The Decarbonization Identity and Pathways to Net-Zero

The scale and impact of committed cumulative carbon emissions and stranded assets in the electricity generation sector on the decarbonisation of the economy

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This dissertation is dedicated to my parents Sabine and Karl Heinz, my grandmother Renate, and my siblings Katharina and Johannes.

Everything I am today
and everything I ever accomplished
I owe to you.

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Abstract

Success or failure of climate policies in limiting warming to beneath particular thresholds depends on several physical, economic and social uncertainties. Whilst scenario analysis can be informative as to the types of policies that are required to achieve these goals, the complexity of scenario analysis often masks the underlying fundamental choices. This dissertation introduces the concept of the 'decarbonization identity' to simply and systematically describe the mutually exclusive and collectively exhaustive range of choices available in future climate policy decisions. The simple identity states that the remaining carbon budget [B] for a given level of warming can be partitioned into four areas: the already committed 'baked-in' emissions from existing capital stock [E]; new commitments arising from investments in additional capital stock yet to be made [N]; less the stranding of existing or future capital stock [S]; and the additional atmospheric space created by negative emissions technologies (NETs) [A]. This dissertation finds that currently operating electricity generators [E] would already emit more CO_2 (~300 $GtCO_2$) then is compatible with currently available generation-only carbon budgets [B] for a temperature rise of 1.5-2°C (~240 $GtCO_2$). In addition, the current pipeline of planned fossil fuel power plants would add almost the same amount [N] of emission commitments (~270 $GtCO_2$) to this capital stock again. Finally, these carbon budgets are inherently uncertain and depend on future, yet to be achieved, reductions of short-lived climate pollutant (SLCP) emissions. Should those reductions not be achieved today's remaining carbon budgets could be up to 37% smaller. Policy makers have now five choices to achieve the Paris climate goals: (1) protect and enhance carbon budgets by early and decisive action on SLCPs; (2) retrofit existing power generators with carbon capture and storage (3) ensure that no new polluting capital stock is added; (4) strand a considerable amount of global electricity generation capacity; and (5) create additional atmospheric space by scaling up NETs. Over the coming years and decades, the challenge will be to identify the most efficient balance of these options.

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1. Net-zero emissions, human development and capital stock inertia

When, in December 2015, the gavel came down to end the 21st Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC), 196 parties had agreed jointly to address the global emissions of greenhouse gases (GHGs) in order to limit climate change to "*well below 2℃ (...) and pursuing efforts to limit the temperature increase to 1.5℃ above pre-industrial levels*" (UNFCCC, 2015). The Paris agreement is in many ways unique, not least because of its Article 4-1, in which the parties agree to "*achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.*" By acknowledging the need to balance residual emissions with the removal of CO_2 from the atmosphere, the parties not only acknowledged the need to fully decarbonize their economies in the second half of the 21st century, but also the latest science in respect to CO_2 emissions and climate change.

In recent years, a growing body of literature has repeatedly emphasized, that what is decisive for climate change is not the *annual* rate of emissions of long-lived climate pollutants (LLCPs), such as carbon dioxide (CO_2),[1] but rather the *cumulative* emissions of such pollutants (Allen *et al.*, 2009; Meinshausen *et al.*, 2009). Most LLCPs, once released into the atmosphere, will remain there for many decades, or even centuries, before being removed by natural processes (Archer *et al.*, 2009; Clark *et al.*, 2016). It is therefore the cumulative amount of

[1] There are other LLCPs, such as, e.g., nitrous oxide, N_2O, but CO_2 is by far the most important one (IPCC, 2014a).

these gases in the atmosphere that will have the biggest influence on the greenhouse effect that is warming our planet (Matthews *et al.*, 2009). This means, however, that to stabilize the climate at any level, not only at 1.5 or 2°C above current temperatures, but virtually any level, eventually, the emission of CO_2 and other GHGs will have to decrease to *near-* or *net-zero*. A balance between sustained emissions and removals by carbon sinks, e.g. oceans and biomass, must be achieved (Matthews and Caldeira, 2008).[2]

For humanity, this connection between cumulative carbon emissions and climate change constitutes a major trade-off. On the one hand, most economies around the world are built on and around the energy extracted from the burning of fossil fuels (Fouquet and Pearson, 2012; IPCC, 2014b). On the other hand, the burning of exactly these fossil fuels releases pollutants into our local environment and the atmosphere, which harms humans locally, and, even more importantly, increases global temperatures, thereby posing a threat to humanity (IPCC, 2014b).

While scientists may still disagree on the tolerable level of climate change, be it 1.5, 2, or even 3°C (Knutti *et al.*, 2015), the international community has decided that efforts should be made to limit it to well below 2°C and this decision has been confirmed with the Paris Accord. The implications are grave. To achieve the Paris goals, the global economy, which has been built around the consumption of fossil fuels, must be decarbonized in the second half of this century. For many reasons, this poses a serious and complex challenge that can be illustrated in a simplified way by the Kaya Identity below (Kaya and Yokobori, 1998).

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[2] See Appendix B.1 for a complete review of relevant decarbonization literature.

$$CO_2\ emissions = Population * \frac{GDP}{Population} * \frac{Energy}{GDP} * \frac{CO_2}{Energy}$$

While the Kaya Identity certainly has its flaws, e.g. the assumption that its four parts are mutually independent,[3] it still points towards an important issue: global population keeps growing and is expected to grow to ~10 bn. individuals by mid-century (United Nations, 2017). At the same time, many people still live in dire conditions and strive for economic development to lift themselves out of poverty (WBG, 2016). Despite advances in poverty alleviation in recent decades, the average per capita income in many developing parts of the world is still considerably lower than in developed nations. The necessary economic growth, however, will also increase the demand for energy by multiple times (see Figure 1), a demand that cannot yet be met fully by means of clean, zero-carbon energy sources, such as solar or wind.[4]

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[3] It is likely that the four parts of the Kaya identity mutually influence each other. For instance population growth and GDP per capita. In economies with high GDP per capita population growth is typically lower than in less affluent economies (WBG, 2017).

[4] The carbon intensity of total primary energy supply has decreased over the last decades but is still considerably larger than zero.

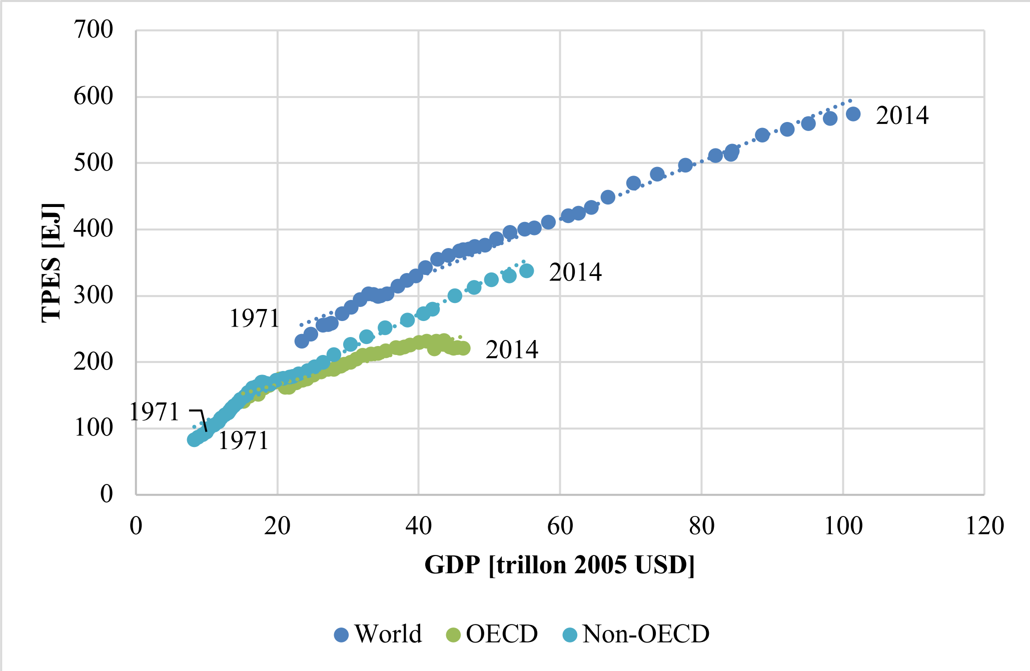

Figure 1: Correlation between GDP and total primary energy supply (TPES), 1971-2014. *Source: OECD/IEA data (IEA, 2016a).*

Acknowledging the technological, institutional and behavioural inertia in the global energy system (Seto *et al.*, 2016),[5] it is therefore likely that, despite the goal to decarbonize, the global economy will see additions to its *polluting capital stock* over the coming years (IEA, 2016b). In the context of this dissertation, the polluting capital stock denotes the aggregate of all currently operating anthropogenic sources of GHG emissions (Pfeiffer *et al.*, 2016). Such assets often have a long lifetime. An economic lifespan of 20-60 years for power generators (EIA, 2011; IEA, 2016b), 10-50 years for industrial installations, and 20-100 years for buildings, is not unusual. Airplanes that burn kerosene and ships that burn heavy bunker fuels are in service for 5-30 years, and even gasoline-fuelled cars are usually operated for more than 10 years before eventually being retired (Rozenberg *et al.*, 2015). Many of these assets will still have a remaining lifetime

[5] See Appendix B.2 for a complete review of relevant carbon lock-in literature.

by the time global emissions must reach net-zero (see Figure 2). Their economic value, however, depends on their ability to operate and burn fossil fuels. If humanity is to reach its climate goals, these assets either must be retrofitted with carbon capture and storage[6] (CCS) or cease operations, thereby becoming stranded assets (Caldecott, Tilbury and Carey, 2014).

Defining stranded assets in this context is challenging: in this dissertation asset stranding occurs when power plants operate below their target utilization. There are, however, many more factors that would influence asset stranding in this definition. Asset owners could, for example decide to transform coal- to biomass-powered generators or retrofit generators with CCS. Both would reduce capacity of coal-fired polluting generation capital stock and hence constitutes stranding in the context of this dissertation. The same applies for the decision to retire certain generators early, thereby increasing utilization rates of the remaining generators, or to mothball capacity or change operating mode of a power plant but receive a compensation, e.g. in form of a capacity contract, for doing so (Caldecott and McDaniels, 2014; Caldecott *et al.*, 2017).

The general assumption in this dissertation is, that deviating from full (expected) utilization of a fossil fuel powered generator is not captured in the original asset value and hence essentially constitutes stranding. Mechanisms as described above can reduce or even completely offset the impact on the balance sheet and bottom line of the asset owner but do not change the general definition of asset stranding. The decisions and investments that are made today, can therefore commit humanity to many years of carbon-intensive economic activity or costly

[6] Also known as Carbon Capture and Sequestration.

adjustments. They affect our future ability to decarbonize our economy and achieve net-zero by the second half of this century, as well as the cost of achieving this (Unruh, 2000; Erickson *et al.*, 2015; Seto *et al.*, 2016).

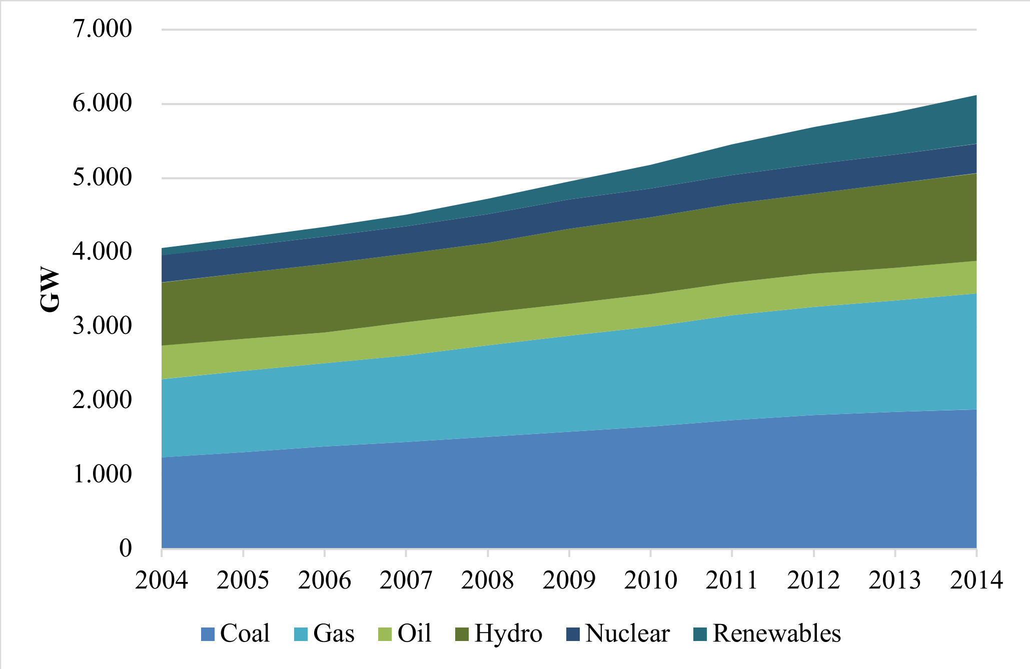

Figure 2: Development of global generation capacity, 2004-2014.
Source: OECD/IEA data (IEA, 2016a).

When decarbonization, especially deep decarbonization, overcomes carbon lock-in, *stranded carbon assets* are likely to occur (Goulder, Hafstead and Dworsky, 2010). According to the most common definition, an asset strands when it experiences an unanticipated or premature write-down, a devaluation, or a conversion to a liability (Caldecott, Tilbury and Carey, 2014). If carbon emitting physical assets, or related financial assets, are affected by this form of stranding they are typically referred to as stranded carbon assets (Caldecott, Lomax and Workman, 2015). In the narrower context of this dissertation, carbon assets of the energy sector can strand when society gradually decides to stop the burning of fossil fuels in general or certain fossil fuels, e.g. coal, to generate energy.[7]

This dissertation introduces a new theoretical framework – the *decarbonization identity* – to analytically describe all choices policy makers have available to avoid such asset stranding. These choices can be described as: (1) protecting and enhancing remaining carbon budgets (e.g. by early and decisive action on non-CO_2 pollutants); (2) retrofitting CCS to operating capital stock; (3) making sure that additions to the capital stock are clean (non-emitting); (4) large-scale stranding of capital stock; or (5) creating additional carbon budget by net-negative emission technologies or the conservation of natural carbon sinks (Griscom *et al.*, 2017).[8]

Policy makers often base their policies on scenarios that are run with integrated assessment models (IAMs). Such models implicitly contain the previously described policy choices but rarely make them explicit. With the decarbonization identity, this dissertation introduces for the first time a mutually exclusive and collectively exhaustive framework that makes these choices, especially the choice to strand assets, explicit. Asset stranding can have different implications for asset owners and social planners, however (Edwards, Kay and Mayer, 1987). For an asset owner a stranding of his investments can mean a financial loss and potentially cause him to default on his debt (Weyzig *et al.*, 2014; Carney, 2015; Battiston *et al.*, 2017). For a policy maker, the potential scale of asset stranding has important implications in respect to the choice and feasibility of future

[7] See Appendix B.3 for a complete review of relevant stranded assets literature.

[8] See Appendix B.4 for a positioning of this dissertation within the field.

environmental, climate and energy policies to achieve decarbonization goals (Baldwin, Cai and Kuralbayeva, 2016; Rozenberg, Vogt-Schilb and Hallegatte, 2017).

This first and third paper of this dissertation (Pfeiffer *et al.*, 2016; Pfeiffer, Hepburn, *et al.*, 2018) find that currently operating electricity generators would emit more CO_2 (~300 $GtCO_2$) than is compatible with currently available generation-only carbon budgets for 1.5-2°C[9] (~240 $GtCO_2$). Currently available generation-only carbon budgets in this context are defined as the share of overall carbon budget for a certain temperature goal, that is allocated to electricity generation. In addition, the current pipeline of planned fossil fuel power plants would add almost the same amount of emission commitments (~270 $GtCO_2$) to this dirty capital stock. The second paper finds that current carbon budgets are inherently insecure and depend on future, yet to be achieved, reductions in SLCP emission rates (Pfeiffer, Millar and Hepburn, 2018). If such reduction efforts cannot successfully be implemented the remaining carbon budgets are even smaller than currently assumed. Assuming the world will follow through with its climate goals, and that negative emissions technologies (NETs) will not play a big role, these findings suggest that much of the currently operating, or future, yet to be built, generation capacity must become stranded in one way or the other. The fourth paper estimates that for coal-fired generation capacity alone this stranding ranges between 410 GW, if current plans for new generators were to be cancelled, and 1,030 GW if the whole pipeline was built (Pfeiffer, Vogt-Schilb,

[9] Throughout this dissertation 1.5-2°C scenarios refer to 430-480 (450) ppm scenarios that would result in warming of likely less than 2°C but more unlikely than likely less than 1.5°C (Hartmann, Tank and Rusticucci, 2013).

et al., 2018).[10] To put this into perspective: this is equivalent 0.8-1.9 trillion USD worth of newly built coal capacity[11] or 20-51% of the ~2,020 GW of total coal capacity globally in 2016 (IEA, 2017). A stranding of this magnitude would increase the cost of climate policy considerably and reduce the likelihood of such policies being implemented, i.e. of the Paris goals being achieved.

The rest of this dissertation is structured as follows: Chapter 2 introduces the theoretical framework that provides the foundation of this analysis. It contains an explanation of the importance of cumulative carbon emissions and carbon budgets for climate change (2.1), the introduction of the idea of committed cumulative emissions (2.2), and how both concepts can be combined in the decarbonization identity (2.3). Chapter 3 analyzes some recent empirical findings from the power generation sector in the context of the decarbonization identity. Chapter 4 discusses the framework and its implications in a wider context of policy choices (4.1), policy instruments (4.2) and a broader research agenda (4.3). Chapter 5 concludes.

2. A new theoretical framework

If humanity wants to stop global warming and stabilize the climate at any level, carbon emissions eventually must be reduced to near- or net-zero. The cumulative amount of LLCP emissions by the time net-zero is reached, together with the sustained rate of future SLCP emissions, will determine the final level of climate change (Allen *et al.*, 2009). Whether the world will meet its climate goals of

[10] 310 EJ vs. 780 EJ, respectively. Assuming a 40-year lifetime and 60% utilization, this corresponds to 410-1,030 GW of newly installed capacity.

[11] Assuming capital cost of 1,867 USD/kW for ultra-supercritical steam coal (IEA, 2016b).

limiting global warming to 1.5-2°C of warming hence depends on whether humanity stays within the carbon budgets for these climate goals (Meinshausen *et al.*, 2009). Many different reasons have been identified that could lead to an overshoot of these budgets. Some of these reasons are the lack of global cooperation (Barrett, 1994), inadequate institutions (Helm, 2010), the lack of a price on carbon (Carbon Pricing Leadership Coalition, 2017; Klenert *et al.*, 2017), and short-sighted voters and politicians (Levy, 2014). One of the biggest obstacles in achieving these goals, however, is carbon lock-in, especially infrastructural carbon lock-in (Seto *et al.*, 2016). Even if humanity stops adding assets to the polluting capital stock, the existing capital stock would probably continue to emit carbon for many years, or even decades. It is possible that these committed emissions have already locked humanity in to more than 1.5-2°C warming and that an achievement of climate goals is only possible if either that capital stock gets retrofitted with CCS or becomes stranded, or new atmospheric space, i.e. additional budget, is created (Pfeiffer *et al.*, 2016).

This Chapter describes the connection between carbon budgets, climate goals, SLCP emissions, committed emissions (infrastructural carbon lock-in), and negative emission technologies. The resulting decarbonization identity is the theoretical framework on which the political analysis in this dissertation is based. It describes all the distinct choices policy makers have, to stay within pre-defined carbon budgets. In the following, the identity is described in general terms, applicable to all polluting capital stock, but in the remainder of this dissertation it is used specifically in the context of the polluting electricity generation capital stock and related carbon budgets. The rest of this Chapter is structured as follows: first, the concept of a carbon budget is briefly summarized (2.1); second, the concept of committed emissions is described and what influences these commitments (2.2); and third, these two concepts are brought together in the decarbonization identity (2.3).

2.1 Carbon budgets

In recent years CO_2 budgets have received greater attention in science, policy making, and even finance. Many scientific contributions base their findings on such budgets (Rogelj *et al.*, 2016), policy makers evaluate their policies based on whether they manage to keep cumulative emissions within these budgets (Fay *et al.*, 2015; UNEP, 2016), and financiers and investors analyze the implications of carbon budgets for their investment portfolios in fossil fuels and related infrastructure (Carney, 2015; Caldecott, Elizabeth, *et al.*, 2016).

CO_2 budgets (or carbon budgets) are inherently uncertain, however. The size of the budgets for different temperature goals (see Table 1), as well as the time it will take to reach or achieve them depends on many factors that are very difficult to predict. Even staying within the 2°C (50% probability) budget of ~1,300 $GtCO_2$ in 2005 (IPCC, 2014b) will not guarantee that humanity stays below the 2°C warming it has set itself as a limit (see Table 1). It rather means that in scenarios that limit cumulative CO_2 emissions to this level or below there is at most a 50% probability of the global warming exceeding 2°C. That also means, however, that even if humanity stays within that budget it is as likely as not that the world's climate will warm by more than 2°C in the global average. Indeed, there is a non-negligible probability that the world would warm beyond 3°C even if humanity were to stay within its 2°C (50%) CO_2 budget.

There are several reasons for this. Whilst uncertainty in the physical climate response is a dominant source of variation, the unknown future emissions of SLCPs also play an important role. SLCPs emissions stem from many different sources, such as fossil fuel extraction, transport and use, agriculture, waste, and from natural emission sources (Saunois *et al.*, 2016) and are inherently uncertain as the future development of these sectors depends on many different factors (e.g. technological progress, demand, etc.). SLCPs are an important factor for climate change since some are much more powerful greenhouse gases (GHGs) than CO_2. Methane (CH_4), for example, has roughly 72-84 times the global warming potential of CO_2 over a period of 20 years (GWP20), Ozone (O3) has a GWP20 of 62-69, and Nitrous Oxide (N_2O) a GWP of ~300 over a period of 100 years (GWP100) (Hartmann, Tank and Rusticucci, 2013). Despite staying in the atmosphere for much less time than, for example, CO_2, the greater potency of SLCPs means that they play an important role in overall anthropogenic global warming.

		IPCC		*Millar et al. (2017)*	
Warming	**Likelihood**	**Remaining in 2011***	**Remaining in 2015***	**Remaining in 2015 (low)***	**Remaining in 2015 (high)****
< 1.5°C	66%	400	243	747	887
	50%	550	393	817	1,110
	33%	850	693	916	n/a

< 2°C	66%	1,000	843	1,447	n/a
	50%	1,300	1,143	1,524	n/a
	33%	1,500	1,343	1,700	n/a
< 3°C	66%	2,400	2,243	n/a	n/a
	50%	2,800	2,643	n/a	n/a
	33%	3,250	3,093	n/a	n/a

Table 1: Remaining total carbon budgets in 2011 and 2015, in GtCO2

* RCP8.5 simulations of CMIP5 models ** RCP2.6 simulations of CMIP5 models

Source: Data from the IPCC, Millar et al., and the Global Carbon Budget (Hartmann, Tank and Rusticucci, 2013; Le Quéré et al., 2015; Millar et al., 2017).

Total human-induced warming arises from the combination of SLCP and LLCP induced warming. The size of a cumulative emissions budget for LLCPs consistent with a specific target peak human-induced warming, as well as the specified probability of achieving that warming goal, hence also depends on the future sustained emissions of SLCPs (e.g. methane). It is the stock of LLCP together with the flow of SLCPs that must be limited for a successful achievement of climate targets. Table 1 provides the latest peer-reviewed budget estimates from the IPCC under the assumption that non-CO_2 forcing follows a business-as-usual scenario (RCP8.5[12]). Non-CO_2 forcing is defined as the fraction of radiative forcing[13] that is caused by non-CO_2 climate pollutants (Myhre *et al.*, 2013).

The most recent research, however, finds a significantly higher remaining CO_2 budget. Millar et al. find that, as of 2015, humanity has a stock of approximately 747-887 $GtCO_2$ left for a 66% chance of limiting global warming to below 1.5°C, depending on the magnitude of the sustained flow of future SLCP emission pathways[14] (Millar *et al.*, 2017). The upward revision has been made after it was recently discovered that most of the complex earth-system-models overestimated the warming we should see at the current level of cumulative emissions. This, however means that they, at the same time, underestimate carbon budgets for a given future temperature goal.

2.2 Committed cumulative carbon emissions

Infrastructure carbon lock-in is typically characterized by committed cumulative carbon emissions, i.e. the cumulative amount of future carbon emissions that would be released into the atmosphere if the underlying infrastructure asset would be fully utilized under normal economic conditions until the end of its useful economic life (see Figure 3).

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[12] RCP8.5 is one of four *Representative Concentration Pathways* (RCPs), which are GHG concentration pathways adopted by the IPCC for its AR5 in 2014.

[13] Radiative forcing or climate forcing is the difference between energy (insolation) received by the earth and energy radiated back to space. Positive radiative forcing therefore causes global warming, negative forcing cooling.

[14] RCP2.6 vs. RCP8.5 simulations.

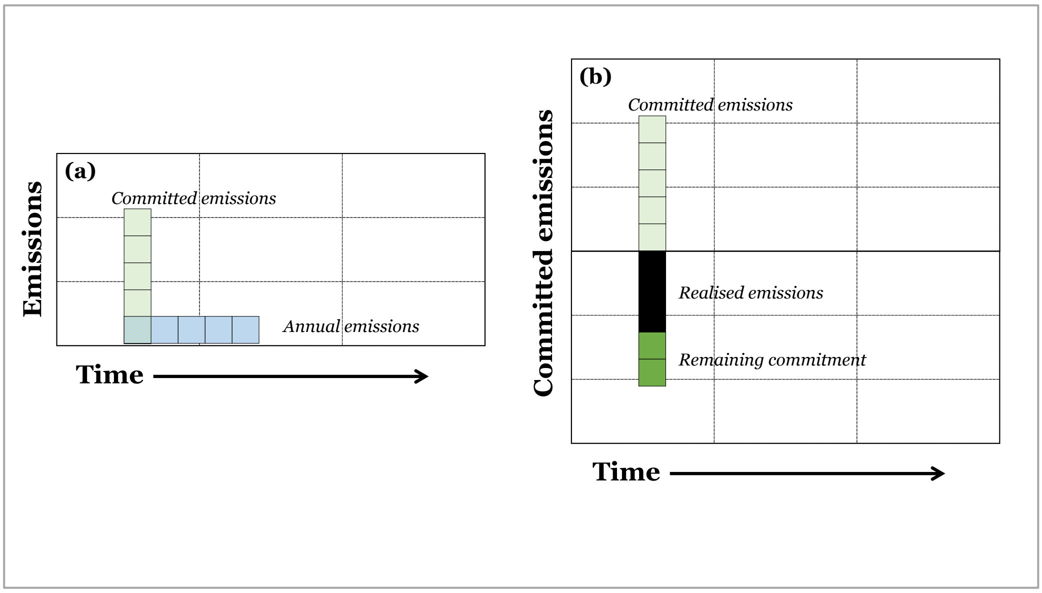

Figure 3: Schematic of committed emissions accounting. (a) Emissions that occur over the lifetime of a carbon emitting asset can instead be analyzed as committed emissions in the year the generator begins operating. (b) Over time the fraction of these committed emissions can be tracked as realized emissions.

Source: Reproduction from Davis & Socolow's (2014) 'Commitment accounting of CO2 emissions'

While the concept of such emission commitments was implicitly known since carbon lock-in first appeared in pertinent literature, it was first explicitly described by Davis et al. (2010) and then in greater detail by Davis and Socolow (2014). In their paper 'Commitment Accounting of CO_2 Emissions' Davis and Socolow describe how these committed emissions develop over time, depending on assumptions regarding future utilization, remaining lifetime and carbon efficiency (Davis and Socolow, 2014). A higher utilization of existing assets or a longer expected lifetime increases emission commitments, while investments that increase carbon efficiency (for example a switch of fuel or retrofitting of CCS), lower utilization, or an early retirement of the underlying asset reduces commitments.

2.3 The decarbonization identity

The connection between carbon budgets and committed cumulative carbon emissions can be expressed in the following identity:

$$B_t(T) \geq E_t + N - S - A$$

where $B_t(T)$ is the remaining carbon budget for a given temperature goal T at a point in time t,[15] E_t is the committed cumulative carbon emissions from existing capital stock at that time t, N is new committed cumulative carbon emissions from future (after t) capital stock, S is the amount of existing and new capital stock that will stranded in the future, and finally A is the additional atmospheric space that can be created by negative emission technologies (NETs) in the future, which hence increases the remaining budget.

Policy makers can choose different actions to ensure this identity is being followed. Any action that actively reduces the cumulative emissions committed from E and N can be understood as stranding S in the context of this identity, since it will likely lead to either cost or a value loss for the owner of the underlying asset as compared to a counterfactual. Additional investments in carbon efficiency enhancing technologies or retrofit CCS, for example, would reduce the asset value as compared to a scenario in which carbon could be emitted unrestricted. Also, early retirement or underutilization would reduce and therefore strand asset value. While stranding is expresses in cumulative emissions (i.e. $MtCO_2$ or $GtCO_2$) in the context of this identity, it could also be expressed

[15] E.g. B_{2015}(1.5°C) is the remaining cumulative carbon budget in 2015 for warming less than 1.5°C. Miller et al. (2017) find that B_{2015}(1.5°C) for a 66% chance is between 747-887 $GtCO_2$, depending on future SLCP emissions.

in stranded capacity (GW) or even stranded capital (USD). With assumptions or knowledge regarding lifetime, utilization, carbon efficiency, and capital cost each of these measures can be converted into any of the other measures.

Carbon Capture and Storage (CCS) is not explicitly mentioned in this decarbonization identity but is implicitly included in each of its components. CCS retrofitted to existing infrastructure will reduce *E* while new infrastructure built with CCS will not appear in *N* (as it can be viewed as 'clean' capital stock). Bioenergy will also not appear in *N* (as its carbon balance would be largely neutral), whereas bioenergy with CCS (BECCS) would appear in *A* as it would be a negative emissions technology and hence create additional atmospheric space.

Since carbon budgets also depend on future uncertain SLCP emissions, an additional choice available to policy makers could be to protect and enhance carbon budgets by decisive action on such SLCP emissions. Millar et al. (2017), for example, find that the 2016 carbon budgets for 1.5°C amount to between 730 to 880 $GtCO_2$, depending on non-CO_2 mitigation.

Given a certain, endogenous, temperature goal and the emission commitments of already operating capital stock, policy makers therefore have five levers to influence the achievement of their climate goals: (1) protecting and enhancing carbon budgets by early and decisive action on non-CO_2 pollutants (e.g. by introducing methane emission targets); (2) retrofitting CCS to operating capital stock (e.g. by subsidizing such retrofit investments); (3) making sure that additions to the capital stock do not lead to additional emission commitments (e.g. by allowing investments only in renewable energies, bioenergy, or fossil fuels with CCS); (4) strand existing or newly built capital stock (e.g. via lower utilization rates, shorter lifetimes, or retrofit CCS); or (5) create additional atmospheric space (e.g. by large scale BECCS, reforestation, or other NETs).

3. Recent findings from the power generation sector

In recent years, a growing body of literature has been analysing the carbon lock-in and the potential for stranded assets in the power generation sector (Unruh, 2000, 2002; Unruh and Carrillo-Hermosilla, 2006; Bertram *et al.*, 2015; Eom *et al.*, 2015; McJeon, 2015; Seto *et al.*, 2016; Rozenberg, Vogt-Schilb and Hallegatte, 2017). Power generation plays an important role in climate change, for at least three reasons. First, it is responsible for a large share of global total primary energy demand (TPED) and an even larger share of anthropogenic CO_2 emissions: today's power generation accounts for ~38% of TPED[16] and ~13.4 $GtCO_2$ p.a., or ~42% of total annual anthropogenic CO_2 emissions from fossil fuel combustion (IEA, 2017). Second, electricity can be used as a substitute for carbon-intensive fossil fuels in many other cases. For instance, road transportation and residential housing, which account together for ~23% of total emissions; and industrial energy consumption, mainly used to produce heat or motion, which accounts for an additional ~19% (IEA, 2016a). Technologies such as electric vehicles, heat pumps and electric furnaces have the potential to replace fossil-fuel based counterparts in these sectors, thereby reducing GHG emissions (Audoly *et al.*, 2017). Third, recent developments show that it is feasible, and probable, that the global electricity generation sector will decarbonize by the

[16] 2016 power generation was 5,252 million tonnes of oil equivalent (Mtoe) and TPED was 13,760 Mtoe (IEA, 2017).

second half of this century. Advances in renewable energy technologies and the rapidly decreasing cost of such technologies, most notably solar PV, have led to strong growth of renewables in recent years (Lazard, 2016; IRENA, 2017). 2015 was the first year in which additions to the generation capacity in the form of renewables were larger than the additions to fossil fuel capacity. A recent cross-comparison study of thousands of different possible future energy sector scenarios suggests that even under growth constraints for additional renewables and nuclear power, pessimistic assumptions for carbon capture and storage, and less ambitious climate goals, a complete decarbonization of the electricity generation sector by the second half of the century is possible in all regions of the world (Audoly *et al.*, 2017). Other leading energy scenarios, such as for instance the International Energy Agency's (IEA) '*450 scenario*' (IEA, 2016b) or '*Sustainable Development Scenario*' (IEA, 2017), also imply that a decarbonization seems possible and likely (see Figure 4). In addition to these characteristics, electricity generation assets typically have a long lifetime of 35 years, e.g. for oil and gas generators, to almost 70 years for hydro generation (EIA, 2011). Within the global polluting capital stock, therefore, electricity generators are amongst the assets with the longest lifetimes and hence particularly suitable for the study of the impact of long-term commitments.

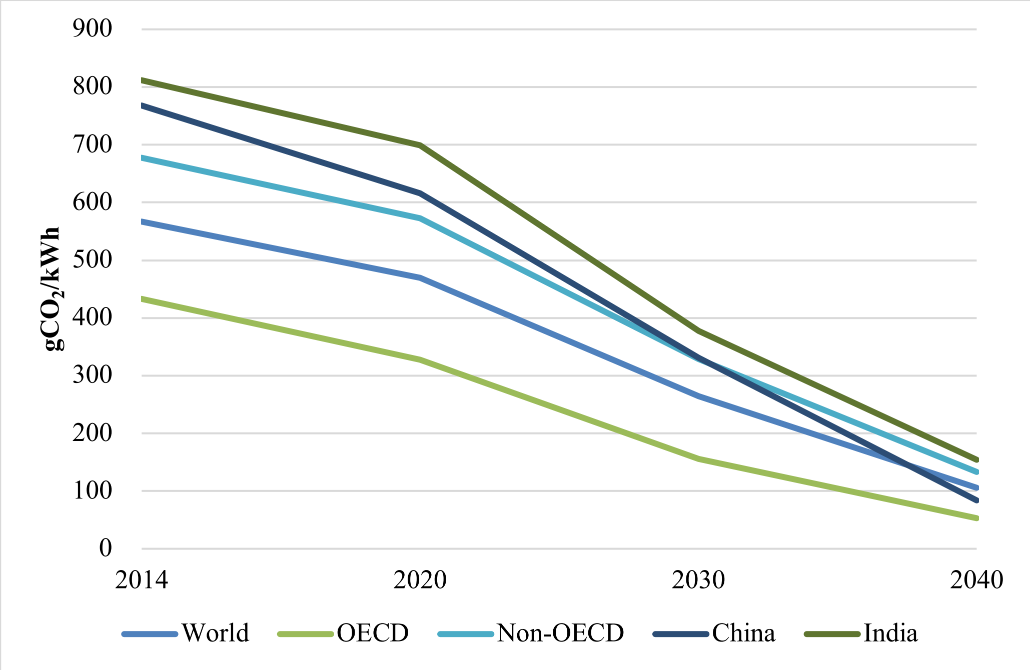

Figure 4: Carbon intensity of electricity generation in IEA's 450 scenario by country and region, 2014-2040.

