greenhouse gas emissions from the permafrost, we are not far from it. Albedo changes and greenhouse gas emissions from a warming arctic could eventually result in a temperature increase of over 4 °C.
6. A 66% chance of meeting the goal implies that there is a 33% chance that the target will be exceeded – this might be seen as too high a risk, particularly considering the ramifications of missing the target

Since determining a "realistic carbon budget" with any accuracy is a very difficult task, another approach would be to determine a reasonable upper bound on what we would be willing to pay this century to avoid the costs of weather-related climate change between now and 2100. That, in turn, would determine the smallest carbon budget that we could expect to not to exceed.

"[A]chieving the European policy aspiration of not exceeding a global temperature rise of 2◦ C is likely to require atmospheric concentrations of below 350ppmv CO2e."
"(Anderson and Bows 2008) argue that without an almost immediate (i.e. by 2015) step change in emissions we are heading for atmospheric concentrations of 650ppmv or more by the end of this century."
http://www.tyndall.ac.uk/sites/default/files/twp147.pdf (December 2010)

"Historical records show temperatures have typically fluctuate up or down by about 0.2°F per decade over the past 1,000 years. But trends over the past 40 years have been decidedly up, with warming approaching 0.4°F per decade. That's still within historical bounds of the past — but just barely."
"By 2020, warming rates should eclipse historical bounds of the past 1,000 years — and likely at least 2,000 years — and keep rising. If greenhouse gas emissions continue on their current trend, the rate of warming will reach 0.7°F per decade and stay that high until at least 2100."
http://www.scientificamerican.com/article/global-warming-could-hit-rates-unseen-in-1-000-years/

(A 0.7°F warming per decade after 2020 would result in a total temperature increase of 4°C by 2100)

"Using decoupled RCP4.5 simulations (see Box 6.4) five CMIP5 ESMs agree that the climate impact on carbon uptake by

both land and oceans will reduce the compatible fossil fuel CO_2 emissions for that scenario by between 6% and 29% between 2006 and 2100 respectively (Figure 6.27), equating to an average of 157 ± 76 PgC (1 standard deviation) less carbon that can be emitted from fossil fuel use if climate feedback (see Glossary) is included."
"Overall, there is high confidence that reductions in permafrost extent due to warming will cause thawing of some currently frozen carbon. However, there is low confidence on the magnitude of carbon losses through CO_2 and CH_4 emissions to the atmosphere. The magnitude of CO_2 and CH_4 emissions to the atmosphere is assessed to range from 50 to 250 PgC between 2000 and 2100 for RCP8.5. The magnitude of the source of CO_2 to the atmosphere from decomposition of permafrost carbon in response to warming varies widely according to different techniques and scenarios."

