Institute for
New Economic Thinking
AT THE OXFORD MARTIN SCHOOL

The '2°C capital stock' for electricity generation: Cumulative committed carbon emissions and climate change

Alexander Pfeiffer
Richard Millar
Cameron Hepburn
Eric Beinhocker

January 2016

INET Oxford Working Paper no. 2015-09
Submitted to Applied Energy – not for circulation without permission

Economics of Sustainability

The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the power sector and the transition to a green economy

Alexander Pfeiffer[a,b], Richard Millar[a,c], Cameron Hepburn*[a,b] and Eric Beinhocker[a,d]

11 January 2016

Abstract

Complete decarbonisation of the electricity sector is a necessary, but not sufficient, condition to limit average temperature increases to below 2°C (with 50% probability). This paper shows that even under the very optimistic assumption that other sectors reduce emissions in line with a 2°C target, no new emitting electricity infrastructure can be built after 2017 for this target to be met, unless other electricity infrastructure is retired early or retrofitted with CCS. If all other sectors continue to develop at business-as-usual, even immediate and complete decarbonisation of the global electricity sector would be insufficient to constrain temperature increases to 2°C (with 50% probability). We arrive at these results by defining the '2°C capital stock' as the global stock of infrastructure which, if operated to the end of its normal economic life, implies mean temperature increases of above 2°C (with 50% probability). Using IPCC carbon budgets and the IPCC's AR5 scenario database, and assuming future emissions from other sectors are compatible with a 2°C pathway, we calculate that the 2°C capital stock for electricity will be reached by 2017 on current trends. Policymakers and investors should question the economics of new long-lived energy infrastructure involving positive net emissions.

* Corresponding author: cameron.hepburn@inet.ox.ac.uk
[a] *Institute for New Economic Thinking, Oxford Martin School, University of Oxford*
[b] *Smith School of Enterprise and Environment, University of Oxford*
[c] *Department of Physics, University of Oxford*
[d] *Blavatnik School of Government, University of Oxford*

Key words

2-degree capital stock; cumulative emissions; carbon budget; stranded assets; net zero emissions; committed cumulative carbon emissions

1. Introduction

The human population has grown over 4-fold from 1.65 billion in 1900 to over 7 billion todays (UN, 1999; UN, 2015). Over a similar period, world average per capita output has increased almost 6-fold from ~$1,300 in 1900 to ~$7,600 in 2008 real GDP in 1990 US dollars (Roser, 2015). This remarkable achievement has been accompanied by significant increases in pressure on the natural environment, and it is accordingly suggested that the current geological era be termed the 'Anthropocene' (Crutzen, 2006). Humans may now be confronting 'planetary boundaries' (Rockström et al., 2009). Environmental concerns have been presented in the past, coupled with calls to arrest economic growth (Jevons, 1906; Mill, 1848; Keynes 1933). So far, price signals have triggered demand efficiencies, substitution, new supplies and new technologies that have moderated concerns about resource scarcity (Hepburn et al., 2015). However, accurate price signals are absent for climate change and other natural capital such as biodiversity and fisheries. The trends are highly adverse, particularly on climate change (Dawson et al., 2011; IPCC WG 2, 2014). Electricity generation (and heating) currently contributes approximately 25% of global anthropogenic greenhouse gas emissions, the main driver of observed climate change (IPCC WG3, 2014). A global transition to clean electricity generation is therefore anticipated (Solomon & Krishna, 2011) and necessary to curtail future climate impacts. How rapid does this transition need to be for reasonable odds of limiting temperature increases to safe levels?

There are two critical inertias associated with addressing climate change that create two stock problems. First, built infrastructure in the energy sector is characterised by long lifetimes. In the EU, for example, approximately 29% of thermal power plant capacity is over 30 years old and 61% over 20 years old (EEI, 2006); today's energy infrastructure even includes assets constructed over 50 years ago[1]. Energy sector investments made today are likely to be operating and emitting carbon dioxide (CO_2) for decades into the future. Building on Davis et al. (2010), Davis and Socolow (2014) [DS] advance a methodology for estimating these future emissions from energy sector assets, which we refer to as 'committed cumulative carbon emissions' (CCCE). An implication of this inertia for policymakers is that greater focus should be upon investments in long-lived infrastructure, such as coal mines, oil and gas fields and power plants, than upon the operation of existing assets.

Second, the climate system has its own inertia. CO_2 emissions remain resident in the atmosphere for centuries and it is the *stock* of atmospheric CO_2 that affects temperatures, rather than the *flow* of emissions in any given year (Solomon et al., 2009). Many of the expected economic damages from climate change depend on

---

[1] E.g. the 'Alpena Huron 07' subcritical coal generator in Alpena, MI (online since 1955 – 60 years) or the 'Anan 1' subcritical oil generator in Anan City, Japan (online since 1963 – 52 years) which are both still in operation according to the June 2015 version of the Platts WEPP database.

peak warming, and peak warming is a function of cumulative carbon emissions ('CCE') (e.g. Allen et al., 2009; Matthews et al., 2009). In recent years some policy makers have acknowledged the existence of carbon budgets and included the implications in their considerations (e.g. UNEP, 2014). Nevertheless, it remains common practice for policymakers to focus on annual CO_2 emission reduction targets – such as reducing emissions by 40% by 2030 (EU, 2014) – which are only indirectly relevant to the core objective of reducing the cumulative stock of carbon in the atmosphere.

This paper introduces the concept of a '2°C capital stock' for the electricity sector by combining DS's concept of CCCE with Allen et al.'s concept of a cumulative carbon budget. We define the '2°C capital stock' as the stock of infrastructure that implies future emissions consistent with a 50% probability of a peak global mean temperature increase of 2°C or less. By making use of integrated assessment model (IAM) scenarios of energy system transitions, we calculate the date at which the installed electricity infrastructure reaches the 2°C capital stock.

The implications for energy policy of this concept are significant. Once the 2°C capital stock for the electricity sector has been reached, all new additions to the stock of generating infrastructure need to be net zero emissions to meet the 2°C target with 50% probability, without subsequent large-scale deployment of carbon capture technologies[2] or without the premature stranding of energy sector assets.

Our core result is that for a 50% probability of limiting warming to 2°C, assuming other sectors play their part, *no new investment in fossil electricity infrastructure (without carbon capture) is feasible from 2017 at the latest*, unless energy policy leads to early stranding of polluting assets or large scale carbon capture deployment. If other sectors remain on business as usual rather than a 2°C consistent pathway, even a stranding (i.e. premature retirement) of the entire global fossil fuel electricity generating capital stock today would not be sufficient to provide a 50% probability of limiting increases to 2°C. The paper highlights a set of choices for policymakers: they can either a) ensure that all new power sector investment is zero carbon from 2017, or b) make major investments in retrofitting carbon capture technologies, which is at present expensive and uncertain to deliver at cost and at scale, c) be prepared to strand substantial parts of the built fossil energy infrastructure, d) invest heavily in negative emissions technologies, or e) abandon the 2°C stabilisation goal and accept the substantial risks of dangerous climate change and the knock-on impacts (IPCC WG2, 2014).

This paper builds upon earlier research on committed emissions. Davis et al. (2010) calculated committed cumulative emissions from combustion of fossil fuels by

[2] Carbon capture technology in this context could include new or retrofitted electricity sector carbon-capture-and-storage (CCS) as well as technologies that remove CO2 from the ambient air, commonly referred to as carbon dioxide removal (CDR) technologies (NRC, 2015).

existing infrastructure between 2010 and 2060 and find that the capital stock in 2010 entailed a commitment to a warming around 1.3°C above the pre-industrial era. Guivarch & Hallegatte (2011) build upon these results by including non-CO_2 greenhouse gases and inertia in transportation infrastructure to conclude that future climate policies need to consider existing polluting infrastructure if the 2°C stabilisation goal is to be met. Lecocq & Shalizi (2014) conclude that mitigation policy should be targeted towards countries where long-lived infrastructure is being built at a rapid rate. Bertram et al. (2015) find that under less stringent near-term policies, most of the near-term emissions come from additional coal-powered generation capacity and conclude that significant coal capacity would have to be retired in the future to meet warming targets. Johnson et al. (2015) find that the timing and rate of the complete phase-out of coal-based electricity generation without CCS will depend mostly on the strength of near-term climate policies. They conclude that an effective strategy for reducing stranded capacity is to minimize new construction of coal capacity (without CCS) in the first place. Finally and perhaps most notably, the International Energy Agency finds in its 2012 World Energy Outlook that "…infrastructure in existence in 2017 and expected to continue to operate through to 2035 would emit all the cumulative emissions allowed in the 450 Scenario" (WEO, 2012; p. 265). Our analysis not only uses the full variety of IPCC models and scenarios, extends the analysis to 2100, presents results for 1.5°C and 3°C carbon budgets, and further tests the sensitivity of the results for the 2°C capital stock to a range of different assumptions and scenarios. Results of the analysis in this paper reinforce these previous findings.

The problems created by 'committed' emissions are also related to the concept of 'carbon lock-in', which defined as "the tendency for certain carbon-intensive technological systems to persist over time, 'locking out' lower-carbon alternatives" (Erickson et al., 2015). For example, Unruh (2000) explored the barriers to the scale-up of low carbon alternatives created path-dependent increasing returns to scale in the fossil energy sector. Kalkuhl et al. (2012) show that market imperfections may trigger lasting dominance of one technology over another for several decades, even if that other technology is more efficient.

Our paper adds to the existing body of literature and extends the existing research by adding future emissions from all sectors as projected in the IPCC 5th Assessment Report [IPCC AR5] scenarios. Focusing on long-lived committed CO_2 emissions, we calculate not only the remaining carbon budgets in 2014 for the polluting electricity generating capital stock but also the year in which the remaining budget will be exhausted. This paper assesses the impact of different levels of mitigation ambition in other sectors across the economy and the simplicity of our approach allows us to identify some of the key features that matter for the lock-in of polluting electricity generating infrastructure.

The paper is structured as follows. Section 2 sets out the data sources employed in the analysis and the methodologies used to analyse the data. Section 3 discusses the results and sensitivities of our analysis. Finally, section 4 examines the policy choices and the implications for policymakers and investors.