Source: World Energy Outlook 2016 (IEA, 2016b).

In the first paper of this dissertation, the '2°C capital stock' is defined as the global stock of infrastructure which, if operated to the end of its normal economic life, implies global mean temperature increases of 2°C or more, with 50% probability (Pfeiffer *et al.*, 2016).[17] Using IPCC carbon budgets and the IPCC's AR5 scenario database, and assuming that future emissions from other sectors are compatible with a 2°C pathway, this paper estimates that the 2°C capital stock for power generation will be reached in 2017. In other words, even under the very optimistic assumption that other sectors reduce emissions in line with a 2°C target, no new emitting power generation infrastructure can be built after 2017 for this target to be met, unless other infrastructure is retired early or retrofitted with carbon capture technologies (see Figure 5).

[17] See Appendix C for an overview of data and methods used.

In the overall context of the decarbonization identity, this paper suggests that future emissions committed by this infrastructure will likely already be as high or even higher than the remaining budgets for the 2°C climate goal, at least under normal lifetime assumptions (40 years). Existing emission commitments, *E*, in the identity are now equal or even larger than the remaining budgets *B(2°C)*. It is no longer possible to achieve climate goals without significant amounts of stranding, *S*, or new atmospheric space, *A*. Every bit of new polluting capital stock, *N*, will make achieving this goal even more difficult.

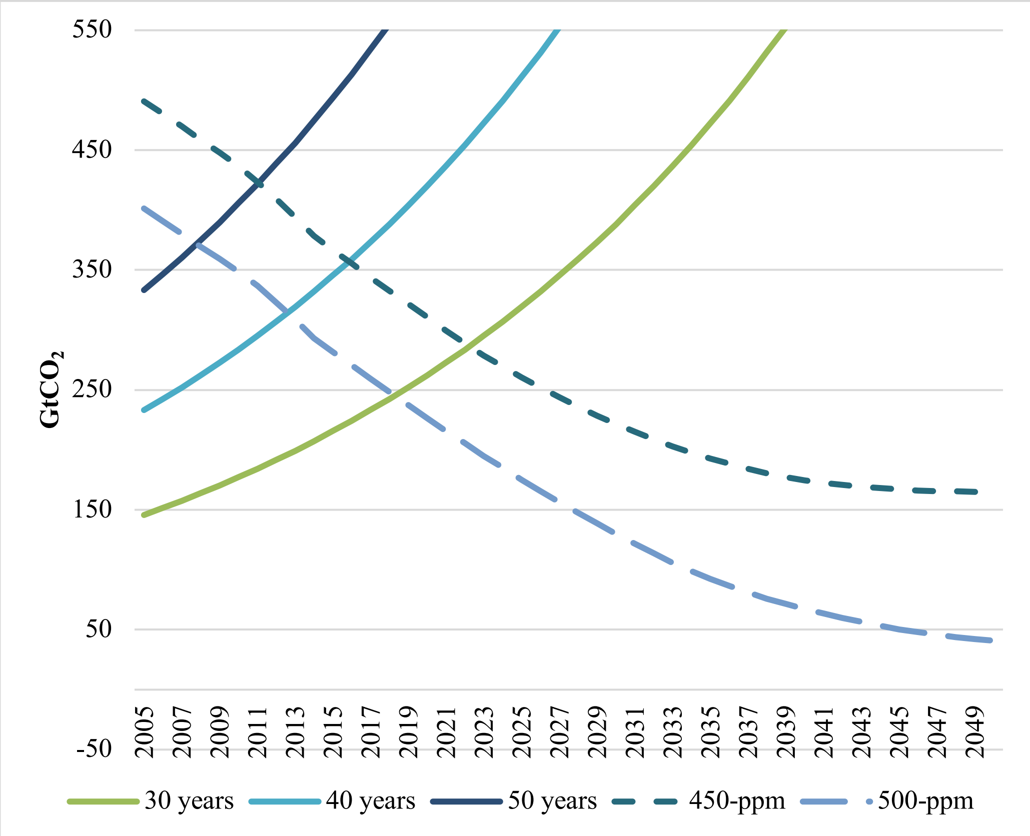

Figure 5: Comparison of forecast carbon budget and CCCE for the power generation sector over time. Straight lines represent CCCE from generation infrastructure with different assumed lifetimes. Dashed lines represent remaining generation-only 2°C (50%) carbon budget if other sectors decarbonize according to the 450- and 500-ppm scenarios.

Source: Reproduction from Pfeiffer et al.'s 2016 'The 2°C Celsius capital stock for electricity generation.

Other recent studies support these findings. Cost-effective transition pathways towards a decarbonized economy will probably require stranded assets, especially in the power generation sector (Bertram *et al.*, 2015; McJeon, 2015; Rozenberg, Vogt-Schilb and Hallegatte, 2017). Such asset stranding can materialize in different ways, such as underutilization or early retirement (Caldecott and McDaniels, 2014; Caldecott, Kruitwagen, *et al.*, 2016). A recent Carbon Tracker Initiative study, for example, finds that, by mid-2016, China had ~900 GW of coal capacity that was running with a utilization of less than 50% (CTI, 2016). Also in other regions, the increasing share of renewables in the energy mix leads to low overall electricity retail prices and subsequent fossil fuel asset stranding (Caldecott *et al.*, 2017). Bertram et al. (2015) explore how different climate policies affect capital stock additions and stranded assets. They find that weak near-term policies lead to an increased amount of asset-stranding, renewable capacity additions, and the need for carbon-dioxide removal (CDR) from the atmosphere in the medium- and long-term. These findings have been supported by many other studies (Johnson *et al.*, 2015; McJeon, 2015; Riahi *et al.*, 2015; Luderer *et al.*, 2016). They all find that weak near-term policies that would allow for the addition of fossil fuel powered generation capacity, especially coal, would lead to an increase of stranded assets in the medium- and long-term.

Based on the methodology described by Davis and Socolow (2014) and Pfeiffer et al. (2016), the other papers of this dissertation update and expand these findings by adding a more detailed analysis of the currently operating and planned power generation capital stock (Pfeiffer, Hepburn, *et al.*, 2018; Pfeiffer, Vogt-Schilb, *et* *al.*, 2018).[18] They find that currently existing generators would commit to ~300 $GtCO_2$ and hence more future carbon emissions than would be compatible with the remaining ~240 $GtCO_2$ generation-only carbon budgets for 1.5-2°C (Pfeiffer, Hepburn, *et al.*, 2018). Remaining generation-only carbon budgets in this context are defined as the share of overall carbon budget for a certain temperature goal, that is allocated to electricity generation. Moreover, the current pipeline of planned fossil fuel power plants would add another ~270 $GtCO_2$ of emission commitments to this dirty capital stock (Shearer *et al.*, 2016, 2017; Pfeiffer, Hepburn, *et al.*, 2018). They conclude that, assuming the world will follow through with its climate goals, and that negative emissions technologies (NETs) will not play a big role, much of the currently operating, or future, yet to be built, generation capacity must become stranded in one way or the other (Pfeiffer, Vogt-Schilb, *et al.*, 2018). A stranding of this magnitude (410-1,030 GW for coal alone) would increase the cost of climate policy considerably and reduce the likelihood of such policies being implemented, i.e. of the Paris goals being achieved. This dissertation furthermore finds, that additional efforts to avoid the addition of new polluting capital stock as well as to alleviate the magnitude and impacts of asset stranding are needed, e.g. by increasing the carbon budgets via ambitious SLCP mitigation efforts (Pfeiffer, Millar and Hepburn, 2018).[19]

4. Discussion

The objective of this dissertation is to analyze the potential for asset stranding in the power generation sector under the framework of the decarbonization identity

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[18] See Appendix C for an overview of data and methods used.

[19] See Appendix C for an overview of data and methods used.

and how this influences the choices policy makers have. Recent findings suggest that currently operating electricity generators would emit more CO_2 than is compatible with currently available generation-only carbon budgets for 1.5-2°C. In addition, the current pipeline of planned fossil fuel power plants would add a large amount of additional emission commitments to this capital stock. If the world is to follow through with its climate goals without NETs playing a big role, these findings suggest that much of the currently operating or future, yet to be built, 'dirty' generation capacity must be retrofitted with CCS or become stranded in one way or the other. This would increase the cost of climate policy considerably and reduce the likelihood of such policies being implemented, i.e. the Paris goals being achieved.

4.1 Policy choices

These findings raise some immediate and significant implications for the electricity sector. As framed analytically by the decarbonization identity, achieving the necessary transformation of the global electricity generation sector is going to require some combination of the following five options:

1. Protecting, or even enhancing, remaining carbon budgets.
2. Retrofitting non-zero existing generators with carbon capture and storage.
3. Reducing the carbon intensity of new generators (100% zero-carbon as soon as possible).
4. Prematurely retiring or underutilizing (stranding) existing fossil assets.
5. Scaling-up NETs to remove carbon from the atmosphere.

All policy choices to achieve a certain carbon budget are explicitly or implicitly a combination of these above five policy choices. The presented findings, however, suggest that for many 430-530 ppm pathways, i.e. scenarios that give humanity a good to fair chance for limiting global warming to around 1.5-2°C, the 'silver bullet' of stopping to invest by the time the 1.5 or 2°C capital stock is reached is not an option anymore, since the existing infrastructure already commits humanity to more emissions than would be consistent with these goals. Achieving warming of just 1.5-2°C will, therefore, necessarily entail some extent of asset stranding, *S*, and negative emissions, *A*. Every additional asset that adds to the polluting capital stock, *N*, will increase the magnitude of this trade-off. Policy makers might want to strive for the most cost-effective combination of these five options, but this will depend strongly upon achievable SLCP emission floors, the rates of decline in the costs of the relevant technologies, including nuclear, renewables (incl. hydro), CCS, associated grid balancing technologies (including storage), and NETs.

Many approaches that aim at identifying cost-optimal climate policies implicitly already consider this trade-off. Most notably, policy evaluation IAMs (PEMs), such as GCAM, IMAGE and MESSAGE, which look at the cost-effectiveness of achieving a specific mitigation target with a given policy, e.g. a carbon price (Farmer *et al.*, 2015). Such models start with an estimate of the global capital stock, much as the polluting generation capital stock in this dissertation, and model the evolution of this capital stock, and its emissions, over time under the respective climate policy and considering the inertia of that capital stock (van Vuuren *et al.*, 2009; Waisman *et al.*, 2012; Bertram *et al.*, 2015; Bauer *et al.*, 2016). PEMs take policies and climate goals, usually defined by 2100 concentration targets, as endogenous variables, and model the development of all sectors subject to these conditions. Arguably, this will include some levels of *N*, *S*, and *A*, which will also depend on the SLCP emission pathway in each scenario.

IAMs, however, rarely make these trade-offs explicit. It is difficult to back-out the implicit assumptions regarding the levels of added and stranded capacity over time. For instance, scenarios that assume a delay of climate policies until after 2030, will likely see considerable additions to the capital stock, which will then have to be stranded later in the century or balanced by NETs (Bertram *et al.*, 2015). Yet, this is often not made clear. Moreover, it is questionable whether the assumption of a consistent (optimal) global climate policy in the future is a good representation of reality. In particular, scenarios that allow for significant capacity addition in the short-term depend on stringent and decisive global policies after 2020 or 2030 to revert to a pathway that achieves the set climate targets (Bertram *et al.*, 2015; Riahi *et al.*, 2015). If past efforts to achieve such climate policies are any indicator for future success, it is highly questionable, at least, whether such efforts will prove successful in the future.

The decarbonization identity explicitly shows the fundamental choices policy makers have in the absence of first-best policy instruments. The IAMs showcase the optimal emission levels as a trade-off between mitigation and damage cost (POMs[20]), or the cost-optimal transition pathways for a given set of policies and climate targets (PEMs). The decarbonization identity, therefore, makes explicit the choices policy makers have if climate goals must be achieved via capital

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[20] POMs often use a ‘damage function’ to calculate whether the total benefits of a policy exceed its costs and how an optimal policy looks like.

formation when other policies are not available. The findings suggest that humanity should have stopped building polluting capital stock several years ago. Policy makers now have five choices to revert to a path that achieves their climate goals. The combination of these choices will depend on the policy instruments we choose and this work highlights how little room for manoeuvre there is. In turn these five choices are briefly considered before examining the policy interventions that could support them.

First, sustainable mitigation action on SLCP emissions can be understood as a hedge against a stronger climate response or the overshooting of the available carbon budgets (Xu and Ramanathan, 2017). Carbon budgets are inherently uncertain and thus staying within identified budgets will not guarantee that global warming stays below a certain threshold, much as it cannot be guaranteed that humanity will not overshoot its budgets despite significant mitigation efforts (Bowerman *et al.*, 2013; Millar *et al.*, 2017). SLCPs play a decisive role in this context. In recent years, annual methane emissions have increased strongly (Saunois *et al.*, 2016). Reversing this trend could prove to be an important mitigation lever.

Second, significant deployment of CCS technologies, with or without carbon use, seems essential (RSC, 2017). Retrofitting of CCS technologies will be needed to enable existing or future, yet to be built, power generators to reduce their committed emissions without being stranded. Whilst CCS technologies are currently amongst the most expensive mitigation options available today (Corsten *et al.*, 2013), nearly all 1.5-2°C consistent scenarios depend on CCS deployment to a certain extent. Such deployment typically allows for continued fossil fuel generation (mostly gas) without, or with reduced, carbon emissions, and provides for net negative emission capabilities (BECCS). Excluding CCS technologies increases the modelled cost of meeting 1.5-2°C by around 2.5 times (Clarke *et al.*, 2014).

Third, given the uncertain success of future climate policies, capital formation should be a priority for policy makers. It is highly questionable whether climate policies that would strand or retrofit capital stock or create new atmospheric space can ever be implemented in the future. Therefore, policy makers should make every effort to avoid the addition of even more polluting capital stock that would increase the severity of the situation. Numerous studies in recent years have showcased the rapid reductions in the cost of renewable energy technologies (Schilling and Esmundo, 2009; IPCC, 2011; Reichelstein and Yorston, 2013), the feasibility of large scale deployment of net- or near-zero emissions technologies including renewables, biomass, hydro, and nuclear (IPCC, 2011; Hong, Bradshaw and Brook, 2015; Mileva *et al.*, 2016), the overall modest economic costs such a programme would entail (IPCC, 2011; The Global Commission, 2014; King *et al.*, 2015; Stern, 2015), and the significant co-benefits of zero-carbon generation (Harlan and Ruddell, 2011). Important challenges remain, both on cost and grid integration (Luo *et al.*, 2015; Wagner, 2015), but large-scale deployment of zero-carbon electricity appears inevitable (Audoly *et al.*, 2017); the question is not if but how fast. Informally, one might argue that policy makers should focus on "*making the good stuff cheap*" as well as "*making the bad stuff expensive*" (Beinhocker, 2017).

Fourth, some of the currently existing, and yet to be built, fossil fuel power plants could be stranded and replaced by zero-carbon generation. This could happen either via underutilization or early retirement of these plants. While it is unlikely that building and then stranding these assets will be economically superior to investing in zero-carbon assets in the first place, there may be some value in delay. Although the costs of zero-carbon technologies are declining rapidly, and although they have reached grid parity in some regions of the world, they currently remain more expensive than fossil fuels in others (Lazard, 2016). Waiting might therefore appear to be a logical decision from a cost perspective. From an economic perspective, there is one flaw to this logic, however. Recent research shows that the decline in the cost of renewables is significantly attributable to increases in cumulative production volumes of zero-carbon technologies (Nagy *et al.*, 2013), thus delay may slow such price declines. Earlier action to shift to investments in zero-carbon new capital stock may avoid the later stranding of assets while also accelerating the decline in costs of zero emissions technologies. As with climate change in general, however, there is also a free rider problem in this specific area. From the perspective of an individual investor, it makes sense to wait until others have invested enough to reduce the price sufficiently. One important task for climate and energy policy is to overcome this commons problem.

Finally, given the status and current trajectory of the global polluting capital stock, and the timeframes required to shift all new additions to zero-carbon, the probability of overshooting the 1.5-2°C capital stock and hence overshooting the remaining emission budgets is significant. In fact, many scenarios consistent with 1.5-2°C assume such an overshoot (Krey *et al.*, 2014; Millar *et al.*, 2017).

Increased investment in NETs could help to mitigate such overshoot and thus help avoid asset stranding (Caldecott, Lomax and Workman, 2015). Given the current costs and technical challenges inherent in widespread CCS deployment, however (Pires *et al.*, 2011), it would not be prudent to rely on NETs in later years as an alternative to rapid current de-carbonization of the electricity generation system (Anderson and Peters, 2016).

4.2 Policy instruments

Global warming ultimately depends on cumulative carbon emissions. Annual CO_2 emission reduction targets hence only indirectly address climate goals. If the lifetime-impacts of climate policies on cumulative emissions are not taken into consideration it is possible to meet short-term flow targets while simultaneously installing new coal-fired power stations, making it economically impossible to meet cumulative emission targets. It would be preferable to target cumulative emissions directly, and even better to implement policies that are a function of an index of attributable warming. Targets that are a function of time do not map directly onto cumulative emissions or to the observed climate response (Millar *et al.*, 2017).

This distinction becomes especially relevant in the debate about the virtue of 'clean coal' or the coal to gas substitution that is often discussed as a policy option (Lecuyer and Vogt-Schilb, 2014). Such substitution would successfully reduce near-term emission flows. A stock-based analysis, however, shows that coal to gas switching is only worthwhile if it reduces total cumulative emissions. 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 or even retired. If new capital expenditure on gas is required, however, the analysis is more complicated. For instance, a new gas plant with a lifetime of 40 years, which is constructed in 2017 to replace an existing power generator with a remaining lifetime of 10 years, might very well reduce annual emissions by half for these first 10 years of its operation. In 2027, however, how effective the original decision to substitute the new plant for the old one is will depend on the technology that is available then to mitigate climate change (see Figure 6).

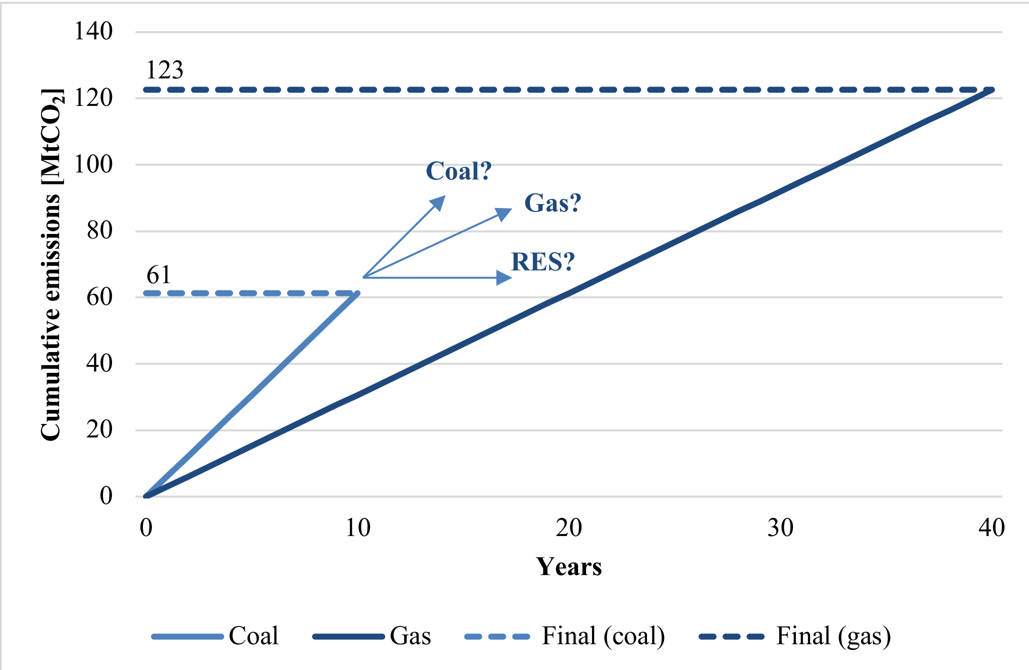

Figure 6: Emission profile of coal-to-gas substitution for exemplary 1GW capacity. A 1GW coal-fired power station with an emissions intensity of 1 tCO2/MWh and a load factor of 70% will emit 6.1 MtCO2 per annum. With a residual lifetime of 10 years, expected future cumulative CO2 emissions are therefore 61MtCO2. Suppose this plant were retired early and replaced by a one GW combined cycle gas turbine (CCGT) plant with emissions intensity of 0.5 tCO2/MWh a load factor of 70%, hence emitting 3.05 MtCO2 per annum. With a lifetime of 40 years, expected future cumulative emissions from the CCGT would be 123 MtCO2, compared to 61 MtCO2 from the coal plant.

If the coal plant could have been replaced in 2027 by zero-carbon technology, i.e. renewables, perhaps driven by continuing deployment and cost declines of such technologies, this substitution was not the right decision (CAT, 2017). In 2027, the gas plant still has three quarters of its useful life (and emissions) remaining, while the coal plant would have emitted less than that in the meantime. In that case, (and assuming the gas plant is not stranded) cumulative emissions would have increased by 50%. Furthermore, a coal-to-gas substitution is suspected to increase fugitive methane emissions from extracting, transporting and burning natural gas. While such fugitive emissions also arise in coal mining the amount is much higher for natural gas, especially from hydraulic fracking (Fulton *et al.*, 2011). As previously described, higher SLCP emissions could lead to lower available carbon budgets. Hence a replacement of coal by gas powered generation could lead to a double-negative impact on climate mitigation – the increase of committed cumulative emissions and the reduction of carbon budgets via higher SLCP emission levels. On paper, however, this policy decision would reduce annual CO_2 rates in the short- and even medium-term. This example illustrates that careful analysis of such decisions, and their implications, is required (Lazarus *et al.*, 2015; Zhang *et al.*, 2016).

In the following Sub-chapters, policy instruments are discussed that are candidates for constraining cumulative emissions to meet a 1.5-2°C target. Each instrument implements one or more of the five previously discussed policy choices.

4.2.1 Carbon prices

After several drawbacks over the last decades, carbon prices have become popular again recently. Since 2016 alone, eight new pricing initiatives have been introduced in several countries (World Bank, 2017), with many more countries having pledged under the Paris Agreement to implement such initiatives over the coming years.

In principle, carbon prices support action on all five options. With the right scientific approach (Allen *et al.*, 2018) SLCP emission reductions can be converted into cumulative CO_2 equivalents and then be appropriately priced as an exhaustible resource (Hotelling, 1931; Acemoglu *et al.*, 2012). Carbon prices also create incentives for investors to invest in new zero-carbon assets (by making the alternatives less economically attractive), to retrofit existing assets with CCS, to retire the highest emitting stock earlier and to develop NETs. Economy-wide carbon prices have several benefits, e.g. being technologically neutral, and create incentives to decarbonize efficiently. They simultaneously address the demand and the supply side by increasing the costs to consumers of fossil fuels and reducing the returns to producers.

Depending on their implementation, carbon prices could also provide an economic 'double dividend' (Goulder, 1994; Parry and Bento, 2000; Bento and Jacobsen, 2007; Jorgenson *et al.*, 2013). While accelerating the transition to a green economy, the additional tax revenues could simultaneously be used to reform the existing tax system, which tends to tax goods, e.g. labour, rather than bads, such as carbon emissions or pollution. Fixing these distortionary taxes could be beneficial to the economy. A differing point of view to the 'double dividend' argues that environmental taxes typically exacerbate, rather than alleviate, pre-existing tax distortion (Bovenberg and de Mooij, 1994). To assume that a carbon tax could provide a 'double dividend' means to assume the absence of other distortions. It should also be pointed out that carbon taxes are often more likely to be successfully implemented when the generated additional tax revenue is 'recycled' (Camerer, Loewenstein and Rabin, 2004; Chetty, Looney and Kroft, 2009; DellaVigna, 2009), e.g. as lump-sum payments to citizens (Klenert *et al.*, 2017). The 'double dividend' approach might be the first best solution, but other solutions might be more feasible and hence preferable.

Another often mentioned obstacle for the successful implementation of carbon prices are concerns about competitiveness and carbon leakage (Jenkins, 2014). Some energy-intensive or trade-exposed industries might require government assistance in responding to a carbon price, e.g. via innovation and adaption (Aldy and Pizer, 2015). This, however might weaken the price signal and create windfall profits for certain companies (Martin *et al.*, 2014). Furthermore, reduced competitiveness and the loss of jobs in certain industries might benefit other industries, e.g. renewables (Hepburn *et al.*, 2006).

In any case, the analysis in this dissertation points out that the required scale and pace of the transformation in the energy sector is dramatic. In accordance with other literature (Acemoglu *et al.*, 2012), it suggests that, without other instruments, the level of carbon prices required to deliver this transformation would be far higher and the implementation period much shorter than is politically feasible in most countries.[21] This is especially true considering that current effective net carbon prices may be negative in many regions if fossil fuel subsidies are accounted for. Even meaningful carbon prices implemented

[21] Moreover, It is unclear what the right level would be. The marginal cost of the ton of carbon that would push the global climate system over its (unknown) tipping points would be astronomically high – it is not straight-forward how this non-linearity could be implemented in carbon prices today.

immediately around the world would be unlikely to prevent the large-scale stranding of generation infrastructure in the future.

This analysis does not mean that carbon prices must be rejected; they should be implemented to the extent politically feasible (whether by a carbon tax or a quantity constraint and trading scheme). In fact, in recent years many regions have seen the introduction of a carbon price, either in form of a carbon tax or in form of a carbon permit trading system. Currently, more than 65 jurisdictions are pricing carbon (>25% of global emissions)[22] and the share of CO_2 emissions covered by a carbon price has more than tripled over the past decade (World Bank, 2017). The idea of pricing carbon (with lump-sum revenue recycling) finds supporters even in traditionally conservative circles, such as the Republicans in the U.S. (Worland, 2017).[23] Nonetheless, additional policy instruments are required to address the carbon lock-in in the energy sector and avoid large scale stranding of generation capacity.

4.2.2 Cumulative cap and trade

Another innovative form of carbon pricing would be an adaptive cumulative emissions cap and trade system (McKibbin and Wilcoxen, 2002) consistent with up-to-date estimates of the remaining carbon budgets. This form of cap and trade carbon pricing is different to existing systems, which largely operate on a period-by-period basis. A cap on total cumulative emissions would provide early transparency in respect to the remaining carbon budget across the full lifetime of

[22] With carbon prices ranging between <1 $/ton (e.g. Mexico) to 140 $/ton (Sweden).

[23] It should be mentioned, however, that market-based policies were innovations developed by conservatives in the Reagan, George H. W. Bush, and George W. Bush administrations (Schmalensee and Stavins, 2010).

the assets. If such a system could be implemented credibly, it would create economically efficient incentives for the decarbonization of new capital stock, and the optimization of the existing portfolio (retrofits and retirements). Such a system that sends a credible signal over a prolonged period would also create "when" flexibility, which is crucial to make cap and trade a cost-effective instrument as it would allow emitters to minimise their compliance costs over time (Fankhauser and Hepburn, 2010). Unfortunately, however, credibility over many periods is almost impossible to achieve in practice, given the nature of changing governments in democratic societies. Nevertheless, the idea of adaptive policy instruments that accommodate new findings regarding the climate response or remaining carbon budgets, should be analyzed and considered more closely (Allen and Frame, 2007).

4.2.3 Licensing requirements

Another approach to avoid an increase in polluting capital stock and thus to prevent large-scale asset stranding, is the establishment of rules to (1) require new power plants to have zero (or close to zero) emissions; and (2) prevent the dirtiest of already existing emitting plants from being granted life extensions. Such licensing rules have the political benefits of being simple and transparent, and could potentially reduce the political economy challenges of allocating permits either within or between countries (Collier and Venables, 2013). A more gradual version of this approach would be to regulate carbon intensity in $kgCO_2/kWh$, e.g. by introducing and implementing a clear roadmap that reduces the carbon intensity of new power plants step-wise over time. China has taken this approach in its 5-year plan, as have several U.S. states (Collier and Venables, 2013). Such rules and roadmaps, however, could have the adverse effect of incentivizing a rush to build high emitting assets before the intensity target decrease ("Green Paradox") and should hence be considered and implemented carefully (Van Der Ploeg, 2011; Smulders, Tsur and Zemel, 2012; van der Ploeg and Withagen, 2012; Cairns, 2014; Baldwin, Cai and Kuralbayeva, 2016). One approach to solve this problem could be to impose carbon intensity targets on the complete power plant fleet of certain utilities, similar to certain requirements towards the fleets of carmakers in some countries.

Similar results could also be achieved with different but related instruments. E.g. *leases* for power plants on public lands, which could be phased-out for existing 'dirty' plants and would not be granted for new power plants that fail to meet certain emission standards. The same could be done with phasing-out *subsidies* (e.g. tax breaks) or, conversely, by imposing a *levy* on polluting plants – as was e.g. in discussion for some lignite plants in Germany in 2014/15 (Amelang *et al.*, 2016). All these instruments would target existing and potential new power generators that fail to meet certain emission standards to prevent the building and subsequent stranding of new infrastructure.

One important disadvantage of such approaches is the unclear effect on cumulative emissions, as showcased in the example of the coal-to-gas substitution. Given constant or growing energy demand, ending the lifetimes of some power plants might have the effect that this generation capacity must be replaced immediately by other generators. Often this replacement will come from other fossil fuel generators that just meet the emission standards at the time but add to the cumulative capital stock. Hence, in some cases, even a lifetime extension for some polluting plants might be sensible if polluting power plants cannot currently be replaced by zero carbon technologies but could be replaced by these technologies in a few years. These policy instruments should therefore be considered carefully and decided on a case-by-case basis.

4.2.4 Technology-based deployment support

Another approach is to regulate, subsidize (or phase-out subsidies), or even penalize, the deployment of specific energy producing technologies. Examples include:

- A general ban on power generation from lignite
- Requiring all new coal plants to have CCS.
- Subsidies or other regulations for accelerated renewable deployment (e.g. a feed-in-tariff or renewable portfolio standard).
- Phase-out of fossil fuel subsidies.
- A levy on all sub-critical coal plants.

Technology-based regulation has several disadvantages, however. It tends to be economically inefficient, and more prone to regulatory capture, i.e. prone to lobbying from certain interest groups, than other broad-based economic instruments. A well-designed ramp down to zero emissions for new electricity generation would be more effective since it would not support one specific technology over another. For instance, renewable portfolio standards ignore potential contributions to decarbonization from other technologies (nuclear, fossil with CCS, demand-side response, storage technologies, etc.).

Moreover, most deployment support is still being directed towards fossil fuels. A 2015 study estimates that total direct energy subsidies within the OECD amount to ~645 bn. USD p.a. globally, of which the majority (~84%) benefits fossil fuels. Only ~100 bn. USD p.a. in subsidies is currently directed towards renewables (King *et al.*, 2015). The effect of such subsidies is that, in many regions of the world, the relative competitiveness of fossil fuel generation compared with renewables generation is artificially increased. This incentivizes the continued operation of otherwise unprofitable existing fossil fuel generation while reducing incentives to make new capacity additions net zero. A good enhancement of technology-based deployment support from the perspective of the decarbonization identity would hence be a phase-out of fossil-fuel directed deployment support, i.e. subsidies (Jakob *et al.*, 2015; Coady *et al.*, 2017).

4.2.5 Research and development support

An important factor in the decarbonization identity is the ability to add zero-carbon generation capital stock. Policy instruments could therefore be designed to support this ability by not only subsidizing deployment but also research and development (R&D) (Dechezleprêtre and Glachant, 2009; Dechezleprêtre and Popp, 2015). An important factor in the large-scale deployment of zero-carbon technologies is the relative cost of clean and dirty technologies. There are well-understood market failures in the research and innovation of clean technologies, and there is a clear and well-accepted role for government to support clean technology research and development (Fischer and Newell, 2008; Fischer, Newell and Preonas, 2014). It is surprising that, compared to implicit or explicit fossil fuel subsidies, currently so little funding is directed towards the development of technologies that are so crucial to solve this problem. Of ~340 bn. USD p.a. government R&D expenditure within the OECD, only ~6 bn. USD p.a. (~1.7%) is being spent on R&D related to renewables. In relation to the 2016 OECD GDP, this amounts to only ~0.01%. Even in the private sector, renewable energy companies spent less on R&D (~2% of revenues) than comparable companies in other sectors such as consumer electronics (5%) and pharmaceuticals (15%) (King *et al.*, 2015). It is hence not surprising that initiatives such as the Apollo programme or the 'Clean Energy Fund' initiative that was announced during the Paris COP and that is led by Bill Gates, call for more government spending on green energy R&D. For instance, the Apollo programme asks its member countries to pledge to spend 0.02% of their GDP on renewables R&D (King *et al.*, 2015). This would increase the size of current R&D spending by roughly 2.5 times but would still only amount to ~15 bn. USD p.a. – a cost that seem acceptable given the importance of the problem this R&D sets out to solve.

It is unclear, however, into which R&D this support should be directed. This applies in a narrower technology-focussed sense, as well as in a wider solution-focussed sense. From a narrower perspective, the question would need to be answered as to which technologies promise the highest potential, e.g. should solar PV be given priority over concentrated solar power (CSP) or is onshore wind superior to offshore wind? In a wider solution-oriented perspective, the decision would have to be made as to which general approaches to follow. Are renewables more likely to lead to a general decarbonization than, maybe, retrofitted CCS? How much effort should be directed towards the enablers of renewables, such as grids, storage, and demand-side response? How prudent is it to direct R&D

money towards NETs? The opinions about the role policy makers and regulators should play in addressing these questions differ (Mazzucato, 2015). Yet, the public hand has at least a questionable track record when it comes to picking ‘winning’ technologies (Schmidt *et al.*, 2016) and it is unclear how policy instruments should be designed to address this.

4.3 Broader questions and directions for future research

Besides the direct implications for policy choices and instruments within the power generation sector, the findings presented in this dissertation raise some broader questions within this specific area of research but also in the overall environmental context.