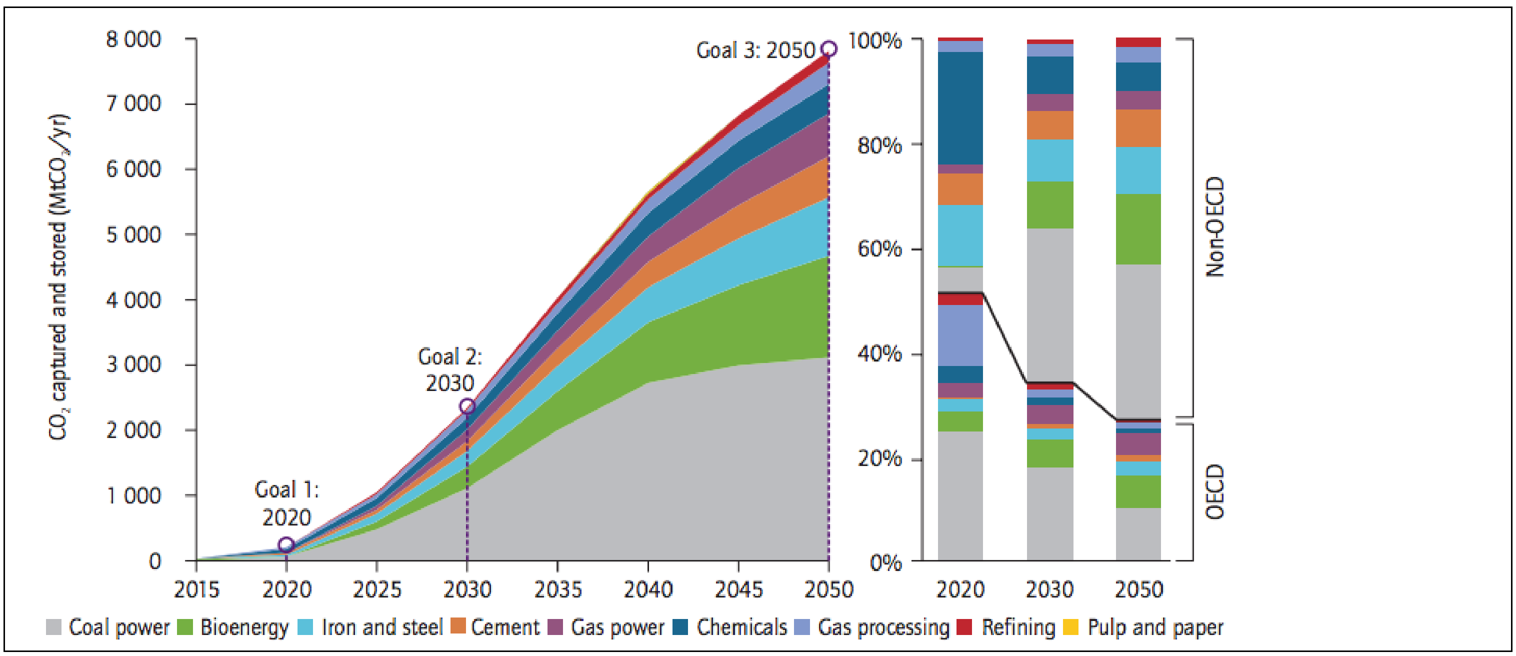
IPCC AR5 Physical Basis (Page 526)

Sequestration

Carbon capture and storage (CCS) technologies can capture up to 90 percent of carbon dioxide (CO2) emissions from a power plant or industrial facility and store them in underground geologic formations. Since the incremental cost of capturing the other 10 percent of emissions is so high, if fossil fuel power plants are to stay in operation in a "net zero emissions" world, significant amounts of CO2 will have to be sequestered by other means. (Fossil fuel power plants with CCS cannot be used to sequester CO2 already in the atmosphere.) The technologies for both capture and storage are unproven at the scale that will be needed.

According to the IEA (https://www.iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2013.html - 2013), CCS is a critical component of meeting the 2°C target. They project that CCS will need to be used to sequester 50 MTCO2/year by 2020, 2,000 MTCO2/year by 2030, and almost 8,000 MTCO2/year by 2050.

- "Under the IEA Energy Technology Perspectives 2012 2°C Scenario (2DS), CCS contributes one-sixth of total CO2 emission reductions required in 2050, and 14% of the cumulative emissions reductions through 2050 against a business-as-usual scenario (6DS)."
- "Governments and industry must ensure that the incentive and regulatory frameworks are in place to deliver upwards of 30 operating CCS projects by 2020 across a range of processes and industrial sectors."
- "CCS is not only about electricity generation. Almost half of the CO2 captured between 2015 and 2050 in the 2DS, is from industrial applications (45%)."
- "Given their rapid growth in energy demand (70% by 2050), the largest deployment of CCS will need to occur in non-Organisation for Economic Co-operation and Development (OECD) countries."



It is likely that the 2020 goal will be met, but the majority of the current CCS plants use the captured CO2 for enhanced oil recovery and hence can capture the CO2 for a profit. But ramping up for the 2030 goal will be problematic as the average "energy penalty" is expected to be about 29 percent ("The energy penalty of post-combustion CO2 capture and storage" Jan 2009) and there will not be a way to recover the costs. For the US, the expected levelized cost of electricity in 2020 is $94/mwh for conventional coal and $144 for advanced coal with CCS. Since 1 MWH of coal produces about 1 metric ton of CO2, the CO2 capture costs are about $50/ton. Therefore the CCS capture costs are expected to be about $400 billion per year in 2050 *assuming that anthropogenic emissions can be mitigated at the rate necessary to meet the IPCC carbon budget and that there are not significant natural emissions from permafrost melt, peat bogs, etc.* (both very unlikely).