2. Methods

To assess when the capital stock consistent with a 50% chance of limiting global warming to 2°C is reached, three elements are required: (1) total cumulative carbon budgets consistent with the latest climate science for multiple peak warming thresholds and at different probabilities; (2) historical and projected committed future cumulative emissions from the power sector and (3) projections for the future emissions from all sectors.

The following subsections detail our methods in each of these areas. Section 2.1 details estimates of the carbon budget for different peak warming and probability threshold combinations. Section 2.2 describes assumptions for the evolution of the committed cumulative emissions from the power sector capital stock. Section 2.3 describes scenarios for the future realised emissions from different sectors.

2.1 Remaining carbon budget and treatment of short-lived climate pollutants

The analysis in the current paper is solely focused on long-lived CO_2 emissions. While the emissions of short-lived climate pollutants (SLCPs), notably methane and black carbon, also provide a radiative forcing on the climate system, long-term temperature stabilization (over the timescale of centuries) is largely a function of the cumulative stock of long-lived greenhouse gases (GHGs), predominantly CO_2, when global net emissions of long-lived gases fall to zero (Solomon et al., 2009). The contribution of SLCPs to peak warming is a function of their rate of emission at the time when net emissions of long-lived GHGs reach zero (Smith et al., 2012). If emissions of SLCPs were then stopped completely, their contribution to long-term irreversible warming would decay to zero, unlike CO_2, from which warming persists for centuries. Due to the essentially irreversible impact of CO_2 emissions on the climate system, we focus our analysis on the risk of locking in irreversible temperature change via committed future cumulative emissions of CO_2 from infrastructure being built over the next few decades. When thinking about temperature changes at specific times over the 21st century, SLCP-induced warming will have an important role to play and the impact of different SLCP mitigation choices needs to be fully considered alongside CO_2 (Rogelj et al., 2014).

Estimates of cumulative CO_2 emission budgets depend on the magnitude of peak warming and probability of restricting warming to beneath this value (due to uncertainty in the physical climate response) being considered. We take estimates for multiple peak warming thresholds at multiple probabilities from Table 2.2 of the IPCC 5th Assessment Synthesis Report (IPCC Syn, 2014), summarised in Table 1. These carbon budgets assume a contribution to peak warming from SLCPs consistent with the RCP8.5 high emissions scenario (Riahi et al, 2011). The probability thresholds given here correspond to percentiles of the CMIP5 Earth System Model distribution and are not equivalent to the calibrated likelihood statements of IPCC Working Group 1 (IPCC WG1, 2013) as those calibrated likelihood statements also assess uncertainty not captured by the models. To calculate historical emissions, we use 2011 cumulative emissions from IPCC AR5 WG1 (515 GtC) updated with emissions data for 2011-2013 from the Global Carbon Budget 2014 (Le Quéré, 2014).

Table 1: 2011 and 2014 remaining cumulative carbon budgets for different peak warming and probability thresholds. Data and information are taken from table 2.2 of IPCC Syn, 2014 with cumulative emissions between 2011-2013 calculated from Le Quéré, 2014.

	Warming*	Likelihood**	Budget (CCE)*** in 2011	Emitted (CCE) 2011-2013	Budget (CCE)*** in 2014
[GtCO2]	< 1.5°	66%	400	116	284
		50%	550	116	434
		33%	850	116	734
	< 2.0°	66%	1000	116	884
		50%	1300	116	1184
		33%	1500	116	1384
	< 3.0°	66%	2400	116	2284
		50%	2800	116	2684
		33%	3250	116	3134
[GtC]^	< 1.5°	66%	109	32	77
		50%	150	32	118
		33%	231	32	200
	< 2.0°	66%	272	32	241
		50%	354	32	322
		33%	408	32	377
	< 3.0°	66%	653	32	622
		50%	762	32	731
		33%	885	32	853

^Conversion factor: 1 GtC = 3.664 GtCO2
* Warming due to CO2 and non-CO2 drivers. Temperature values are given relative to the 1861-1880 period
** Fractions of scenario simulations meeting the warming objective with that amount of CCE
*** CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO2 forcing follows the RCP8.5 scenario (similar emissions are implied by the other RCP scenarios). For the most scenario-threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of the CO2 emissions these figures provide an indication of the cumulative CO2 emissions implied by simulations under RCP-like scenarios. Values are rounded to the nearest 50.

For our analysis we focus mainly on a budget to achieve ≤ 2°C peak warming with a 50% probability. For peak warming of 2°C the remaining budget is 322 GtC (1184 $GtCO_2$). The budget varies between 77 GtC (284 $GtCO_2$) for <1.5°C (66% probability) and 853 GtC (3,134 $GtCO_2$) for <3°C (33% probability).

2.2 The committed cumulative carbon emissions of electricity infrastructure

Using emission intensity and generation data from 2009 (CARMA database), DS analyse the currently existing polluting electricity infrastructure and find that *new* fossil fuel power plants (i.e. oil, coal, and gas) built in 2012 will alone cumulatively emit approximately 5.2 GtC if their average lifetime is 40 years. The corresponding estimate of ‘committed’ emissions from *all* fossil fuel power plants operating in 2012 is 84 GtC.[3]

DS not only analyse the currently existing capital stock of polluting electricity infrastructure, but also how this capital stock has developed in the past. New coal-fired power plants continue to be built, and more have been built in the past decade than in any previous decade.”[4] According to their calculations, worldwide, an average of 89 gigawatts per year (GW yr^{-1}) of new coal generating capacity was added between 2010 and 2012, 23GWyr^{-1} more than in the 2000–2009 time period and 56GWyr^{-1} more than in the 1990–1999 time period.”[5] Overall they conclude that the world’s committed emissions from electricity infrastructure have grown by approximately 4% p.a. over the last decade.

Much of that accelerated growth over the past decade comes from renaissance of coal (described e.g. by Steckel et al., 2015) and given the current pipeline of planned coal-fired power stations, our central scenario assumes a continuation of 4% p.a. growth in committed cumulative emissions from the electricity capital stock in the coming decades. We examine sensitivities to this growth rate in the range 0-7% p.a. An exponential growth pathway of committed cumulative emissions is likely to be unrealistic in the long run. However, given planned investments over the next decade and the limited time remaining until the 2^{o}C capital stock is reached, these growth assumptions remain broadly plausible in the relatively short timeframes under consideration.

2.3 Future realised emissions

The electricity sector is not the only source of CO_2 emissions within the economy. Industry, land-use, transport and other non-electricity sectors also contribute to global emissions. Given an overall cumulative emissions budget, cumulative emissions across the century from other sectors reduce the cumulative emissions that can be emitted from the electricity sector.

For ranges of possible scenarios of cumulative emissions from other sectors, we use IAM database compiled for IPCC AR5 WG3[6]. IAM scenarios aim to find a cost-optimal energy system transition to meet a goal for CO_2-equivalent (incorporating the impacts of some non-CO_2 climate forcing agents) atmospheric concentrations in 2100, given certain constraints on policy action and technological availability (Clarke et al., 2014). IAMs are highly idealised and often assume globally coordinated policy action that can start immediately. These emission scenarios are not harmonised – in

---

[3] According to DS and depending on the assumed average lifetime of energy infrastructure, committed emissions in 2012 vary from 26.8 GtC (20 years lifetime) up to 157.5 GtC (60 years lifetime).

[4] Davis & Socolow (2014), p.1.

[5] Ibid.

[6] Found at https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=about

other words, different scenarios have different assumed histories over 2005-2015 that can be different to the actual historical emissions. However, the spread of different scenarios gives a range of futures for 21st century cumulative emissions from non-power sectors under varying degrees of climate policy ambition.

In these scenarios, the emission pathways in the different sectors are highly connected to each other. Thus, in any given scenario, the budget remaining for power sector emissions (after accounting for emissions from the other sectors) is itself a function of the power sector emissions assumed in that scenario. The endogenous nature of the power sector increases the complexity of comparative scenario analysis. In order to explore the year in which the 2°C power sector capital stock is reached under different assumptions, we consider different (exogenous) rates of growth in future emissions from the power sector, holding other features of the scenarios constant. Results are reported below in our sensitivity analyses. It is also notable that in many scenarios, emissions from non-electricity sectors have not reached zero in 2100, our cut-off year. As we do not account for post-2100 emissions from these sectors, our calculations for the remaining emissions budget for the power sector is likely to be an overestimate.

Scenarios can be grouped by their 2100 CO_2-eq atmospheric concentration (Krey et al., 2014). Scenarios with 2100 concentrations in the range 430-480-ppm correspond to an IPCC assessed *likely* (>66%) probability of warming in the 21st century remaining beneath 2°C, when assessed under representative climate response uncertainty (IPCC WG3, 2014). 480-530-ppm scenarios correspond to >50% probability (when concentrations do not overshoot 530-ppm) and to <50% probability when overshoots do occur. All other scenario groupings for higher 2100 concentrations are consistent with successively less likely probabilities of limiting warming to beneath 2°C.