First, the implications for policy choices raise some immediate and urgent questions. As the decarbonization identity illustrates, a successful achievement of the 1.5-2°C climate goals will always encompass a combination of the five options: (1) protect and enhance carbon budgets; (2) retrofit existing polluting capital stock with CCS; (3) avoid the addition of new polluting capital stock; (4) strand existing polluting capital stock; or (5) create new atmospheric space by scaling-up NETs. It is unclear, however, what the most effective combination of these five options is. The best choice will depend on the economic cost of these options, as well as on scalability, technological availability, likelihood of success, political feasibility, and their interdependencies with each other. Plenty of research exists that focusses on each individual question, be it on carbon budgets (Millar *et al.*, 2017; Allen *et al.*, 2018), retrofit CCS (Corsten *et al.*, 2013), the potential of renewables (IPCC, 2011), stranding (Riahi *et al.*, 2015), or NETs (van Vuuren *et al.*, 2013). IAMs implicitly consider these policy choices and optimize the trade-off. Yet, so far, no approaches exist that tie these separate research areas together and make the policy choices explicit under the framework of the decarbonization identity.

Second, this research and the approach it takes, has implications not only for the downstream power generation sector, but also for the mid and upstream power sector (a), the energy sector in total (b), and even other CO_2 emitting sectors (c):

(a) Assessing the level of carbon lock-in in the electricity generation sector, or even more precisely *generator carbon lock-in*, only encompasses a small fraction of overall connected carbon lock-in. Closely related to the lock-in identified in this dissertation is, for instance, lock-in in transmission and distribution grids, transport infrastructure (e.g. pipelines, harbours, train tracks, etc.), and even carbon lock-in in the labour market. If the generator carbon lock-in was to be broken up to be taken back on track for a 1.5-2°C target, e.g. by large-scale stranding of power generators, it would have immediate and important impacts on connected infrastructure, local economies and even the job market. Decarbonization efforts to achieve this must bear those effects in mind.

(b) in addition to the immediate impacts that a break-up of generator lock-in would have, there are some wider implications for the overall energy sector. The demand for fossil fuels would decrease drastically if the world were to decarbonize its power generation capital stock (Piggot *et al.*, 2017). Across the globe, coal mines would become unnecessary and cease operations. Sectors along the value chain would change fundamentally – fossil fuel extraction, processing and transport. More research should be undertaken to understand the impacts such a decarbonization would have.

(c) The approach taken in this dissertation could be applied to other CO_2 emitting sectors. Carbon lock-in does not only exist in the energy sector. In fact, electricity and heat production only accounts for a fraction of overall emissions from fossil fuel combustion. Other sectors that emit CO_2 and are affected by carbon lock-in are industry (especially iron, steel and cement), transport, buildings (mostly heating) and agriculture. Calculating the emission commitments of currently existing capital stock in these sectors and applying the decarbonization identity to them could help to identify effective decarbonization pathways.

Finally, the approach, presented in this dissertation could be applied to a wider range of environmental *stock problems*. In a well-known study from 2009, Rockström et al. outline a safe operating space for humanity (Johan Rockstrom *et al.*, 2009). Within this study, the authors identify ten environmental areas that will greatly affect humanity's ability to live on this planet and that are in turn being strongly affected by anthropogenic activity. While some of these areas constitute *flow* problems (e.g. rate of biodiversity loss, nitrogen cycle, phosphorus cycle, or global freshwater use), most can be described as a *stock* problem (climate change, stratospheric ozone depletion, ocean acidification, land-use change, atmospheric aerosol loading, and chemical pollution, e.g. by plastic in the oceans). Using the approach presented in this dissertation, global '*pollution commitments*' arising from existing anthropogenic infrastructure could be calculated for a wider set of environmental stock problems. This would help to identify areas in which there is still time to avoid the worst outcomes by simply avoiding the addition of more polluting capital stock, or other areas where capital must become stranded to avoid such outcomes.

The human population has grown by almost five-fold from 1.6 billion in 1900 to over 7.5 billion today. Over a similar period, world average per capita output has increased almost 6-fold from 2,668 USD in 1913 to 14,717 USD in 2015.[24] 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), since humans may now be confronting planetary boundaries. The analysis in this dissertation 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, ocean acidification, or aerosol loading. Much greater effort is required to create economic incentives and policies to ensure that individuals and corporations protect the natural environment.

5. Conclusion

Over the last centuries, the consumption of energy, especially from fossil fuels, has helped humanity to develop and to create the wealth of industrialized nations today. If the currently developing and least-developed nations follow the same path, however, the negative external effects of burning fossil fuels will affect the livelihoods of billions of people around the world. The international community has therefore decided to decarbonize its economy and reduce carbon emissions to net-zero to limit global warming to below 1.5-2°C. One important obstacle for the successful achievement of that goal is carbon lock-in. This dissertation finds

[24] Real GDP in international dollar (Roser, 2017).

that current power plants would emit more CO_2 in the future than the 1.5-2°C goal would allow. Moreover, currently planned generators, and those already under construction, would add a significant amount of additional emission commitments to this capital stock. Policy makers now have five choices to achieve the Paris climate goals: (1) protect and enhance carbon budgets; (2) retrofit existing power generators with CCS; (3) ensure that no new polluting capital stock is added; (4) strand a considerable amount of global electricity generation capacity; and (5) create additional atmospheric space by scaling up NETs. Over the coming years and decades, the challenge will be to identify the most effective balance of these options. Given the uncertain success of future climate policies, however, policy makers are well advised to try to avoid further lock-in by avoiding additional polluting capital stock.

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Appendix

Appendix table of contents

A. Abbreviations

AMPERE	Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
AR	Assessment Report
BaR	Budget at Risk
BAU	Business as Usual
BECCS	Bioenergy with Carbon Capture and Storage
Bn.	Billion
BTU	British Thermal Unit
CARMA	Carbon Monitoring for Action database
CCCE	Committed Cumulative Carbon Emissions
CCS	Carbon Capture and Storage
CDP	Carbon Disclosure Project
CDR	Carbon Dioxide Removal
CH_4	Methane
CO_2	Carbon Dioxide
CO_2eq.	Carbon Dioxide equivalent
COP	Conference of the Parties
CSP	Concentrated Solar Power
CTI	Carbon Tracker Initiative
DEFRA	U.K. Department for Environment, Food, and Rural Affairs
D&A	Depreciation and Amortisation
EIA	Energy Information Agency
EJ	Exajoule (= 10^{18} Joule = ~277.8 TWh)
EPA	Environmental Protection Agency

EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
$GtCO_2$	Gigatons of Carbon Dioxide (= 10^9 tCO_2)
GW	Gigawatt
GWh	Gigawatt Hour (= 10^9 Wh)
GWP	Global Warming Potential
IAM	Integrated Assessment Model
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
$KtCO_2$	Kilotons of Carbon Dioxide (= 10^3 tCO_2)
kWh	Kilowatt Hour (= 10^3 Wh)
LAM	Latin America
LCOE	Levelized Cost of Electricity
LLCP	Long-Lived Climate Pollutant
MAF	Middle East and Africa
Mbtu	Million British Thermal Units
Mmbtu	Million British Thermal Units
$MtCO_2$	Megatons of Carbon Dioxide (= 10^6 tCO_2)
Mtoe	Million tonnes of oil equivalent
MWh	Megawatt Hour (= 10^6 Wh)
N_2O	Nitrous Oxide
NET	Negative Emissions Technology
OECD	Organization for Economic Co-operation and Development

PEM	Policy Evaluation Model
POM	Policy Optimization Model
PV	Photovoltaic
RCP	Representative Concentration Pathway
REF	Reforming Economies (former Soviet Union)
R&D	Research and Development
SLCP	Short-Lived Climate Pollutant
SPM	Summary for Policy Makers
SSP	Shared Socioeconomic Pathways
TCFD	Task Force on Climate-related Financial Disclosures
TPED	Total Primary Energy Demand
TPES	Total Primary Energy Supply
TWh	Terawatt Hour (= 10^{12} Wh)
U.K.	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
WEPP	World Electric Power Plants
WBG	World Bank Group
WG	Working Group
WMO	World Meteorological Organization

B. Extended literature review

The research presented in this dissertation builds on, and adds to, three distinctive but related bodies of literature: (1) the *decarbonization* and *deep decarbonization* literature and its significance for policy makers and regulators; (2) the *carbon lock-in* literature, which describes one of the most important obstacles for successful deep decarbonization; and (3) the *stranded assets* literature, which describes the effects successful deep decarbonization policies could have on fossil fuel resources, reserves, and other assets of the polluting capital stock that are affected by carbon lock-in.

B.1 Decarbonization and deep decarbonization

Decarbonization describes the need to, and process of, reducing anthropogenic emissions to net-zero. It implies that a certain industry, sector, country, and even the global economy, must eventually balance its residual GHG emissions with removals from the atmosphere if the world is to be successful in stabilizing the climate at any level. After the UNFCCC was founded in 1992, much climate change related literature focussed on the stabilization of GHG concentrations in the atmosphere (Meehl *et al.*, 2005; Wigley, 2005; Stern *et al.*, 2006). It was assumed that stable or slightly decreasing atmospheric concentrations of such GHGs would eventually lead to decreasing temperatures (Friedlingstein and Solomon, 2005). Even though significant shares of LLCPs, such as CO_2 and N_2O, are being removed from the atmosphere by natural sinks, however, much of it will remain in the atmosphere for centuries or even millennia (Archer, Kheshgi and Maier-Reimer, 1997; Archer, 2005; Archer and Brovkin, 2008; Archer *et al.*, 2009). A 2007 study found that one quarter of CO_2 emissions will have a lifetime in the atmosphere of over 5,000 years (Montenegro *et al.*, 2007), and a more recent study even finds that a considerable amount of carbon emitted today will remain in the atmosphere for tens or even hundreds of thousands of years (Clark *et al.*, 2016). Moreover, even if a stabilization of atmospheric concentrations of GHGs were reached, the global climate would continue to warm for many centuries (Hansen *et al.*, 1985; Matthews, 2006). The slow response timescale of the climate system is caused, for example, by the heat trapping potential of the oceans (Solomon *et al.*, 2009). These findings together imply that decreasing, rather than stabilized, concentrations of long-lived GHGs in the atmosphere would be required to stabilize global climate on human timescales.

Modelling studies and further research confirm this implication. A one-off pulse of GHG increases global temperature by an amount that largely remains constant for several centuries, even in the absence of additional emissions. To stabilize climate change at a given temperature goal hence requires near- or net-zero future emissions (Matthews and Caldeira, 2008). Any non-zero anthropogenic emissions of LLCPs beyond that climate goal, that are neither removed by natural carbon sinks or actively removed from the atmosphere (Keith, Ha-Duong and Stolaroff, 2006), would lead to excess warming that would essentially be irreversible on human timescales (Allen *et al.*, 2009; Matthews *et al.*, 2009; Meinshausen *et al.*, 2009).

To measure this long-term effect of climate pollutants on global temperatures, the *global warming potential* (GWP) is widely used, a relative measure of how much heat a GHG traps in the atmosphere. The GWP is expressed as a factor of CO_2 as it compares the amount of heat trapped by the emission of a certain GHG to the amount trapped by a similar pulse of CO_2, and is calculated over a specific period, e.g. 20 or 100 years (Lashof and Ahuja, 1990; IPCC, 2013). The GWP100 has been widely used for over 20 years in research (IPCC, 1990; Rogelj, Reisinger, *et al.*, 2015) and within the UNFCCC and the Kyoto Protocol (UNFCCC, 1998) and has helped to establish policy priorities and market-based emission reduction mechanisms (Allen *et al.*, 2016). In recent years, however, the GWP has seen considerable criticism (Solomon *et al.*, 2009; Smith *et al.*, 2012; Joos *et al.*, 2013; Huntingford *et al.*, 2015; Allen *et al.*, 2016, 2018) and a variety of alternative metrics have been suggested (Peters *et al.*, 2011; Johansson, 2012; Smith *et al.*, 2012; Lauder *et al.*, 2013; Deuber, Luderer and Sausen, 2014; Allen *et al.*, 2016, 2018). The scientific community has yet to agree on a metric that is suitable to replace the GWP metric as the debate among researchers is still ongoing (Fuglestvedt *et al.*, 2003, 2010; Berntsen, Tanaka and Fuglestvedt, 2010; Aamaas, Peters and Fuglestvedt, 2013; Deuber, Luderer and Edenhofer, 2013; Ekholm, Lindroos and Savolainen, 2013; Moura *et al.*, 2013).

One important criticism of the GWP, and a central difference between all metrics, is how the warming effect of short-lived climate pollutants (SLCPs), such as methane (CH_4), is calculated, and how the emissions of such GHGs are hence considered and prioritized within climate policies. For the two most important GHGs, the LLCP carbon dioxide and the SLCP methane, different metrics suggest different prioritization. While some studies find that early action on SLCPs is crucial (Wallack and Ramanathan, 2009; UNEP/WMO, 2011; Shindell *et al.*, 2012) others suggest that such early action on CH_4 and other SLCPs could slow down action on CO_2 and should hence be delayed (Boucher and Reddy, 2008; Berntsen, Tanaka and Fuglestvedt, 2010; Myhre *et al.*, 2011; Shoemaker and Schrag, 2013). More recent research suggests that early action on SLCPs, such as CH_4, cannot replace distinctive action on LLCPs, such as CO_2, and might eventually only 'buy time' for climate change adaption (Bowerman *et al.*, 2013).

Despite sometimes very strong radiative effects, SLCPs remain in the atmosphere for much less time than LLCPs, sometimes for only a few years. Unlike with LLCPs, therefore, it is not the cumulative amount of SLCP emissions that determines their effect on global warming, but rather the sustained rate of emissions of such pollutants (Smith *et al.*, 2012). The atmospheric concentration anomaly associated with a one-off pulse emission of a LLCP decays very slowly, with a large fraction of the emissions still resident in the atmosphere over timescales relevant to anthropogenic climate change in this century. A similar-sized one-off pulse of SLCPs, e.g. methane, however, would be negligible after only 20 years, and thus has little residual effect on atmospheric concentrations of the gas after 60-80 years. Whilst concentrations (and induced warming) continue to rise with constant LLCP emissions, a constant rate of emissions of an SLCP, on the other hand, would lead to stabilised concentrations of the pollutant in the atmosphere and approximately constant associated warming. Since total human-induced warming arises from the combination of SLCP and LLCP induced warming, the size of a cumulative emissions budget for LLCPs consistent with a specific target peak human-induced warming hence also depends on the future sustained emission rate of SLCPs (Rogelj *et al.*, 2016).

The cumulative emissions of LLCPs by the time net-zero has been achieved, together with the sustained level of SLCP emissions, will therefore determine the level of long-term global warming above pre-industrial levels, with all its implications for global systems (Allen *et al.*, 2009; Matthews *et al.*, 2009; Meinshausen *et al.*, 2009). Under certain assumptions, these cumulative emissions can therefore be translated into carbon budgets compatible with limiting human-induced warming to below a given threshold, such as 1.5-2°C (IPCC, 2013). While uncertainty in the physical climate response (Gillett *et al.*, 2013) is a dominant source of variation in these budgets, unknown future emissions of SLCPs – over which humanity does have some control – also play an important role (Bowerman *et al.*, 2013; Hamilton *et al.*, 2014; Rogelj *et al.*, 2014; Rogelj, 2015; Rogelj *et al.*, 2016).

In this context, *Deep decarbonization* is hence often understood as a more restrictive description of the previously defined *decarbonization* process. A balancing of residual carbon emissions with the removal of carbon sinks must be achieved to eventually stop global warming and this must be fully achieved by the time the carbon budgets for a given temperature goal, e.g. 1.5-2°C, have been consumed. Deep decarbonization is typically connected with steep emission cuts of around 5% p.a. before 2050 (Raupach *et al.*, 2014), or even steeper emission cuts afterwards (Rogelj *et al.*, 2011; Bertram *et al.*, 2015; Loftus *et al.*, 2015). While current climate goals are sometimes debated (Knutti *et al.*, 2015), for the purpose of this dissertation it is assumed that a stabilization of climate around 1.5-3°C warming feasible and around 1.5-2°C desirable. Dedicated research groups [1] and a growing body of literature have started to analyze different geographical or sectoral systems to identify pathways to achieve such deep decarbonization (Jenkins and Thernstrom, 2017).

[1] E.g. the Deep Decarbonization Pathways Project (DDPP, 2017).

One important extension to the decarbonization and deep decarbonization literature is the broad and growing body of research into negative emissions technologies (Fuss *et al.*, 2013, 2014; Klein *et al.*, 2014). Since anthropogenic global warming depends mostly on the cumulative emissions of LLCPs, especially CO_2, the implied carbon budgets for different climate goals can be increased by creating additional atmospheric space, i.e. by actively removing carbon from the atmosphere (Humpenöder *et al.*, 2014). Such efforts should not be confused with CCS, which describes the process of capturing carbon emissions at the point where they originate, i.e. where the fuel is burned, and then transporting them to a reservoir where they can be stored safely for hundreds or thousands of years (Smith, Fahrenkamp-Uppenbrink and Coontz, 2009). While CCS, as an add-on to fossil fuel powered processes, usually avoids the additional release of fossil carbon into the atmosphere, NETs actively remove carbon from the atmosphere that had been released previously. The most prominent example of a NET is bioenergy with CCS (BECCS), where biomass captures carbon from the atmosphere as the plants grow and is then burned to harvest the energy. The resulting carbon emissions are being captured and stored (Azar, Johansson and Mattsson, 2013; Creutzig *et al.*, 2015), which makes BECCS a process that can have the net effect of reducing the concentration of CO_2 in the atmosphere. Other examples of NETs are direct air capture, biochar, or the enhancement of natural carbon sinks, e.g. by reforestation or ocean fertilization (Anderson and Peters, 2016; Buck, 2016; Fuss *et al.*, 2016; Heck *et al.*, 2016).

Many scientists believe that NETs, such as BECCS, could, or even have to, play an important role in humanity's attempt to stay within its carbon budgets (Anderson and Peters, 2016). Yet, its current and future success is at least questionable (Kriegler *et al.*, 2013; van Vuuren *et al.*, 2013; Creutzig *et al.*, 2015; Kreidenweis *et al.*, 2016; Smith *et al.*, 2016; Vaughan and Gough, 2016; Bhave *et al.*, 2017). For the purposes of this dissertation, we explicitly assume NETs to play a minor role in the future and hence the growing body of literature analyzing these questions has only been of peripheral importance.

B.2 Carbon lock-in

One important obstacle to achieving the deep decarbonization required to achieve climate goals, is *carbon lock-in*. Carbon lock-in is the inertia of carbon emissions, which is caused by mutually reinforcing physical, economic and social constraints on the reduction of carbon emissions, put in place by existing technologies, institutions and behavioural norms (Seto *et al.*, 2016).

To achieve a deep decarbonization, the fundamental transformation of vast, interconnected, and deeply rooted, systems of infrastructure, institutions and human behaviours would be required (Pfenninger, Hawkes and Keirstead, 2014; Rogelj, Luderer, *et al.*, 2015). The global energy system is the largest and most interconnected network of assets ever built (Seto *et al.*, 2016). These assets reflect centuries of technological development, investments of tens of trillions of dollars (Seto *et al.*, 2016), and invaluable economic importance, in the sense of being the backbone of the modern global economy (Unruh and Carrillo-Hermosilla, 2006). The global energy system has co-evolved, and is supported by, today's institutions, laws, regulation, consumer preferences, social and behavioural norms and technologies, and is hence closely intertwined with these building blocks of modern society (Smil, 2010; Fouquet and Pearson, 2012).

The inertia in existing infrastructure, institutions, behaviour and technology restricts the speed and extent to which an energy system of such scale can change and transition into a different state, in this case away from fossil fuels. The initial state at the beginning of a transition, together with increasing economies of scale, behavioural dynamics, expectations, and vested economic interests can lead to a path-dependency under which innovation and competitiveness of technological, in this case low-carbon, alternatives are inhibited (Krugman, 1991; Unruh, 2000, 2002; Unruh and Carrillo-Hermosilla, 2006; Aghion *et al.*, 2014; Erickson *et al.*, 2015; Mattauch, Creutzig and Edenhofer, 2015; Seto *et al.*, 2016). This path dependence of interacting systems is commonly referred to as lock-in, with lock-in being a normative neutral term as it can preserve either positive or negative states of a system.

In the case of carbon lock-in, however, the term must be interpreted negatively. It refers to a specific form of lock-in linked to systems that emit carbon to the atmosphere. Currently, ~81% of the energy delivered by the global energy system is thermally extracted from fossil fuels (IEA, 2017) and hence potentially affected by carbon-lock in. Acknowledging the need to decarbonize our society, carbon lock-in must be interpreted in a negative way because it inhibits the changes required in the transition to a low- or even zero-carbon economy. Overcoming carbon lock-in within the energy system is therefore crucial to achieve a successful deep decarbonization and stay within desired limits of climate change.

Three separate, but intertwined, forms of carbon lock-in are often mentioned in pertinent literature (Seto *et al.*, 2016): (1) *infrastructural* or *technological lock-in*, which refers to the infrastructure and technologies that indirectly or directly emit carbon; (2) *institutional lock-in*, which describes the policies, regulation, governance, institutions and decision-making procedures affecting energy-related production and consumption; and (3) *behavioural carbon lock-in*, which relates to the societal and individual behaviours, habits and norms shaping the demand for energy-related goods and services. All three forms of lock-in are closely connected and mutually reinforcing. A successful break up of carbon lock-in can therefore best be accomplished if all three types of lock-in are approached decisively and simultaneously.

For this dissertation, research examining infrastructural carbon lock-in has been most relevant. Within this broader body of literature, two different focus areas are typically identified: (1) demand side infrastructural carbon lock-in, which relates to all infrastructure that consumes energy in different forms, quantities and geographical locations (Rozenberg *et al.*, 2015); and (2) supply side infrastructural carbon lock-in, referring directly to the reserves and resources of fossil fuels, and to infrastructure and assets that extract and transport fossil fuels, transform them, and transmit energy (CTI, 2011). Within this field, this dissertation analyses supply side lock-in and, more specifically, downstream supply side infrastructural carbon lock-in, i.e. power generators, as opposed to upstream supply side lock-in, e.g. fossil fuel extraction and transport.

In recent years, several studies and papers have been published that have set out to assess the current and expected level of downstream supply side carbon lock-in and its implications for policy making (Guivarch and Hallegatte, 2011b; Stern, 2014; Bertram *et al.*, 2015; Erickson *et al.*, 2015; Steckel, Edenhofer and Jakob, 2015). Consistently, these studies find that power generators, and other supply side assets, such as transmission and distribution networks, pipelines, etc., create a commitment to many decades of carbon-intensive economic activity in the future (CTI, 2016b; Rozenberg, Vogt-Schilb and Hallegatte, 2017). Existing infrastructure already increases the difficulties of achieving a climate policy consistent with the Paris goals (Johnson *et al.*, 2015; Baldwin, Cai and Kuralbayeva, 2016). Weak near-term energy policies that allow the building of even more polluting capital stock will make it even harder for climate policies to succeed in the future as the amount of asset stranding required to meet the climate goals increases (McJeon, 2015; Caldecott, Bouveret, *et al.*, 2017; Rozenberg, Vogt-Schilb and Hallegatte, 2017).

B.3 Stranded assets

When decarbonization, especially deep decarbonization, overcomes carbon lock-in, *stranded carbon assets* are likely to occur (Goulder, Hafstead and Dworsky, 2010). According to the most common definition, an asset strands when it experiences an unanticipated or premature write-down, a devaluation, or a conversion to a liability (Caldecott, Tilbury and Carey, 2014). If carbon emitting physical assets, or related financial assets, are affected by this form of stranding they are typically referred to as stranded carbon assets (Caldecott, Lomax and Workman, 2015). In the narrower context of this dissertation, carbon assets of the energy sector can strand when society gradually decides to stop the burning of fossil fuels in general or certain fossil fuels, e.g. coal, to generate energy.

The concept of asset stranding caused by economic evolution is well known in economic history and is often described in economic literature as *creative destruction* (Schumpeter, 1942). This refers to the product and process innovation mechanism by which new production units replace outdated ones. Schumpeter described it as an "*essential fact about capitalism*" (Schumpeter, 1954). In recent years, however, stranded assets caused by environmental factors, such as climate change, have become an increasingly important subject of environmental policy and research. The scale of stranding, and especially carbon stranding, that could take place because of climate change makes this specific form of creative destruction especially relevant to policy makers (CTI, 2011; The Global Commission, 2014). A transition of the global energy system towards low- or zero-carbon energy, driven by climate change and society's response to it, could potentially strand entire economic sectors, regions, and industries within a very short period (CTI, 2015b). This would lead to direct and indirect impacts on economies, the financial sector, jobs, and the livelihood of many millions or even billions of people (Newell and Mulvaney, 2013; Caldecott, Dericks, *et al.*, 2017).

Such stranding can happen for different reasons and in different ways. In the relevant literature, six different lenses on stranding can be found (Caldecott, Howarth and McSharry, 2013; Caldecott, Dericks, *et al.*, 2017). These lenses are: (1) a changing resource landscape such as e.g. shale gas abundance, water scarcity, and phosphate availability; (2) falling clean technology costs; (3) changing government regulations, e.g. introduction of carbon pricing or emission standards; (4) environmental change, e.g. storm, flooding, or biodiversity loss; (5) litigation and changing statutory interpretations, i.e. changing interpretations of existing laws and regulation; and (6) evolving social norms, e.g. divestment campaigns, etc. Analyzing asset stranding through each of these six lenses can provide insights into the factors that, individually or combined, can lead to the stranding of a physical asset for environmental reasons.

An asset is said to be stranded when it experiences a devaluation. The value of an asset, however, depends on the perspective and the calculation method used. From an accounting perspective, it can be defined as (1) the remaining book value of that asset, i.e. the original investment value, or capital cost, plus all further investments in that asset minus the depreciation and amortisation (D&A). From an investor or financial perspective, the value of an asset reflects (2) the discounted value of all future net cash-flows that can be generated with that asset (Damodaran, 2002).[2] From an economic perspective, avoiding the sunk cost fallacy, the value of an asset is defined as (3) the future marginal revenue less marginal cost, with and without policies or taking into account externalities (Edwards, Kay and Mayer, 1987). Finally, from a social planner or welfare perspective, the value of an asset can be defined more broadly as (4) the social value of that asset, including the economic value, social opportunity costs, externalities, etc. Each of these perspectives has the potential to provide answers to specific questions, but the value of an asset, and the calculation of the cost of stranding, depends on the perspective and the political economy, i.e. who must bear that cost.

As the value of an asset is not always clearly defined the ways in which stranding risks materialize are manifold. An asset can become stranded because it must be retired prematurely (e.g. power plants) or cannot be burned anymore (e.g. coal reserves), for instance for regulatory reasons, or because the cost for input factors, such as clean water, coal, gas, or emission permits, increase to the extent that it cannot be operated or extracted profitably anymore (Caldecott, Elizabeth, *et al.*,

[2] Alternative definitions from an investor's perspective include the scrap value, i.e. the material value of the asset, the replacement value, and market- or transaction values.

2016). An asset stranding also takes place if the price of the output of that asset decreases, e.g. lower oil or electricity prices, or when the utilization decreases compared to the previously expected utilization. Often these materialization pathways are mutually entwined. Higher carbon prices can lead to increased input prices for power plants and reduce profit margins. At the same time these higher carbon prices provide an incentive for the development of renewable energies which in turn reduce utilization of coal plants and lead to lower wholesale electricity prices in the market thereby putting even more pressure on the profit margins of traditional power plants (Caldecott, Tulloch, *et al.*, 2017). A final definition for stranded assets in the environmental or climate change related context has yet to be found and a consistent taxonomy of stranding reasons and pathways is yet to be defined.

In the context of this dissertation, however, a stranded asset can be defined by summarizing previously discussed literature and applying the carbon lock-in framework (Seto *et al.*, 2016). In this context, a *stranding* of carbon-related energy assets can occur by any action that is aimed at *decarbonizing* the energy sector, and that can break up infrastructural, institutional, and/or behavioural, *carbon lock-in*. When such an action leads to a permanent loss of asset value for its owner, compared to a counterfactual in which this attempt would not have been made, stranding takes place.

Asset stranding from this perspective has always been described in the overall context of decarbonization and carbon lock-in (Unruh, 2000, 2002; Unruh and Carrillo-Hermosilla, 2006). In many theoretical approaches, it has been shown that the transition towards a low- or zero-carbon energy system can lead to stranded assets, which in turn hardens carbon lock-in and makes the transition more difficult (Acemoglu *et al.*, 2012; Rozenberg, Vogt-Schilb and Hallegatte, 2017). For a long time, however, the extent to which the energy system's carbon lock-in would be affected by decarbonization, could only be speculated about. It was not until the concept of a cumulative carbon budget gained popularity in the scientific community, that research was undertaken to compare the implied future carbon emissions in the global energy system with these carbon budgets for 1.5 or 2°C global warming (Allen *et al.*, 2009; Meinshausen *et al.*, 2009).

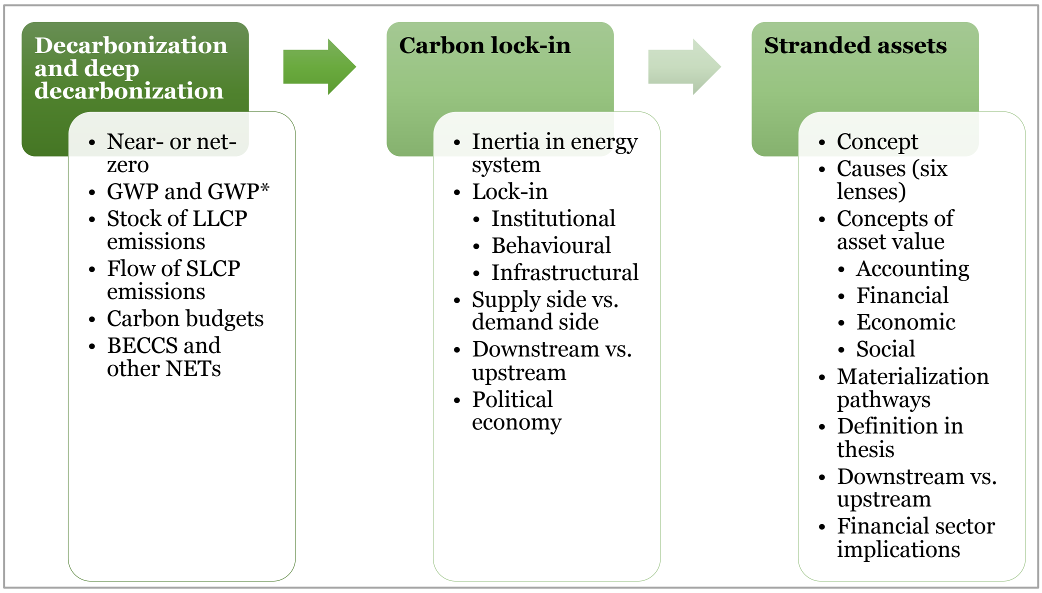
The first efforts focussed on the upstream supply side by comparing known and proved reserves of coal, oil and gas with the carbon budgets for different climate goals (Meinshausen *et al.*, 2009). Subsequent reports and studies focussed on the estimation of the financial and systemic impact of the identified excess carbon in the ground (CTI, 2011; McGlade and Ekins, 2014) and on the allocation of this 'unburnable carbon' to geographic regions (CTI, 2013a, 2014c; McGlade and Ekins, 2015), financial markets (CTI, 2013b), and even companies (CTI, 2014a, 2014b, 2015a; Rook and Caldecott, 2015b). These studies overwhelmingly found that by far the largest share of known coal reserves, but also a significant share of oil, and potentially even gas, reserves, will have to remain unburned or 'in the ground' if the world is to meet its climate goals. Moreover, much of this 'unburnable carbon' has been developed, or is being developed, by publicly traded companies, or financed with publicly traded debt, potentially leading to 'wasted capital' of trillions of dollars (CTI, 2013b). Soon the notion of a 'carbon bubble' started to gain traction in media coverage of the research, i.e. the risk that a rapid devaluation of financial assets linked to these physical reserves in the ground could lead to a collapse of financial markets and hence a crisis like the sub-prime mortgage crisis of 2008/09 (Page, 2011; McKibben, 2012). These risks (Fuss, 2016), and the lack of reaction of the financial markets on the disclosure of these risks (Griffin *et al.*, 2015), eventually even caused the Bank of England and other financial authorities, to launch an investigation into the risks these assets pose for financial stability (Robins, 2014; Weyzig *et al.*, 2014; Carney, 2015; Diaz-Rainey, Robertson and Wilson, 2017; Harnett, 2017). Moreover, a growing movement calls for carbon disclosure, i.e. the publication of financial and business risks caused by carbon exposure at a company level.[3]

Since then, researchers at universities, institutes and think-tanks around the world have picked up the concept of stranded environmental assets and either described it from a broader perspective (Rook and Caldecott, 2015a) or applied it to other upstream energy supply infrastructure (Caldecott, Tilbury and Ma, 2013; Caldecott, Dericks, *et al.*, 2016), energy demand assets (Caldecott, Elizabeth, *et al.*, 2016; Caldecott, Dericks, *et al.*, 2017), the financial industry (Robins, 2014; Paun, Knight and Chan, 2015), and even other industries and areas outside the energy or financial sector (Caldecott, Howarth and McSharry, 2013; Morel *et al.*, 2016).

In recent years, especially, the power generation sector has been analyzed within a growing body of literature, since any attempt to decarbonize the global economy will inevitably fundamentally change the way this sector operates (Davis, Caldeira and Matthews, 2010; Bertram *et al.*, 2015; Johnson *et al.*, 2015; van Breevort *et al.*, 2015; CTI, 2016a). This research has so far produced convincing

[3] E.g. the Carbon Disclosure Project (CDP) or the Task Force on Climate-related Financial Disclosures (TCFD).

evidence that existing power generators already face a substantial risk of becoming stranded if the 1.5-2°C climate goal is to be reached. Additional investments in the polluting infrastructure capital stock would either require large scale retrofit CCS, substantial deployment of NETs, or large amounts of asset stranding in the future. In any case, they would increase the cost to achieve the climate goals and hence make an achievement of those less probable.



Box 1: Relevant bodies of literature

B.4 Contribution of this dissertation

This dissertation adds to all three previously mentioned bodies of literature. It adds to the decarbonization and carbon budget literature (second paper), the carbon lock-in literature (first, third and fourth papers), and the relatively new body of literature on stranded assets (third and fourth papers).

The first paper builds on the concept of a cumulative carbon budget proposed by Matthews et al. (2009) and Allen et al. (2009), and adds to the findings of Davis et al. (2010, 2014) regarding future and committed CO_2 emissions of energy infrastructure. It introduces the concept of a *2℃ capital stock* for electricity generation, and answers the question of when the infrastructural carbon lock-in on the downstream energy supply side will commit humanity to more CO_2 emissions then would be consistent with a 1.5-2°C climate goal. Using data from 2012, it finds that this cut-off year for dirty capital stock additions is 2017. It concludes that the identified carbon lock-in will either lead to a failure to achieve climate goals, to the large-scale deployment of retrofit CCS or NETs, or to the massive stranding of generation assets. The first paper thereby introduces the two concepts – the 2°C capital stock and the decarbonization identity – that set the stage for the following papers.