Carbon dioxide removal (CDR) techniques are used to remove CO_2 from the atmosphere. One of the main CDR techniques being considered is bioenergy carbon capture and storage (BECCS).

BECCS consists of burning biomass such as wood, and then capturing the emitted carbon through readily available carbon capture and storage (CCS) technology. Since almost all emission scenarios will result in more CO_2 emissions than are allowed by a realistic carbon budget, BECCS is the "method of choice" for sequestering the CO_2 "overshoot". Estimated BECCS costs are about $60-$250 per ton of CO_2 - $200-$1000/ton of carbon (National Academy of Sciences - http://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration). (BECCS costs are higher that CCS costs because the fuel costs for biomass are significantly higher that fuel costs for fossil fuels.) At the scale needed, other carbon dioxide removal (CDR) techniques are more expensive than either CCS or BECCS. Unfortunately, implementing BECCS at a reasonable scale requires a lot of land. For instance, to reduce overall CO_2 by 1 billion tons per year using BECCS would require a landmass of 218-990 million hectares of land which is 14-65 times as much land as the US uses to grow corn for ethanol.

"If 2.5 tC yr^{-1} per hectare can be harvested on a sustainable basis (Kraxner et al., 2003) on about 4% (~500 million hectares, about one tenth of global agricultural land area) of global land (13.4 billion hectares) for BECCS, approximately 1.25 PgC yr^{-1} could be removed or about 125 PgC in this century." (Page 549)

"Biological and most chemical weathering CDR methods cannot be scaled up indefinitely and are necessarily limited by various physical or environmental constraints such as competing demands for land. Assuming a maximum CDR sequestration rate of 200 PgC per century from a combination of CDR methods, it would take about one and half centuries to remove the CO_2 emitted in the last 50 years, making it difficult—even for a suite of additive CDR methods— to mitigate climate change rapidly. Direct air capture methods could in principle operate much more rapidly, but may be limited by large-scale implementation, including energy use and environmental constraints." (Page 633)

IPCC AR5 Physical Basis

"Most of the two degrees scenarios identified by the IPCC see BECCS providing over five per cent of global electricity supplies and storing 2-10 gigatonnes of carbon dioxide (1-3 GTC) per year in 2050.

For comparison total world coal emissions stand at about 12 gigatonnes per year with a capacity of around 2,096 gigawatts. To reach 10 gigatonnes of carbon dioxide removal through BECCS would therefore require around 1,500 gigawatts of BECCS capacity in 2050, equivalent to three-quarters of current coal capacity.

There are currently no operational BECCS plants anywhere in the world."

http://www.skepticalscience.com/2-degrees-will-we-avoid-dangerous-climate-change.html

"Sommer estimates that soil could store up to 9 percent of total emissions in the first few decades of concerted effort to sequester carbon in soil."
http://ccafs.cgiar.org/blog/new-study-estimates-mitigation-potential-soil-carbon-sequestration#.VU52VY5VhBe
Helpful, but anywhere near making much of a difference

The 2°C Target

It is generally accepted that we must keep the atmospheric temperature increase since pre-industrial times to a maximum of 2°C. Based on modeling, the IPCC estimates that 1.6°C of this warming can come from anthropogenic sources, and that that the "post 2011 carbon budget" for carbon dioxide is about 280 GTC (which would result in an atmospheric concentration of CO2 of about 450PPM if no CO2 was sequestered). The models also anticipate that we will overshoot the "atmospheric PPM target that results in 2°C increase at equilibrium" and that after all reasonable mitigation efforts are made there will be significant CO2 emissions. To allow for this, the models assume a significant amount of carbon dioxide will need to be removed from the atmosphere on on-going basis.

It is hard to tell from the IPCC reports how much carbon dioxide was expected to be sequestered by CCS and BECCS. In the AR5 "Physical Basis" report (page 1422), the atmospheric concentration of CO2 for RCP2.6 (the "2°C"scenario) peaks at 442 PPM in 2050 and is reduced to 420PPM in 2100. Based on the "post 2011 carbon budget", this could imply that the models expect that 30PPM of CO2 would need to be removed this century. At about $1 trillion to remove 1PPM of CO2, the sequestration costs for anthropogenic CO2 emissions would be about $30 trillion IF the post-2011 CO2 emissions could be limited to 280GTC (and since that is unlikely, sequestration costs are likely to be much higher).