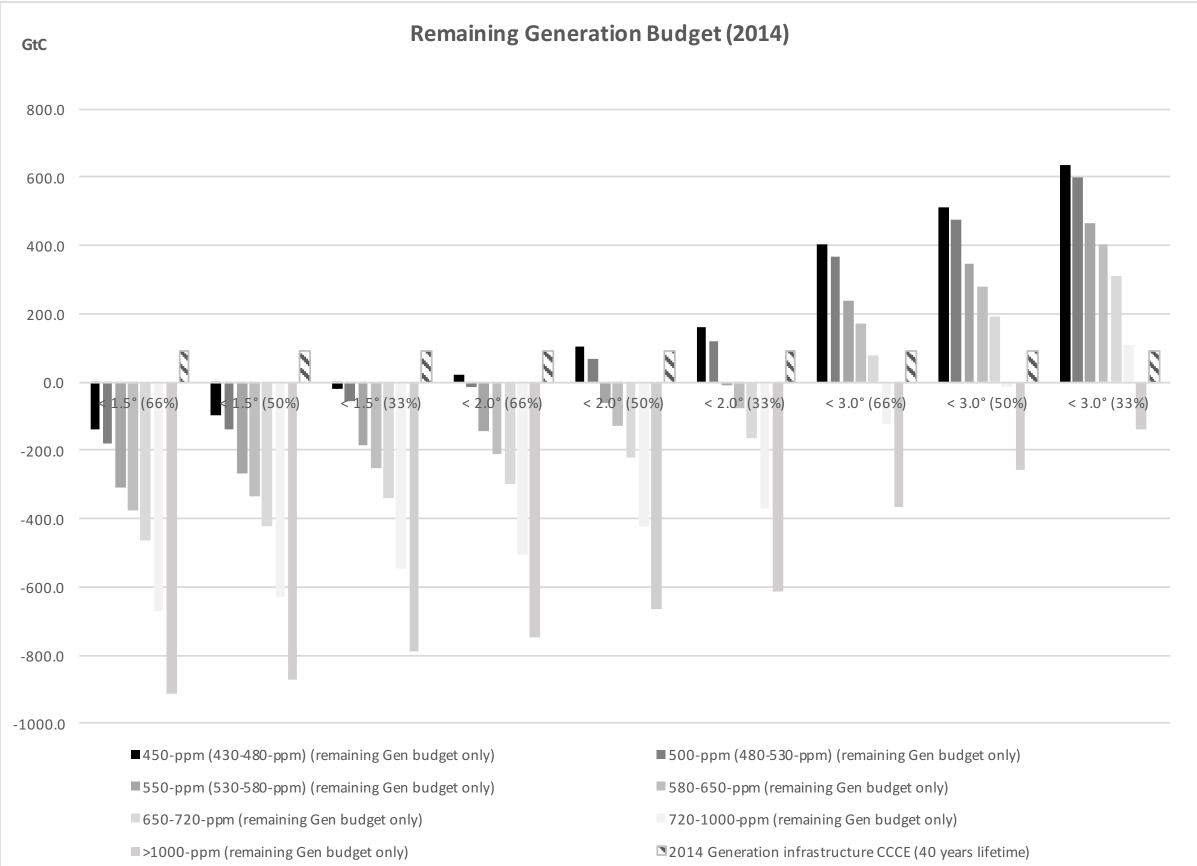
We use these scenarios for estimates of emissions from outside the power sector across the century but also for estimates of *realised* power sector emissions over time. In the near-term, there are very small differences between scenarios in the degree to which realised emissions reduce the size of the remaining carbon budget. This is despite likely significant differences in electricity sector investments and partially reflects the inertia of realised emissions to previously locked-in emissions. However, a useful area for further work would be to enable the committed cumulative emissions to be calculated directly from the reported IAM output for a given emission scenario, in order to more precisely capture the relationship between growth in committed and realised emissions in the power and other sectors.

3. Results

3.1 Remaining electricity sector cumulative emissions budget in 2014

Using the scenarios described in section 2.3, it is possible to assess the present-day (2014) remaining carbon budgets for electricity generation, dependent on the level of ambition in non-electricity sectors. As shown in Figure 1, if future emissions from all sectors follow the mean of the 430-480-ppm scenarios, and today's electricity infrastructure has an average lifetime of 40 years, by 2014 we were already committed to 89% (or 136% for 480-530-ppm non-electricity pathways) of the remaining 2014-2100 electricity generation budget for a 2°C peaking warming target with 50% probability through existing infrastructure. For a ≤ 2°C goal (33% probability), more than half (57%) (or 75% for 480-530-ppm) of the remaining electricity generation budget has already been committed. Mean transition pathways in the non-electricity sectors that are less ambitious than the 430-480 ppm and 480-530 ppm groupings are likely to entail that the 2°C electricity capital stock has already been reached. Too much carbon emitting electricity capital stock has already been installed to be consistent with a peak warming goal more ambitious than 2°C with 66% probability, irrespective of the non-electricity emissions pathway.

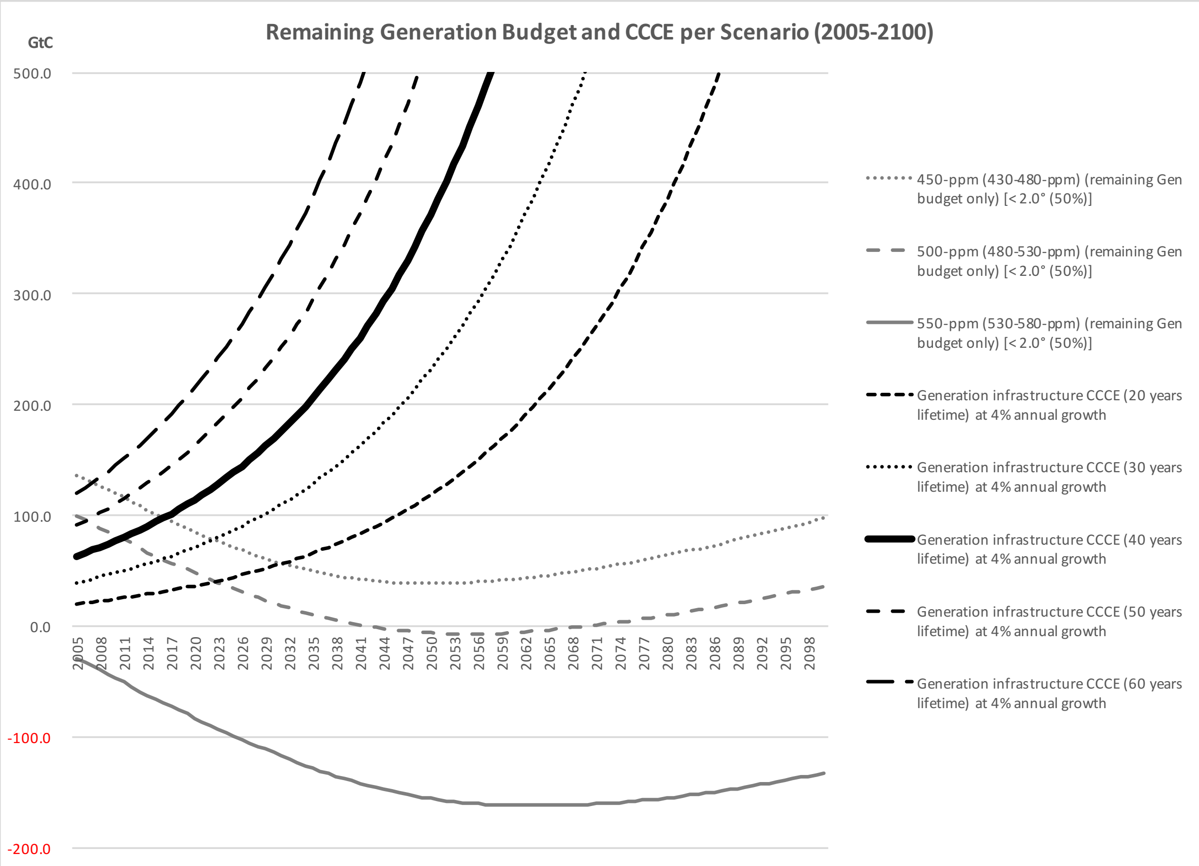
Figure 1: Remaining 2014 carbon budget for electricity generation, for different peak warming magnitudes and probabilities, decomposed by groupings of emissions pathways (denoted by scenario 2100 concentrations). The 2014 CCCE from electricity generation infrastructure (40 years lifetime) is shown by the hatched bar for each case.



3.2 Commitment year for 2°C (50% probability) electricity infrastructure capital stock

Assuming committed cumulative emissions from the electricity sector continue to increase at 4% p. a. (following DS and Tidball et al. (2010)) the date at which the electricity sector 2°C capital stock can be calculated, dependent on the alternative futures of realised emissions. As shown by the solid black line in Figure 2, if all other emissions follow a mean scenario consistent with overall 2100 430-480-ppm concentrations, we will have built the electricity generating capital stock consistent with a ≤ 2°C (50% probability) budget, by 2017. Such a scenario implies very significant mitigation action in all sectors, and even if this could be realised, all new electricity capital would have be to zero carbon by 2017, or rely on future carbon capture technology in order to remain consistent with an overall ≤ 2°C (50% probability) budget.

Figure 2: Future development of CCCE from electricity infrastructure (assuming different lifetimes and a 4% growth p.a.) and remaining generation budget for 430-580-ppm pathways, 2005-2100, assuming a ≤ 2°C (50% probability) overall budget.



If emissions from other sectors are only slightly higher, following a 480-530-ppm path instead of a 430-480-ppm path, the 2°C electricity capital stock was installed in 2011. If realised emissions in all sectors follow pathways consistent with concentrations above 530-ppm, new electricity generating assets needed to be zero carbon long ago to meet the 2°C (50% probability) target (see table 2). These findings are largely consistent with existing integrated assessment literature (reviewed e.g. in Krey, 2014) examining the question of delayed action on climate change mitigation.

If electricity sector mitigation is delayed, the 2°C target will be hard to achieve due to the locked in emissions from the existing energy infrastructure.

Table 2: Year in which generation budget is committed (assuming 40 years lifetime and 4% growth p.a.) for mean realised emissions scenario groupings and peak warming budgets.