The second paper builds on these results, and on the findings of Smith et al (2012), Rogelj et al. (2014, 2016) and Allen et al. (2016, 2017), regarding the influence of SLCPs on carbon budgets. It analyzes what needs to be done to protect and increase the remaining amount of CO_2 humanity can emit given a certain climate goal. It finds that the remaining carbon budgets would be much smaller if humanity were to miss its projected methane emission reductions. On the other hand, the remaining carbon budgets could be increased significantly if methane emissions could be reduced below expected levels. The size of the remaining carbon budget is a crucial determinant of the required amount of asset stranding for different climate goals.

The third paper builds on recent reports and findings regarding planned capacity additions in coming years, e.g. the work of Bertram et al. (2015), Johnson et al. (2015), Rozenberg et al. (2015) and Shearer et al. (2016, 2017). It improves on the first paper by updating the current polluting generation capital stock to 2016 and by improving the database and calculation method. It furthermore adds an analysis of the current pipeline of planned power plants and hence the expected development of the polluting capital stock and carbon lock-in over coming years. It finds that after these updates, estimates of committed emissions are higher, and that current plans would add roughly the same amount of committed emissions to the capital stock over the coming decade as are currently already in operation.

The fourth and final paper extends this analysis to 2100 and finds that weak short-term climate and energy policies would lead to the addition of much fossil fuel powered generation capacity until 2030-50. It furthermore quantifies the amounts of asset stranding that would be required to achieve climate targets under such policies. It thereby adds to the recent findings of Luderer et al. (2013), Riahi et al. (2015) and McJeon et al. (2015) that, under weak current policies, mitigation cost, increase and the eventual achievement of climate goals becomes less likely.

Overall, this dissertation uses applied interdisciplinary scientific methods to approach the identified questions. It does not extend theoretical boundaries or introduce new methods in physics or economics, but it applies analytical approaches with rigour to relevant questions in energy and climate policy. Within geography and the environment, this dissertation might be considered as an application of concepts from geosystem sciences, analyzing the interaction between anthropogenic energy and atmospheric systems, to derive results that are relevant to climate policy and the economic and financial risks faced by private firms investing in fossil infrastructure and the wider economy and society.

C. Data and methods

This dissertation does not extend theoretical boundaries or introduce new methods in physics or economics, but it applies data analytic and quantitative approaches with suitable scholarly rigour to questions in energy and climate policy.

In all papers of this dissertation, certain parts of carbon budgets, or carbon budgets in total, are compared with the committed emissions from electricity generation capital stock. The same set of databases and sources are used in all the papers, but different methods and approaches are employed depending on the research question of the respective paper (see Box 2). This Chapter sets out to describe these data sources and methods.

	Paper	2-degree Celsius capital stock	Carbon budgets and SLCPs	The 2016 capital stock	Dead on arrival
Databases and sources	1 IPCC AR5 scenario database	X	X		X
	1 AMPERE scenario database		X		X
	2 Platt's WEPP UDI database	X		X	X
	2 Other asset level databases (Kiko, Greenpeace, etc.)			X	X
	3 Complementary data sources (IEA, EIA, EPA, etc.)	X	X	X	X
Methods		• IPCC AR 5 database (unharmonized) is used to calculate emission pathways and carbon budgets for all sectors • WEPP and CARMA databases (taken from Davis & Socolow, 2014) are used to simulate CCCE development	• Scenario databases (unharmonized) are used to calculate emission pathways and carbon budgets (CO2 and CH4) for different climate goals • GWP* (Allen et al., 2017) is used to calculate *Budget at Risk* (BaR)	• WEPP and other asset level databases are used to estimate current 2016 capital stock and simulate future CCCE development • Several other data sources (IEA, EIA, EPA, etc.) are used to complete missing data in asset level databases	• Asset level databases (unharmonized and harmonized) are used to simulate future development of 2016 capital stock • Scenario databases are used to compare simulation with scenarios and identify investment (and stranding) needs

Box 2: Overview of data sources and methods for each paper

The rest of this Chapter is structured as follows: first, all databases and sources are described (C.1); second, the methods used in each paper are explained (C.2); and third, important assumptions and limitations are discussed (C.3).

C.1 Data sources

Throughout the whole dissertation, the same set of databases and sources are used. These can be clustered into three broad categories: (1) scenario databases that provide possible pathways for the development of the energy sector and its emissions between now and 2100; (2) power generator databases that contain and describe the global capital stock for electricity generation and its development over time on a granular level; and (3) complementary data sources that provide statistical insights to inform assumptions made in the calculations.

C.1.1 Scenario databases

In this dissertation, two different sets of pathways for electricity generation and SLCP and LLCP emissions between 2005 and 2100 are used: the AMPERE database and the IPCC's AR5 database.[4] From each of the analyzed scenarios either the model output for power generation of different technologies (e.g. coal with and without CCS, bioenergy with and without CCS, nuclear, etc.) or sectoral emissions through 2100, are used. The AMPERE database provides regional and, in some cases, even country-specific, model outputs while the IPCC's AR5 database provides only global results for the required outputs.

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[4] These data sets are chosen as they are freely available online (IIASA, 2014a, 2014b). Other recent studies such as EMF27 (Kriegler *et al.*, 2014) or the SSP dataset (Riahi, van Vuuren, *et al.*, 2015) are of similar scope, use a broader variety of models and assumptions, and reach qualitatively and quantitatively similar results, but are unfortunately currently not publicly available online (at least not in the required granularity).

First, for insights on a global and local level, a set of ~400 pathways to 2100 is used, generated by a variety of scenarios processed with eight different IAMs[5] for a recent IAM comparison study: AMPERE (Riahi, Kriegler, *et al.*, 2015). Different scenarios cover a wide range of different technology scenarios (e.g. 'No CCS', 'No new nuclear', etc.), long-term concentration targets (e.g. 450-ppm, 500-ppm, etc.), and short-term targets for 2030 (e.g. low or high short-term target vs. optimal policy short-term target).

Second, for further insights on a global, the full IPCC AR5 database is analyzed, consisting of 1,184 pathways from a wide range of scenarios processed with 31 IAMs (Krey *et al.*, 2014). Scenarios processed in the AR5 database can be classified along five dimensions: (1) different climate targets, determined by 2100 CO_2eq. concentrations (e.g. 450-ppm, 500-ppm, etc.); (2) overshoot of these 2100 levels between 2005 and 2100; (3) scale of deployment of carbon dioxide removal (CDR) or NETs; (4) availability of mitigation technologies, especially CDR and NETs; and (5) policy category (e.g. immediate vs. delayed mitigation, etc.).

IAMs have been the key tools for the analysis of climate change impacts since the foundation of the IPCC (Clarke *et al.*, 2009). They are now used for the economic assessment of climate change policies in the IPCC's ARs and by governments around the world. IAMs can be classified either as policy optimization models (POMs) or policy evaluation models (PEMs) (IPCC, 2001). POMs include a 'damage function' and focus on a full cost-benefit analysis of climate change mitigation action and optimal policy. PEMs, on the other hand,

[5] GCAM, IMACLIM, IMAGE, MERGE-ETL, MESSAGE-MACRO, POLES, REMIND, and WITCH. The database also includes the DNE21+ model. However, this has been excluded as it only models the period through to 2050.

look at the cost-effectiveness of achieving an exogenous mitigation target by means of a specific policy (Farmer *et al.*, 2015). The databases used in this dissertation focus on PEMs (IPCC, 2014a), which compute cost-effective pathways and energy system transitions under different socio-economic and policy assumptions and constraints set by climate targets. They factor in a wide range of parameters, such as long-term demographic evolution, availability of natural resources and countries' participation in emission-reduction efforts. Technology costs and maximum penetration rates are calibrated using a mix of historical uptake rates and assumptions on learning by doing and autonomous technical progress (Wilson *et al.*, 2013; Iyer *et al.*, 2014). IAMs are regularly peer-reviewed in comparison exercises (Clarke *et al.*, 2009; van Vuuren *et al.*, 2009; Edenhofer *et al.*, 2010; Kriegler *et al.*, 2014, 2015) and occasionally evaluated against historical data (Guivarch, Hallegatte and Crassous, 2009; Wilson *et al.*, 2013).

C.1.2 Power generator databases

Generation capacities were determined by manually merging all power plants and generators from the most recent versions of the following databases: (a) CoalSwarm (Feb 2017); (b) Platt's UDI World Electric Power Plants (WEPP) database (Q4 2016); (c) Greenpeace's database of planned coal generators in China; (d) Sekitan's Japan coal-fired power plant database (Q1 2016); and (e) Kiko Network's Japan coal-fired power plant database (Q1 2016). Several different databases are merged because all databases have individual known weaknesses and incomplete data. By merging several databases, the quality of the estimate of the global generation capital stock can be improved substantially. The sources are merged by manually confirming unique power plant names, locations, current statuses, online years[6] and capacity, and supplementing the result with internet research as required. The most recent data is used where matched plants have conflicting fields (for example different operating statuses). The resulting database effectively defines the locations of all the world's power plants and generators, their ownership, age, fuel type, technology, and capacity. It is particularly current and comprehensive for coal-fired power stations.

C.1.3 Complementary databases

Three different additional sources of data are used for the calculation of committed CO_2 emissions: (1) current and historic heat rates from the U.S. Energy Information Agency (EIA) and the U.S. Environmental Protection Agency (EPA); (2) emission factors for individual fuels from the EIA and the U.K. Department for Environment, Food, and Rural Affairs (DEFRA); and (3) global technology-specific load factors (utilization rates) for power generators from the IEA World Energy Outlooks (WEO) 2005-15. The EIA and EPA provide data on current and historic heat rates for different generators, turbine types and fuels.[7] Datasets obtained from the EIA and DEFRA contain emission factors for different fuels, i.e. the amount of CO_2 in relationship to the energy content of e.g. coal, lignite, oil, etc.[8]

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[6] The online year refers to the year in which the generator started operations.

[7] Historic EIA data on technology level goes back to 2001 and aggregated data for all fossil fuels back to 1949 (EIA, 2017).

[8] See Appendix D.1 for some additional, minor, sources of data.

C.2 Methods

This dissertation compares carbon budgets in total, or for certain sectors, with committed emissions. The basic methods for the estimation of these inputs have been developed in the first, peer-reviewed, paper[9] but have since been improved and refined. This Sub-chapter describes the original methods and how they were refined in the subsequent papers.

C.2.1 Carbon budgets

Two different methods are used throughout this dissertation to estimate remaining carbon budgets for different sectors and climate goals. In the first paper, the IPCC's 2011 CO_2 budgets from table 2.2 of its AR5 (IPCC, 2014b) are updated with historical CO_2 emissions between 2011 and 2013 (Le Quéré *et al.*, 2015) to estimate remaining carbon budgets for 2014. The resulting budgets represent the cumulative post-2014 total emission of CO_2 that would limit global warming to a certain level (e.g. 2°C) with a certain probability (e.g. 50%). These figures are then combined with unharmonized median cumulative 2014-2100 emissions for all non-generation sectors from the IPCC's AR5 scenario database (IIASA, 2014b) in order to estimate the remaining generation-only CO_2 budget for different scenarios in 2014. Unharmonized, in this context, means that the applied scenarios, which start from 2005, were not scaled to the then current, 2014, levels.

The second method, applied in the subsequent papers, uses a slightly different approach. The cumulative CO_2 emissions between 2005 and 2100 for each individual scenario from the applied scenario databases are clustered in categories

[9] "The 2°C capital stock for electricity generation" (Pfeiffer *et al.*, 2016).

depending on their 2100 atmospheric concentration of CO_2eq.. Based on pertinent literature, the scenarios are clustered, for example, in the 450 (430-480) ppm, the 500 (480-530) ppm, and the 550 (530-580) ppm category (Krey *et al.*, 2014). The 430-480 ppm category typically contains all scenarios that provide a good to fair chance of keeping global warming below 1.5-2°C.[10] These estimated 2005 CO_2 budgets have then been updated with historic emissions up to the respective years (e.g. 2016) (Le Quéré *et al.*, 2016). The generation-only budget in this approach is estimated, where applicable, by applying the original share of the generation-only budget in 2005 to the updated total budget figure. If, for example, the median generation-only budget share in the 430-480 ppm scenarios in 2005 was 14% of the total CO_2 budget, and the total median CO_2 budget in that category has decreased from ~1,333 GtCO_2 to ~964 GtCO_2 between 2005 and 2015, then the generation-only budget has decreased from ~187 (14% of 1,333) to ~135 (14% of 964) GtCO_2 in the same period.

Both methods have advantages and disadvantages. The first method is based on peer-reviewed and widely used numbers from the IPCC that assign budgets to warming-likelihood combinations. Such budgets are well suited to inform policy makers and the public since they are easy to understand and interpret. They depend, however, on certain assumptions regarding non-CO_2 forcing, e.g. by SLCPs. In the case of the relevant budgets from table 2.2 of the IPCC's AR5, the assumptions regarding non-CO_2 forcing here those of the RCP8.5, i.e. business-as-usual, scenario (van Vuuren *et al.*, 2011). The resulting budgets are, therefore,

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[10] The estimate of the median 2011 430-480 ppm carbon budget with this methodology is ~1,100 GtCO_2 which compares to the IPCC's budgets for a 66% (1,000 GtCO_2) to 50% (1,300 GtCO_2) chance of limiting global warming to less than 2°C (Table 1).

likely to underestimate budgets in climate stabilization scenarios as they assume virtually no non-CO_2 mitigation efforts (Millar *et al.*, 2017). The second approach addresses these limitations and estimates scenario-specific carbon budgets and considers the development of all climate forcers as well as their interactions with each other and is therefore better suited for scientific purposes.

C.2.2 Committed emissions

Two different approaches are used to estimate the emissions committed from generation infrastructure. In the first paper, the 2012 results from a peer-reviewed paper (Davis and Socolow, 2014) are used to calculate the emission commitments of the polluting capital stock for electricity generation in 2014 and beyond. Davis and Socolow merge the generation capacity from Platt's WEPP UDI database with emission and utilization data from the Carbon Monitoring for Action CARMA (CARMA, 2010), and find that power generators operating in 2012 committed to 307 $GtCO_2$, assuming a lifetime of 40 years. Furthermore, they find that these commitments had grown by 4% p.a. over the previous decade. In the first paper of this dissertation their estimates are used to extrapolate the emission commitments to 2016 and beyond. For example, for 2016 the extrapolation results in emission commitments of operating power generators of ~360 $GtCO_2$.[11]

Davis & Socolow rely in their calculations on several databases and assumptions. Most notably they use a merger of Platt's UDI WEPP database and the CARMA database as a representation of the emissions of the global fossil fuel power generation capital stock. They then use the mean online years for generators with

[11] $\sim 360 = 307 \times (1 + 4\%)^4$

similar capacity, the same fuel, and in the same countries to complete missing online years. Finally, they assume different lifetimes (20, 30, 40, 50, and 60 years) for their calculations.

One criticism of their approach is that they make the "*arbitrary assumption that CARMA's emissions and energy data for 2009 (or, occasionally, 2004) are an accurate estimate throughout a plant's lifetime*" (Davis and Socolow, 2014). 2009 was in many respects not a representative year for global energy consumption and emissions – in fact, with the financial and economic crisis at its height, 2009 was one of the few years in recent decades in which global emissions decreased year-on-year. In subsequent papers within this dissertation the approach described by Davis & Socolow was therefore refined.

First, a broader and updated (early-2017) base of power generators was used that completes known gaps in the Platt's UDI WEPP database, e.g. in microgeneration and in China (see Sub-chapter C.1.2). Second, for generators with unknown online year, a similar but more granular methodology was used to the one described by Davis & Socolow. Most importantly, the estimation of online years and lifetimes is conducted based not only on technology, capacity and country, but also considering generator and turbine type, online year (for lifetimes), and steam-type (e.g. subcritical vs. supercritical). Third, actual lifetimes where simulated by using a Poisson distribution around the expected lifetimes of the power generators. This simulates managerial discretion as to when power generators are retired, and accommodates the fact that generators are rarely retired in the exact year of their estimated end of life. Fourth, instead of using the CARMA database for the annual emissions of these generators, a different approach was applied. Generator-specific technical data was combined with (year-specific) heat rates and fuel emission factors from the U.S. Energy Information Agency (EIA) and U.S. Environment Protection Agency (EPA) to calculate the annual maximum emissions per generator. When multiplied with the simulated lifetime of each generator and historic (average) utilization rates from the IEA, this results in an estimate of actual historic, current and expected electricity generation and emissions. By using historic average utilization rates over many years (ten years between 2004-2014) instead of a point estimate (CARMA uses 2009 utilization rates), a more realistic estimate of future utilization can be achieved. Global utilization rates are applied to balance regional and country-specific variations. A detailed description of this methodology can be found in Appendix D.2.

The described approach results in an emission commitment estimate of ~300 $GtCO_2$ in 2016. This estimate is ~17% lower than the extrapolated estimate in the first paper. This implies that currently operating capital stock commits to significantly less future emissions than expected only four years ago. While the methodological differences explain some of the variance, the real-world explanation for this is that in recent years, since Davis & Socolow's paper, the growth rate of committed emissions was much lower than expected. Between 2012 and 2016, emission commitments grew only by 2.1% p.a. globally instead of the 4% p.a. expected based on Davis & Socolow's results. In some regions, emission commitments even decreased significantly in this period. Paper 3 discusses these findings in greater detail.

C.2.3 Complementary methods

In addition to the previously described methods, some additional approaches have been used throughout the dissertation: (1) a method to assess the carbon budget impact of methane emissions; and (2) a method to simulate capital stock additions and asset stranding post-2025.

To assess the long-term impact of a sustained rate of methane emissions a new multi-gas aggregation metric has been used. This metric, termed GWP* (Allen *et al.*, 2016, 2018), is based on the traditional, and often criticized, global warming potential (GWP) of different climate pollutants. GWP* equates carbon dioxide emissions with changes in sustained rates of emission of SLCPs such as methane, unlike the conventional GWP metric which equates absolute rates of SLCP emission with carbon dioxide emissions. It can be applied to the absolute annual change of SLCP emissions to calculate the CO_2 one-off pulse equivalent that would have the same impact on peak warming as a constant and sustained change in the rate of SLCP emissions, as measured in that year. GWP* offers a more direct way to relate changes in emissions of SLCPs to their impact on peak warming, and to provide indicative weights relative to CO_2 emissions. Under GWP*, LLCPs, which are physically like CO_2, are traded against CO_2 in the same way as in the conventional GWP framework. GWP* is a better predictor of peak warming under ambitious mitigation than conventional metrics (Allen *et al.*, 2018). In paper 2, a methane GWP* of 2,800 tCO_2/tCH_4 is used. This can be interpreted such that methane emissions at a constant and sustained rate of one ton per year would have the same impact on radiative forcing and peak warming as a one-off pulse of 2,800 tons of CO_2. A detailed description of this method can be found in Appendix D.3 and D.4.

In order to forecast capital stock additions and stranding post-2025, a four-step approach is applied to calculate the stranded capacity: (1) the depreciation of the currently operating global generation capacity is simulated over the coming decades; (2) the remaining portion of that capacity in any given year in the future is compared with the generation in that year in the respective scenario; (3) by employing target utilization bands (based on historical utilization rates), for any given year, the amount of capacity that would need to be added to the capital stock to meet the scenario forecast is estimated; and finally (4) the amount of stranding that takes place in a given year, defined by the underutilization of operating capacity, is calculated. Underutilization in this case is defined by utilization rates below their historical bands. A detailed description of this method can be found in Appendix D.5.

C.3 Limitations of this approach

The approach of this dissertation builds on the theoretical framework of committed cumulative carbon emissions and the cumulative decarbonization identity. Furthermore, the calculations rely on several databases, sources, estimations and assumptions, most notably the scenario databases from the IPCC and AMPERE, and the asset level databases for power generators. The findings and insights are subject to uncertainty and have several limitations. They should therefore be interpreted with caution. In general, five different categories of limitations can be identified: (1) technical limitations; (2) scenario limitations;

(3) limitations regarding the use of carbon budgets; (4) limited insights; and (5) conceptual limitations.

In some cases, these limitations affect the direct implications or detailed insights of the findings presented in this dissertation, especially on a granular level. They affect the aggregate result to a lesser extent, however. The databases used are either peer-reviewed and (back-) tested multiple times, as in the case of the IPCC's AR5 and the AMPERE database (Clarke *et al.*, 2009; van Vuuren *et al.*, 2009; Edenhofer *et al.*, 2010; Kriegler *et al.*, 2014, 2015), or used in peer-reviewed studies, as for example the WEPP UDI database (Davis and Socolow, 2014; Pfeiffer *et al.*, 2016). To solve the issue of harmonization to 2000 or 2005, in paper 4, the scenario databases are harmonized to 2015 using a peer-reviewed approach (Rogelj *et al.*, 2011). The limitations of the assumptions made (see C.3.1 [a] to [f]) are not likely to distort the overall result of this dissertation. Important data-relevant assumptions are based on acknowledged (e.g. IEA, EPA, etc.) or even peer-reviewed (Le Quéré *et al.*, 2016; Saunois *et al.*, 2016) data sources, and important method-relevant assumptions are based on peer-reviewed approaches (Davis, Caldeira and Matthews, 2010; Davis and Socolow, 2014; Pfeiffer *et al.*, 2016). Overall, the global findings of the approach are believed to provide a realistic representation of the currently operating and planned generation capital stock and carbon budgets.

C.3.1 Technical limitations

The calculations and estimations throughout this dissertation depend on a variety of databases, sources and assumptions. Most notably the asset-level databases containing the generators (Platt's WEPP UDI, Kiko Network, Sekitan, etc.), the

IPCC AR5 and AMPERE scenario databases, and the historical data containing energy insights (IEA World Energy Outlooks) and carbon emission data (Global Carbon Budget and Global Methane Budget Projects). It should not be assumed that these databases and sources are exhaustive or perfectly accurate. In some cases, important information is missing in the databases. For instance, the online years of many power generators, an important input to the calculation of committed emissions, are missing in the WEPP UDI database and must be estimated. The same applies to lifetimes, fuel-types, generator and turbine technologies, and even the geographical location of some generators. Moreover, the status of generators in the database is often missing or can be presumed to be wrong. Some generators that came online in the early 20th century are still included as '*operating*' or '*stand-by*' in the database, while others, that came online just a few years ago, are already '*retired*'. The update to the Platt's WEPP UDI database and the merger with several other databases, which is described in Sub-chapter C.1.2, has improved our estimation of the global generation capital stock in some respects. It is possible, however, that it still does not contain all power generators, or contains some power generators that are not operating anymore.[12]

The estimation of the current generator pipeline is based on the same sources. Many of the generators included in the pipeline have the status '*delayed*', '*deferred*', '*under construction*', or '*planned*'. Generators that are '*cancelled*' are

[12] To put this into perspective: An extrapolation of 2013 and 2014 generation capacities, reported by the IEA, suggests 1,946 GW of global coal capacity in 2016 (IEA, 2016). This dissertation finds 2,136 GW (~10% more). Using the same methodology for gas and oil the results in this dissertation are 18% lower for gas and 4% lower for oil. Differences could stem from different classification (e.g. coal vs. coal-gasification, etc. or different status of generator).

explicitly excluded from this pipeline. To the best of knowledge these cancelled generators include all planned generators that have been cancelled before early-2017, e.g. the announcement of the cancellation of ~100 GW in China in early 2017. It is possible, however, that our current estimate of the pipeline still includes generators that were once planned but are now not planned anymore. Often it is not even clear whether a plant is (still) planned or not. For instance, the database includes eight planned coal-generators (~2.5 GW in total) in Australia, five of which are in Queensland. Closer research, however, reveals that the local government strongly opposes the addition of new coal capacity while the national government proposes such a move (Murphy, 2017). The company that would oversee the extension, CS Energy, is on record as being opposed to the idea but not ruling it out entirely (Cooper, 2017). It is therefore often not clear, what the likelihood is of some of the planned power generators in the database ever operating; it is, however, clear that, for each of these generators, plans exist, and it is likely that many will eventually be built.

In addition to these database limitations, several other technical limitations can be identified: (a) online years and generator status are often estimated; (b) the total and remaining lifetimes of currently operating power generators are either estimated or simulated; (c) the carbon intensity of generation is estimated; (d) future utilization of generators is estimated based on global historic average utilization rates of a certain fuel type; (e) no carbon intensity improvements or voluntary utilization reductions are assumed (e.g. due to the slow ramp-down of old generators over several years or the conversion into a capacity reserve); and finally (f) the decision to add or strand generators in the long-term simulation method of paper 4 does not include any foresight of the agents in the model.

C.3.2 Scenario limitations

The applied scenario databases (IPCC AR5 and AMPERE) also have several limitations. All scenarios used in this dissertation are the outputs of integrated assessment models. IAMs have recently come under increasing criticism (Revesz *et al.*, 2014) among prominent mainstream economists (Pindyck, 2013; Stern, 2013; Weitzman, 2013), even going so far to call their outputs "*close to useless*" (Pindyck, 2013). Criticism of IAMs can broadly be categorized into five categories (Farmer *et al.*, 2015): (1) the way they handle uncertainty and especially 'fat tail' events[13] in economic and physical climate systems (Pindyck, 2013; Stern, 2013); (2) aggregation and distributional issues, i.e. the 'representative agent' (Stern, 2013; Iyer *et al.*, 2015); (3) technological change and how innovation is modelled (Farmer and Lafond, 2016); (4) the damage functions (Pindyck, 2013, 2015; Burke *et al.*, 2015); and (5) other issues such as behavioural assumptions (Tversky and Kahneman, 1974; Kahneman and Tversky, 1979) and the equilibrium assumption (Arent *et al.*, 2014). While these limitations play a decisive role when it comes to the evaluation of policy options, they affect the results of this dissertation to a lesser extent. The objective of this dissertation is not to evaluate policy options but rather to model how different climate goals and scenario assumptions will affect the fundamental choices policy makers have. The model outputs of scenarios are sufficient, therefore, as long as they appropriately and consistently model the interaction of different generation

[13] A *fat tail* or *black swan* event is an unexpected event that has a major effect and is often rationalized in hindsight (Taleb, 2007).

technologies with each other, with overall energy demand, and with carbon budgets.

In addition to the inherent limitations of IAM scenario outputs, in the context of this dissertation, the main limitation is that they are mostly harmonized to either 2000 or 2005. Most model outputs (such as annual electricity generation or carbon emissions) start around 2005. Since then, however, over a decade has passed and global emissions have so far developed along the upper end of scenarios, close to a business-as-usual scenario, as represented by RCP8.5. Several emission pathways that would have been realistic or at least possible just 10 years ago appear now outlandish. On the other hand, the deployment of renewables has developed much faster than was deemed realistic in many scenarios in 2005. It is now much more realistic that renewables will provide a significant share of global electricity supply by 2050. Using scenarios harmonized to 2000 or 2005 will therefore distort the pathways that are likely today.

C.3.3 Carbon budget limitations

The previous Sub-chapter C.3.2 describes, amongst other limitations, the shortcomings of IAMs with regards to how uncertainty is handled. The modelled uncertainty in the physical climate response fundamentally affects CO_2 budgets (Roe and Baker, 2007; Lenton *et al.*, 2008). Together with the uncertain development of future emissions from other long- and short-lived pollutants, this leads to a wide range of budget estimates for one and the same climate goal (Rogelj *et al.*, 2016; Millar *et al.*, 2017). This dissertation uses median values for each climate category as point estimates (e.g. 430-480 ppm, 480-530 ppm, etc.), since such estimates enhance the understanding of the presented results amongst a wider audience. Uncertainties are addressed to a certain extent by presenting the findings of all analyzed climate stabilization categories, i.e. the 430-480, 480-530, and 530-580 ppm categories. Nevertheless, future research could focus on the sensitivity of these findings to variations in the carbon budget estimates. The same applies to different socio-economic assumptions (population growth, GDP growth, distributional effects, etc.), fuel price assumptions, policy assumptions, technology assumptions (e.g. cost of renewables) and the interplay between them. Using median values across all scenarios of a climate category neglects the opportunity to present the effect different assumptions regarding these factors would have on the result. Future research might very well take advantage of this opportunity and provide valuable insights.

C.3.4 Limited insights

Some important, and potentially useful, insights cannot be derived from the results of this dissertation, or only in a limited way. The underlying framework, the decarbonization identity, addresses the global stock of cumulative future carbon emissions rather than the flow of such emissions. In principle, it treats the individual elements ($B_t(T)$, E_t, N, S, and A) as mutually independent and only connected by the operators ('≥', '+', and '-'). It furthermore treats the identity for the power generation sector in total as independent from budgets and activities in other sectors. Conceptually this mutual independence between the elements is correct. In practice, however, there may be some knock-on effects from one element to the other. New N and stranded S infrastructure could have reciprocal effects on each other, and influence, and are, in-turn, influenced by, carbon budgets, *B*, and NETs, *A*. For instance, the large-scale deployment of BECCS would not only affect *A* but also *N* and *S*, since it would add generation capacity to the capital stock meaning that fewer new polluting generators would be needed (or existing ones stranded). Less *A*, however, would have the opposite effect: should BECCS not be available, this generation capacity must be added by other technologies, e.g. gas. This would increase *N* and eventually *S*. Adding more gas capacity would increase *N* less than, for example, coal capacity would; but it would, however, probably also increase fugitive methane emissions more and hence decrease *B*. Ignoring these mutual connections means that only limited insights can be derived as to when stranding should take place, which assets should be built or stranded, or whether it is preferable to strand existing capital stock, *E*, to create new capital stock, *N*.

Treating the identity for electricity generation as independent from identities for other sectors leads to similar limitations. All elements of the identity depend on activity in other sectors. The eventual scale of BECCS will depend on activity in agriculture and land-use (and vice versa), and carbon budgets for generation-only depend strongly on the overall carbon budget but also on the activity in other sectors, for instance methane emissions from agriculture (Smith *et al.*, 2016). Isolating carbon budgets and decarbonization identities for an individual sector will therefore only provide an incomplete picture and limited insights. More research could, and should, be undertaken to examine these interconnections closely, together with their implications for effective climate policy; for instance, by developing a model that takes choice variables as inputs that affect *E*, *N*, *S*, and *A* in all sectors.

C.3.5 Conceptual limitations

Finally, it is controversial whether the term *committed* is the right term to describe the future cumulative emissions of existing capital stock. In this dissertation, the term has been adopted from the pertinent literature (Guivarch and Hallegatte, 2011a; Carlson *et al.*, 2012; Davis and Socolow, 2014; Rozenberg *et al.*, 2015). The word *committed*, however, implies that these emissions are 'baked-in' and inevitable. In practice, they are everything but that, as this dissertation points out. Cumulative future emissions depend on several future choices. They could, for instance, be reduced by lower utilization rates, earlier retirement, retrofit CCS, fuel switches (e.g. lignite to biomass), or other efficiency enhancing technologies (lower heat rates, cogeneration, etc.). On the other hand, CCCE would grow if these generators are run at higher utilization rates or retired later than originally expected. It is unclear which of these choices would constitute a 'normal' managerial or regulatory decision and which would constitute a *stranding* in the closer sense of this dissertation.

D. Additional information

D.1 Additional data sources

In addition to the mentioned databases and sources some other, less important, data sources have been used, e.g. historical CO_2 and methane (CH_4) emission data from the World Bank, the Global Carbon Budget Project (Le Quéré *et al.*, 2015, 2016) and the Global Methane Budget Project (Saunois *et al.*, 2016). The historical data is used to determine national and regional methane emissions, update 2005 CO_2 budgets to 2015, and to compare 2014 methane emissions to 2005 and 2100 emission levels from the models. The global level of annual methane emissions is derived from the Global Methane Budget data. Country- and region-level World Bank data is used to assess how these global emissions are split between countries.

D.2 Detailed description of the calculation method for committed emissions

To calculate total and remaining CCCE the described databases and sources are merged on generator level. For oil, gas, and biomass generators, the decisive factor for the heat rate is, in addition to fuel, the turbine type. For coal, the approach is more granular and considers, in addition to the turbine type, the capacity, fuel type (e.g. lignite, bituminous, sub-bituminous, etc.), and steam type (e.g. critical, subcritical, supercritical, etc.). For all generators, year-specific heat rates are assigned based on the online year of the generator to adjust for advances in technology over time. Annual maximum emissions of a given generator are then calculated with the information about its maximum capacity (MWh), heat rate (mbtu/MWh), and the emission factor of the used fuel (gCO_2/mbtu).

The CCCE of each generator are calculated by multiplying these annual maximum emissions (assuming historic average load factors) with the expected or simulated lifetime of that generator. Missing information about online years and expected lifetimes of generators in the database can be estimated by using information available from similar clusters within the database [14] Finally, lifetimes are simulated by applying random numbers from a *Poisson* distribution with the expected lifetime of that generator as a mean. The simulation accounts for the fact that generators are rarely retired exactly after their expected lifetime but are rather retired at some point around their expected retirement date. Within the database, many generators are still in operation long after their original planned retirement date, while others retire long before their expected retirement.[15]

[14] E.g. median lifetime of generators from the same country, manufacturer, fuel, type, etc.

[15] For generators that are still in operation in 2016 but have a simulated retirement year before 2016 a 10-year phase-out period is used in which every year the then oldest decile of generators is retired.

D.3 Detailed description of the method to calculate the impact of methane emissions on the carbon budget

To assess the effect of a failure to reduce annual methane emission levels from a given year to their assumed 2100 levels, in that scenario a three-step approach is applied:

1. Calculate the difference between annual methane emissions in that year (e.g. 300 $MtCH_4$ in 2015) and the assumed 2100 level (e.g. 200 $MtCH_4$)
2. Multiply that difference with the GWP* metric to calculate equivalent CO_2 cumulative emissions for this change, or Budget at Risk, BaR: 100 $MtCH_4$ x 2,800 $MtCO_2/MtCH_4$ = 280,000 $MtCO_2$ = 280 $GtCO_2$
3. Calculate the share of this BaR of available total CO_2 budget in that year (e.g. 1,000 $GtCO_2$): 280 $GtCO_2$ / 1,000 $GtCO_2$ = 28%

In this example, an assumed 33% reduction of methane emission levels between 2015 and 2100 can be translated into a BaR of 280 $GtCO_2$ or 28% of the overall currently available CO_2 budget.

D.4 Additional assumptions for the calculation of the impact of methane emissions on the carbon budget

Three important assumptions have been made that are critical to the calculation of the CO_2 Budget at Risk (BaR) from a failure to reduce methane emissions over the course of the century.

Annual levels of methane emissions in 2100 (as derived from the analyzed scenarios) represent potential emissions floors in these gases from which further mitigation may be very challenging or even impossible. Given the uncertain future technological development and demand for sources of methane emissions, it is unclear whether this assumption holds true. As the impact of a failure to achieve these emissions is analyzed, however, even lower emissions after 2100 would only serve to support and even strengthen the presented findings.

Second, lower sustained 2100 levels of methane emissions would leave more space for CO_2-only emissions between 2005 and 2100, given constant radiative forcing and global warming. The science of the influence of SLCPs on CO_2 budgets strongly suggests the validity of this assumption (Bowerman *et al.*, 2013; Rogelj *et al.*, 2014, 2016).