In addition to removing anthropogenic CO2 emissions, there will also be a need to remove CO2 to account for the feedbacks caused by a warming world (albedo changes in the Arctic, greenhouse gas emissions from both the thawing of permafrost and the drying of peat bogs, etc.). These have already started with the atmospheric concentration of CO2 at 400 PPM, and will likely increase as the Earth continues to warm. A reasonable estimate for the additional warming is that it will be equivalent to emissions of 3-10GTC/year after 2050. Given CDR costs of about $300/tonC, this represents an additional cost of $1-3 trillion per year.

According to the UNFCCC, "[t]he 'guardrail' concept, in which up to 2 °C of warming is considered safe, is inadequate and would therefore be better seen as an upper limit, a defence line that needs to be stringently defended, while less warming would be preferable" ("Report on the structured expert dialogue on the 2013–2015 review" http://unfccc.int/resource/docs/2015/sb/eng/inf01.pdf). So if we want to "defend the 2 °C line", we had better be prepared to spend well over $1 trillion per year. (This is very unlikely – see "Financing" below.)

Sequestration Costs for CO2 Emissions Scenarios

It is impossible to predict accurately what the greenhouse gas emissions will be in the coming years – there are just too many variables involved. Since it is generally agreed that net emissions must become zero later this century in order to reduce the effects of climate change, it is fairly easy to lay out general "aspirational" scenarios for CO2 emissions based on an expected annual increase in emissions, a year in which the emissions peak, and either a specific year when the net emissions become zero or an average annual emissions reduction rate. If our society decides to undertake serious emission reduction efforts, the actual emissions will likely be relatively close to one of these. It is also very doubtful that *total* greenhouse gas emissions will ever become zero – there just too many sources of such emissions (agriculture, transportation, manufacturing, energy production, etc.). So it is reasonable to assume that some quantity of CO2 (perhaps 1GTC) will need to be sequestered annually.

When thinking about reasonable future emissions scenarios, it also helps to look at the forecasts of the primary organizations that make such forecasts (see Table 7 below). Note that NONE of these forecasts expect that emissions will decline before 2050 and all forecast that the entire IPCC "post 2015 budget" will be "used up" by around 2040.

There is no doubt that anthropogenic emissions will "overshoot" any realistic carbon budget. In addition, once greenhouse gas emissions are mitigated to the greatest extent practical, significant CDR will be needed to offset these "residual" emissions. ("Residual" greenhouse gas emissions include those from fossil fuel power plants with CCS (because it is impractical to capture all of the CO2), transportation (not all vehicles, planes, and ships can be converted to electricity), some industrial processes, agriculture, etc.). In addition, greenhouse gas emissions need to be brought under control BEFORE global warming feedbacks start contributing significantly to the Earth's temperature, as an additional equivalent amount of CO2 wound then need be sequestered, driving the costs even higher. (I.e., if we want to prevent disruptive climate change, we can't wait for technologic advances to significantly reduce the costs of CDR before employing it aggressively.) (See Table 8 for costs to sequester various amounts of CO2)

The first two tables below show the total CO2 emissions for the case where emissions increase linearly (at the indicated "Growth Rate") to a peak year (2025 or 2030) and then decrease linearly at the indicated "Emissions Reduction Rate" rate to zero. The third table shows total CO2 emissions for the case where emissions increase linearly (at the indicated "Growth Rate") to a peak year and then decrease linearly to zero in 2050. (These both use a starting value of 11.1 GTC in 2015.)

Total Net CO2 Emissions Starting in 2015 for Linear Growth Rate to Peak Year Then Linear Decline To Zero Emissions (GTC)

	2025	Peak Year			
Growth Rate	**Emissions Reduction Rate**				
	1	**2**	**3**	**4**	**5**
0.5	708	417	320	271	242
1	739	434	332	281	251
1.5	770	451	345	292	260
2	802	469	358	302	269
2.5	833	486	370	312	278

Table 1

	2030	Peak Year			
Growth Rate	**Emissions Reduction Rate**				
	1	**2**	**3**	**4**	**5**
0.5	781	483	384	334	304
1	830	511	405	351	319
1.5	879	539	426	369	335
2	928	567	447	386	350
2.5	976	595	467	404	366