Lifetime of capital stock 40 years at 4% annual growth					Year of budget commitment (2006-2100)*****						
	Warming*	Likelihood**	Budget (CCE)*** in 2014	Committed CCE**** in 2014	Cat. 1 450-ppm (430-480-ppm)	Cat. 2 500-ppm (480-530-ppm)	Cat. 3 550-ppm (530-580-ppm)	Cat. 4 580-650-ppm	Cat. 5 650-720-ppm	Cat. 6 720-1000-ppm	Cat. 7 >1000-ppm
[GtC]	< 1.5°	66%	77	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	118	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		33%	200	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
	< 2.0°	66%	241	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	322	90	**2017**	2011	<2006	<2006	<2006	<2006	<2006
		33%	377	90	**2024**	**2019**	<2006	<2006	<2006	<2006	<2006
	< 3.0°	66%	622	90	**2048**	**2045**	**2032**	**2025**	2013	<2006	<2006
		50%	731	90	**2055**	**2053**	**2042**	**2036**	**2027**	<2006	<2006
		33%	853	90	**2062**	**2059**	**2051**	**2045**	**2038**	**2017**	<2006

* Warming due to CO2 and non-CO2 drivers. Temperature values are given relative to the 1861-1880 period
** Fractions of scenario simulations meeting the warming objective with that amount of CCE
*** CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO2 forcing follows the RCP8.5 scenario (similar emissions are implied by the other RCP scenarios). For the most scenario-threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of the CO2 emissions these figures provide an indication of the cumulative CO2 emissions implied by simulations under RCP-like scenarios. Values are rounded to the nearest 50.
**** only electricity generation capital stock based on Davis & Socolov (2014): CCCE of 307 Gt CO2 (84 GtC) in 2012 growing by 4% p.a.
***** Considers and subtracts emissions for everything else then electricity generation in each scenario from the overall available budget (i.e. remaining budget is only for electricity generation). Hence year of budget committment is the year in which enough electricity generation capital is built to consume remaining budget for only electricity generation.

As shown in table 2, even in the most stringent IPCC scenarios we have already committed to more electricity generation emissions with today's infrastructure than any scenario contains which would give us a realistic chance to 1.5°C global warming. Meeting a 1.5°C target without CCS or asset stranding would have required that all additions to the electricity sector were zero carbon from 2006 onwards, at the latest.

3.3 Sensitivity of results

The year at which the 2°C electricity capital stock is reached depends on a number of assumptions. The assumptions for future cumulative carbon emissions from non-electricity sectors have a significant effect on the remaining budget for electricity, and hence upon the point in time at which committed emissions from the electricity sector imply temperature increases of 2°C. While we use the different IPCC scenarios and models to cover a wide range of possible non-electricity sector emissions in our approach, this section tests the sensitivity of our results towards other relevant assumptions as well. In particular, we test the sensitivity of our results towards: (1) the assumed lifetime of polluting electricity-generating infrastructure; (2) the annual growth rate of committed cumulative carbon emissions; (3) the influence of CCS in later decades of this century on the remaining carbon budgets; and (4) the variance of emissions pathways within a certain IPCC ppm range.

Lifetime of polluting capital stock

Figure 2 shows the development of CCCE from the electricity sector under different assumed plant lifetimes. For all realised emissions pathways a reduction (or increase) of the mean lifetime of power plants has significant impact on the commitment year.

If for example the average economic lifetime of existing and future fossil-fuelled power plants could be reduced from 40 to 30 years, the commitment year for the 2°C (50% probability) capital stock would be between 2016 (480-530-ppm pathways) and 2023 (430-480-ppm pathways) instead of 2011-2017. Table 3 shows an overview of commitment years under the 30 years lifetime assumption for all budgets and scenarios. Given that historically the average economically useful life of power generating infrastructure is 40 years, (Tidball et al., 2010; Davis & Socolow, 2014) this would imply stranding assets 10 years before the end of their useful life.

When generating capacity is prematurely retired, the type of replacement plant is highly relevant. Coal to gas substitution may not, for instance, reduce CCCE. As discussed further below, if coal-fired generation capacity is replaced immediately by new CCGTs with 40-year lifetimes, CCCE may actually be higher than if the coal-fired plant were instead replaced later, at the end of its economic life, with zero carbon generation.

Table 3: As for table 2 but assuming a 30 year mean lifetime of existing electricity sector generation stock.

Lifetime of capital stock 30 years at 4% annual growth					**Year of budget commitment (2006-2100)*******						
	Warming*	**Likelihood****	**Budget (CCE)*** in 2014**	**Committed CCE**** in 2014**	**Cat. 1** 450-ppm (430-480-ppm)	**Cat. 2** 500-ppm (480-530-ppm)	**Cat. 3** 550-ppm (530-580-ppm)	**Cat. 4** 580-650-ppm	**Cat. 5** 650-720-ppm	**Cat. 6** 720-1000-ppm	**Cat. 7** >1000-ppm
[GtC]	**< 1.5°**	66%	77	56	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	118	56	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		33%	200	56	<2006	<2006	<2006	<2006	<2006	<2006	<2006
	< 2.0°	66%	241	56	2009	<2006	<2006	<2006	<2006	<2006	<2006
		50%	322	56	**2023**	**2016**	<2006	<2006	<2006	<2006	<2006
		33%	377	56	**2032**	**2026**	<2006	<2006	<2006	<2006	<2006
	< 3.0°	66%	622	56	**2060**	**2056**	**2041**	**2032**	**2019**	<2006	<2006
		50%	731	56	**2068**	**2065**	**2053**	**2045**	**2034**	<2006	<2006
		33%	853	56	**2074**	**2072**	**2062**	**2056**	**2046**	**2023**	<2006

* Warming due to CO2 and non-CO2 drivers. Temperature values are given relative to the 1861-1880 period
** Fractions of scenario simulations meeting the warming objective with that amount of CCE
*** CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO2 forcing follows the RCP8.5 scenario (similar emissions are implied by the other RCP scenarios). For the most scenario-threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of the CO2 emissions these figures provide an indication of the cumulative CO2 emissions implied by simulations under RCP-like scenarios. Values are rounded to the nearest 50.
**** only electricity generation capital stock based on Davis & Socolov (2014): CCCE of 307 Gt CO2 (84 GtC) in 2012 growing by 4% p.a.
***** Considers and subtracts emissions for everything else then electricity generation in each scenario from the overall available budget (i.e. remaining budget is only for electricity generation). Hence year of budget committment is the year in which enough electricity generation capital is built to consume remaining budget for only electricity generation.

Different growth rates of polluting capital stock

Figure 3 shows the development of CCCE of generation capital stock under different growth assumptions. Given the short time until the expected commitment year, only dramatic reductions of the annual growth rate of CCCE can have a meaningful impact. In the analysed scenarios of 430-530-ppm pathways, a small reduction in the growth rate has an insignificant impact on the commitment year. If for example the annual growth rate of existing and future generation CCCE could be reduced from 4% to 3% p.a., the relevant years for the 2°C (50% probability) capital stock remain as before, namely between 2011 (480-530-ppm pathways) and 2017 (430-480-ppm pathways). Table 4 shows an overview of commitment years under the 3% p.a. growth assumption for all budgets and scenarios.

Figure 3: As for figure 2 but for different post-2012 rates of increase in committed cumulative emissions (CCCE) for the electricity sector.

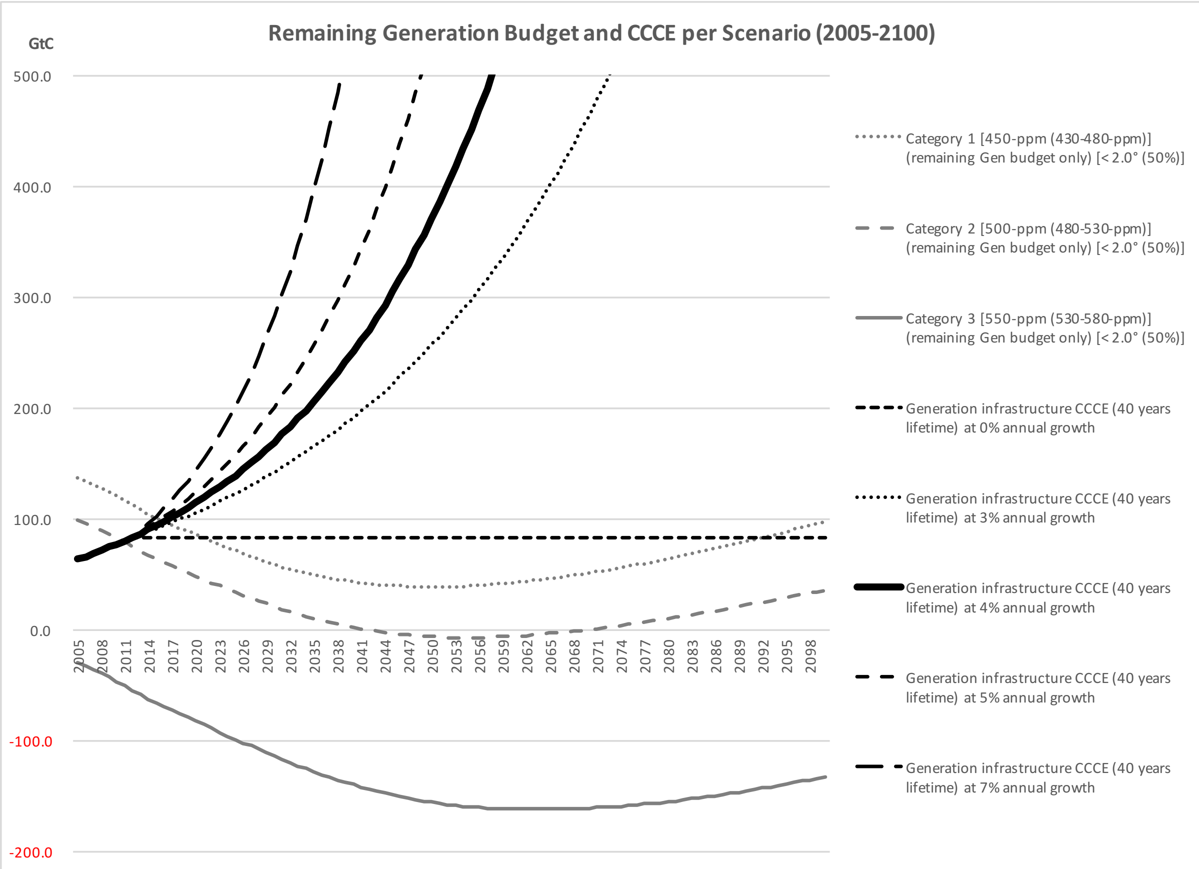


Table 4: As for table 4 but assuming a 3% p. a. growth rate of CCCE from 2012 on.