Third, only budgets between now and 2100 are considered, even though peak warming occurs in advance of 2100 in many scenarios. An alternative analysis could be conducted that uses methane emissions at the time of peak warming as its reference point, but a focus on the full-century budget is chosen here (indicative of 2100 levels of warming) as this has been a common policy focus.

D.5 Detailed description of the capital stock additions and stranding estimation method

In the first step, the development of currently operating global generation capacity is simulated. Expected lifetimes for each generator are calculated, and their expected lifespan estimated to derive the expected future annual generation profile of the total capital stock. In cases where the simulated lifespan is shorter than the observed lifespan (i.e. over-aged generators that 'should' have been retired but are observably still in operation today) a phase-out period over the subsequent years is assumed (starting with the oldest generators in year one and so on).

Second, the AR5 and AMPERE pathway databases (both harmonized to 2015[16]) are used to calculate representative (median) generation profiles for different global warming scenarios. These scenarios are then compared with the annual remaining generation of today's capital stock.

Third, to assess the amount of fossil fuel capacity that would need to be added in any given year for it to match the scenario's generation profile, the then operating capital stock is compared with realistic utilization assumptions (historic 10-year average utilization rates). If utilization would be higher than the historic average, new capacity is added to the capital stock.

Finally, the amount of stranding that takes place in every year is calculated. In many scenarios, the decrease of fossil-fuel powered generation is steeper than the 'natural' decrease of generation capacity (retirements). This leads to decreasing utilization rates. Stranding is defined here as the difference between the historic minimum utilization rate (over the period 2004-2014) and actual utilization and express it in Exajoule[17] (EJ) of 'unproduced' electricity.

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[16] Pathways in the AR5 and AMPERE databases are based and harmonized on the years 2005 and 2000, respectively. Historical generation data (IEA, 2016) and a peer-reviewed harmonization approach (Rogelj *et al.*, 2011) are used to harmonize scenarios with historic observations.

[17] One Exajoule is equal to 10^{18} (one quintillion) joules or ~278 terawatt hours (TWh).

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<u>Paper 1:</u> *'The 2℃ Celsius Capital Stock for Electricity Generation: Committed Cumulative Carbon Emissions from the Electricity Generation Sector and the Transition to a Green Economy.'*

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Attachments (4 papers)

Paper 1 [*Applied Energy*]

Alexander Pfeiffer, Richard Millar, Cameron Hepburn, and Eric Beinhocker. 2016. 'The 2°C Capital Stock for Electricity Generation: Committed Cumulative Carbon Emissions from the Electricity Generation Sector and the Transition to a Green Economy.' Applied Energy 179: 1395–1408. doi:10.1016/j.apenergy.2016.02.093.

Paper 2 [*Target Journal: Climatic Change*]

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Paper 3 [*Target Journal: Environmental Research Letters*]

Pfeiffer, Alexander, Cameron Hepburn, Adrien Vogt-Schilb, and Ben Caldecott. 2018. 'Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement' Working Paper. Oxford, UK.

Paper 4 [*Target Journal: Energy Policy*]

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

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HIGHLIGHTS

- Defines '2°C capital stock' as infrastructure that gives a 50% chance of 2°C warming.
- The '2°C capital stock' for electricity generation will be reached by 2017 on current trends.
- New electricity generation assets globally must then be zero carbon to avoid stranding, CCS or CDR.
- Risk of stranded assets is relevant to investors and policy makers.

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ABSTRACT

This paper defines the '2°C capital stock' as the global stock of infrastructure which, if operated to the end of its normal economic life, implies global mean temperature increases of 2°C or more (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 based on current trends. In other words, 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 carbon capture technologies. Policymakers and investors should question the economics of new long-lived energy infrastructure involving positive net emissions.

1. Introduction

The human population has grown over 4-fold from 1.65 billion in 1900 to over 7 billion today [1,2]. Over a similar period, world average per capita output has increased almost 6-fold from ~$1300 in 1900 to ~$7600 in 2008 real GDP in 1990 US dollars [3]. 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' [4]. Humans may now be confronting 'planetary boundaries' [5]. Environmental concerns have been presented in the past, coupled with calls to arrest economic growth [6–8]. So far, price signals have triggered demand efficiencies, substitution, new supplies and new technologies that have moderated concerns about resource scarcity [9]. 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 [10,11]. Electricity generation (and heating) currently contributes approximately 25% of global anthropogenic greenhouse gas emissions, the main driver of observed climate change [12]. A global transition to clean electricity generation is therefore anticipated [13] 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

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capacity is over 30 years old and 61% over 20 years old [14]; 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. [15], Davis and Socolow [16] [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 policy-makers 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 [17]. Many of the expected economic damages from climate change depend on peak warming, and peak warming is a function of cumulative carbon emissions ('CCE') (e.g. [18,19]). In recent years some policy makers have acknowledged the existence and implications of carbon budgets (e.g. [20]). Nevertheless, it remains common practice for policy-makers to focus on annual CO_2 emission reduction targets – such as reducing emissions by 40% by 2030 [21] – which are only indirectly relevant to the core objective of limiting 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 policy-makers: they can either (a) ensure that all new electricity generation 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 [11].

This paper builds upon earlier research on committed emissions. Davis et al. [15] calculated committed cumulative emissions from combustion of fossil fuels by 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 and Hallegatte [23] 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 and Shalizi [24] conclude that mitigation policy should be targeted towards countries where long-lived infrastructure is being built at a rapid rate. Bertram et al. [25] 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. [26] 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 reports 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" ([27]; p. 265). This paper goes beyond the IEA in that we not only use the full variety of models and scenarios from the Intergovernmental Panel on Climate Change (IPCC), we also extend the analysis to 2100, present results for 1.5°C and 3°C carbon budgets, and further test 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 is defined as "the tendency for certain carbon-intensive technological systems to persist over time, 'locking out' lower-carbon alternatives" [28]. For example, Unruh [29] explored how 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. [30] 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

[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.

[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 CO_2 from the ambient air, commonly referred to as carbon dioxide removal (CDR) technologies [22].

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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 electricity generation and (3) projections for 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 electricity generation 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 [17]. 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 [31]. If emissions of SLCPs were then stopped completely, their contribution to long-term irreversible warming would eventually 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 [32].

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 [33], summarised in Table 1. These carbon budgets assume a contribution to peak warming from SLCPs consistent with the RCP8.5 high emissions scenario [34]. 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 [35] 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 (515GtC) updated with emissions data for 2011–2013 from the Global Carbon Budget 2014 [36].

For our analysis we focus mainly on a budget to achieve $\leqslant$2°C peak warming with a 50% probability. For peak warming of 2°C the remaining budget is 322GtC (1184GtCO_2). The budget varies between 77GtC (284GtCO_2) for <1.5°C (66% probability) and 853GtC (3134GtCO_2) for <3°C (33% probability).

2.2. The CCCE of electricity infrastructure

Using emission intensity and generation data from 2009 (CARMA database; see www.carma.org), 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 5.2GtC if their average lifetime is 40 years. The corresponding estimate of 'committed' emissions from *all* fossil fuel power plants operating in 2012 is 84GtC.[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 (GWyr^{-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 the renaissance of coal (described e.g. by Steckel et al. [37]) 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°C capital

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 [33] with cumulative emissions between 2011 and 2013 calculated from Le Quéré et al. [36].

	Warming[b]	Likelihood[c] (%)	Budget (CCE)[d] in 2011	Emitted (CCE) 2011–2013	Budget (CCE)[d] in 2014
[GtCO_2]	<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][a]	<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

[a] Conversion factor: 1GtC = 3.664GtCO_2.
[b] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 period.
[c] Fractions of scenario simulations meeting the warming objective with that amount of CCE.
[d] CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO_2 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 CO_2 emissions these figures provide an indication of the cumulative CO_2 emissions implied by simulations under RCP-like scenarios. Values are rounded to the nearest 50.

[3] According to DS and depending on the assumed average lifetime of energy infrastructure, committed emissions in 2012 vary from 26.8GtC (20 years lifetime) up to 157.5GtC (60 years lifetime).
[4] Davis and Socolow [16], p.1.
[5] Ibid.

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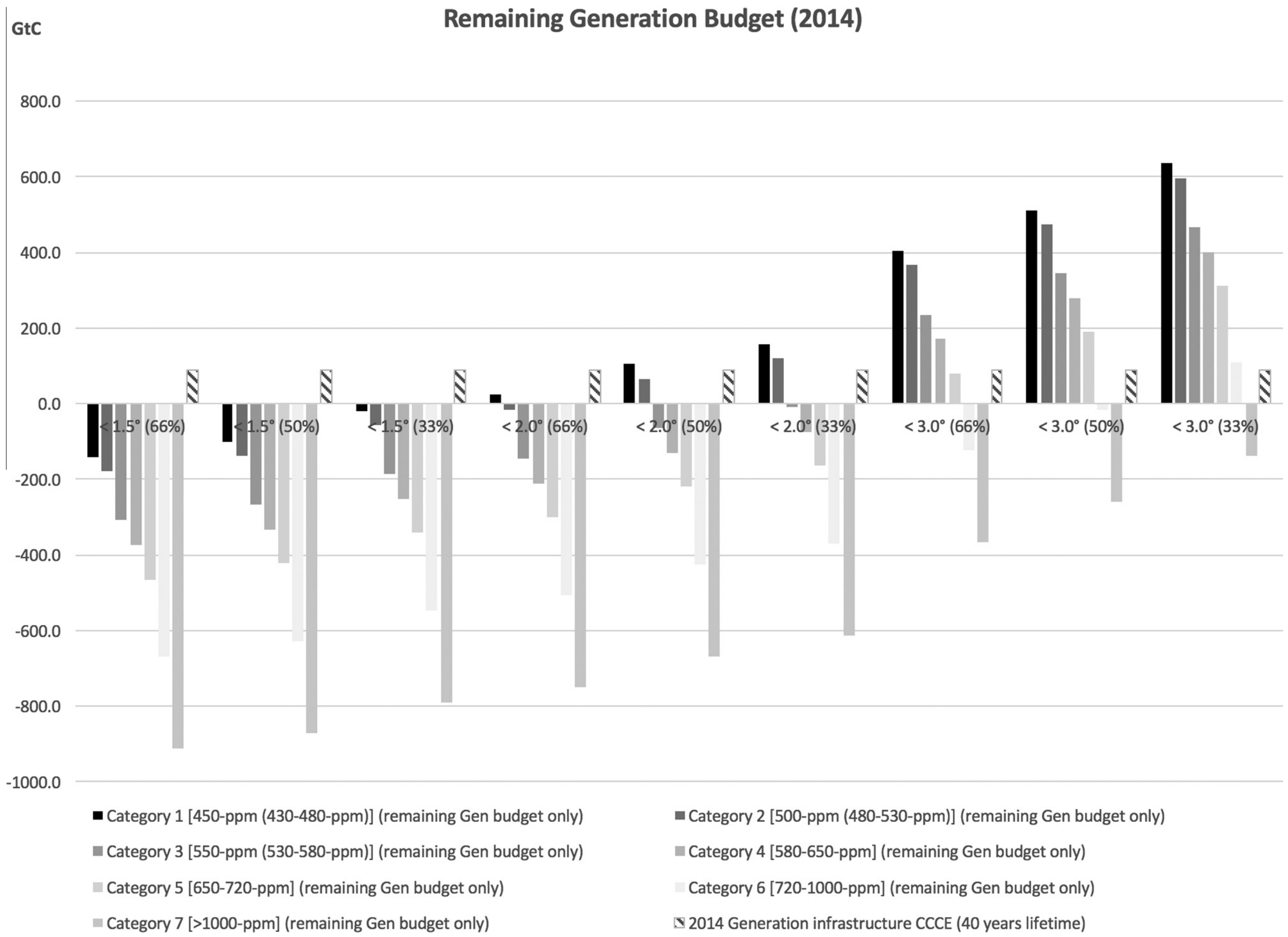

Fig. 1. Remaining 2014 carbon budget for electricity generation, for different peak warming magnitudes and probabilities, decomposed by groupings of emissions pathways (denoted by scenario 2100 concentrations). The 2014 CCCE from electricity generation infrastructure (40 years lifetime) is shown by the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

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 the 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 [38]. IAMs are highly idealised and often assume globally coordinated policy action that can start immediately. These emission scenarios are not harmonised – in 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 sectors other than electricity generation 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 electricity generation emissions (after accounting for emissions from the other sectors) is itself a function of the electricity generation 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 electricity generation capital stock is reached under different assumptions, we consider different (exogenous) rates of growth in future emissions from the electricity generation, 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 electricity generation is likely to be an overestimate.

Scenarios can be grouped by their 2100 CO_2-eq atmospheric concentration [41]. 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 [12]. 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 sectors other than electricity generation across the century but also for estimates of *realised* electricity generation emissions over time. In the near-term, there are very small differences between

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

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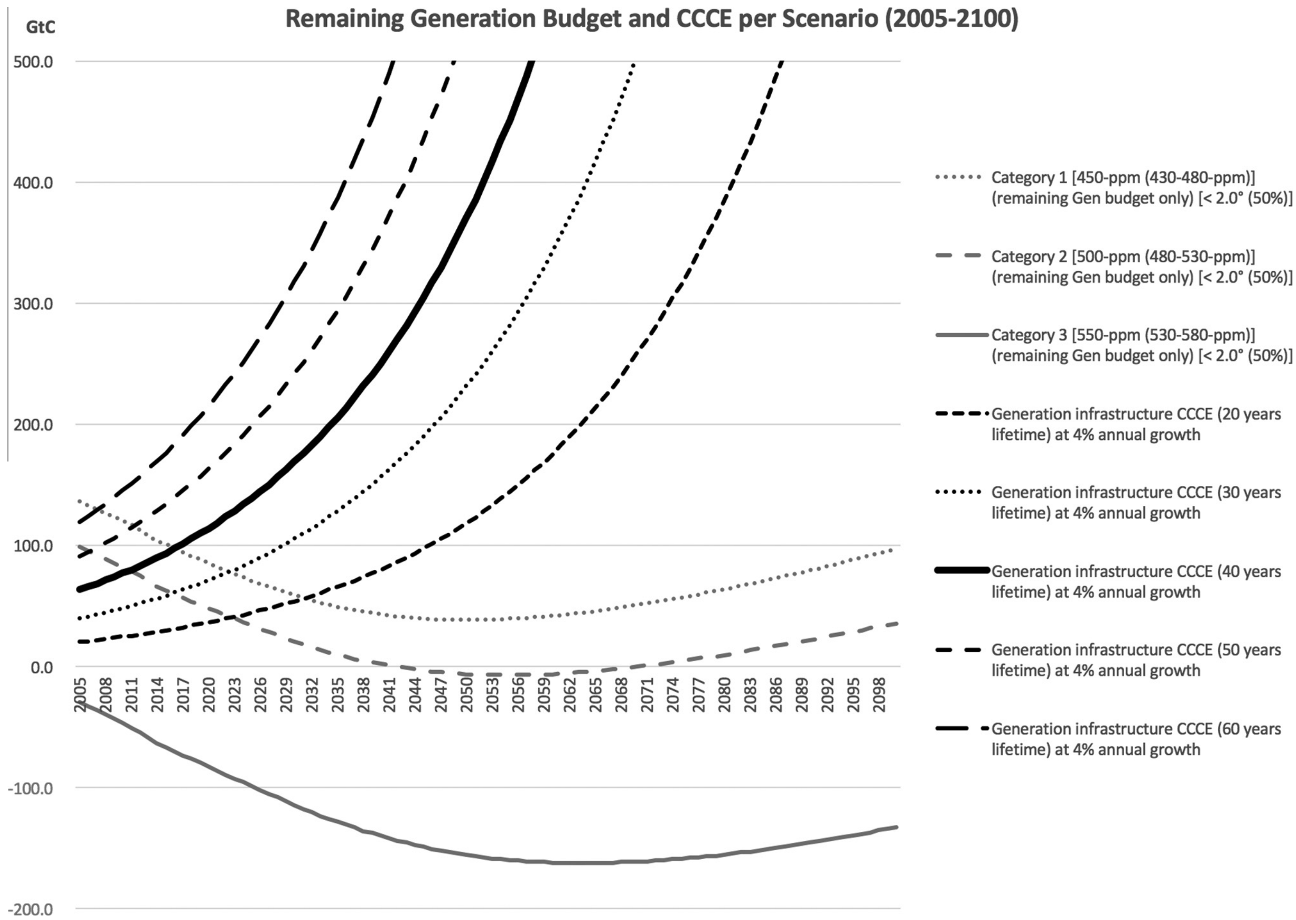

Fig. 2. Future development of CCCE from electricity infrastructure (assuming different lifetimes and a 4% growth p.a.) and remaining generation budget for 430–580-ppm pathways, 2005–2100, assuming a ⩽2°C (50% probability) overall budget.

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 electricity generation 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 of future mitigation in non-electricity sectors. As shown in Fig. 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 87% (or 136% for 480–530-ppm non-electricity pathways) of the remaining 2014–2100 electricity generation budget for a 2°C peak 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.

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. [40]) 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 Fig. 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.

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

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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 [39]) 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.

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. 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 CCCE; (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.

3.3.1. Lifetime of polluting capital stock

Fig. 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 electricity generating infrastructure is 40 years [40,16], 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.

3.3.2. Different growth rates of polluting capital stock

Fig. 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

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 (bold years are future years, after 2015).

Lifetime of capital stock 40 years at 4% annual growth				Year of budget commitment (2006–2100)[e]						
Warming[a]	Likelihood[b] (%)	Budget (CCE)[c] in 2014	Committed CCE[d] 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

[a] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 period.
[b] Fractions of scenario simulations meeting the warming objective with that amount of CCE.
[c] CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO_2 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 CO_2 emissions these figures provide an indication of the cumulative CO_2 emissions implied by simulations under RCP-like scenarios.
[d] Only electricity generation capital stock based on Davis and Socolov [3]: CCCE of 307GtCO_2 (84GtC) in 2012 growing by 4% p.a. (assuming a 40 year lifetime).
[e] Year of budget commitment is the year in which enough electricity generation capital stock is built to consume remaining budget for only electricity generation.

Table 3
As for Table 2 but assuming a 30 year mean lifetime of existing electricity sector generation stock (bold years are future years, after 2015).

Lifetime of capital stock 30 years at 4% annual growth					Year of budget commitment (2006–2100)[e]						
	Warming[a]	Likelihood[b] (%)	Budget (CCE)[c] in 2014	Committed CCE[d] 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

[a] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 period.
[b] Fractions of scenario simulations meeting the warming objective with that amount of CCE.
[c] CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO_2 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 CO_2 emissions these figures provide an indication of the cumulative CO_2 emissions implied by simulations under RCP-like scenarios.
[d] Only electricity generation capital stock based on Davis and Socolov [16]: CCCE of 307GtCO_2 (84GtC) in 2012 growing by 4% p.a. (assuming a 30 year lifetime).
[e] Year of budget commitment is the year in which enough electricity generation capital stock is built to consume remaining budget for only electricity generation.

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.

This insensitivity is due to the large already existing commitments from the energy sector compared to the ⩽2°C (50% probability) budget (87%, see Fig. 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).

3.3.3. Sensitivity to carbon capture technology assumptions

Assuming realised emissions from all sectors consistent with 430–480 ppm 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 carbon dioxide 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 budget for electricity generation, 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 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 sectors other than electricity generation. As a consequence, there is a larger share of cumulative carbon budget available for electricity generation, which hence has more time before reaching the 2°C capital stock.

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 to 480-ppm pathways assume no CCS between 2005 and 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.

3.3.4. 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

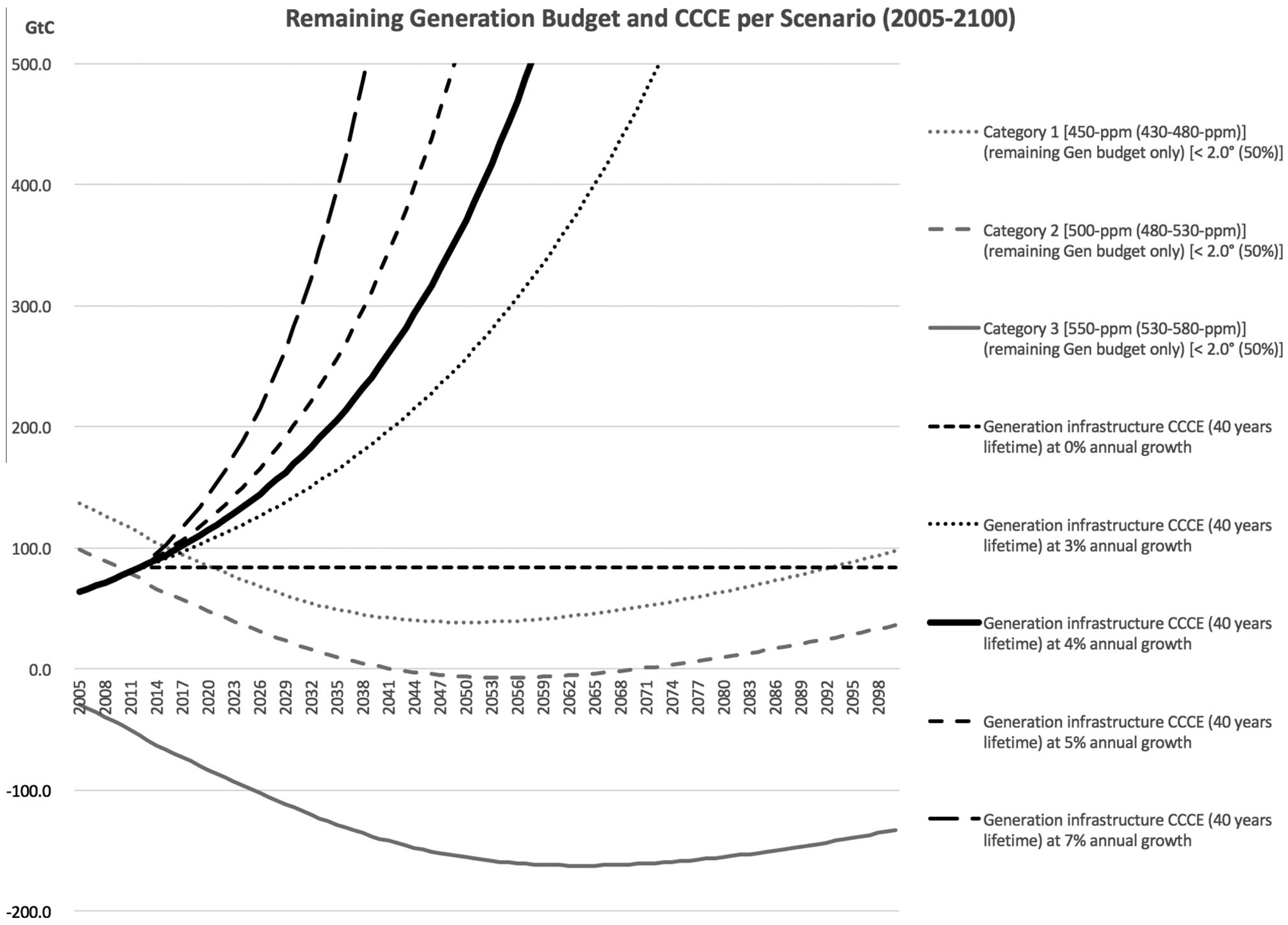

Fig. 3. As for Fig. 2 but for different post-2012 rates of increase in committed cumulative emissions (CCCE) for the electricity sector.

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.

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.

3.3.5. 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 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 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.

4. Discussion

4.1. Policy choices

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. The main finding of this paper, however, is that the '2°C capital

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Table 4
As for Table 4 but assuming a 3% p.a. growth rate of CCCE from 2012 on (bold years are future years, after 2015).

Lifetime of capital stock 40 years at 3% annual growth					Year of budget commitment (2006–2100)[e]						
	Warming[a]	Likelihood[b] (%)	Budget (CCE)[c] in 2014	Committed CCE[d] 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

[a] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 period.
[b] Fractions of scenario simulations meeting the warming objective with that amount of CCE.
[c] CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO_2 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 CO_2 emissions these figures provide an indication of the cumulative CO_2 emissions implied by simulations under RCP-like scenarios.
[d] Only electricity generation capital stock based on Davis and Socolov [16]: CCCE of 307GtCO_2 (84GtC) in 2012 growing by 3% p.a. after 2012. (assuming a 40 year lifetime).
[e] Year of budget commitment is the year in which enough electricity generation capital stock is built to consume remaining budget for only electricity generation.

Table 5
As for Table 4 but only scenarios that don't use CCS in the next century are included in the grouping means (bold years are future years, after 2015).

Lifetime of capital stock 40 years at 4% annual growth					Year of budget commitment (2006–2100)[e] Without CCS						
	Warming[a]	Likelihood[b] (%)	Budget (CCE)[c] in 2014	Committed CCE[d] 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

[a] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 period.
[b] Fractions of scenario simulations meeting the warming objective with that amount of CCE.
[c] CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO_2 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 CO_2 emissions these figures provide an indication of the cumulative CO_2 emissions implied by simulations under RCP-like scenarios.
[d] Only electricity generation capital stock based on Davis and Socolov [16]: CCCE of 307GtCO_2 (84GtC) in 2012 growing by 4% p.a. (assuming a 40 year lifetime).
[e] Year of budget commitment is the year in which enough electricity generation capital stock is built to consume remaining budget for only electricity generation.

stock' for the global electricity generation 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 Section 4.3 below, but they also raise immediate and significant implications for the electricity sector. Logically, achieving the necessary transformation of the global electricity generation sector is going to require some combination of the following four options:

(1) New electricity generation 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.
(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 [42–44], the feasibility of large scale deployment of zero emissions technologies including renewables, biomass, hydro, and nuclear [43,45,46], the overall modest macroeconomic costs such a program would entail [43,47,48], and the significant co-benefits of widespread zero carbon deployment [49,50]. Challenges remain, both on cost and grid integration [51,52], but large-scale deployment of zero carbon electricity 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 [12,38].

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 [53], 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 CCS deployment [54] it would not be prudent to rely

Table 6
As for Table 5 but only scenarios that use CCS in the next century are included in the grouping means (bold years are future years, after 2015).

Lifetime of capital stock 40 years at 4% annual growth					Year of budget commitment (2006–2100)[e] With CCS						
	Warming[a]	Likelihood[b] (%)	Budget (CCE)[c] in 2014	Committed CCE[d] 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

[a] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 period.
[b] Fractions of scenario simulations meeting the warming objective with that amount of CCE.
[c] CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO_2 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 CO_2 emissions these figures provide an indication of the cumulative CO_2 emissions implied by simulations under RCP-like scenarios.
[d] Only electricity generation capital stock based on Davis and Socolov [16]: CCCE of 307GtCO_2 (84GtC) in 2012 growing by 4% p.a. (assuming a 40 year lifetime).
[e] Year of budget commitment is the year in which enough electricity generation capital stock is built to consume remaining budget for only electricity generation.

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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 (bold years are future years, after 2015).

Lifetime of capital stock 40 years at 4% annual growth					Year of budget commitment (2006–2100)[e]							
	Warming[a]	Likelihood[b] (%)	Budget (CCE)[c] in 2014	Committed CCE[d] in 2014	450-ppm (430–480-ppm)				500-ppm (480–530-ppm)			
					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**

[a] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 period.
[b] Fractions of scenario simulations meeting the warming objective with that amount of CCE.
[c] CCE at the time the temperature threshold is exceeded that are required for 66%, 50%, and 33% of the simulations assuming non-CO_2 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 CO_2 emissions these figures provide an indication of the cumulative CO_2 emissions implied by simulations under RCP-like scenarios.
[d] Only electricity generation capital stock based on Davis and Socolov [16]: CCCE of 307GtCO$_2$ (84GtC) in 2012 growing by 4% p.a. (assuming a 40 year lifetime).
[e] Year of budget commitment is the year in which enough electricity generation capital stock is built to consume remaining budget for only electricity generation.

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 (bold years are future years, after 2015).

Annual growth rate of CCCE[a] (%)	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)
	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

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

on CDR in later years as an alternative to rapid de-carbonization of the electricity generation 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 1GW coal-fired power station with emissions intensity of 1tCO$_2$/MWh and a load factor of 70% will emit 6.1MtCO$_2$ per annum.[9] With a residual lifetime of 10 years, expected future cumulative CO_2 emissions are therefore 61MtCO$_2$. Suppose this plant were retired early and replaced by a 1GW combined cycle gas turbine (CCGT) plant with emissions intensity of 0.5tCO$_2$/MWh a load factor of 70%, hence emitting 3.05MtCO$_2$ per annum. With a lifetime of 40 years, expected future cumulative emissions from the CCGT would be 122MtCO$_2$, compared to 61MtCO$_2$ 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 [55,56].

We now examine policy instruments that are candidates for constraining cumulative emissions to meet a 2°C target. Each

[9] 1GW × 365 days/year × 24h/day × 70% load factor = 6132GWh × 1000 MWh/GWh = 6,132,000 or 6.132 mio. MWh × 1 tCO$_2$/MWh = 6.132 mio. tons of CO_2 per annum.

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instrument incentivises one or more of the four options in Section 4.1.

4.2.1. 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' [57–60] 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 [52]. 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.

4.2.2. Cumulative cap and trade

One more novel form of carbon pricing would be a *cumulative* emissions cap and trade system (cf [61]) 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.

4.2.3. Licensing 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 [62]. 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 [63]. Such rules could have the perverse effect of incentivizing a rush to build high emitting assets before the intensity target ratchets down to zero, but our analysis suggests the target should reach zero faster than the time it takes to plan and consent a new power plant.

4.2.4. 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 electricity 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).

4.2.5. 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 [63]. 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 [62]). 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 electricity generation 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 electricity generation assets being zero carbon from now onwards, the role of both CCS and CDR are brought into focus [12]. 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 [64].

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Carbon Budget at Risk (BaR): Methane emissions and the impact on asset stranding

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Abstract

The concept of an all-time CO_2 budget has become an established policy tool to assess the cumulative level of CO_2 emissions compatible with restricting global warming to beneath specific thresholds. Recent research, however, suggests that these CO_2 budgets are strongly affected by annual emissions of short-lived climate pollutants, such as methane. Nevertheless, the connection between CO_2 and non-CO_2 emissions is often neglected in climate policies. Here, we analyze a large set of peer-reviewed scenarios to estimate the extent to which current CO_2 budgets depend on future methane emission reductions. The application of a recently introduced measure, the so-called GWP*, reveals that scenarios consistent with a chance for less than 1.5-2°C global warming depend heavily on future reductions in methane emissions. We therefore introduce the concept of the *Budget at Risk* (BaR) to capture the extent to which these uncertain reductions could affect CO_2 budgets. We find that the BaR is considerable (25-37% of today's remaining carbon budgets) and can affect economies by increasing or reducing the cost of future asset stranding by ~15%. Reporting of targets for individual gas emissions as part of the Paris Agreement pledge and review process would further help to understand and offset these risks.

Keywords: stranded assets, carbon budget, short-lived climate pollutants SLCPs, non-CO_2 forcing, GWP, methane *JEL:* Q01; Q4; Q54; Q5

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1. CO_2 budgets and short-lived climate pollutants

To stabilize temperatures at any level, global emissions of long-lived climate pollutants (LLCPs), such as carbon dioxide (CO_2), must eventually be reduced to net-zero. To achieve this, any residual anthropogenic emissions must be balanced with removal by anthropogenic sinks (Matthews and Caldeira, 2008). The cumulative emissions of LLCPs by the time net-zero has been achieved will determine the level of long-term global warming above pre-industrial levels, with all its implications for global systems (Allen *et al.*, 2009; Matthews *et al.*, 2009; Meinshausen *et al.*, 2009). These cumulative emissions can, therefore, be translated into budgets for such pollutants, compatible with limiting human-induced warming to below a given threshold, such as 1.5-2°C (IPCC, 2013). Such budgets depend on several factors, such as uncertainty in the strength of the climate response to CO_2 and the emission of non-CO_2 pollutants at peak warming (Rogelj, Schaeffer, *et al.*, 2016). This paper contributes to the understanding of how the emission of short-lived climate pollutants (SLCPs) affects cumulative CO_2 budgets and, thereby, the potential stranding of assets.

In recent years, LLCP budgets, especially CO_2 budgets, have received greater attention in science, policy making and even finance. Many scientific contributions base their findings on such budgets (Fay *et al.*, 2015; Rogelj, Elzen, *et al.*, 2016), policy makers evaluate their policies based on whether they manage to keep cumulative emissions within these budgets (UNEP, 2016), and financiers and investors analyze the impact of carbon budgets on their investment portfolios in fossil fuels and related infrastructure (CTI, 2013; Carney, 2015). One important implication of such finite budgets is that, under certain circumstances, already operating, or yet to be built, infrastructure and other assets might not be able to be fully utilized to the end of their economically useful lifespans if the world were to stay within set budgets (Rozenberg, Vogt-Schilb and Hallegatte, 2014; Rozenberg *et al.*, 2015; Pfeiffer *et al.*, 2016, 2017, 2018). Under a strict climate policy such assets could hence become *stranded assets* when their future cumulative carbon emissions exceed the remaining CO_2 budget allocated to this asset, sector or country (CTI, 2011).[1] Especially in sectors such as fossil fuel extraction and transport, electricity generation, steel- and cement-production and transport, this has become a topic of interest for investors and policy makers alike in recent years (Davis, Caldeira and Matthews, 2010; CTI, 2013; Rozenberg *et al.*, 2015; Caldecott *et al.*, 2016; Rozenberg, Vogt-Schilb and Hallegatte, 2017).

CO_2 budgets (or carbon budgets), however, are inherently uncertain (Rogelj, Schaeffer, *et al.*, 2016; Millar *et al.*, 2017). Staying within the 2°C (50%) budget of ~1,300 $GtCO_2$ in 2005 (IPCC, 2014) will not guarantee that humanity stays below the 2°C warming it has set itself as a target. It rather means that in 50% of all scenarios the IPCC assessed for its *5th Assessment Report* (AR5), global warming stayed below 2°C if CO_2 emissions didn't overshoot this budget. It also means, however, that even if the world stays within that budget it is as likely as not that the world's climate will warm by more than 2°C in the global average. Indeed, there is a non-negligible probability that the world would warm beyond 3°C, even if humanity were to stay within its 2°C (50%) CO_2 budget.

There are several reasons for this. Whilst uncertainty as to the actual response of climate is a dominant source of uncertainty (Roe and Baker, 2007), unknown future emissions of SLCPs – over which humanity does have some control – also play an important role (Rogelj *et al.*, 2014). Some SLCPs are much more powerful greenhouse gases (GHGs) than CO_2. Measured by its global warming potential (GWP), a measure of the heat-trapping potential of a gas relative to CO_2, Methane (CH_4), for example, has roughly 72-84 times the global warming potential of CO_2 over a period of 20 years (GWP20), Ozone (O3) has a GWP20 of 62-69, and Nitrous Oxide (N_2O) a GWP of as much as ~300 over a period of 100 years (GWP100).

Despite these very strong radiative effects, SLCPs remain in the atmosphere for much less time than LLCPs, sometimes for only a few years.[2] Unlike LLCPs,

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[1] Such assets could become stranded e.g. via underutilization, early retirement, or the retrofit of expensive efficiency or Carbon Capture and Storage (CCS) upgrades.