Table 2

Total Net CO2 Emissions (for Linear Growth Rate to Peak Year) for 2015 Through 2050 (With Zero Emissions at end 2050) (GTC)

Growth Rate	**Peak Year**			
	2015	**2020**	**2025**	**2030**
0.5	201	233	265	297
1	203	240	277	314
1.5	205	247	289	331
2	207	254	301	349
2.5	209	261	313	366

Table 3

For a specific net CO2 emissions amount, the following tables can be used to calculate a rough cost for sequestering the CO2 needed to meet the corresponding budget (the first table uses a sequestration cost of $200/TonC and the second table uses $300/TonC). (BECCS cannot be realistically deployed at sufficient scale to sequester really significant quantities of CO2 before 2100. Since costs for other techniques for sequestration are greater that costs for BECCS, $300/TonC seems to be a reasonable lower bound on average CDR costs.)

Carbon Budget	PPM	Temp Incr (°C)	Total CDR Removal Costs in Trillions of Dollars (at $200/TonC) To Meet a Carbon Budget for Total CO2 Emissions (Assuming 1 GTC Annual CO2 Emissions after 2050)														
			Total CO2 Emissions Through 2100														
			200	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**
255	**450**	**2.00**		9	19	29	39	49	59	69	79	89	99	109	119	129	139
138	**425**	**1.75**	22	32	42	52	62	72	82	92	102	112	122	132	142	152	162
20	**400**	**1.50**	46	56	66	76	86	96	106	116	126	136	146	156	166	176	186
-97	**375**	**1.25**	69	79	89	99	109	119	129	139	149	159	169	179	189	199	209
-215	**350**	**1.00**	93	103	113	123	133	143	153	163	173	183	193	203	213	223	233

Table 4

Carbon Budget	PPM	Temp Incr (°C)	Total CDR Removal Costs in Trillions of Dollars (at $300/TonC) To Meet a Carbon Budget for Total CO2 Emissions (Assuming 1 GTC Annual CO2 Emissions after 2050)														
			Total CO2 Emissions Through 2100														
			200	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**
255	**450**	**2.00**		14	29	44	59	74	89	104	119	134	149	164	179	194	209
138	**425**	**1.75**	34	49	64	79	94	109	124	139	154	169	184	199	214	229	244
20	**400**	**1.50**	69	84	99	114	129	144	159	174	189	204	219	234	249	264	279
-97	**375**	**1.25**	104	119	134	149	164	179	194	209	224	239	254	269	284	299	314
-215	**350**	**1.00**	140	155	170	185	200	215	230	245	260	275	290	305	320	335	350

Table 5

Some examples using specific values for the following variables to determine the total emissions based on Tables 1-3 above

1. Annual Emissions Increase
2. Peak year
3. Annual reduction percent or 0 emissions at the end of 2050 or 2090

Based on the total emissions and "desired budget" (with corresponding atmospheric CO2 PPM and temperature increase) the expected sequestration costs through 2100 can be calculated based on Tables 4 and 5 above.

Annual Emissions Increase (%)	Peak Year	Annual Reduction Percent	Total Emissions (GTC)	Desired Budget (GTC)	PPM	Temp Incr (°C)	Sequestration Costs ($200/TonC)	Sequestration Costs ($300/TonC)
1.5	2025	3	345	138	425	1.75	52	79
1.5	2025	0 Emissions in 2050	289	138	425	1.75	40	61
1.5	2025	3	345	20	400	1.5	75	112
1.5	2025	0 Emissions in 2050	289	20	400	1.5	64	96
1.5	2050	0 Emissions in 2090	830	20	400	1.5	172	255

Table 6

	Source
1	Total GHG emissions go from about 56GTCE (=GTC Equivalent – needed because not all emissions are carbon-based) in 2015 to about 19.4 GTCE in 2050, for a total of about 607 GTCE, and emissions will still be increasing (the IPCC "Post 2015" Budget is 455 GTC) MIT - "Expectations for a New Climate Agreement" http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt264.pdf