Lifetime of capital stock 40 years at 3% annual growth					Year of budget commitment (2006-2100)*****						
	Warming*	**Likelihood****	**Budget (CCE)*** in 2014**	**Committed CCE**** in 2014**	**Cat. 1** 450-ppm (430-480-ppm)	**Cat. 2** 500-ppm (480-530-ppm)	**Cat. 3** 550-ppm (530-580-ppm)	**Cat. 4** 580-650-ppm	**Cat. 5** 650-720-ppm	**Cat. 6** 720-1000-ppm	**Cat. 7** >1000-ppm
[GtC]	**< 1.5°**	66%	77	89	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	118	89	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		33%	200	89	<2006	<2006	<2006	<2006	<2006	<2006	<2006
	< 2.0°	66%	241	89	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	322	89	**2017**	2011	<2006	<2006	<2006	<2006	<2006
		33%	377	89	**2026**	**2020**	<2006	<2006	<2006	<2006	<2006
	< 3.0°	66%	622	89	**2060**	**2055**	**2036**	**2027**	2013	<2006	<2006
		50%	731	89	**2070**	**2066**	**2050**	**2041**	**2029**	<2006	<2006
		33%	853	89	**2079**	**2075**	**2063**	**2054**	**2043**	**2017**	<2006

* Warming due to CO2 and non-CO2 drivers. Temperature values are given relative to the 1861-1880 period
** Fractions of scenario simulations meeting the warming objective with that amount of CCE
*** CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO2 forcing follows the RCP8.5 scenario (similar emissions are implied by the other RCP scenarios). For the most scenario-threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of the CO2 emissions these figures provide an indication of the cumulative CO2 emissions implied by simulations under RCP-like scenarios. Values are rounded to the nearest 50.
**** only electricity generation capital stock based on Davis & Socolov (2014): CCCE of 307 Gt CO2 (84 GtC) in 2012 growing by 3% p.a. after 2012.
***** Considers and subtracts emissions for everything else then electricity generation in each scenario from the overall available budget (i.e. remaining budget is only for electricity generation). Hence year of budget committment is the year in which enough electricity generation capital is built to consume remaining budget for only electricity generation.

This insensitivity is due to the large already existing commitments from the energy sector compared to the ≤ 2°C (50% probability) budget (89%, see figure 1). Even a significant structural change in future investments in this capital stock would, without a premature shut-down of polluting capacity, only marginally affect the relevant 'cut-off' year. For instance, under the assumption of a 7% p.a. growth rate, the commitment year is only slightly earlier. Under the assumption of 0% annual growth of CCCE (i.e. new investment in polluting generation capacity only replaces retiring capacity), the remaining generation budget is still used up in the early 2020s (see table 8).

Sensitivity to carbon capture technology assumptions

Assuming realised emissions from all sectors consistent with 430-480ppm scenarios, new generating infrastructure has to be net zero carbon by 2017. This finding does not imply that no new fossil generation investment is possible from 2017 onwards. It implies that any new committed fossil emissions from 2017 must be eliminated by incorporating carbon capture, offset by retrofitting carbon capture for existing infrastructure or by CO_2 removal (CDR) technologies to remove the same amount of cumulative carbon from the atmosphere as the newly built infrastructure will emit over its lifetime.

IPCC scenarios that assume more carbon capture tend to involve greater near-term emissions (precisely because the capture technologies operate in the future). This implies a *lower* available near-term power sector budgets, which moves the date of the 2°C capital stock (with assumed CCS in the future) earlier in time. Carbon capture deployment is particular prevalent in the 430-530-ppm groupings.

Table 5: As for table 4 but only scenarios that don't use CCS in the next century are included in the grouping means.

Lifetime of capital stock 40 years at 4% annual growth					Year of budget commitment (2006-2100)***** Without CCS						
	Warming*	Likelihood**	Budget (CCE)*** in 2014	Committed CCE**** in 2014	Cat. 1 450-ppm (430-480-ppm)	Cat. 2 500-ppm (480-530-ppm)	Cat. 3 550-ppm (530-580-ppm)	Cat. 4 580-650-ppm	Cat. 5 650-720-ppm	Cat. 6 720-1000-ppm	Cat. 7 >1000-ppm
[GtC]	< 1.5°	66%	77	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	118	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		33%	200	90	2012	<2006	<2006	<2006	<2006	<2006	<2006
	< 2.0°	66%	241	90	**2017**	2008	<2006	<2006	<2006	<2006	<2006
		50%	322	90	**2029**	**2019**	<2006	<2006	<2006	<2006	<2006
		33%	377	90	**2035**	**2027**	2007	<2006	<2006	<2006	<2006
	< 3.0°	66%	622	90	**2054**	**2050**	**2038**	**2030**	<2006	<2006	<2006
		50%	731	90	**2060**	**2056**	**2047**	**2039**	<2006	<2006	<2006
		33%	853	90	**2065**	**2062**	**2054**	**2048**	**2021**	**2019**	<2006

* Warming due to CO2 and non-CO2 drivers. Temperature values are given relative to the 1861-1880 period
** Fractions of scenario simulations meeting the warming objective with that amount of CCE
*** CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO2 forcing follows the RCP8.5 scenario (similar emissions are implied by the other RCP scenarios). For the most scenario-threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of the CO2 emissions these figures provide an indication of the cumulative CO2 emissions implied by simulations under RCP-like scenarios. Values are rounded to the nearest 50.
**** only electricity generation capital stock based on Davis & Socolov (2014): CCCE of 307 Gt CO2 (84 GtC) in 2012 growing by 4% p.a.
***** Considers and subtracts emissions for everything else then electricity generation in each scenario from the overall available budget (i.e. remaining budget is only for electricity generation). Hence year of budget committment is the year in which enough electricity generation capital is built to consume remaining budget for only electricity generation.

Table 5 shows the calculations under the assumption that CCS has no significant impact to 2100. In scenarios in which no CCS is deployed new power plants must be net zero several years later (2019-2029). This is explained by the fact that a 430-530-ppm consistent pathway without CCS (which primarily affects the electricity sector) requires stronger and faster decarbonisation in the non-power sectors. As a consequence, there is a larger share of cumulative carbon budget available for the power sector, which hence has more time before reaching the 2°C capital stock.

Table 6: As for table 5 but only scenarios that use CCS in the next century are included in the grouping means.

Lifetime of capital stock 40 years at 4% annual growth					Year of budget commitment (2006-2100)*****						
					With CCS						
	Warming*	Likelihood**	Budget (CCE)*** in 2014	Committed CCE**** in 2014	Cat. 1 450-ppm (430-480-ppm)	Cat. 2 500-ppm (480-530-ppm)	Cat. 3 550-ppm (530-580-ppm)	Cat. 4 580-650-ppm	Cat. 5 650-720-ppm	Cat. 6 720-1000-ppm	Cat. 7 >1000-ppm
[GtC]	< 1.5°	66%	77	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	118	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		33%	200	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
	< 2.0°	66%	241	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	322	90	**2016**	2010	<2006	<2006	<2006	<2006	<2006
		33%	377	90	**2023**	**2018**	<2006	<2006	<2006	<2006	<2006
	< 3.0°	66%	622	90	**2048**	**2044**	**2031**	**2024**	2013	<2006	<2006
		50%	731	90	**2055**	**2052**	**2041**	**2035**	**2026**	<2006	<2006
		33%	853	90	**2061**	**2059**	**2050**	**2045**	**2037**	**2015**	<2006

* Warming due to CO2 and non-CO2 drivers. Temperature values are given relative to the 1861-1880 period
** Fractions of scenario simulations meeting the warming objective with that amount of CCE
*** CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO2 forcing follows the RCP8.5 scenario (similar emissions are implied by the other RCP scenarios). For the most scenario-threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of the CO2 emissions these figures provide an indication of the cumulative CO2 emissions implied by simulations under RCP-like scenarios. Values are rounded to the nearest 50.
**** only electricity generation capital stock based on Davis & Socolov (2014): CCCE of 307 Gt CO2 (84 GtC) in 2012 growing by 4% p.a.
***** Considers and subtracts emissions for everything else then electricity generation in each scenario from the overall available budget (i.e. remaining budget is only for electricity generation). Hence year of budget committment is the year in which enough electricity generation capital is built to consume remaining budget for only electricity generation.

Similarly, in scenarios in which significant CCS is deployed, we find that the 'cut-off' date moves closer to the present (table 6). Assuming that CCS will capture most of the emissions from generating infrastructure in future decades of this century would require committed emissions to stop growing by 2010 (480-530-ppm pathways) and by 2016 (430-480-ppm). Scenarios that assume that most of the electricity sector emissions will be captured in later decades of the century allow for a slower decarbonisation of other sectors and hence leave less generation budget to the electricity sector today.

In nearly all 430-530-ppm scenarios, CCS plays an important role. Only 7 scenarios from the 430-480-ppm pathways assume no CCS between 2005-2100 (108 scenarios assume CCS) and only 21 scenarios assume no CCS in the 480-530-ppm pathways (254 scenarios assume CCS), raising the question about the plausibility of reaching a ≤ 2°C (50% probability) goal without significant CCS deployment.

Sensitivity to non-electricity emission pathways

In our approach, we use simple averages of the emissions of all IPCC scenario-model combinations within a certain ppm range (e.g. 430-480-ppm). However, within this range the emission pathways of the combinations can be significantly different from each other. We also test the sensitivity of our results to different emission pathways within the 430-480-ppm and the 480-530-ppm ranges.

Table 7: Year in which generation budget is committed (assuming 40 years lifetime and 4% growth p.a.) for mean, median, min, and max electricity emission pathways in 2 different scenario groupings and peak warming budgets.