[2] Methane, one of the most important SLCPs, for example, is mostly removed from the atmosphere by a chemical process after roughly 12 years. There are even some SLCPs, such as black and organic carbon (BC and OC) and some Hydrofluorocarbon molecules (e.g. HFC 152a)

therefore, it is not the *cumulative* amount of SLCP emissions that determines their effect on global warming, but rather the sustained *rate* of emissions of such pollutants (Smith *et al.*, 2012). The atmospheric concentration anomaly associated with a one-off pulse emission of a LLCP decays very slowly, with a large percentage of the emissions still resident in the atmosphere over timescales relevant to human climate change in this century (Montenegro *et al.*, 2007). A similar-sized one-off pulse of SLCPs, e.g. methane, however, would be negligible after only 20 years, and thus has little residual effect on atmospheric concentrations of the gas after 60-80 years (Allen *et al.*, 2016). Whilst concentrations (and induced warming) continue to rise with constant LLCP emissions, a constant rate of emissions of an SLCP, on the other hand, would lead to stabilised concentrations of the pollutant in the atmosphere and only very slowly rising associated warming. Since total human-induced warming arises from the combination of SLCP and LLCP induced warming, the size of a cumulative emissions budget for LLCPs that is consistent with a specific target peak human-induced warming, hence, also depends on the future sustained emissions of SLCPs (e.g. methane), as well as the specified probability of achieving the warming goal (Rogelj, Schaeffer, *et al.*, 2016).[3] This means that it is the stock of LLCPs, together with the flow of SLCPs, that must be limited if climate targets are to be achieved.

This paper assesses the impact on total CO_2 budgets that assumed methane emission reductions from current to sustained emission levels in 2100 would have. It furthermore quantifies the effect that a failure to achieve these reductions would have on asset stranding in the power generation sector. Methane is arguably the most important source of SLCP-induced global warming[4] and is therefore very important for effective climate policy. We find that the currently remaining cumulative CO_2 budgets between present-day and 2100 in most climate stabilization scenarios (430-580 ppm) could need to be ~37% lower if

that only remain in the atmosphere for a few (1-10) years. Nitrous oxide (N_2O) and carbon dioxide (CO_2), the two most important LLCPs, on the other hand, stay in the atmosphere for several hundred or even thousand years (EDF, 2017).

[3] Figure 1 visualizes this relationship.

[4] The Environmental Defence Fund (EDF) estimates that ~25% of manmade global warming experienced today is caused by methane emissions (Le Quéré *et al.*, 2016).

modelled future reductions of annual methane emissions from current levels turn out to be unfeasible. Annual methane emissions increased by ~3.6% between 2005 and 2014 (Saunois *et al.*, 2016), which increased the share of the overall CO_2 *Budget at Risk* (BaR) – i.e. the share of the currently available CO_2 budget that is at risk from a potential failure to achieve these future methane emission reductions – from 25% to 37% (in the median 430-480 ppm scenario). Such a failure could potentially increase the amount of asset stranding in the generation sector, required to meet climate goals by 15% to ~650 GW. This could considerably increase the cost of mitigating climate change.

The rest of this paper is structured as follows: In section 2 we describe the datasets used (2.1), the methods we apply to calculate the budget risks of higher methane emissions (2.2), and the main assumptions of our approach (2.3). In section 3 we present the results of our analysis of methane emission levels over the course of the century and how this could affect carbon budgets (3.1), the CO_2 BaR from these emissions (3.2), regional results (3.3), an update of these findings to 2014/15 (3.4), and how this might affect asset stranding in the electricity generation sector (3.5). In section 4 we discuss these findings in a wider economic and political context. Section 5 concludes the paper.

2. Data and Methods

To calculate the impact of different methane emission reductions on a wide range of different scenarios under different assumptions, we apply Allen et al.'s GWP* approach (Allen *et al.*, 2017) to all global scenarios of the IPCC and AMPERE databases. The following paragraphs describe the databases and other sources used, as well as the approach applied.

2.1 Databases and sources

Two different sets of pathways for electricity generation and SLCP and LLCP emissions between 2005 and 2100 are used: the AMPERE database and the IPCC's AR5 database. The AMPERE database provides regional and, in some cases, even country-specific model outputs, while the IPCC's AR5 database provides only global results for the required outputs.

First, for insights on a global and local level, a set of ~400 pathways through to 2100 is used, generated by a variety of scenarios processed with eight different integrated assessment models (IAMs) for a recent IAM comparison study: AMPERE (Riahi *et al.*, 2015). Different scenarios cover a wide range of different technology scenarios (e.g. 'no CCS', 'no new nuclear', etc.), long-term concentration targets (e.g. 450 ppm, 500 ppm, etc.), and short-term targets for 2030 (e.g. low or high short-term target vs. optimal policy short-term target).

Second, for further insights on a global and regional level, the full IPCC AR5 database is analyzed, consisting of 1,184 pathways from a wide range of scenarios processed with 31 IAMs (Krey *et al.*, 2014). Scenarios processed in the AR5 database can be classified along five dimensions: (1) different climate targets, determined by 2100 CO_2-equivalent (CO_2-eq.) concentrations (e.g. 430-480 ppm, 480-530 ppm, etc.); (2) overshoot of these 2100 levels between 2005 and 2100; (3) scale of deployment of carbon dioxide removal (CDR) or negative emissions technologies (NETs); (4) availability of mitigation technologies, especially CDR and NETs; and (5) policy category (e.g. immediate vs. delayed mitigation, etc.).

IAMs can be classified either as policy optimization models (POMs) or policy evaluation models (PEMs) (IPCC, 2001). POMs focus on a full cost-benefit analysis of climate change mitigation action and optimal policy. PEMs, on the other hand, look at the cost-effectiveness of achieving an exogenous mitigation target by means of a specific policy (Farmer *et al.*, 2015). The databases used in this dissertation focus on PEMs (IPCC, 2014), which compute cost-effective pathways and energy system transitions under different socio-economic and policy assumptions and constraints set by climate targets. They factor in a wide range of parameters, such as long-term demographic evolution, availability of natural resources, and countries' participation in emission-reduction efforts. Technology costs and maximum penetration rates, in particular, are calibrated using a mix of historical uptake rates and assumptions on learning by doing and autonomous technical progress (Wilson *et al.*, 2013; Iyer *et al.*, 2014). IAMs are regularly peer-reviewed in comparison exercises (Clarke *et al.*, 2009; van Vuuren *et al.*, 2009; Edenhofer *et al.*, 2010; Kriegler *et al.*, 2014, 2015), and occasionally evaluated against historical data (Guivarch, Hallegatte and Crassous, 2009; Wilson *et al.*, 2013).[5]

2.2 Approach and methods

In order to assess the long-term impact of a sustained rate of methane emissions, we use a new multi-gas aggregation metric, termed GWP* (Allen *et al.*, 2016, 2017), based on the traditional, and often criticised, global warming potential (GWP) of different climate pollutants (Smith *et al.*, 2012; Joos *et al.*, 2013; Reisinger *et al.*, 2013; Huntingford *et al.*, 2015). GWP* is calculated as GWP_H x H tonnes of CO_2 (denoted CO_2-e*) where GWP_H is the value of that SLCP's GWP for the time-horizon H. It equates carbon dioxide emissions with changes in sustained rates of emission of SLCPs such as methane, unlike the conventional GWP metric which equates absolute rates of SLCP emission with carbon dioxide emissions. It can be applied to annual SLCP emissions (or the absolute annual change of such emissions) to calculate the CO_2 one-off pulse equivalent that would have the same impact on peak warming as a constant and sustained change in the rate of SLCP emissions as measured in that year (see Appendix A.2 for an example calculation).

GWP* offers a more direct way to relate changes in emissions of SLCPs to their impact on peak warming and to provide indicative weights relative to CO_2 emissions. LLCPs, which are physically like CO_2, are traded against CO_2 in the same way as in the conventional GWP frame under GWP*. The use of GWP* performs as a better predictor of peak warming under ambitious mitigation than conventional metrics (Allen *et al.*, 2017). In this paper we use a GWP* of 2,800 tCO_2/tCH_4 for a change in the sustained methane emissions rate (Allen *et al.*, 2016). This can be interpreted such that methane emissions at a constant and sustained rate of 1 ton per year would have the same impact on peak warming as a one-off pulse of 2,800 tons of CO_2 (see Figure 1).

[5] See Appendix A.1 for further description of databases and sources.

2.3 Important assumptions

We make three important assumptions that are critical to our calculation of the CO_2 BaR from a failure to reduce methane emissions over the course of the century.

First, we assume that the annual levels of methane emissions in 2100 derived from the analyzed scenarios represent potential emission floors in these gases, below which further mitigation may be very challenging or even impossible. Given the uncertainty surrounding future technological development and demand for sources of methane emissions, we cannot be sure that this assumption holds true. As we analyze the impact of a failure to achieve these emissions, however, even lower emissions after 2100 would only serve to support and even strengthen our findings.

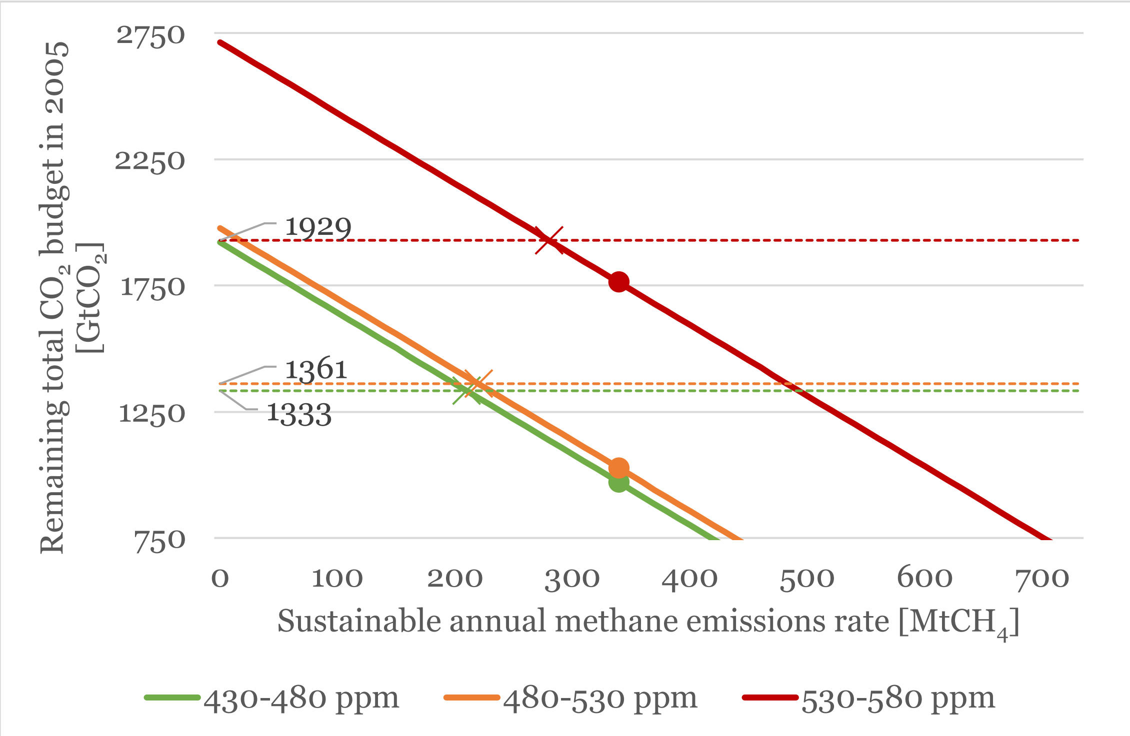
Second, we assume that lower sustained 2100 levels of methane emissions would leave more space for CO_2-only emissions between 2005 and 2100, given constant radiative forcing and global warming. The science of the influence of SLCPs on CO_2 budgets strongly suggests the validity of this assumption (Bowerman *et al.*, 2013; Rogelj *et al.*, 2014; Rogelj, Schaeffer, *et al.*, 2016). Implicitly, this also assumes that methane and CO_2 emissions can be considered independently from each other. While this is true for some sources of CO_2, e.g. agriculture, it is not realistic for others, e.g. gas flaring, and therefore idealized. However, this assumption is necessary for the analysis and valid because it does not change the general outcome and implications of this paper.

Third, we consider budgets between now and 2100, even though peak warming occurs in advance of 2100 in many scenarios. An alternative analysis could be conducted that uses methane emissions at the time of peak warming as its reference point, but we choose to focus on the full-century budget (indicative of 2100 levels of warming) as this has been a common policy focus.

3. Findings

We find that, in most climate stabilization scenarios (430-580 ppm), the currently remaining CO_2 budgets through to 2100 depend on future reductions of annual methane emissions from current levels. Especially in the more ambitious scenarios in which it is more likely than unlikely or even likely to keep global warming below 2°C (430-530 ppm scenarios), remaining CO_2 budgets could need to be reduced by 15-25% (in 2005) to remain compatible with the same climate outcome if modelled future annual methane emission reductions cannot be achieved (see Figure 1).

Figure 1 *Trade-off between annual methane and cumulative CO_2 emissions*



The total cumulative remaining CO_2 budget in 2005 depends on the future sustained rate of annual methane emissions. Circles represent annual methane emission levels today and crosses represent median expected 2100 emission level in respective climate scenario. Based on the IPCC and AR5 databases the overall carbon budgets for the 430-480 and 480-530 ppm scenarios are almost similar. This might be caused by different assumptions with regards to carbon removal from the atmosphere.

Source: IPCC AR5 database (IIASA, 2014) *and Global Methane Project 2016* (Saunois *et al.*, 2016).

The biggest expected methane emission reductions (in relation to current emission levels) are modelled to be in OECD countries (-72%)[6] and reforming

[6] Member countries of the Organization for Economic Co-operation and Development (OECD).

economies (-72%).[7] Countries in the Middle East and Africa are expected to increase their annual methane emissions by 15% by 2100. Consistent with modelled emissions in all analyzed scenarios (2005 base), actual annual methane emissions have increased by ~3.6% from ~332 to 344 $MtCH_4$ between 2005 and 2014, which increased the share of overall CO_2 BaR from a potential failure to achieve these future methane emission reductions from 25% to 37% (in the median 430-480 ppm scenario). A failure to achieve the modelled methane emission reductions could, therefore, increase the required amount of asset stranding, i.e. the fraction of fossil fuel powered generation capacity that needs to be underutilized or retired early to meet climate goals, considerably.

3.1 Current CO_2 budgets assume future methane reductions

In most analyzed scenarios (430-580 ppm scenarios) annual methane emissions in 2100 are lower than in 2005. Especially in the more ambitious scenarios, in which it is likely or at least more likely than unlikely to limit global warming to below 1.5-2°C above pre-industrial levels (namely the 430-480 and 480-530 ppm scenarios), methane emissions are expected to decrease substantially over the course of the 21st century. We find that the median expected methane emission reduction between 2005 and 2100 is 36% across all analyzed 430-480 ppm scenarios (compared to a 31% reduction for 480-530 ppm and a 10% reduction for 530-580 ppm scenarios; see Figure 4 in Appendix B).

The corresponding CO_2 BaR for each year changes with annual methane emission levels and, per definition, converges towards zero in 2100 (see Figure 5 in Appendix B). It is defined as the equivalent reduction in cumulative CO_2 emissions that would be required to give identical expected warming in 2100, if methane emissions could not be reduced. We find that the median 430-480 ppm scenario has a CO_2 BaR of 332 $GtCO_2$ in 2005 (244 $GtCO_2$ in the 480-530 ppm and 88 $GtCO_2$ in the 530-580 ppm scenario). This is equivalent to over eight years of total global CO_2 emissions at current levels.[8]

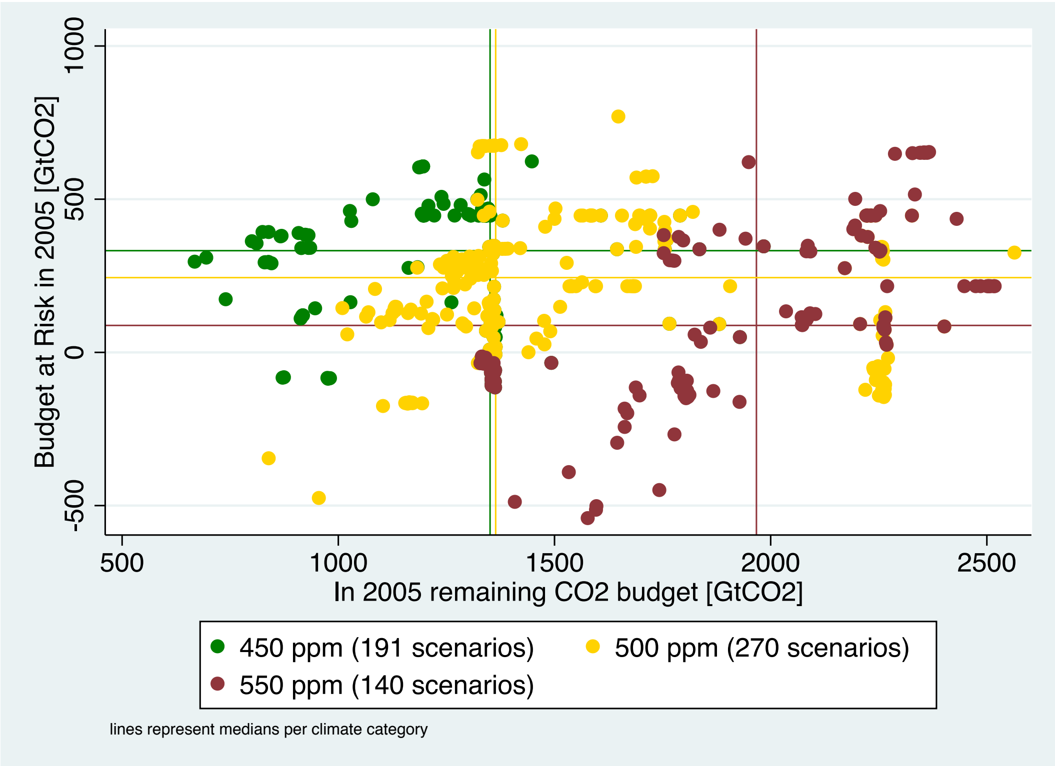
7 Reforming Economies of Eastern Europe and the Former Soviet Union (REF), sometimes also referred to as Economies in Transition (EIT).

8 Annual CO_2 emissions reached 40.3 $GtCO_2$ in 2014 (Kriegler *et al.*, 2013).

3.2 Future methane reductions have large effect on current budgets

In Figure 2 we compare these BaR figures in 2005 for each scenario (y-axis) with the remaining total CO_2 budget in 2005 for the same scenario (x-axis).[9] We find that more ambitious climate scenarios, typically connected with lower total CO_2 budgets, also have a higher total CO_2 risk from uncertain future methane emission reductions, indicating the relatively more important role that the mitigation SLCPs plays under very ambitious mitigation scenarios.

Figure 2 *Carbon budget at risk*



Global CO_2 Budget at Risk (BaR) in 2005 compared to overall remaining CO_2 budget in 2005, by climate category (respective medians represented by vertical and horizontal lines).

We interpret this as showing that climate scenarios that have a chance to limit global warming to below 1.5-2°C above pre-industrial levels typically require not only rapid and steep CO_2 emission reductions, but also assume comparatively low levels of methane emissions in 2100. Otherwise, these already lower CO_2 budgets would be even lower to be consistent with the same climate outcome.

9 See Figure 6 in Appendix B for distribution of 2005 available total CO_2 budgets.

Consistent with the previously described finding, we find that in the 430-480 and 480-530 ppm scenarios, a considerable share of the overall CO_2 budget in 2005 depends on uncertain future methane emission reductions (25% of budget in 430-480 ppm and 15% of budget in 480-530 ppm scenarios). In the 530-580 ppm scenarios, however, a much smaller fraction of the CO_2 budget available in 2005 depends on future methane emission reductions (a median of only 4%).

3.3 Methane effect more important than CO_2 budget itself in some regions

In Table 1 we analyze which global regions see the highest reduction of methane emissions between 2005 and 2100 in 430-480 ppm scenarios and how this compares to these regions' overall contribution to global CO_2 budget adherence.[10]

Table 1 *Regional methane emission reductions and BaR in the 430-480 ppm scenario*

(430-480 ppm scenarios)	**Number of scenarios in sample**	**Median reduction in 2005-2100 CH_4 emissions**	**Median share of BaR of regional 2005 CO_2 budget**
Asia	171	-29%	14%
Latin America	148	-39%	6%
Middle East and Africa	165	15%	-26%
OECD90	190	-72%	37%
Reforming Economies	145	-72%	65%
World	**191**	**-36%**	**25%**

Required methane emission reductions from current methane emission levels in 2005 and the share of the remaining regional CO_2 Budget at Risk (BaR), for 430-480 ppm climate scenarios.

We find that especially OECD countries and reforming economies (i.e. countries of the former Soviet Union) are modelled to undertake steep reductions in their methane emission levels (median of -72% between 2005 and 2100). In comparison with their overall CO_2 budget in 2005 (as a measure of their contribution to global CO_2 budget adherence) this deep cut of methane emissions

[10] For 480-530 and 530-580 ppm scenarios see Appendix C – Tables 3 and 4

is particularly important in reforming economies where it amounts to two thirds of their remaining CO_2 budget in 2005.[11] One interpretation of this finding is that, for global climate goals, it is almost indifferent whether these countries overshoot their assumed CO_2-only budget by 65% or whether they fail to reduce their methane emissions from 2005 levels to the 2100 levels, as assumed in these scenarios. Countries in the Middle East and Africa are expected to have higher methane emissions in 2100 than in 2005, equivalent to one quarter of their modelled 2005 remaining CO_2 budget. These countries could emit up to 26% more CO_2 until 2100 if they just kept their methane emission levels constant to 2005 levels instead of increasing them as assumed in the models. Considering development needs and energy access in many of these countries, our findings suggest that determined mitigation action on SLCPs in these countries could allow for a slower decarbonization process without changing the contribution to global warming. More research should be undertaken to assess this implication.

Asian economies are modelled to undertake relatively small methane emission cuts (29%; global average of 36%). A country specific analysis for countries where data is available, however, shows that taking the aggregated view of all Asian economies potentially conceals very heterogeneous developments within this economic area (see Table 2). Steep methane emission cuts in China (80%), where these future reductions amount to the equivalent of 29% of 2005 available CO_2 budget, and Japan (76% emission reductions and 5% of 2005 CO_2 budget) are offset by higher methane emissions in India (+42%). India's 2005 available CO_2 budget could be up to 29% higher should it not realise any of the increase in its methane emissions by 2100, as indicated in the analyzed scenarios.

The same applies to Brazil. Overall methane emission reductions in Latin America only amount to 39%, but the median reduction in Brazil in all analyzed 430-480 ppm scenarios, however, was 50%, making methane reduction more important to Brazil's global climate targets than adherence to its overall remaining CO_2 budget in 2005.

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[11] While referring to country-specific CO_2 budgets, this paper does not explicitly allocate normative CO_2 budgets to geographic regions or countries. We analyze existing scenarios from the IPCC AR5 and AMPERE databases in which specific climate goals are achieved and only descriptively use country-specific CO_2 budgets from these scenarios.

Table 2 *Country-specific methane emission reductions and BaR in the 430-480 ppm scenario*

Region (430-480 ppm scenarios)	**Number of scenarios in sample**	**Median reduction in 2005-2100 CH_4 emissions**	**Median share of 2005 CO_2 BaR**
Brazil	33	-50%	120%
China	95	-80%	29%
EU	95	-80%	34%
India	95	42%	-29%
Japan	63	-76%	5%
Russia	76	-82%	80%
USA	95	-75%	32%
World	**191**	**-36%**	**25%**

Required methane emission reductions from current methane emission levels in 2005, and the share of the remaining CO_2 Budget at Risk (BaR), for selected countries' 430-480 ppm climate scenarios.

Table 2 also reveals that the EU, Japan, Russia and the USA are all expected to reduce their methane emissions by 75-82%, and hence must achieve much steeper reductions than the global or even regional average suggests.

3.4 Potential effect increased over past decade

All analyzed scenarios are harmonized based on 2005 levels. However, we also compare these findings with updated numbers for 2014 (see Table 5). Annual global methane emissions in 2014 were 3.6% higher than in 2005. This means that the change required to achieve median 2100 methane emission levels (in 430-480 ppm scenarios) has increased by two percentage points, from a 36% to a 38% reduction, and that CO_2 BaR has increased by 11%.

Over the same period (2005-2014), cumulative global CO_2 emissions amounted to 329 $GtCO_2$, reducing the remaining CO_2 budget in 2014 to 1,004 $GtCO_2$, or by 25% as compared to 2005. Overall, we find that the importance of future methane emission reductions, as measured by the share of currently available CO_2 BaR, has increased by 12 percentage points, from 25% of the available budget in 2005 to 37% of the available budget in 2014.

The increase in annual methane emissions over the past decade has led to a linear increase in absolute BaR. Especially in the 430-480 and 480-530 ppm scenarios, however, the increase in the share of the overall remaining CO_2 budget that has become BaR has been amplified by a rapid decline in remaining total CO_2 budgets. This has resulted in an almost exponential increase of BaR share in the observed period (see Figure 8 in Appendix B).

3.5 Effect on asset stranding in the power sector

Power generation plays an important role in climate change. It is responsible for a large share of global total primary energy supply (TPES) and an even larger share of anthropogenic CO_2 emissions: today's electricity and heat generation accounts for ~15% of TPES and ~13.6 $GtCO_2$ p.a., or ~42% of total annual anthropogenic CO_2 emissions from fossil fuel combustion (IEA, 2016). Applying the median 2005 share of the electricity generation CO_2 budget[12] to the remaining 2015 CO_2 budget (~923 $GtCO_2$ in 430-480 ppm scenarios) leaves the remaining net generation-only CO_2 budget available in 2015 at ~129 $GtCO_2$. In addition to this net budget, ~1,330 EJ (or 370k TWh) of cumulative 2005-2100 bioenergy with CCS (BECCS) generation in the median 430-480 ppm scenario could add an additional 110 $GtCO_2$.[13] Overall this leads to an estimate of the generation-only CO_2 budget in 2015 at ~240 $GtCO_2$ (see Figure 3).

In a recent working paper (Pfeiffer *et al.*, 2018) we analyze existing and planned electricity generation capital stock and find that ~6,200 GW of currently operating power generators commit to ~300 $GtCO_2$ emissions in the remainder of their lifetime. Furthermore, an additional ~3,450 GW are currently under construction or planned, committing to a further ~270 $GtCO_2$ emissions. Compared with the remaining generation-only carbon budget in the 430-480 ppm scenario this implies that ~58% of this operating and planned infrastructure would need to be underutilized, retired early, or retrofitted with carbon capture

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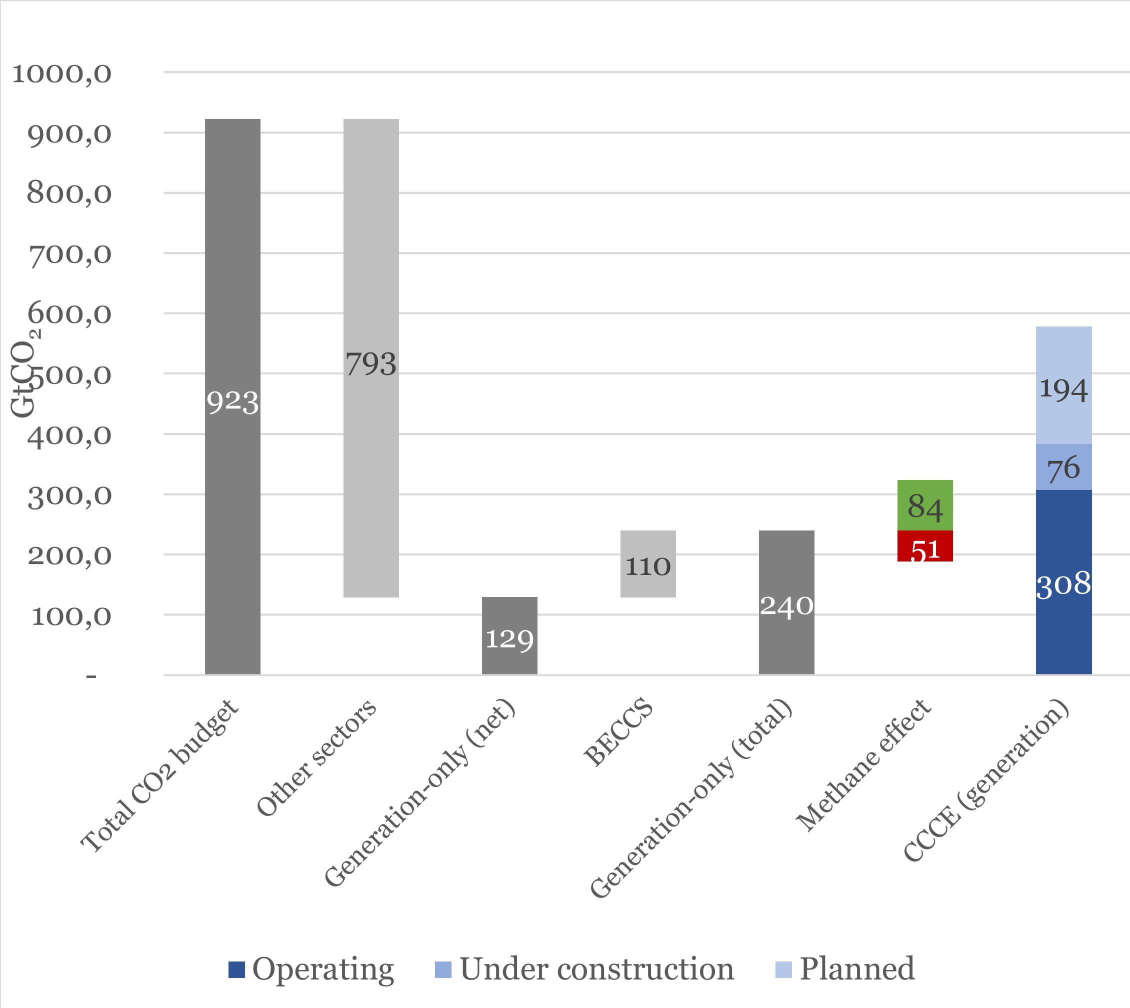
[12] In 430-480 ppm scenarios, the share of cumulative CO_2 emissions from electricity generation between 2005 and 2100 is ~14% of overall CO_2 emissions in the same period.

[13] Assumed CCS rate of 83 $MtCO_2$/EJ BECCS electricity generation (Pfeiffer *et al.*, 2018).

and storage (CCS) – in other words stranded in some form – if the world were to meet its climate goals.

Figure 3 *Carbon budgets and committed emissions*



Composition of 2015 available total and generation only CO_2 budget in median 430-480 ppm scenario (grey shades), potential down- and up-side effect of failure (or exceedance) of pro-rata methane emission reductions (green/red shades), and 2016 electricity sector committed cumulative CO_2 emissions (blue shades).

As shown in this paper, the median BaR in the 430-480 ppm scenarios in 2014/15 is 367 $GtCO_2$ (see Table 3). If this is allocated pro-rata to the electricity generation-only budget (14%), a failure to reduce emissions from 2014 levels would reduce this budget by ~51 $GtCO_2$ to ~188 $GtCO_2$, and hence increase the required level of stranding from ~58% to ~67%, a ~15% increase. A reduction of methane emissions below levels currently assumed in climate scenarios in the 430-480 ppm category, on the other hand, could reduce stranding (see Figure 7 in Appendix B). If the global methane emission level could be reduced to zero instead of the currently assumed median 2100 level of ~215 $MtCH_4$ p.a. the remaining pro-rata generation only CO_2 budget Could be ~84 $GtCO_2$ higher.[14] This Could reduce stranding from ~59% to ~44% (by 25%).

4. Discussion of findings

Eventually, emissions of LLCPs, such as CO_2, must be reduced to net-zero if the global climate is to be stabilized at any level. The most significant impact on overall warming above pre-industrial levels, by the time this balancing between carbon sinks and residual emissions is achieved, arises from the cumulative emissions of such LLCPs. Recent literature emphasizes, however, that SLCPs, such as methane, also have an important effect on global warming, despite their relatively short lifetime in the atmosphere. Sustained emission rates of such SLCPs have a considerable impact on radiative forcing and hence global warming. Particularly for very ambitions mitigation goals, the realised level of SLCP mitigation is likely to have an important impact of the relative size of the permissible cumulative emissions of LLCPs.

This paper estimates the implicit effect a failure to reduce sustained methane emission rates from current levels would have on today's available overall CO_2 budgets. In our assessment, we consider CO_2 and CH_4 as independent levers for climate change mitigation. Our method probably overestimates the contribution of methane emission reductions on overall mitigation as CO_2 and CH_4 are often closely connected (e.g. gas flaring) and hence cannot and should not be viewed as totally independent mitigation levers. Nonetheless, it can still provide a good approximation of this effect. It furthermore emphasizes the importance of a closer assessment of likely SLCP emission floors beyond which a further reduction would be difficult or not feasible. To identify such floors would improve the accuracy of currently available CO_2 budgets and enable policy makers and investors alike to optimize their policies and investment decisions to minimize the cost of the transition that will be required to reduce LLCP emission levels to net-zero.

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[14] 14% x 215 $MtCH_4$ x 2,800 $MtCO_2/MtCH_4$ = 84 $GtCO_2$.

We find that currently assumed CO_2 budgets would be considerably smaller should it turn out that methane emissions cannot be reduced as assumed from current levels. In our assessed 'worst' case, in which methane emissions remain at current levels, we find that, in the electricity sector alone, asset stranding would increase by 15%. To put this into perspective: according to our estimates, currently ~340 $GtCO_2$ of committed emissions from the electricity sector would need to become stranded if the whole pipeline were to be built and the world still wanted to achieve its climate goals in the 430-480 ppm scenario. If, however, the required methane emission reductions would not take place ~390 $GtCO_2$ would need to be stranded for the same global warming goal. The difference (~50 $GtCO_2$) equals ~650 GW of newly installed fossil fuel powered capacity.[15] If demand remains unchanged, this capacity would need to be replaced with CO_2-neutral capacity, such as wind or solar. In its 2016 World Energy Outlook, the IEA estimates the capital cost of 1 GW solar PV capacity completed in 2015 to be 1.7 billion USD.[16] Replacing 650 GW of fossil fuel powered capacity with solar PV would hence amount to ~1.1 trillion USD (~1.5% of global GDP in 2016[17]). On the opposite end of this calculation, a successful reduction from current methane levels to zero could save up to 1.8 trillion USD (~2.4% of 2016 GDP) in costly capacity replacements. Although a recently published study finds that the overall amount of the carbon budget for 1.5-2°C might be slightly higher than originally estimated, it confirms that future SLCP emission pathways will have an important effect on the final size of that budget (Millar *et al.*, 2017) and hence on asset stranding.

There are many things this calculation does not consider; demand side responses, discount rates or decreasing capital costs of solar PV are not reflected, for example. Furthermore, it is highly unlikely that such a large-scale stranding and replacement of fossil-fuel infrastructure would take place overnight. Nevertheless, the example illustrates the scale of the economic cost that could

[15] Planned and under construction power plants in 2016 (3,450 GW) commit to 270 $GtCO_2$ cumulative. Hence 1 $GtCO_2$ cumulative emissions equals ~12.8 GW newly installed fossil fuel powered capacity (WBG, 2017).