2	Energy consumption from coal, oil, and natural gas will increase from 11,240 million tons of oil equivalent (mtoe) in 2015 to 14,054 mtoe in 2035 (1.2%/year) and will still be increasing. Assuming CO2 emissions of 11.1 GTC in 2015 and a 1.2% increase/year to 2035, the CO2 emissions from 2015 to 2035 would be about 250 GTC (the entire IPCC "post 2015 carbon budget") BP Energy Outlook 2035: February 2015 http://www.bp.com/en/global/corporate/about-bp/energy-economics/energy-outlook.html
3	US energy-related CO2 emissions will go from about 5,500 MTCO2 in 2015 to between 5,175 MTCO2 (low growth) and 5,979 MTCO2 (high growth) in 2040. This "low growth" provides only a 10 percent drop in emissions between now and 2040 – not even close to a emissions reduction path the gets to zero net emissions this century EIA ANNUAL ENERGY OUTLOOK 2015 http://www.eia.gov/forecasts/aeo/section_carbon.cfm
4	"This entire budget [1,000 gigatonnes of CO2 from 2014 onwards] will be used up by 2040 in our central scenario. Since emissions are not going to drop suddenly to zero once this point is reached, it is clear that the 2 °C objective requires urgent action to steer the energy system on to a safer path." International Energy Agency (IEA) https://www.iea.org/Textbase/npsum/WEO2014SUM.pdf

Table 7

Cost to Reduce Atmospheric CO2/Temperature for Various CDR Costs (Trillion $)										
Amount To Reduce				**Carbon Dioxide Removal (CDR) Cost - $/GTC**						
PPM	**°C**	**°F**	**GTC**	**100**	**200**	**300**	**400**	**500**	**600**	**700**
1	**0.01**	**0.0**	**5**	0.5	1	1.5	2	2.5	3	3.5
10	**0.1**	**0.2**	**50**	5	10	15	20	25	30	35
20	**0.2**	**0.4**	**100**	10	20	30	40	50	60	70
30	**0.3**	**0.5**	**150**	15	30	45	60	75	90	105
40	**0.4**	**0.7**	**200**	20	40	60	80	100	120	140
50	**0.5**	**0.9**	**250**	25	50	75	100	125	150	175
60	**0.6**	**1.1**	**300**	30	60	90	120	150	180	210
70	**0.7**	**1.3**	**350**	35	70	105	140	175	210	245
80	**0.8**	**1.4**	**400**	40	80	120	160	200	240	280
90	**0.9**	**1.6**	**450**	45	90	135	180	225	270	315
100	**1.0**	**1.8**	**500**	50	100	150	200	250	300	350
110	**1.1**	**2.0**	**550**	55	110	165	220	275	330	385
120	**1.2**	**2.2**	**600**	60	120	180	240	300	360	420
130	**1.3**	**2.3**	**650**	65	130	195	260	325	390	455
140	**1.4**	**2.5**	**700**	70	140	210	280	350	420	490
150	**1.5**	**2.7**	**750**	75	150	225	300	375	450	525

Table 8

1 ppm by volume of atmosphere CO_2 = 2.13 GtC (http://cdiac.ornl.gov/pns/convert.html#3.)
The "airborne fraction" of emitted CO2 is about 42%
So emitting 5 GTC Carbon will result in adding about 1 PPM to the atmosphere
At the expected cost of at least $300/TonC, removing 1 PPM CO2 from the atmosphere will cost at least $1.5 Trillion

Financing

Given a realistic CO_2 emissions scenario and a realistic carbon budget, the sequestration costs between now and 2100 will be many tens of trillions of dollars (and very likely over $50 trillion).

Money spent on removing CO_2 from the atmosphere provides no net economic benefit in the "normal economic sense" as it does not build "useful" infrastructure (roads, buildings, etc) and provides no revenue stream. Even though the money spent on the "energy production side" of a BECCS power plant does provide a "normal economic" investment, the money spent to capture and sequester the CO_2 does not.

Governments are expected to contribute $100 billion annually to the UNFCCC's Green Climate Fund, half of which will be used for mitigation and half for adaptation. It will be a "stretch" to even come close to this level of financing, and that level of funding is far short of what is needed for sequestration.