Lifetime of capital stock 40 years at 4% annual growth					Year of budget commitment (2006-2100)*****							
					450-ppm (430-480-ppm)				500-ppm (480-530-ppm)			
	Warming*	Likelihood**	Budget (CCE)*** in 2014	Committed CCE**** in 2014	Average	Median	Min	Max	Average	Median	Min	Max
[GtC]	< 1.5°	66%	77	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		50%	118	90	<2006	<2006	<2006	<2006	<2006	<2006	<2006	<2006
		33%	200	90	<2006	<2006	<2006	2008	<2006	<2006	<2006	2007
	< 2.0°	66%	241	90	<2006	<2006	<2006	2014	<2006	<2006	<2006	2013
		50%	322	90	**2017**	**2016**	2006	**2024**	2011	2013	<2006	**2023**
		33%	377	90	**2024**	**2024**	2014	**2029**	**2019**	**2021**	<2006	**2029**
	< 3.0°	66%	622	90	**2048**	**2049**	**2043**	**2048**	**2045**	**2046**	**2031**	**2048**
		50%	731	90	**2055**	**2056**	**2052**	**2055**	**2053**	**2054**	**2041**	**2054**
		33%	853	90	**2062**	**2062**	**2059**	**2061**	**2059**	**2060**	**2051**	**2060**

* Warming due to CO2 and non-CO2 drivers. Temperature values are given relative to the 1861-1880 period

** Fractions of scenario simulations meeting the warming objective with that amount of CCE

*** CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO2 forcing follows the RCP8.5 scenario (similar emissions are implied by the other RCP scenarios). For the most scenario-threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of the CO2 emissions these figures provide an indication of the cumulative CO2 emissions implied by simulations under RCP-like scenarios. Values are rounded to the nearest 50.

**** only electricity generation capital stock based on Davis & Socolov (2014): CCCE of 307 Gt CO2 (84 GtC) in 2012 growing by 4% p.a.

***** Considers and subtracts emissions for everything else then electricity generation in each scenario from the overall available budget (i.e. remaining budget is only for electricity generation). Hence year of budget committment is the year in which enough electricity generation capital is built to consume remaining budget for only electricity generation.

For each ppm range, we report the average and median values of each relevant set of scenarios along with the scenario with the maximum and minimum *cumulative 2005-2100 carbon emissions* from the electricity sector. The max scenario hence assumes the emissions trajectory of the model-scenario-combination with the highest possible electricity-sector emissions within the respective ppm range[7] (relatively lower non-electricity-sector emissions) and the min scenario the trajectory of the combination with the lowest electricity-sector emissions[8] (relatively higher non-electricity-sector emissions).

Table 7 shows that the differences between the max and min values. Assuming, for example, that non-electricity sector emissions follow a pathway with relatively steep decarbonisation over the next decades (max scenario) would leave until 2024 (430-480-ppm scenarios) or 2023 (480-530-ppm scenarios) to completely decarbonise new electricity sector investments (for the 2°C (50% probability) target). Assuming that non-electricity sector emissions follow a pathway with relatively high emissions (min scenario) would imply that we already reached the date from which on new electricity sector investments would have been required to be net zero in 2006 or before to stay within the 2°C (50% probability) budget.

---

[7] MERGE-ETL_2011 + AMPERE2-450-LimSW-HST for the 430-480-ppm range and GCAM 3.0 + EMF27-550-EERE for the 480-530-ppm range.

[8] MERGE_EMF27 + EMF27-450-FullTech for the 430-480-ppm rage and IMACLIM v1.1 + AMPERE2-450-NucOff-LST for the 480-530-ppm range.

Combined sensitivities to emission pathways and CCCE growth rates

We also briefly consider sensitivities to combinations of the assumed CCCE growth rate and the variance in emission pathways. Specifically, we test the sensitivity of the year in which we will have committed to 2°C (50% probability) warming given annual CCCE growth rates of 0-7% in combination with different possible pathways (min, max, median, average) within the 430-480-ppm and the 480-530-ppm categories.

We find that, assuming extremely low growth rates of CCCE (0-2% p.a.) and emission pathways for non-electricity sectors at the low boundary of the span of possible pathways, the commitment year can be pushed to the late 2020s or even early 2030s. Assuming more likely growth rates of CCCE close to the average growth rates over the past decade of 3-6%, and the same very optimistic non-electricity sector emission pathways the commitment year comes closer to today (2021-2025). Assuming non-electricity sector emissions at the upper boundary of the span of possible 430-480-ppm and 480-530-ppm pathways the annual growth rate of CCCE does not matter as we would have already committed to 2°C in 2006 or before.

Table 8: Year in which generation budget for ≤ 2°C (50% probability) is committed (assuming 40 years lifetime and different annual growth rates of CCCE) for mean, median, min, and max realised emissions in 2 different scenario groupings and peak warming budgets.

	Year of budget commitment (2006-2100) for < 2°C (50% probability)								
	Cat. 1 450-ppm (430-480-ppm)				**Cat. 2** 500-ppm (480-530-ppm)				**Cat. 3-7** [>530-ppm]
Annual growth rate of CCCE*	Average	Median	Min	Max	Average	Median	Min	Max	Average
0%	**2021**	**2021**	2006	**2033**	2011	2014	<2006	**2034**	<2006
1%	**2019**	**2019**	2006	**2030**	2011	2013	<2006	**2030**	<2006
2%	**2018**	**2018**	2006	**2027**	2011	2013	<2006	**2027**	<2006
3%	**2017**	**2017**	2006	**2025**	2011	2013	<2006	**2025**	<2006
4%	**2017**	**2016**	2006	**2024**	2011	2013	<2006	**2023**	<2006
5%	**2016**	**2016**	2006	**2022**	2011	2013	<2006	**2022**	<2006
6%	**2016**	**2016**	2006	**2021**	2011	2013	<2006	**2021**	<2006
7%	**2015**	**2015**	2006	**2020**	2011	2013	<2006	**2020**	<2006

***Assumed annual growth rate of CCCE from 2012; assumed 40 year lifetime of capital stock.**

4. Discussion

4.1 Policy choices

A 'planetary boundary' is plausibly thought to be situated at around 350ppm concentration of carbon dioxide (Rockström et al., 2009). Nation states affirmed the target to limit warming to below 2°C in 2011 at COP 17 in Durban, and again in 2015 at COP 21 in Paris. This corresponds to around 400ppm carbon dioxide concentrations. The main finding of this paper, however, is that the '2°C capital stock' for the global power sector will be reached in 2017. Even this finding assumes emissions from other sectors shift onto a 2°C consistent pathway, which may well be optimistic. In short, the energy system is now at risk of undermining climate stability, perhaps the most important aspect of our natural capital and a key asset of a 'green economy'.

Our findings raise several fundamental questions, discussed in 4.3 below, but they also raise immediate and significant implications for the electricity sector. Logically, achieving the necessary transformation of the global power sector is going to require some combination of the following four options:

1) new power assets are 100% zero carbon as soon as possible;
2) existing fossil assets are retrofitted with carbon capture;
3) existing fossil assets are stranded early, replaced by zero carbon assets; and
4) CDR technologies are used to hold temperatures below 2°C.

The most cost-effective combination of these four options will depend strongly upon the rates of decline in the costs of the relevant technologies, including nuclear, renewables including hydro, carbon capture, associated grid balancing technologies (including storage) and negative emission technologies. We briefly consider the four options in turn before examining the policy interventions that could support them.

First, numerous studies document the rapid cost declines of renewable energy (Schilling & Esmundo, 2009; IPCC, 2011; Reichelstein & Yorston, 2013), the feasibility of large scale deployment of zero emissions technologies including renewables, biomass, hydro, and nuclear (IPCC, 2011; Hong et al, 2015; Mileva et al, 2016), the overall modest macroeconomic costs such a program would entail (NCE, 2014; IPCC, 2011; Stern, 2014; Stern, 2015), and the significant co-benefits of widespread zero carbon deployment (Omer, 2008; Harlan & Ruddell, 2011). Challenges remain, both on cost and grid integration (Luo et al, 2015; Wagner et al, 2015), but large-scale deployment of zero carbon power appears inevitable; the question is not if but how fast.

Second, significant carbon capture deployment seems essential to enable existing or soon to be created carbon-emitting infrastructure to be retrofitted in order to reduce committed cumulative emissions (especially if mitigation in other sectors turns out harder than expected). Whilst CCS technologies are amongst the most expensive mitigation options available today, nearly all 2°C consistent pathways depend on significant CCS deployment in order to provide net negative emission capabilities, and excluding CCS technologies increases the modelled cost of meeting 2°C by around 2.5 times (IPCC WG3, 2014; Clarke et al., 2014).

Third, new fossil assets deployed after reaching the 2°C capital stock could be retired early and replaced by zero carbon assets. While this is unlikely to economically superior to investing in zero carbon assets in the first place, there may be some value in delay; the costs of zero carbon technologies are declining rapidly and on average remain more expensive than fossil fuels. However, recent research shows that the cost declines are significantly attributable to increases in cumulative production volumes of zero carbon technologies (Nagy et al., 2013), thus delay may significantly slow such price declines. Thus earlier action to shift to investments in zero emissions new capital stock may not only avoid later stranding of assets, but also accelerate the decline in costs of zero emissions technologies.

Finally, given the current trajectory of the global energy system and timeframes required to shift all new global energy investment to zero carbon, the probability of overshooting the 2°C capital stock is significant. Increased investments in CDR technologies might help mitigate such overshoot and to minimize asset stranding. However, given the current costs and technical challenges with widespread CDR deployment (Pires et al., 2011) it would not be prudent to rely on CDR in later years as an alternative to rapid de-carbonization of the power system.

4.2 Policy instruments

In the introduction to this paper, we noted that annual CO_2 emission reduction targets only indirectly address the ultimate goal; it is possible to meet short-term flow targets while simultaneously installing new coal-fired power stations that make it economically impossible to meet cumulative emission targets. Better is to directly target cumulative emissions, and better still are policies that are a function of an index of attributable warming. In contrast, targets that are a function of time do not map directly onto cumulative emissions or to the observed climate response.

This distinction becomes relevant in the debate about the virtue of coal to gas substitution, which would reduce near-term emission flows. A stock-based analysis makes clear that coal to gas switching is only worthwhile if it reduces the expected future CCE. This may well be achieved if the fuel switching from coal to gas involves no new construction; existing gas-fired plants are run at a higher load factors, coal-fired plants are run at lower load factors. However, if new capital expenditure on gas is required, the analysis is more complicated. For instance, a 1 GW coal-fired power station with emissions intensity of 1 tCO_2/MWh and a load factor of 70% will emit 6.1 Mt CO_2 per annum.[9] With a residual lifetime of 10 years, expected future cumulative CO_2 emissions are therefore 61 Mt CO_2. Suppose this plant were retired early and replaced by a 1 GW combined cycle gas turbine (CCGT) plant with emissions intensity of 0.5 tCO_2/MWh a load factor of 70%, hence emitting 3.05 Mt CO_2 per annum. With a lifetime of 40 years, expected future cumulative emissions from the CCGT would be 122 Mt CO_2, compared to 61 Mt CO_2 from the coal plant. While annual emissions are cut in half over the first ten years, it is impossible to determine whether such switching reduces emissions unless it is specified what occurs after the coal-fired power station is closed in 10 years. If it would have otherwise been replaced with clean renewable energy, perhaps driven by continuing cost declines, then the strategy of switching from coal to gas will have been counterproductive. More careful analysis is required (Lazarus et al., 2014; Zhang et al. 2015).