[16] Approximately 1,700 USD/kW.

[17] Global GDP 2016 equalled ~75.6 trillion USD (Pfeiffer *et al.*, 2018).

occur if mitigation pathways are not carefully planned and adjusted over time to reflect latest developments and scientific discoveries. A sustained level of SLCP emissions and when this will be reached cannot be foreseen with certainty, meaning that early and decisive reduction of such emissions seems prudent to avoid having to make much more disruptive adjustments to the global energy sector and other GHG emitting capital stock later in the century. The science on the correlation between radiative forcing,[18] cumulative LLCP emissions, and the (sustained) level and timing of SLCP emissions is clear. It tells us that, for constant climate goals, lower sustained levels of SLCP emissions, such as methane, allow for higher cumulative LLCP (e.g. CO_2) emissions. Reducing SLCP emissions (when valued in terms of GWP*) early is therefore a sensible way to hedge against adverse climate impacts from a failure fully to achieve CO_2 targets, provided that such mitigation is not conducted at the expense of direct CO_2 mitigation. At the same time, early and decisive action on such SLCPs might enable us to reduce the costs involved in stranding CO_2 emitting assets at a time when adverse effects from anthropogenic climate change force us to take such decisive action.

Due to the aggregated nature of most current climate emissions reporting, it is difficult to disentangle expected progress in reducing SLCP emissions from CO2 and other LLCPs. Most Nationally Determined Contributions (NDCs) to date only set partial SLCP targets, or total CO_2-eq. reduction targets that ignore eventually sustained rates of methane and other SLCP emissions (emission floors). A consideration of SLCP emissions within a consistent framework for climate pledges is necessary to derive global warming contributions and hence CO_2 budgets for each pledge. One such framework, the GWP* measure, has been used throughout this paper to assess the impact of 2100 methane emission levels. It reveals that INDCs and other climate policies should focus more on long-term SLCP emission reduction strategies, and perhaps even set concrete reduction goals as a timeline for such reductions. Only if concrete goals and pathways for all important climate pollutants, short- and long-lived, are set, can an evaluation

[18] Radiative forcing or climate forcing is the difference between energy (insolation) received by the earth and energy radiated back to space. Positive radiative forcing therefore causes global warming, negative forcing cooling.

of these pledges reveal the extent to which they will achieve global climate goals, or how actual CO_2 budgets (or other pollutants) need to be adjusted to achieve these goals.

Finally, these pledges for all important climate pollutants must be regularly updated. One of the results of the Paris climate conference was a regular stock take and ratcheting mechanism that should be based on up-to-date climate science. To fulfil this ambition, emission pathways must be updated regularly based on the cumulative amount of emitted LLCPs and the likely future pathways of SLCP emissions relative to peak warming. Current INDCs are not taking these interactions sufficiently into account.

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Appendix

Appendix A: Additional information

A.1 Additional information about databases and sources

In addition to the mentioned IPCC AR5 and AMPERE databases we use historical CO_2 and methane (CH_4) emission data from the World Bank, the Global Carbon Budget Project (Le Quéré *et al.*, 2016) and the Global Methane Budget Project (Saunois *et al.*, 2016). The historical data is used to determine national and regional methane emissions, update 2005 CO_2 budgets to 2015, and to compare 2014 methane emissions to 2005 and 2100 emission levels from the models. The global level of annual methane emissions is derived from the Global Methane Budget data. We use the country- and region-level World Bank data to assess how these global emissions are split between countries.

For the assessment of the impact of risky CO_2 budgets (BaR) on stranded assets we use findings from a currently unpublished working paper by two of the authors of this paper.[19] In this paper the authors analyze a range of power generator data sets (e.g. Platt's WEPP UDI, Greenpeace, Kiko, etc.) to estimate the (remaining) lifetimes and cumulative emissions of currently operating and planned electricity generators around the world. The methodology is based on peer-reviewed publications (Allen *et al.*, 2016, 2017) and the results of this analysis will be published in several reports and papers throughout 2017 and 2018.

A.2 Additional information about methodology

To assess the effect of a failure to reduce annual methane emission levels from a given year to their assumed 2100 levels in any individual scenario we follow a three-step approach:

1. Calculate the difference between annual methane emissions in that year (e.g. 300 $MtCH_4$ in 2015) and the assumed 2100 level (e.g. 200 $MtCH_4$)

2. Multiply that difference with the GWP* metric (Saunois *et al.*, 2016) to calculate equivalent CO_2 cumulative emissions for this change, or Budget

[19] Unpublished (Pfeiffer *et al.*, 2018).

at Risk, BaR: 100 $MtCH_4$ x 2,800 $MtCO_2/MtCH_4$ = 280,000 $MtCO_2$ = 280 $GtCO_2$

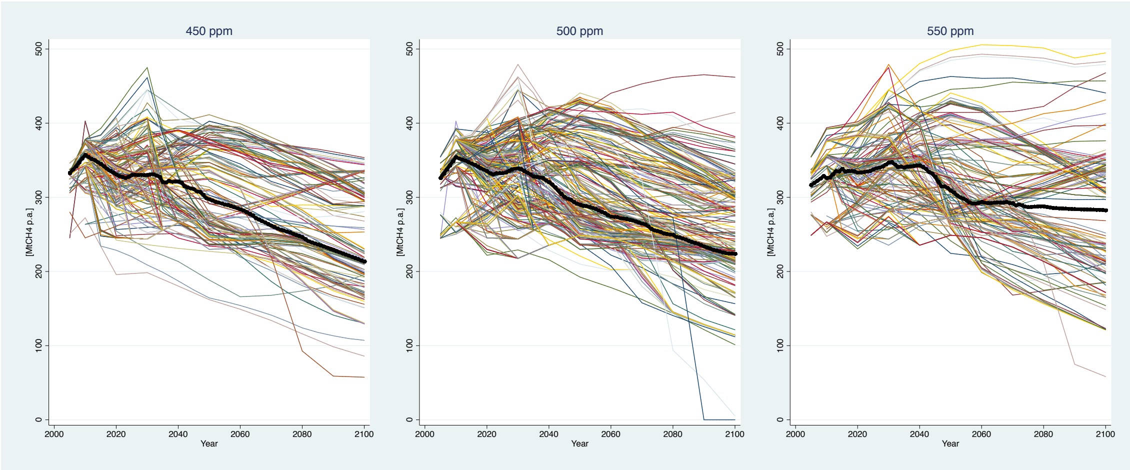
3. Calculate the share of this BaR of available total CO_2 budget in that year (e.g. 1,000 $GtCO_2$): 280 $GtCO_2$ / 1,000 $GtCO_2$ = 28%

In this example, an assumed 33% reduction of methane emission levels between 2015 and 2100 can be translated into a BaR of 280 $GtCO_2$ or 28% of overall currently available CO_2 budget if this reduction took not place.

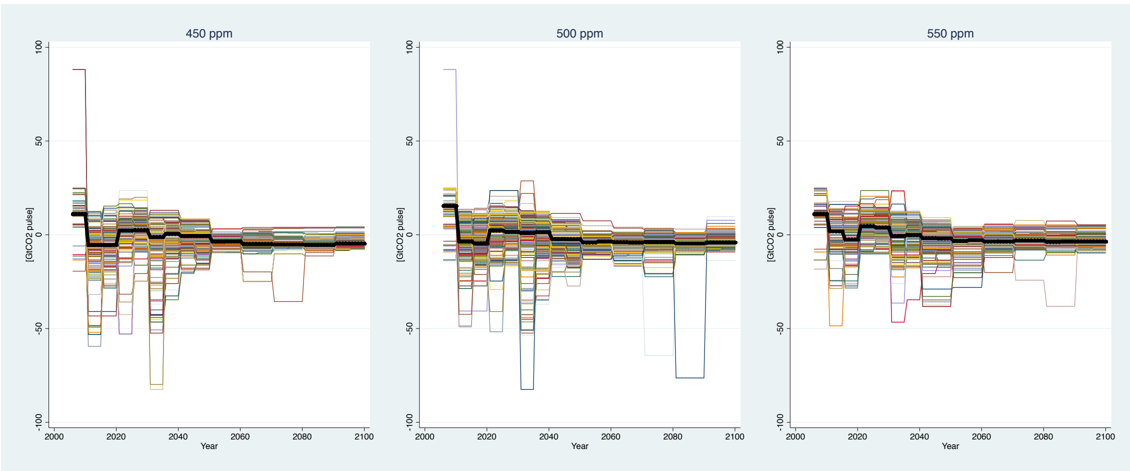
Appendix B: Additional figures

Figure 4 *Methane emission reductions, by climate category*

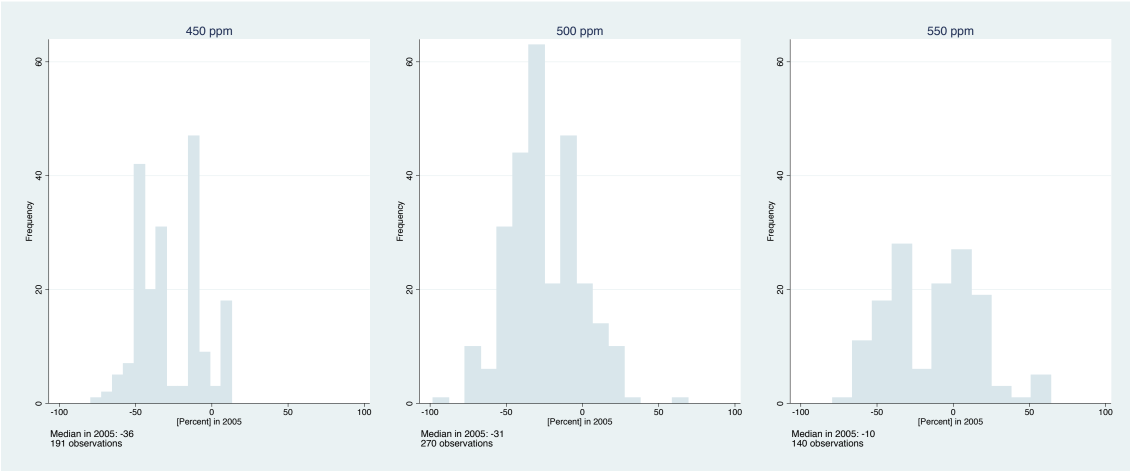
(a)



(b)



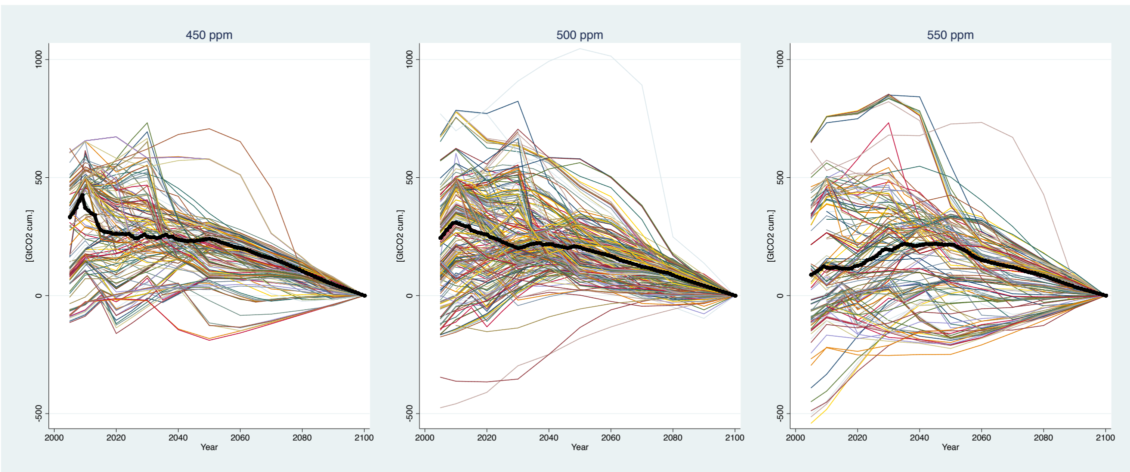
(c)



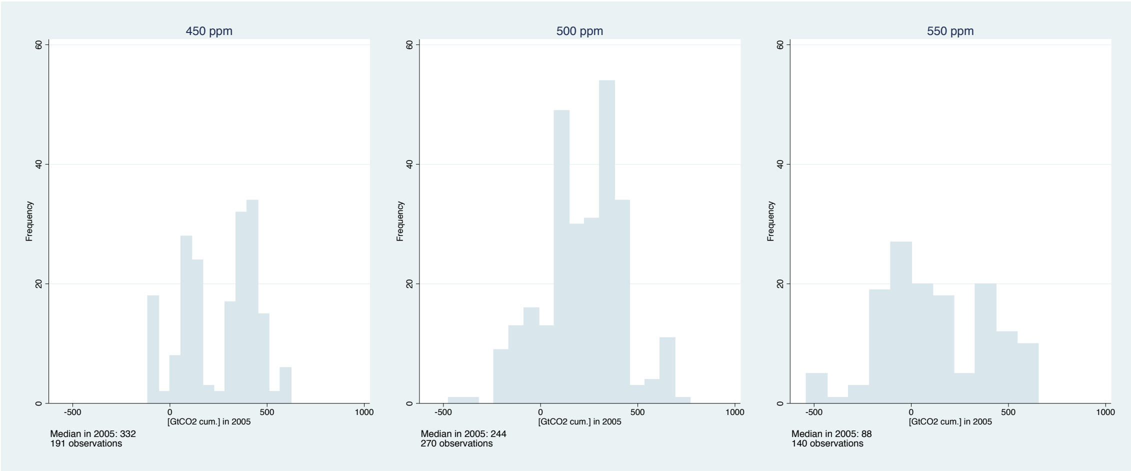
Global methane emissions over time in different scenarios (Panel a), GWP-weighted annual methane emission changes (Panel b), and required reductions in methane emission from 2005 to 2100 (Panel c).*

Figure 5 *CO_2 Budget at Risk (BaR) from the difference between annual and 2100 methane emission levels, by climate category*

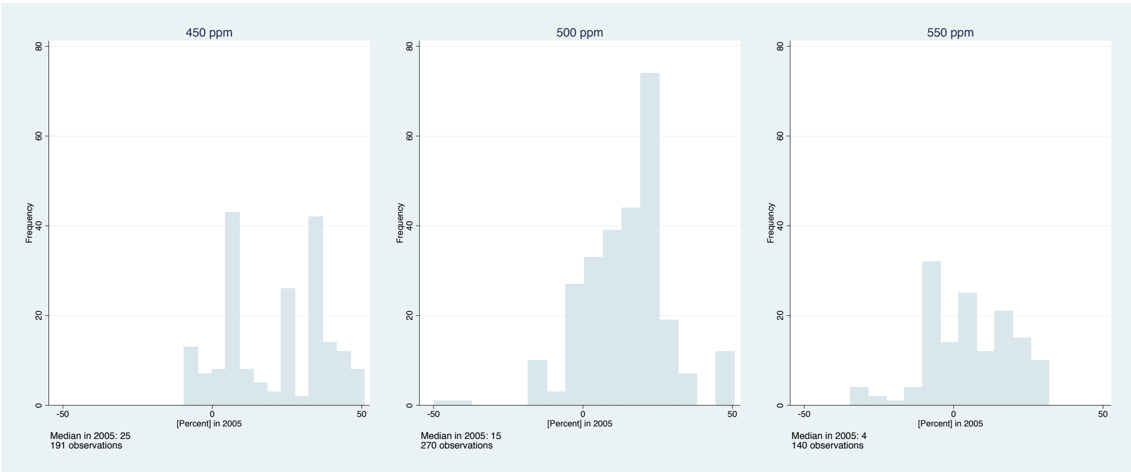
(a)



(b)

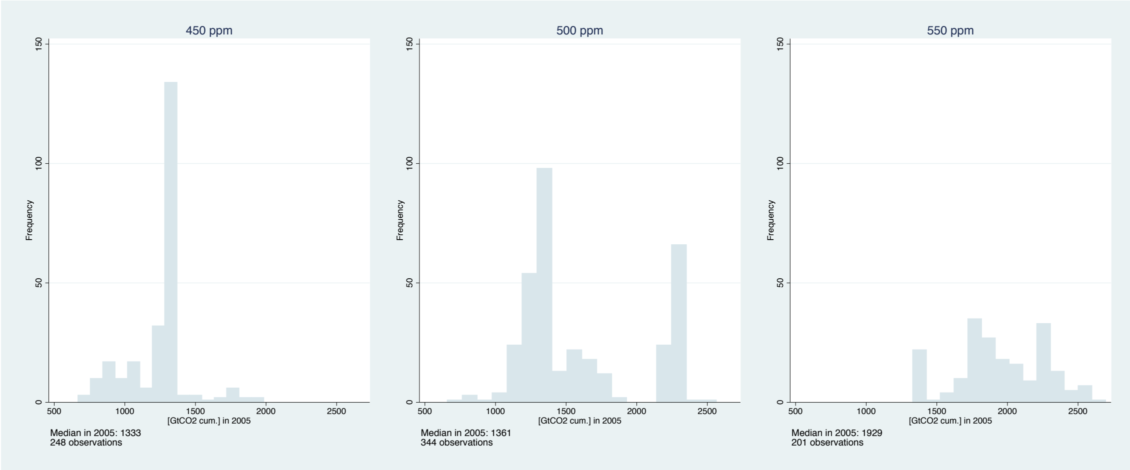


(c)



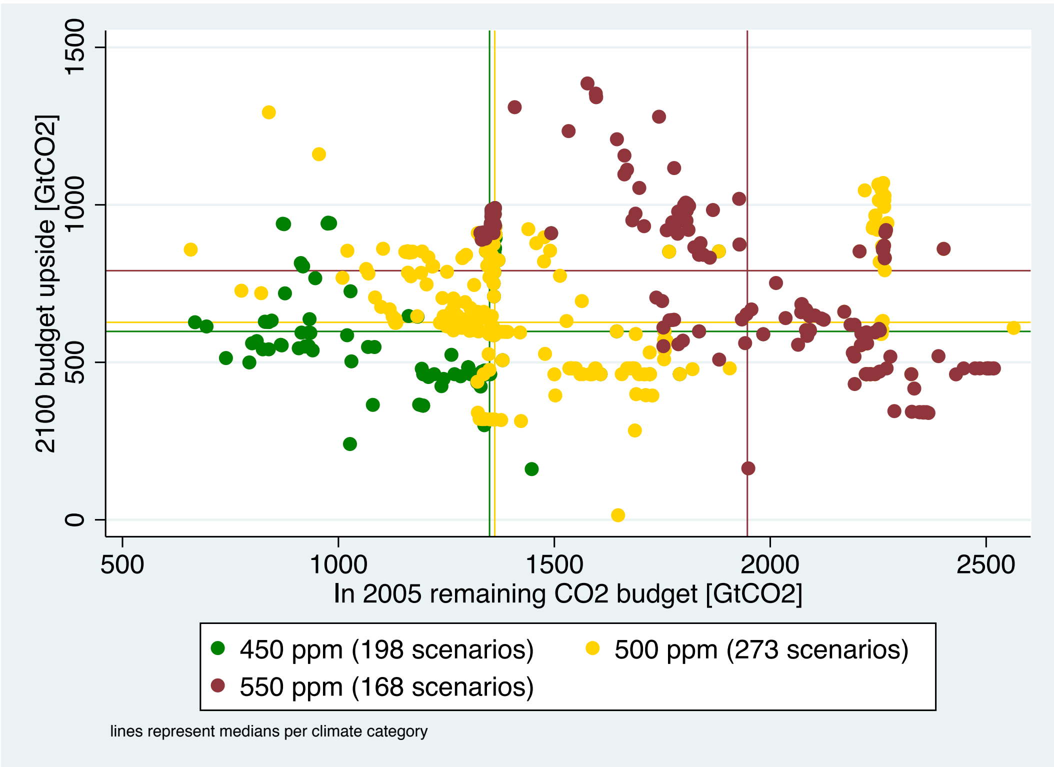
CO_2 BaR over time (Panel a), BaR distribution over category (Panel b), and BaR share of total carbon budget distribution over category (Panel c).

***Figure 6** Remaining global CO_2-only budget in 2005, by climate category*



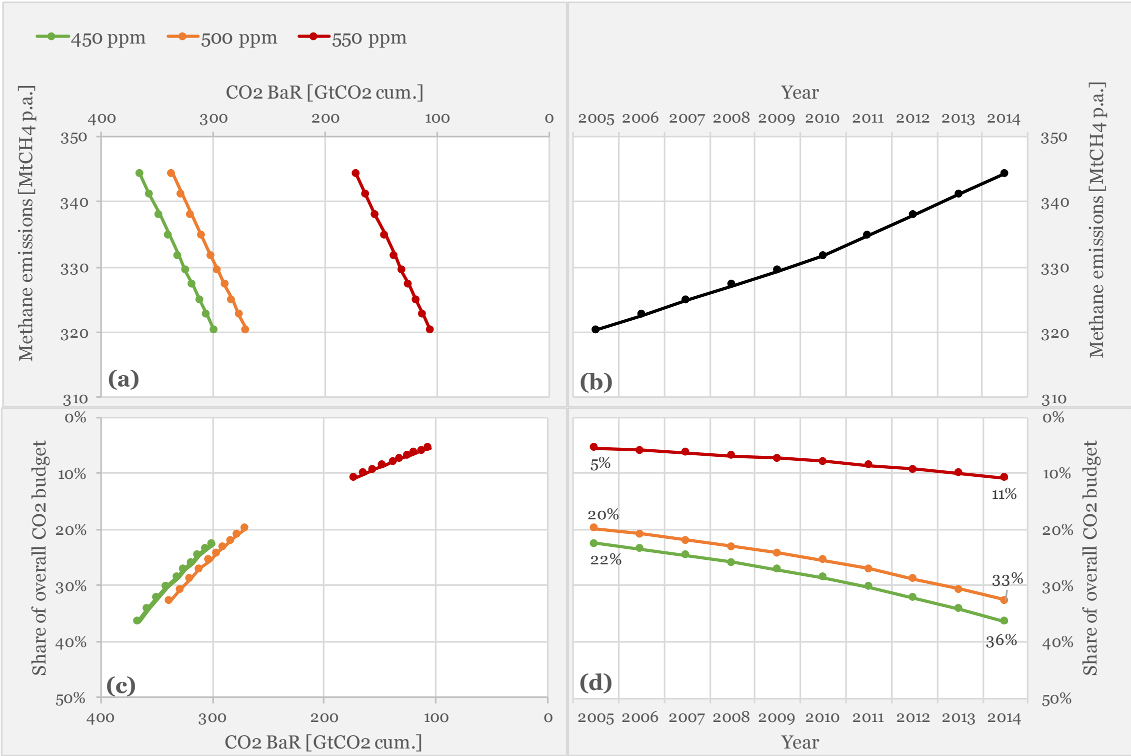
Differences in 2005 available CO_2 budget within a certain category are partially caused by different expected methane emission pathways.

***Figure 7** Global CO_2 Budget upside potential in 2005 compared to overall remaining CO_2 budget in 2005, by climate category (medians represented by vertical and horizontal lines)*



For more ambitious scenarios the upside potential of reducing methane emissions below their expected 2100 levels is much smaller as substantial methane emission reductions from current levels are already expected.

Figure 8 *Annual methane emission levels and BaR*



The relationship between annual methane emission levels and CO_2 BaR (panel a), development of methane emissions 2005-14 (panel b), BaR share 2005-14 (panel c), and relationship between CO_2 BaR and BaR share (panel d).

Appendix C: Additional tables

Table 3 *Regional methane emission reductions and BaR in the 480-530 and 530-580 ppm scenarios*

Region	480-530 ppm scenarios			530-580 ppm scenarios		
	Number of scenarios in sample	Median reduction in 2005-2100 CH_4 emissions	Median share of BaR of regional 2005 CO2 budget	Number of scenarios in sample	Median reduction in 2005-2100 CH_4 emissions	Median share of BaR of regional 2005 CO2 budget
Asia	254	-29%	15%	140	-16%	7%
Latin America	252	-11%	6%	115	-3%	34%
Middle East and Africa	254	43%	-22%	119	39%	-25%
OECD90	269	-56%	24%	140	-60%	21%
Reforming Economies	202	-51%	48%	100	-70%	36%
World	**270**	**-31%**	**15%**	**140**	**-10%**	**4%**

Required methane emission reductions and share of remaining CO_2 Budget at Risk (BaR) from current methane emission levels in 2005 by region, for 480-530 and 530-580 ppm climate scenarios.

Table 4 *Country-specific methane emission reductions and BaR in the 480-530 and 530-580 ppm scenarios*

Country	480-530 ppm scenarios			530-580 ppm scenarios		
	Number of scenarios in sample	Median reduction in 2005-2100 CH_4 emissions	Median share of BaR of regional 2005 CO2 budget	Number of scenarios in sample	Median reduction in 2005-2100 CH_4 emissions	Median share of BaR of regional 2005 CO2 budget
Brazil	26	-46%	54%	0	-	-
China	65	-79%	18%	0	-	-
EU	65	-79%	24%	0	-	-
India	65	50%	-22%	0	-	-
Japan	44	-74%	4%	0	-	-
Russia	53	-74%	58%	0	-	-
USA	65	-72%	19%	0	-	-
World	**270**	**-31%**	**15%**	**140**	**-10%**	**4%**

Required methane emission reductions and share of remaining CO_2 Budget at Risk (BaR) from current methane emission levels for selected countries in 2005, for 480-530 and 530-580 ppm climate scenarios.

Table 5 *Comparison between 2005 and 2014 in the 430-480 ppm scenario*

430-480 ppm scenarios	**2005**	**2014**	**Change**
Annual methane emissions [$MtCH_4$ p.a.]	332[A]	344[B]	+3.6%
Median 2100 level of methane emissions [$MtCH_4$]	213	213	-
Required change 2005-2100	-36%	-38%	+2 pp
CO_2 BaR [$GtCO_2$]	332	367	+11%
Median remaining total CO_2 budget [$GtCO_2$]	1,333	1,004[C]	-25%
BaR share of total CO_2 budget	**~25%**	**~37%**	**+12 pp**

A Based on analyzed databases. More recent data from the Global Methane Budget 2016 suggests 2005 methane emissions amounted to 320 $MtCH_4$ (Le Quéré *et al.*, 2016).

B According to the Global Methane Budget 2016 (ibid.).

C According to the Global Carbon Budget 2016 (Clark *et al.*, 2016) 329 $GtCO_2$ cumulative CO_2 emissions 2005-2014.

Annual global methane emissions between 2005 and 2014 have increased by 3.6% to ~344 $MtCH_4$ per year. Therefore, to meet expected 2100 levels of ~213 $MtCH_4$ per year (median 430-480 ppm scenario) emission levels must decrease by 38% (or ~131 $MtCH_4$ per year). This, yet to be achieved, decrease can be converted into ~367 $GtCO_2$ cumulative carbon budget that would have the same warming effect as a sustained rate of 131 $MtCH_4$. 367 $GtCO_2$ is equivalent to ~37% of overall remaining carbon budget in 2014 (median 430-480 ppm scenario).

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[i] First author: **Alexander Pfeiffer** (INET, SSEE) Co-authors: **Richard Millar** (INET) – Helped developing the methodology, provided substantial input to introduction, methodology, and literature review sections; and **Cameron Hepburn** (INET, SSEE) – Overall comments and small edits, provided substantial input to introduction section.

Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement

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Abstract

Over the coming decade, the power sector is expected to invest ~7.2 trillion USD in power plants and grids globally, much of it into CO_2-emitting coal and gas plants. These assets typically have a long lifetime and commit large amounts of (future) CO_2 emissions. Here, we analyze the historic development of emission commitments from power plants and compare the emissions committed by current and planned plants with remaining carbon budgets. Based on this comparison we derive the likely amount of stranded assets that would be required to meet the 1.5-2°C global warming goal. We find that even though the growth of emission commitments has slowed down in recent years, currently operating generators still commit us to emissions (~300 $GtCO_2$) above the levels compatible with the average 1.5-2°C scenario (~240 $GtCO_2$). Furthermore, the current pipeline of power plants would add almost the same amount of additional commitments (~270 $GtCO_2$). Even if the entire pipeline was cancelled, therefore, ~20% of global capacity would need to be stranded to meet the climate goals set out in the Paris Agreement. Our results can help companies and investors re-assess their investments in fossil-fuel power plants, and policymakers strengthen their policies to avoid further carbon lock-in.

Keywords: life cycle assessment, stranded assets, carbon budget, committed emissions, electricity generation, climate policy *JEL:* Q01; Q4; Q54; Q5

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1. Committed CO_2 emissions and carbon budgets in the power sector

The power sector is expected to invest about 7.2 trillion USD in power plants and transmission and distribution grids over the next decade (IEA, 2016). The average expected lifetime of generators can range from 20-25 years for solar PV up to 70 years and longer for hydro-electric generators (EIA, 2011; IEA, 2016). Coal-, gas- and oil-powered generators have a typical lifetime of between 35-40 years (Davis and Socolow, 2014). These lifetimes probably represent only economic rather than technical lifetimes, however, since many power generators operate long beyond their expected end of life. The relatively long payback periods for such assets expose investments to the risk of future changes in economic and regulatory conditions. Changes in input prices, the competitive landscape, or regulation can have large impacts on the profitability and economic viability of such assets, before they have a chance to pay their investment back (Caldecott *et al.*, 2017).

These long lifetimes mean that any investment made today in carbon dioxide (CO_2) emitting infrastructure will have a considerable effect on the ability to achieve required CO_2 emission reductions in the future – even if these desired reductions are many years away (Davis, Caldeira and Matthews, 2010; Rozenberg *et al.*, 2015). In recent years, therefore, the concept of (expected) *committed cumulative carbon emissions* (hereafter referred to as *committed emissions*) has been developed, and gained popularity within the scientific community (Guivarch and Hallegatte, 2011; Davis and Socolow, 2014; Pfeiffer *et al.*, 2016; Shearer *et al.*, 2017). Committed emissions are the cumulative emissions an asset would emit over its remaining lifetime under normal economic conditions, i.e. if it were to be operated at normal utilization (Davis and Socolow, 2014).

To stabilize global warming at any level, not just 1.5°C or 2°C but virtually any level, anthropogenic emissions of long-lived climate pollutants (LLCPs) must eventually reach net-zero (Matthews and Caldeira, 2008). Therefore, global warming can be seen as a function of the cumulative emissions of such LLCPs, chiefly CO_2, rather than of annual emission rates (Matthews and Caldeira, 2008; Allen *et al.*, 2009; Matthews *et al.*, 2009; Meinshausen *et al.*, 2009). The cumulative future emissions of currently operating and planned infrastructure, are therefore likely to be much more relevant to climate outcomes than the individual annual emissions of such assets (Millar *et al.*, 2015, 2016). In this regard, it should be noted that power and heat generation was responsible for ~38% of total global emissions in 2014 (IEA, 2016; Le Quéré *et al.*, 2016), more than any other sector. Committed emissions from power plants are, therefore, particularly important for climate policies.

Davis and Socolow (2014) suggest a methodology for *Commitment Accounting of CO_2 Emissions* in the power sector, and find that, under standard lifetime assumptions, in 2012, assets in the power sector were committed to ~307 $GtCO_2$ future emissions and that these commitments had been growing at ~4% per year over the previous decade. Based on their results Pfeiffer et al. (2016) calculated that 2017 would be the year when the global *2 ℃ Capital Stock for Electricity Generation* was reached, i.e. when existing power generators would commit to enough CO_2 emissions, to consume the remaining generation-only carbon budget for a 50% chance for global warming below 2°C. Other studies have since used the same or similar methodologies to calculate the CO_2 emission commitments of different assets or sectors and assess their impact on climate policies, investments and the consequent costs of achieving climate goals (Bertram *et al.*, 2015; Johnson *et al.*, 2015; Rozenberg *et al.*, 2015; Sanchez *et al.*, 2015; Shearer, Fofrich and Davis, 2017).

This paper updates previous efforts, especially those of Davis & Socolow (2014) and Pfeiffer et al. (2016), by using an improved generator database and updating this data to late-2016. Moreover, for the first time, we include generators currently under construction, or in different stages of the planning process, to estimate the development of future committed emissions from the global pipeline of currently planned power generators. Finally, we use a significantly improved estimate of the currently remaining generation-only carbon budgets for different climate scenarios (compared to Pfeiffer et al., 2016), and compare this new estimate with the emission commitments. This effort allows us to derive the likely cumulative amount of power sector stranding each climate scenario would imply.

The updated capital stock and budget numbers suggest that 2017, the previous estimate for the commitment year for the 2-degree Celsius capital stock (Pfeiffer *et al.*, 2016), might have been too optimistic – however, not by far. The cross-comparison with recently updated carbon budget figures (Millar *et al.*, 2017) suggests that the commitment year for a realistic chance to limit warming to only 2°C was probably sometime between 2011 and 2016. Consequently, we find that the committed cumulative future emissions from currently operating power plants (~300 $GtCO_2$) would now already surpass the currently available generation-only carbon budget for the average 430-480 ppm scenario (~240 $GtCO_2$). In addition, plants in various stages of the planning process would add almost the same amount of commitments (~270 $GtCO_2$) as those plants currently operational. Even if all currently planned projects are immediately suspended, up to 20% of global fossil-fuel generation capacity would still have be stranded (that is, prematurely decommissioned, underutilized, or subject to costly retrofitting) if humanity is to meet the climate goals set out in the Paris Agreement.

2. Data and Methods

We calculate historic and current committed emissions from currently operating, planned and already retired power generators.[1] Since these are not typically reported in any publicly available source, we use existing databases on generator capacity vintages (in GW), combined with (historic) average annual utilization rates (in percent), heat rates (in mbtu per GWh), fuel emission factors (in tCO_2/mbtu), and expected operational lifetimes. In the rest of this section we describe the databases and sources used (2.1), and how we calculate the

[1] We differentiate between generator and plant. The generator is the device that generates the electrical power for use in an external circuit. A plant can consist of several generators. We calculate committed emissions on a generator level since generators within plants are often replaced, such that the remaining lifetime of a plant is less helpful than the remaining lifetime of a generator.

committed emissions and how this differs from previously used methodologies (2.2).

2.1 Databases and sources

We determine generation capacities by merging all generators from the most recent versions of five databases: (1) CoalSwarm (Feb 2017); (2) Platt's UDI World Electric Power Plants (WEPP) database (Q4 2016); (3) Greenpeace's database of planned coal generators in China; (4) Sekitan's Japan coal-fired power plant database (Q1 2016); and (5) Kiko Network's Japan coal-fired power plant database (Q1 2016). We merge these sources by manually confirming unique power plant names, locations, current statuses, online years and capacity, using internet research as required.[2] The most recent data is used where matched generators have conflicting fields (for example different operating statuses). The resulting database effectively defines the locations of all the world's power generators, their ownership, age, fuel type, technology, expected lifetime and capacity. It is particularly current and comprehensive for coal-fired power generators, the most carbon-intensive assets.[3]

We use three additional sources to calculate committed emissions: (1) current and historic heat rates from the U.S. Energy Information Agency (EIA) and the U.S. Environmental Protection Agency (EPA) (EPA, 2009; EIA, 2017);[4] (2) emission factors for individual fuels from the EIA (EIA, 2016);[5] and (3) global technology specific utilization rates for power generators from the International Energy Agency, IEA's World Energy Outlooks (WEO) 2005-15.