It is generally assumed that private financing will play major role in funding the Green Climate Fund as there are insufficient public funds available. Because there is no "return on investment" for spending on CDR, it is highly unlikely that private financing will provide any money for CDR projects. Because minimal private financing will be available for CDR projects, the only source of funding is likely the public sector. But with current global tax revenues at about $8 trillion per year, the required public sector funding would represent about 10% of total tax revenue.

The need for funds for CDR will be competing with the costs for sea level rise, ocean acidification, an aging population, poverty reduction, etc.

BECCS cannot be realistically deployed at sufficient scale to sequester really significant quantities of CO_2 before 2100. Since costs for other techniques for sequestration are greater that costs for BECCS, $300/TonC seems to be a reasonable lower bound on average CDR costs.

With almost no economic benefit from spending money on CDR, it would be nearly impossible to have an enforceable global treaty that would commit countries to spend the necessary $1 trillion per year. So no country would have an incentive to fund CDR projects.

Incremental spending on CDR projects does not make economic sense – unless there is a reasonable expectation that sufficient funds could be committed to CDR so that CO_2 levels could be reduced to below that needed to avoid disruptive climate change, it's hard to image that any meaningful investments will be made in CDR.

What is probably the maximum amount that society would be willing to tax themselves to spend on CDR? I would imagine that this has to be less than $500 billion dollars/year (or $25 trillion from 2050-2100). This amount is an order of magnitude greater that the amount which hoped to be raised for the mitigation part of the "Green Fund" and significantly less than what is required under any reasonable emission scenario and realistic carbon budget.

Side note:

"Reducing greenhouse gases to manageable levels will cost up to four per cent of global GDP by 2030, according to a draft version of a report to be published in Berlin on Sunday by the Intergovernmental Panel on Climate Change (IPCC)." (May 2015) http://www.dailymail.co.uk/sciencetech/article-2602474/Could-SUCK-UP-climate-change-Excess-carbon-dioxide-absorbed-specially-developed-crops.html

How will this be financed?

Cost Benefit Analysis of Sequestration (costs through 2100)

Review of Assumptions

Assumption	Value	Notes
Revised Carbon Budget	138 GTC	Likely still too large
CO2 Emissions Scenario	345 GTC	Likely greatly underestimates what will realistically be emitted
Annual “Post 2050” Emissions	1 GTC	Possibly a bit low
CDR Costs	$300/Ton Carbon	Possibly a bit high – perhaps by a factor of 2 or 3 if major technological advances are made

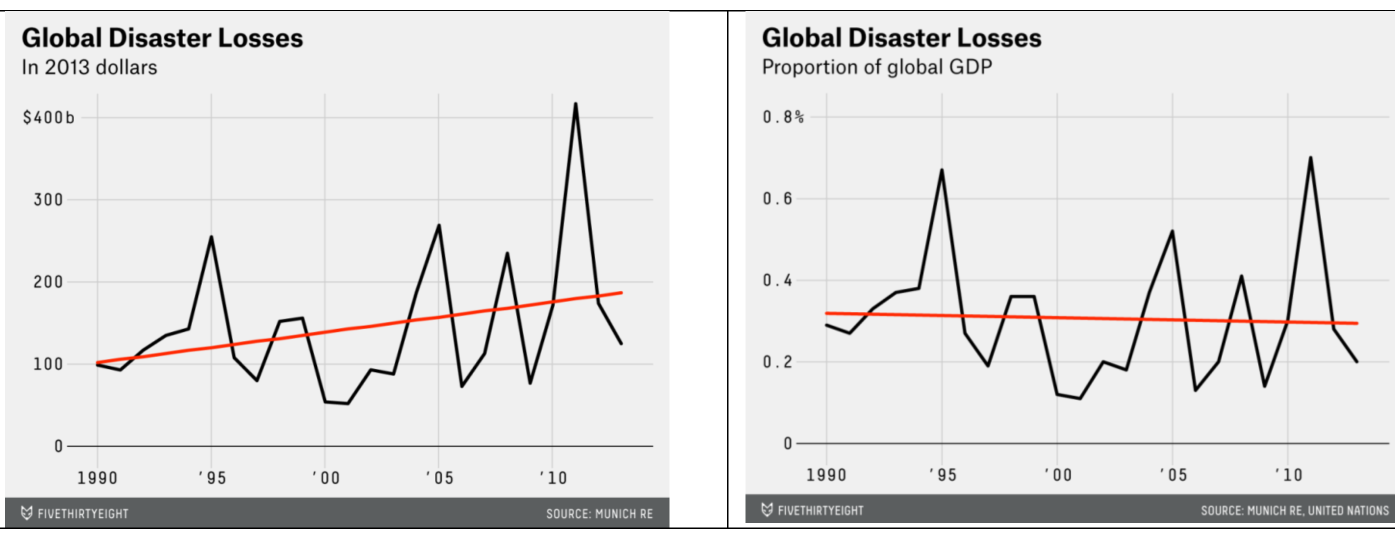
A reasonable LOWER estimate for sequestering carbon is $77 trillion (and this does not include compensating for the emissions and albedo changes in a warming Arctic region).