---

[9] 1 GW x 365 days/year x 24 hours/day x 70% load factor = 6,132 GWh x 1,000 MWh/GWh = 6,132,000 or 6.132 mio. MWh x 1 tCO_2/MWh = 6.132 mio. tons of CO2 per annum.

We now examine policy instruments that are candidates for constraining cumulative emissions to meet a 2°C target. Each instrument incentivises one or more of the four options in section 4.1.

***Carbon prices*:** Carbon prices support action on all four options. They create incentives for actors to invest in new zero carbon assets, to retrofit (where economically and technically feasible) existing assets with carbon capture, to retire the highest emitting stock earlier and to develop negative emissions technologies. Carbon prices have the benefits of being technologically neutral and create incentives to de-carbonize efficiently. They work simultaneously on the demand and the supply side, increasing the costs to consumers of polluting fossil fuels, and reduce the returns to producers. They may also provide an economic 'double dividend' (Jorgenson, 2013) of accelerating the transition to a green economy while simultaneously permitting reform and greater efficiency of the existing tax system, which tends to tax goods rather than bads.

However, the analysis in this paper makes clear that the scale and pace of the energy sector transformation required is dramatic. The level of carbon prices required to deliver, without other interventions, this rapid transformation would be far higher than is politically feasible in most countries, especially when it is considered that current effective net carbon prices may be negative, accounting for fossil fuel subsidies (Wagner et al 2015). But this does not mean that carbon prices should be rejected; they should be implemented to the extent politically feasible (whether by a carbon tax or a quantity constraint and trading scheme). Pragmatism requires additional policy instruments.

Cumulative cap and trade: One more novel form of carbon pricing would be a *cumulative* emissions cap and trade system (cf McKibbon and Wilcoxen, 2002) consistent with estimates of the remaining carbon budget and the energy sector's appropriate share of that budget. This is different to existing cap and trade systems, which largely operate on a period-by-period basis, even if future emissions trajectories are sometimes described decades into the future. A cap on cumulative emissions would provide visibility of the carbon budget across the full lifetime of the assets. If it were credible, it would create incentives for de-carbonization of new capital stock and optimization of the existing portfolio (retrofits and retirements). Unfortunately, however, credibility over many decades is very difficult to achieve in practice, given the nature of changing governments in democratic societies.

***Licencing requirements*:** Rules could be established to (1) require all new power plants to have zero (or close to zero) emissions; and (2) prevent high-emitting plants from being granted life extensions. Licensing rules have the political benefits of simplicity and clarity, and could potentially reduce the political economy challenges of allocating permits either within or between countries (Collier & Venables, 2014). This approach might also reduce the political economy challenges of asset stranding. A more gradual version is to regulate carbon intensity in $kgCO_2/kWh$. China has taken this approach in its 5-year plan, as have several U.S. states (Fischer and Newell, 2008). Such rules could have the perverse effect of incentivizing a rush to build high emitting assets before the intensity target ratchets down to zero (Jensen et al, 2015), but our analysis suggests the target should reach zero faster than the time it takes to plan and consent a new power plant.

***Technology-based deployment support*:** Another approach is to regulate, subsidize, or tax specific energy producing technologies. Examples include:

- Subsidies or other regulations for accelerated renewable deployment (e.g. a feed-in-tariff or renewable portfolio standard);
- Subsidies for nuclear plans;
- Requiring all new coal plants to have CCS.

However, technology-based regulation has significant disadvantages. They tend to be inefficient, and more prone to regulatory capture than broad-based economic instruments. A well-designed ramp down to zero emissions for new power generation would be more effective, for it would not support one specific technology over another. For instance, renewable portfolio standards ignore potential contributions from non-renewable zero carbon sources (nuclear, fossil with CCS).

***Research and development support*:** Finally, given that one of the most important variables is the relative cost of clean and dirty technologies, and given that there are well-understood market failures in research and innovation, there is a clear and well-accepted role for government to support clean technology research and development (Fischer and Newell, 2008). The surprise is that so little funding, relative for instance to implicit fossil fuel subsidies, is directed towards the brainpower that might actually provide solutions to vital human problems. The recent announcement at the first day of the COP21 of a coalition of countries and private sector investors to invest several billion dollars in clean energy R&D is well grounded in economic and political logic. The initiative is being led by Bill Gates and includes at least 20 countries (e.g. the U.S., France, India and others), which are expected to double the amount of R&D investment for clean energy from $5 to $10 billion over the next five years.

In addition, a policy offering a balance of effectiveness, efficiency, and political tractability may be an agreement that all *new* electricity generation (and any lifetime extensions) be zero carbon by a date in the near future, with countries agreeing their own ramps to that goal (cf Collier & Venables, 2014). Careful thought would need to go into designing such an agreement to minimize gaming during the transition period, but a zero carbon new build target by a fixed date has the advantages of simplicity and ease of monitoring.

4.3 Broader questions and directions for future research

Our finding that the 2°C capital stock for the global power sector will have been built by 2017 is based on the assumption that the transport, industry, land-use, etc. sectors also transition to a 2°C compatible pathway. Further detailed analysis of the committed emissions of these other sectors of the economy is needed. Taking into account the lifetime of transport assets (i.e. ships, trucks, cars, airplanes), industry assets (factories, mines, etc.), and residential assets (buildings, etc.) a closer analysis of the historic and expected development in these sectors would likely suggest that we have already passed the point of a 50% probability of 2°C without negative emissions or asset stranding.

Given the implausibility of all new power sector assets being zero carbon from now onwards, the role of both CCS and CDR are brought into focus (IPCC WG3, 2014). How realistic is it to expect the successful large-scale deployment of CCS and CDR technologies? At present, rates of investment and deployment of these technologies are entirely negligible compared to the scale at which they appear to be required. Without major changes in policy or remarkable reductions in cost, both potentially important areas for further research, it does not appear realistic to expect these technologies to be deployed at scale.

If so, the only remaining logical outcomes are either that there is significant early stranding of fossil assets over the coming few decades – perhaps because accelerated cost declines in clean energy make this economically rational – or humanity accepts risks above 50% of exceeding 2°C warming. The implications for risks to investors in fossil fuels are rapidly becoming obvious. Further research is urgently needed on both the technologies, policies and institutions that could bring the costs of clean energy down as quickly as possible. So too is research on managing the process of asset stranding.

Finally, the analysis in this paper also raises a range of broader questions about the sustainability of our energy and economic systems. Existing policies are clearly inadequate to tackle global environmental problems, such as climate change or biodiversity loss. Much greater effort is required to create prices – including carbon prices – and economic incentives to ensure that individuals and corporations protect the natural environment. Carbon and other environmental prices form part of a broader shift in green fiscal policy away from taxing goods (labour) to taxing bads (pollution). Such a tax shift can generate a 'double dividend'. It is certainly time, as the IMF has argued, to cut subsidies for fossil fuel use (Coady et al. 2015).

Acknowledgements

The authors acknowledge useful discussions with Alex Kazaglis, Alex Teytelboym, Alexandra Tzvetkova, Charlotte Adema, Myles Allen, Robert Hahn, Robert Socolow, Seth Collins, Steven Davis, Sonia Medina, and participants at the Global Stranded Assets Conference in Oxford in September 2015. We also thank Alex Teytelboym, Luis Mundaca, Robert Hahn and three anonymous referees for extremely helpful written comments. We are also grateful to Robert Socolow and Steven Davis for input and assistance in processing and analysing the WEPP and CARMA databases. The authors also acknowledge financial support from the Institute for New Economic Thinking and the Children's Investment Fund Foundation.

References

Acemoglu et al. (2011): Acemoglu, D., Aghion, P., Bursztyn, L. and Hemous, D. 'The Environment and Directed Technical Change'. London, Centre for Economic Policy Research (2011).

Aghion et al. (2014): Aghion, P., Hepburn, C., Teytelboym, T. and Zenghelis, D. "Path dependence, innovation and the economics of climate change." London School of Economics, Grantham Research Institute on Climate Change and the Environment, Policy paper. November (2014).

Allen et al. (2009): Allen, M. et al. "Warming caused by cumulative carbon emissions towards the trillionth tonne." *Nature* 458.7242 (2009): 1163-1166.

Bertram et al. (2015): Bertram, C. et al. "Carbon lock-in through capital stock inertia associated with weak near-term climate policies." *Technological Forecasting and Social Change* 90 (2015): 62-72.

Caldecott et al. (2014): Caldecott, B., Tilbury, J. and Carey, C. "Stranded assets and scenarios." Smith School of Enterprise and the Environment, Stranded Assets Program, Discussion Paper (2014).

Clarke et al. (2014): Clarke, L. et al., Assessing Transformation Pathways. 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. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Coady et al. (2015): Coady, D., Parry, I. W. H., Sears, L. and Shang, B. "How Large Are Global Energy Subsidies?" IMF Working Paper 15/105, May (2015).

Collier & Venables (2014): Collier, P. and Venables, J. “Closing coal: Economic and moral incentives.” Oxford Review of Economic Policy, Volume 30, Number 3, 2014, pp. 492–512

Crutzen (2006): Crutzen, P. The “anthropocene”. (pp. 13-18). Springer Berlin Heidelberg 2006.

Davis et al. (2010): Davis, S., Caldeira, K., & Matthews, H. “Future CO2 emissions and climate change from existing energy infrastructure.” *Science*, 329(5997) (2010): 1330-1333.