To see that this is “in the ballpark”, assume the mitigation alone results in an atmospheric concentration of CO2 of 460 PPM (the RCP2.6 pathway assumes a significant amount of CCS/BECCS) and that the target should be about 400PPM (for a 1.5°C increase). Then 60 PPM needs to be removed from atmosphere. With 2.1 GTC/PPM and an airborne fraction of 42%, then 60 * 2.1/ .42 = 300 GTC. At $300/ton C, the cost would be about $90 trillion. Add to this 1 GTC/year of BECCS for 50 years (50 years * $300/ton C = $15 trillion) and the total cost is over $100 trillion.

A more likely amount is around $250 trillion (peak in 2050, zero emissions in 2090 results in about 830 GTC of emissions).

Cost/Benefit Analysis – note that all benefits are AVOIDED costs

Costs	
$77 Trillion	CDR Removal to keep the temperature from rising an additional .5°C
Costs Avoided	
$10 Trillion	Costs associated with sea level rise – Perhaps with CDR the seas will rise three feet instead of four feet by 2100. What will the incremental cost be of one additional foot of sea level rise by 2100?
$0	Consequences of ocean acidification (zero because mitigation is supposed to keep the atmosphere below the 450PPM tipping point for the southern ocean)
$10 Trillion	Weather-related natural disasters (floods, droughts, hurricanes, etc.). Society has always had to pay for weather-related natural disasters, and there is no general agreement as to how much the increased cost of weather-related natural disasters has to do with climate change (see Figure D1). What would the additional annual costs of weather-related natural disasters be if the temperature went up 2.5°C instead of only 2°C? Likely less than $200 billion/year (or $10 trillion over 50 years)?



http://fivethirtyeight.com/features/disasters-cost-more-than-ever-but-not-because-of-climate-change/

Figure D1

Conclusions

The high cost of carbon dioxide removal (CDR) is the "Achilles' heel" of any serious effort to "solve climate change". The positive feedbacks from a warming world (albedo changes in the Arctic, greenhouse gas emissions from both the thawing of permafrost and the drying of peat bogs, etc.) are already starting with the atmospheric concentration of CO2 at 400 PPM. Since without CDR efforts it will be socially and politically impossible to keep future anthropogenic CO2 emissions from adding less than another 50 PPM of CO2 to the atmosphere, the 450 PPM IPCC 2°C target will be exceeded from anthropogenic emissions alone – positive feedbacks will likely add the equivalent of at least 10 PPM CO2 by 2050. "Solving climate change" would therefore require an absolute minimum removal of 30 PPM of atmospheric CO2 (a more realistic minimum removal amount is about 100 PPM). According to the National Academy of Sciences, it will cost between $1 trillion and $5 trillion to remove 1 PPM of CO2 (based on the range of $200-$1000/ton of carbon for CDR). So removing sufficient CO2 would cost from $30 trillion to $150 trillion. Since spending on CDR only avoids future costs and provides no return on investment, no politician will ever recommend that really significant monies be spent on CDR – costs will always be passed on to future generations. In addition, with continued anthropogenic greenhouse gas emissions, there is only limited time before the magnitude of the positive feedbacks becomes a significant fraction of anthropogenic emissions – and the probability of preventing that is pretty close to zero.

Questions

1. Did I miss something?
2. Are my assumptions valid?
3. Are my estimated costs and benefits in the right "ballpark"?
4. Are my conclusions reasonable?
5. Have many other people reached the same conclusions?
6. Are you aware of other similar analyses?