Davis & Socolow (2014): Davis, S. and Socolow, R. "Commitment accounting of CO2 emissions." *Environmental Research Letters* 9.8 (2014): 084018.

Dawson et al. (2011): Dawson, T., et al. "Beyond predictions: biodiversity conservation in a changing climate." *Science* 332.6025 (2011): 53-58.

EEI (2006): “European Energy Infrastructure: The Chalmers databases 2006” AGS Pathways Report (2006): EU1, p. 14.

Erickson et al. (2015): Erickson, P., Kartha, S., Lazarus, M. & Tempest, K. “Assessing Carbon Lock-In.” *Environmental Research Letters* 10(8) (2015): 084023.

EU (2014): European Commission, “Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on A policy framework for climate and energy in the period from 2020 to 2030” 22 January 2014, COM (2014) 15 final

Fischer & Newell, 2008: Fischer, C. and Newell, R. "Environmental and technology policies for climate mitigation." *Journal of environmental economics and management* 55.2 (2008): 142-162.

Guivarch & Hallegatte (2011): Guivarch, C. and Hallegatte, S. “Existing Infrastructure and the 2C Target.” *Climatic Change* 109 (3-4) (2009): pp.801-805.

Harlan & Ruddell (2011): Harlan, S. and Ruddell, D. "Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation." *Current Opinion in Environmental Sustainability* 3.3 (2011): 126-134.

Harvey et al. (2013): Harvey, H., Orr, F. and Vondrich, C. "A trillion tons." *Daedalus* 142.1 (2013): 8-25.

Hepburn & Bowen (2013): Hepburn, C. and Bowen, A. "Prosperity with growth: Economic growth, climate change and environmental limits." Handbook of Energy and Climate Change, Cheltenham: Edward Elgar Publishing (2013): 617-38.

Hepburn et al. (2015): Hepburn, C., Pfeiffer, A. and Teytelboym A. "Green Growth" in Clark, G.L., Feldman, M., Gertler, M. and Wójcik, D. (eds) The New Oxford Handbook of Economic Geography, Oxford University Press.

Hong et al. (2015): Hong, S., Bradshaw, C. and Brook, B. "Global zero-carbon energy pathways using viable mixes of nuclear and renewables." *Applied Energy* 143 (2015): 451-459.

IPCC (2011): Edenhofer, O., Sokona, Y., et al. “Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.” Cambridge University Press, Cambridge, United Kingdom and New York, NY USA.

IPCC Syn (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC WG1 (2013): Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC WG2 (2014): Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IPCC WG3 (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.

Jevons (1906): Jevons, W. *The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines*. Macmillan, 1906.

Johnson et al. (2015): Johnson, N. et al. “Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants.” *Technological Forecasting and Social Change* 90 (2015): 89-102.

Jorgenson (2013): Jorgenson, D. W., Goettle, R. J., Ho, M. S., & Wilcoxen, P. J. (2013). Double dividend: Environmental taxes and fiscal reform in the United States. MIT Press.

Kalkuhl et al. (2012): Kalkuhl, M., Edenhofer, O. and Lessmann, K. “Learning or lock-in: Optimal technology policies to support mitigation.” *Resource and Energy Economics* 34(1) (2012): 1-23.

Keynes (1933): Keynes, J. "Economic possibilities for our grandchildren” *Essays in persuasion*. London: Macmillan, 1931.

Krey et al. (2014): Krey, V. et al. Annex II: Metrics & Methodology. 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. 1281.

Krey (2014): Krey, V. "Global energy & climate scenarios and models: a review." *Wiley Interdisciplinary Reviews: Energy and Environment* 3(4) (2013), 363-383.

Lazarus et al. (2015): Lazarus, M. et al. "Natural Gas: Guardrails for a Potential Climate Bridge." New Climate Economy contributing paper. Stockholm Environment Institute, Stockholm, Sweden, and Seattle, WA, US.

Lecocq & Shalizi (2014): Lecocq, F. and Shalizi, Z. "The economics of targeted mitigation in infrastructure." *Climate Policy* 14(2) (2014): 187-208.

Le Quéré et al. (2014): Le Quéré, C. et al. "Global carbon budget 2014." *Earth System Science Data Discussions* 7.2 (2014): 521-610.

Luo et al. (2015): Luo, X. et al. "Overview of current development in electrical energy storage technologies and the application potential in power system operation." *Applied Energy* 137 (2015): 511-536.

Matthews et al. (2009): Matthews, H. et al. "The proportionality of global warming to cumulative carbon emissions." *Nature* 459.7248 (2009): 829-832.

McKibbin & Wilcoxen (2002): McKibbin, W. and Wilcoxen, P. "The role of economics in climate change policy." *Journal of Economic Perspectives* (2002): 107-129.

Mileva et al. (2016): Mileva, A. et al. "Power system balancing for deep decarbonization of the electricity sector." *Applied Energy* 162 (2016): 1001-1009.

Mill (1909): Mill, J. *Principles of Political Economy with some of their Applications to Social Philosophy*. William J. Ashley, ed. 1909. Library of Economics and Liberty. Retrieved November 27, 2015 from the World Wide Web: http://www.econlib.org/library/Mill/mlP61.html

Moss et al. (2010): Moss, R. et al. "The next generation of scenarios for climate change research and assessment." *Nature* 463.7282 (2010): 747-756.

Nagy et al. (2013): Nagy, B., Farmer, J., Bui, Q. & Trancik, J. "Statistical basis for predicting technological progress." *PloS one* 8.2 (2013): 1-7.

NASA (2011): "Earth's Climate History: Implications for Tomorrow." NASA Science Briefs, July 2011. Retrieved November 27, 2015 from the World Wide Web: http://www.giss.nasa.gov/research/briefs/hansen_15/

Neuhoff (2005): Neuhoff, K. "Large-scale deployment of renewables for electricity generation." *Oxford Review of Economic Policy* 21.1 (2005): 88-110.

NRC (2015): National Research Council. Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. Washington, DC: The National Academies Press, (2015).

Omer (2008): Omar, A. "Energy, environment and sustainable development." *Renewable and sustainable energy reviews* 12.9: 2265-2300.

Pires et al. (2011): Pires, J., Martins, F., Alvim-Ferraz, M. & Simões, M. "Recent developments on carbon capture and storage: an overview." *Chemical Engineering Research and Design* 89.9 (2011): 1446-1460.

Reichelstein & Yorston (2013): Reichelstein, S. and Yorston, M. "The prospects for cost competitive solar PV power." *Energy Policy* 55: 117-127.

Riahi et al. (2011): Riahi, K. et al. "RCP 8.5—A scenario of comparatively high greenhouse gas emissions." *Climatic Change* 109.1-2 (2011): 33-57.

Rockström et al. (2009): Rockström, J. et al. "Planetary boundaries: exploring the safe operating space for humanity." *Ecology and Society* 14(2) (2009): 32.

Solomon & Krishna (2011): Solomon, B., and Krishna, K. "The coming sustainable energy transition: History, strategies, and outlook." *Energy Policy* 39.11: 7422-7431.

Rogelj (2014): Rogelj, J. et al. "Disentangling the effects of CO2 and short-lived climate forcer mitigation." *Proceedings of the National Academy of Sciences* 111.46 (2014): 16325-16330.

Rogelj (2015): Rogelj, J. et al. "Mitigation choices impact carbon budget size compatible with low temperature goals." *Environmental Research Letters* 10.7 (2015): 075003.

Roser (2015) – Roser, M. “GDP Growth Over the Last Centuries”. Published online at OurWorldInData.org. Retrieved November 27, 2015 from the World Wide Web: http://ourworldindata.org/data/growth-and-distribution-of-prosperity/gdp-growth-over-the-last-centuries/

Schilling & Esmundo (2009): Schilling, M. & Esmundo, M. "Technology S-curves in renewable energy alternatives: Analysis and implications for industry and government." *Energy Policy* 37.5 (2009): 1767-1781.

Smith et al. (2012): Smith, S. et al. "Equivalence of greenhouse-gas emissions for peak temperature limits." *Nature Climate Change* 2.7 (2012): 535-538.

Solomon et al. (2009): Solomon, S. et al. "Irreversible climate change due to carbon dioxide emissions." *Proceedings of the national academy of sciences* 106.6 (2009): 1704-1709.

Steckel et al. (2015): Steckel, J., Ottmar, E., and Jakob, M. "Drivers for the renaissance of coal." *Proceedings of the National Academy of Sciences* 112.29 (2015): E3775-E3781.

Stern (2014): Stern, N. "Better Growth Better Climate. The New Climate Economy Report" The Global Commission on the Economy and Climate. Retrieved November 27, 2015 from the World Wide Web: http://newclimateeconomy.net/

Stern (2015): Stern, N. *Why Are We Waiting?: The Logic, Urgency, and Promise of Tackling Climate Change*. Cambridge, Massachusetts: MIT Press.

Tidball et al. (2010): Tidball, R., Bluestein, J., Rodriguez, N., & Knoke, S. "Cost and Performance Assumptions for Modeling Electricity Generation Technologies" *Contract* 303 (2010): 275-3000.

UNEP (2014): "The Emissions Gap Report 2014". United Nations Environment Programme (UNEP), Nairobi.

UN (1999): Department of Economic and Social Affairs, Population Division. "The World at Six Billion" Part 1, Table 1, World Population From Year 0 to Stabilization, p. 5.

UN (2015): Department of Economic and Social Affairs, Population Division. "World Population Prospects: The 2015 Revision, Key Findings and Advance Tables". Working Paper No. ESA/P/WP.241.

Unruh (2000): Unruh, G. "Understanding carbon lock-in." *Energy policy* 28(12) (2000): 817-830.

Wagner et al. (2015): Wagner, G. et al. "Energy policy: Push renewables to spur carbon pricing." *Nature* 525.7567 (2015): 27-29.

Waisman et al. (2012): Waisman, H., Guivarch, C., Grazi, F., & Hourcade, J. "The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight." *Climatic Change* 114(1) (2012): 101-120.

WEO (2012): The IEA World Energy Outlook 2012

Zhang et al. (2015): Zhang, X. et al. "Climate benefits of natural gas as a bridge fuel and potential delay of near-zero energy systems." *Applied Energy* (2015).