2.2 Approach and methods

Davis & Socolow's (2014) *Commitment Accounting of CO_2 Emissions* marks the first time a comprehensive methodology has been described to calculate future emissions from existing power generators. One criticism of their approach, however, applies to CARMA,[6] one of the databases they use. They make the "*arbitrary assumption that CARMA's emissions and energy data for 2009 (or, occasionally, 2004) are an accurate estimate throughout a plant's lifetime*" (Davis and Socolow, 2014). 2009 was in many respects not a representative year for global energy consumption and emissions – in fact, with the financial and economic crisis at its height, 2009 was one of the few years in recent decades in which global emissions decreased year-on-year (Le Quéré *et al.*, 2016). In this paper, we therefore refine the approach described by Davis & Socolow.

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[2] Most generators could be matched using an algorithm. Only generators that did not match were manually confirmed.

[3] See Appendix A.2 for additional limitations of the final database used.

[4] The EIA and EPA provide data on current and historic heat rates for different generators, turbine types, and fuels. Historic EIA data on technology level goes back to 2001 and aggregated data for all fossil fuels back to 1949.

[5] Datasets obtained from the EIA contain emission factors for different fuels, i.e. the amount of CO_2 in relation to the energy content of e.g. coal, lignite, oil, etc.

[6] CARMA: Carbon Monitoring for Action (CARMA, 2010).

First, a broader and updated (late-2016) base of power generators is used that completes known gaps in the Platt's UDI WEPP database, e.g. in microgeneration and in China (see Section 2.1). Second, for missing online years[7] a similar, but more granular, methodology was used as the one described by Davis & Socolow. Most importantly, the estimation of online years and lifetimes is conducted based not only on technology, capacity and country, but also by taking account of generator and turbine type, online year (for lifetimes), and steam-type (e.g. subcritical vs. supercritical).

Third, actual lifetimes were simulated by using a Poisson distribution around the expected lifetimes of the power generators. This simulates managerial discretion as to when power generators are retired, and accommodates the fact that generators are rarely retired in the exact year of their estimated end of life. As expected lifetimes we use the median end-of-life age of already retired generators with the same fuel and technology, and similar nameplate capacity. Expected lifetime represents the economic rather than the technical lifetime (taking the maximum lifetime of similar already retired generators would come closer to the technical lifetime).

Fourth, instead of applying the CARMA database for the annual emissions of these generators, a different approach was applied. Generator-specific technical data was combined with (year-specific) heat rates and fuel emission factors from the EIA and EPA to calculate annual maximum emissions per generator. When multiplied by the simulated lifetime of each generator, and the historic (average) utilization rates, from the IEA, this results in an estimate of actual historic, current and expected electricity generation and emissions. By using historic average utilization rates over many years (ten years between 2004-2014) instead of a point estimate (CARMA uses 2009 utilization rates), a more realistic estimate of future utilization can be achieved. A detailed description and discussion of this methodology and in particular the use of historic average utilization rates can be found in Appendix A.1.

The described approach results in an emission commitment estimate of ~300 $GtCO_2$ in 2016. This estimate is ~14% lower than an extrapolation of Davis & Socolow's results suggests, and implies that currently operating capital stock commits to significantly less future emissions than expected only four years ago. While the methodological differences explain some of the variance, the real-world explanation for this is that, in recent years, since Davis & Socolow's paper, the growth rate of committed emissions was much lower than expected. Between 2012 and 2016 emission commitments grew only by 2.1% p.a. globally instead of the 4% p.a. as expected based on Davis & Socolow's results. In some regions, emission commitments even decreased significantly in this period (see Section 3.1). These results are particularly sensitive towards generator lifetimes and utilization rates. We discuss these sensitivities in section 3.4.

3. Findings

We find that currently operating generators would already commit to more future CO_2 emissions (~300 $GtCO_2$) than would be consistent with the remaining

[7] The online year refers to the year in which the generator started operations.

generation-only carbon budget in the median 430-580 ppm scenarios. For a good chance for warming below 2°C (430-480 ppm scenarios) ~20% of currently operating capital stock would have to be stranded. Instead, the pipeline of currently planned generators would add another ~270 $GtCO_2$ to the capital stock.

3.1 Committed emissions of generators operating in late-2016

In late-2016, a global total of ~161,000 generators in our database were labelled as *operating*, *idle*, *stand-by*, or with a similar status indicating that a power generator was still in operation (Table 1). This comprises ~6,200 GW of installed capacity, which has, on average, operated since 1997, and which had a remaining lifetime of 18 years in 2016 (see Appendix C.1 for a full table with descriptive statistics).

Table 1: Installed capacity and remaining committed emissions of electricity generators operating in 2016.

	Capacity [GW]	**Remaining cum. generation** [TWh]	**Remaining cum. emissions**[8] [$GtCO_2$]
COAL	2,136	263,959	220.1
GAS	1,385	92,534	65.9
OIL	428	11,245	7.6
WASTE	296	12,697	11.2
BIOENERGY	57	5,475	2.9
RENEWABLES*	1,522	134,256	-
OTHER**	384	17,106	0.1
Total	**6,207**	**537,272**	**307.7**

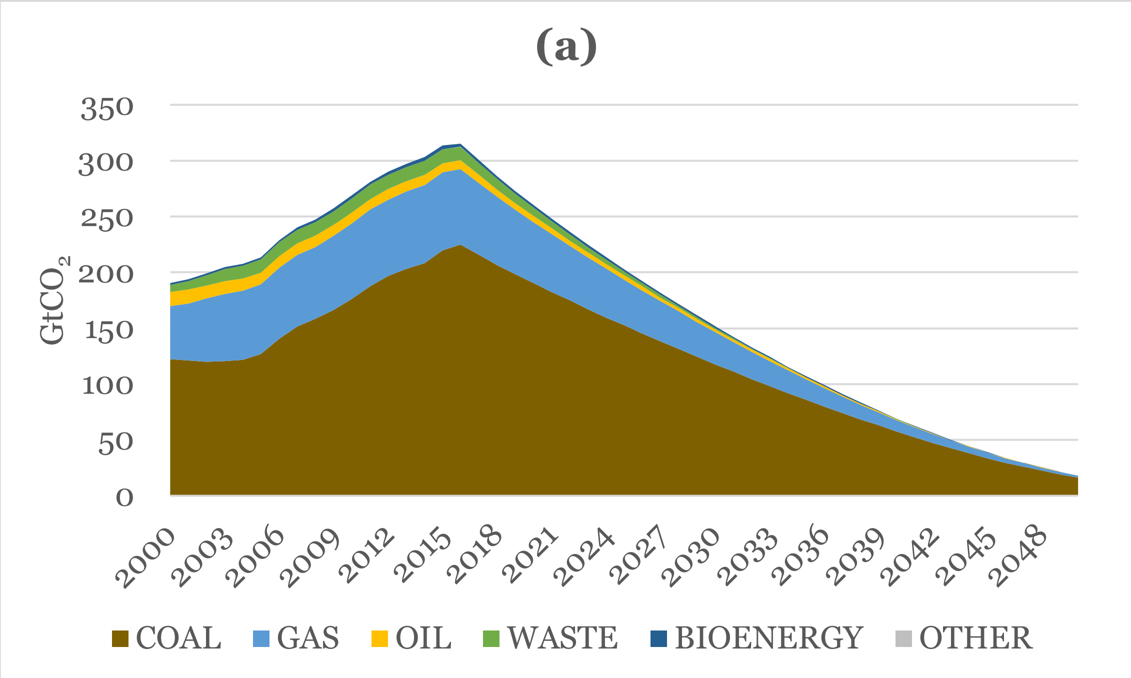
** Renewables include hydro, solar and wind, and do not result in committed emissions.*
*** Other includes nuclear and geothermal; the non-zero committed emissions associated with these generators stems from a small amount of fugitive emissions from geothermal power generation.*

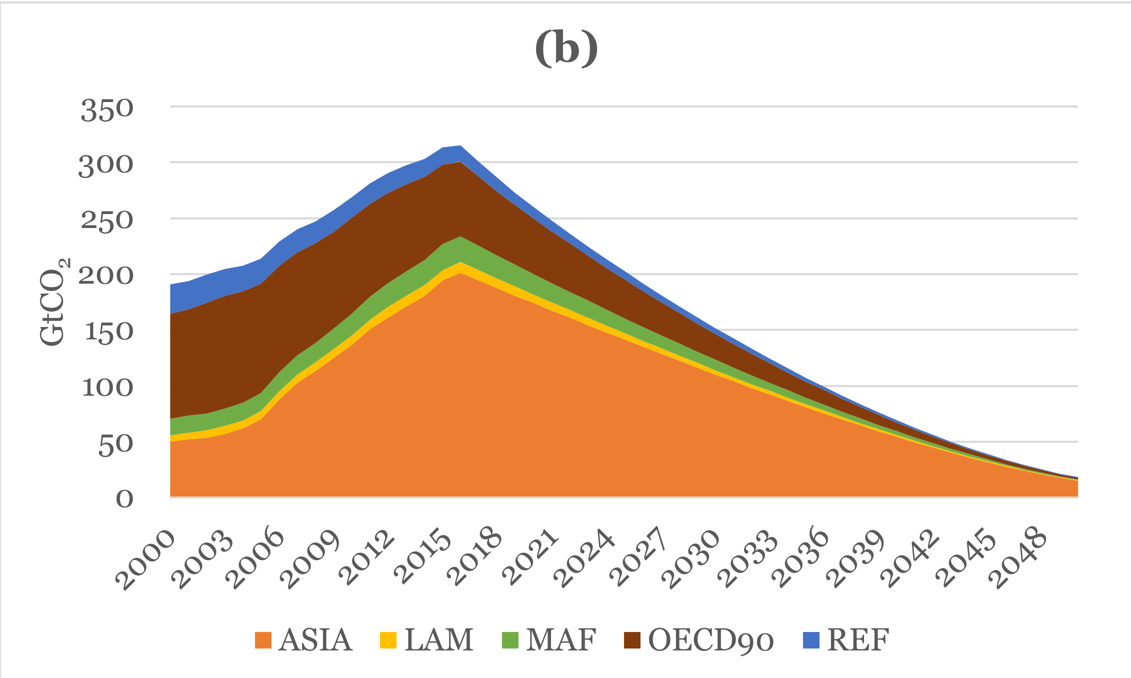
Overall, this capacity, if operated over its full remaining lifetime at current utilization rates, could generate ~537k TWh (~23 years of generation at current levels)[9] and would emit ~300 $GtCO_2$ over the coming decades (i.e. ~7 years-worth

[8] Cumulative CO_2 emissions that can be expected from the future operation of these generators over an expected economic lifetime under standard economic conditions.

[9] According to the IEA the 2014 global electricity generation was 23,808 TWh.

of current total global CO_2 emissions)[10]. These committed emissions are largely locked-in by coal generators (~71%) and located in Asian countries (~64%).[11]





ASIA: All non-OECD Asian countries | LAM: All non-OECD Latin American countries | MAF: Middle East and Africa | OECD90: OECD countries | REF: Reforming Economies of the former Soviet Union (also known as Economies in Transition, EIT)

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[10] According to the Global Carbon Budget Project, total CO_2 emissions (Fossil Fuel & Industries and Land-use) in 2015 were 41 $GtCO_2$ (Le Quéré *et al.*, 2016).

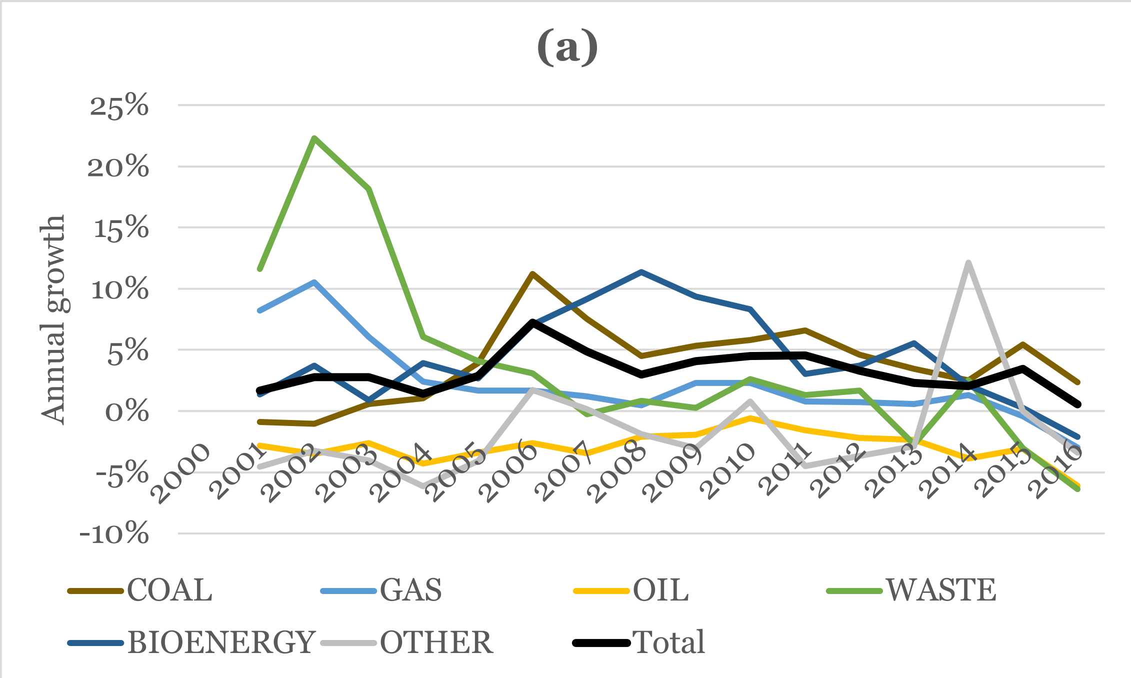
[11] See Appendix C.2 for the full regional split.

Figure 1: Historic development of committed emissions from electricity generators in operation in 2016, by technologies (panel a) and regions (panel b). *The strongest growth between 2005 and 2016 took place in Asia and comes from coal emission commitments. After 2016, emission commitments would decrease as indicated if no further investments in polluting capital stock take place.*

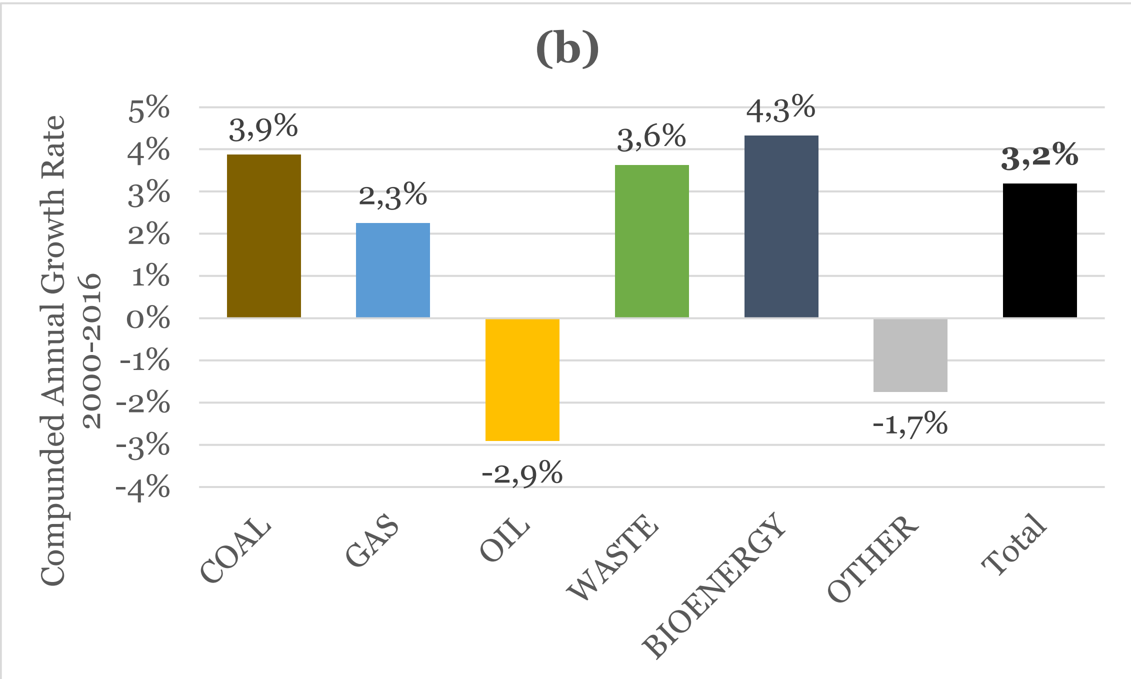
Figure 1 shows the development of committed emissions over time by technologies (panel a) and regions (panel b). After the present day, we show decreasing commitments as they 'realize' into actual emissions. Committed emissions from coal decreased by 1.4% between 2000 and 2003, presumably because coal capacity was replaced by gas, which grew by ~26.8% in the same period. Most of the growth in committed emissions after 2005, however, comes from coal-fired generators which accounted for 59% of total committed emissions in 2005 and account for 71% today. In recent years, Asia[12] has seen an especially strong increase in commitments. In 2000, committed emissions in Asia accounted for approximately one quarter of the global total but this share had increased to almost two thirds in 2016. Especially after 2004, most of the overall growth in emission commitments has come from the addition of fossil-fuel-powered generators in Asia.

Figure 2 provides more details on annual growth rates of committed emissions. Countries of the former Soviet Union and OECD countries (since 2004) have seen a decrease in overall commitments from power generators, indicated by negative annual growth rates (panel c). This development indicates that annual retirements or realizations of committed emissions are larger than additions to the capital stock. Panel a confirms the previous finding that the growth rates of gas capital stock between 2000 and 2003 crowded out coal infrastructure (negative growth rates) but were subsequently replaced by coal again. The overall annual growth of coal capital stock remains strong in 2016 (~2.1% p.a.) while all other CO_2 emitting capital stock has decreased over the last couple of years.

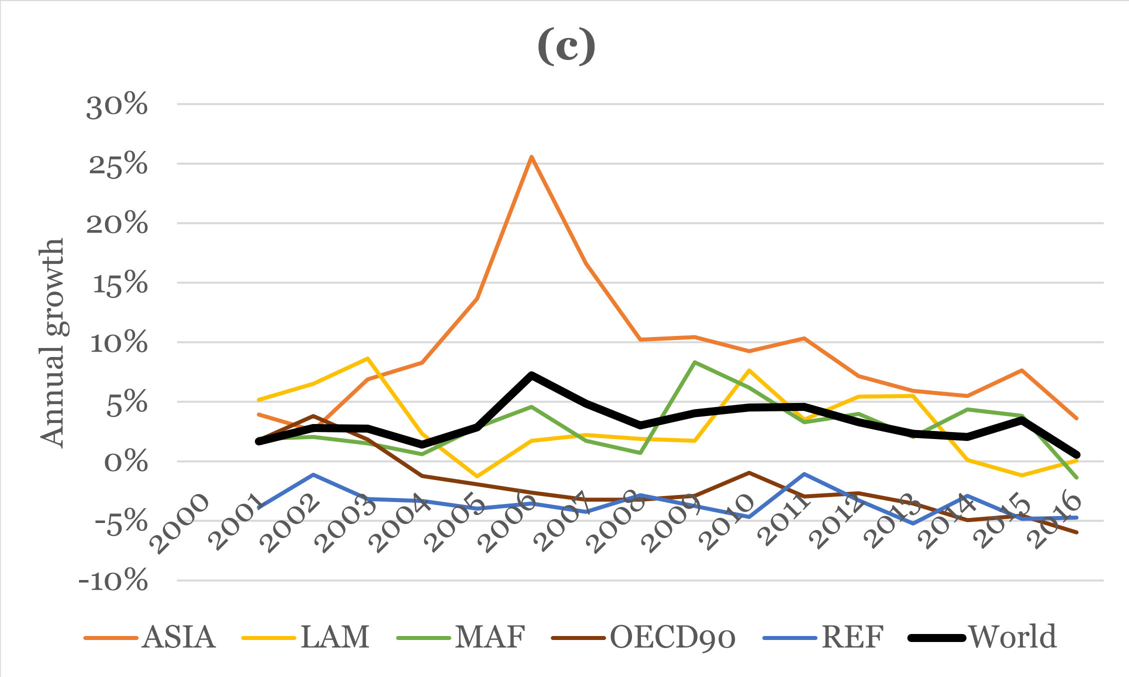
[12] Our definition of Asia includes all non-OECD Asian countries (i.e. most Asian countries except the Middle East, Japan and countries of the former Soviet Union.



(a)
25%
20%
15%
10%
5%
0%
-5%
-10%
Annual growth
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
COAL
GAS
OIL
WASTE
BIOENERGY
OTHER
Total



(b)
Compunded Annual Growth Rate 2000-2016
5%
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
3,9%
2,3%
-2,9%
3,6%
4,3%
-1,7%
3,2%
COAL
GAS
OIL
WASTE
BIOENERGY
OTHER
Total



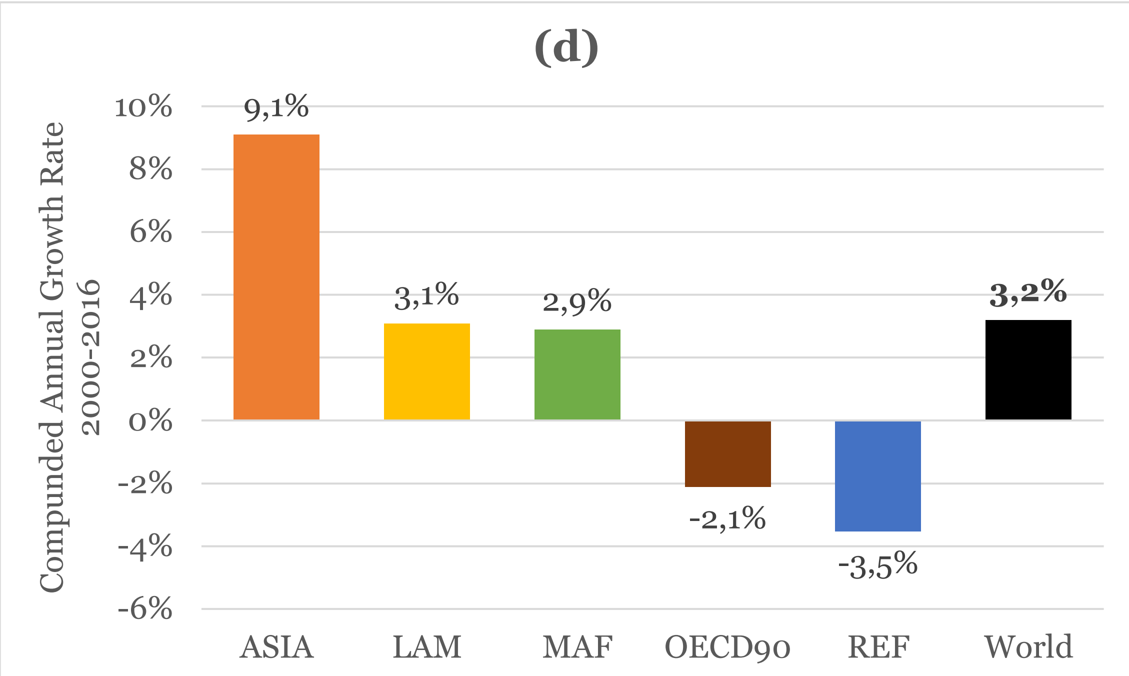


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Figure 2: Historic annual growth rates and compounded annual growth rates (CAGR) between 2000 and 2016 of emission commitments from electricity generators in operation in 2016, by technologies (panels a and b) and regions (panels c and d). *Countries in the OECD and REF have seen a reduction of their commitments over the past 16 years. On the technology side, oil, in particular, has seen less additions than realizations (or retirements) of commitments (negative growth rates).*

We find that, on average, emission commitments from electricity generators grew by 3.2% per year between 2000 and 2016, and that most of that overall growth came from coal generators (3.9% p.a.) and happened in Asia (9.1% p.a.). The only technologies with stronger or similar committed emissions growth rates to coal were bioenergy (4.3% p.a.) and waste (3.6% p.a.). Growth in these technologies took place from a much lower base, however, and was hence negligible for overall committed emissions growth. Besides Asia, countries in Latin America (3.1% p.a.) the Middle East and Africa (2.9% p.a.) experienced committed emissions growth in the analyzed period, while OECD countries (-2.1% p.a.), and countries of the former Soviet Union (REF) (-3.5% p.a.), decreased their remaining committed emissions from electricity capital stock.

3.2 The pipeline of planned electricity generators in early 2017

In addition to the previously described operating generators, in early-2017 ~24,000 further generators were either under construction (845 GW in ~5,200 generators) or in some stage of the planning process (2,597 GW in ~18,900 generators). Overall, this pipeline of generators would add ~3,440 GW to the global capital stock and add ~270 $GtCO_2$ to the committed future carbon emissions.

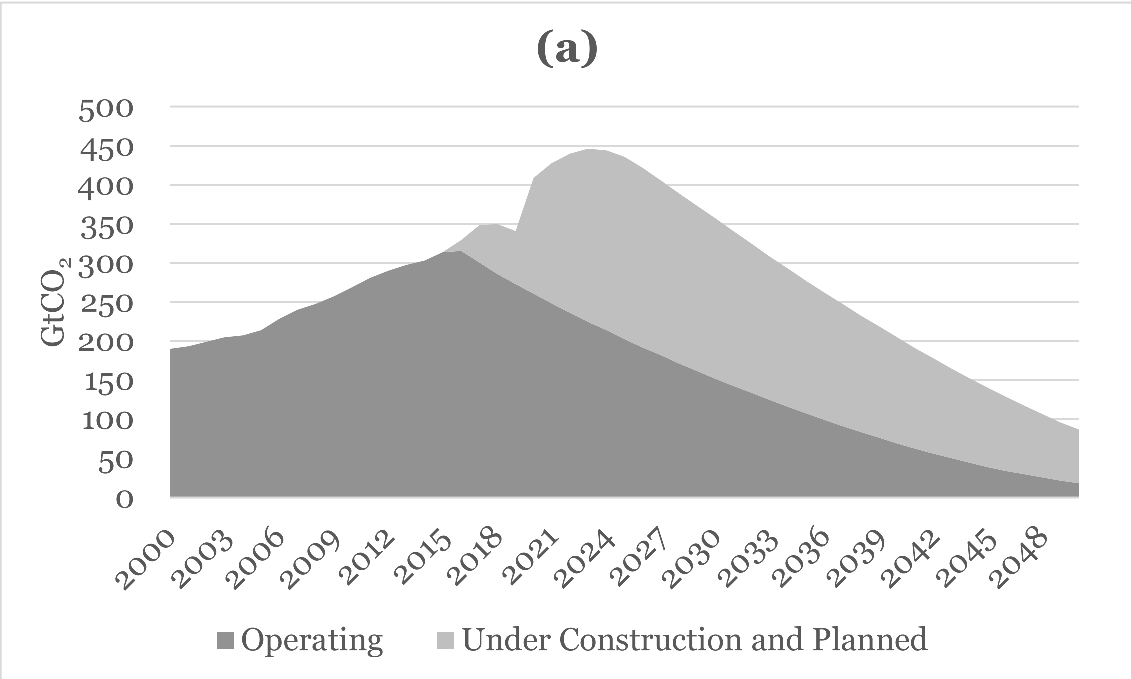
Table 2: Cumulative emissions of electricity generators under construction or planned in early 2017, by technologies and regions.

[$GtCO_2$]	**Asia**	**Latin America**	**Middle East & Africa**	**OECD 90 countries**	**Reforming Economies (former USSR)**	**Global**
Coal	162.4	2.6	13.1	23.1	8.8	210.0
Gas	11.3	3.1	12.3	18.0	3.8	48.7
Oil	0.4	0.3	1.6	0.2	0.0	2.5
Waste	1.1	0.7	2.4	3.2	0.5	7.8
Bioenergy	0.4	0.2	0.1	0.9	0.1	1.6
Renewables*	-	-	-	-	-	-
Other**	0.1	0.0	0.0	0.1	0.0	0.2
Total	**175.6**	**6.9**	**29.5**	**45.5**	**13.2**	**270.8**

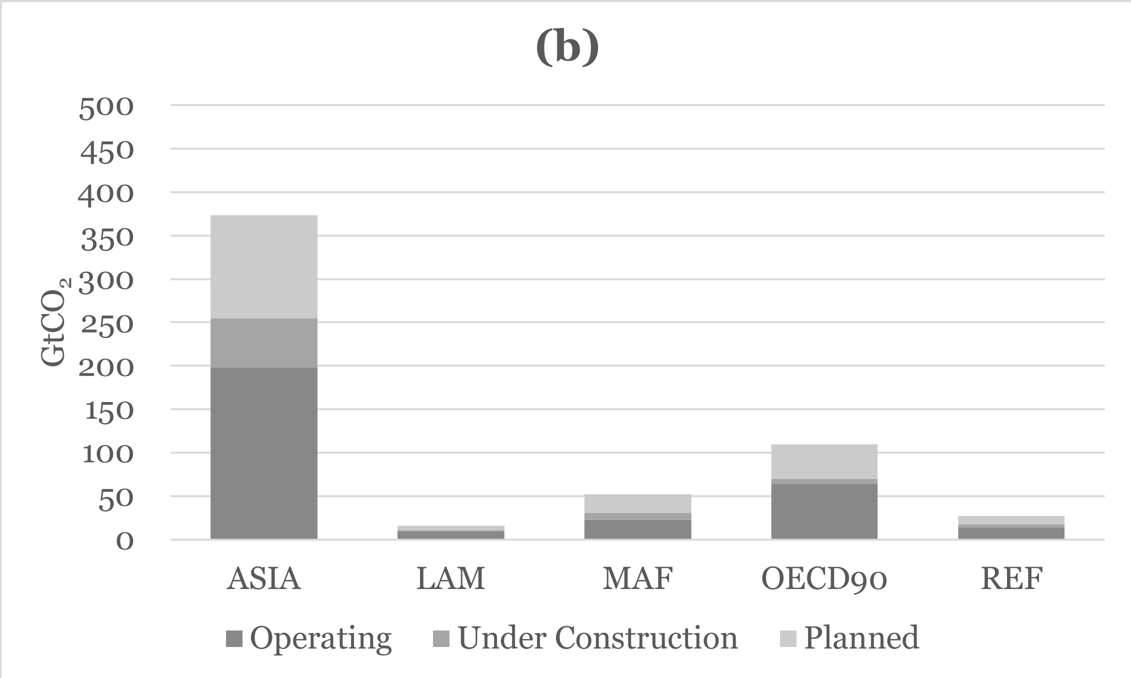
** Renewables include hydro, solar and wind, and do not result in committed emissions. ** Other includes nuclear and geothermal; the non-zero committed emissions associated with these generators stems from a small amount of fugitive emissions from geothermal power generation.*

In Table 2 we split this pipeline of committed emissions by technologies and regions. Consistent with the development in recent years already illustrated above, by far the largest share of planned committed emissions is occupied by coal (~78%) and is planned in Asia (~65%). Just by finalizing all planned coal-fired generators, the world would add an additional five years of total global CO_2 emissions at current levels. Gas-fired generators follow with 18% and are expected to add ~50 $GtCO_2$ to the global capital stock (~1.2 years of current total emissions).

If all current plans and construction projects for carbon emitting power generators were to be stopped, however, the remaining committed emissions in 2050 would amount to ~20 $GtCO_2$. If, however, all planned generators were to be built and come online, then remaining commitments in 2050 would be 4-5 times higher (~90 $GtCO_2$). Figure 3 (panel a) illustrates this. Panel d shows the regional split of the current pipeline. In Asia, almost as much polluting capital stock is either planned (119 $GtCO_2$) or already under construction (57 $GtCO_2$) as is currently operating (198 $GtCO_2$).[13]



[13] See Appendix B.1 for split by technologies.



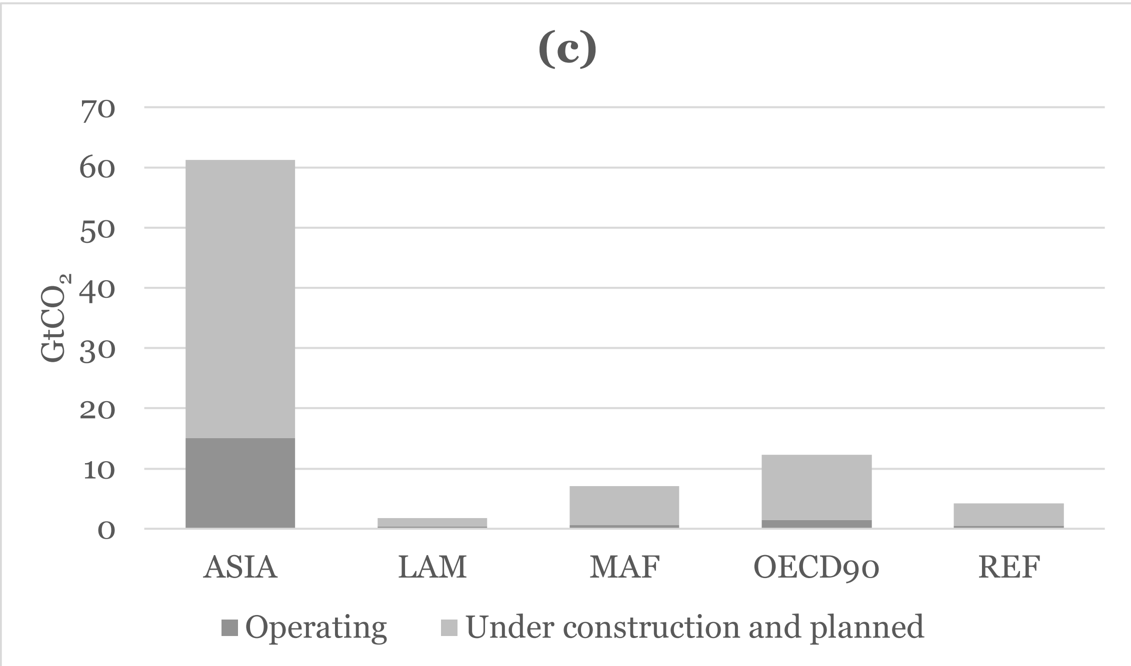


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Figure 3: Historic (until 2016) and expected (thereafter) development of committed emissions from electricity generators in operation, under construction, or planned in 2016, by status (panel a), 2016 committed emissions by regions (panel b), and remaining emission commitments in 2050 if 2016 under construction of planned generators will be built (panel c). *The dent between 2018 and 2020 in panel (a) stems from the methodology that has been used to assign online year to generators that are delayed (after construction start) or deferred (before construction start) in 2016.*

These findings consider all generators that were either planned or under construction in early 2017. This should include most changes, especially cancellations in the global coal pipeline, that were made before February 2017.[14] In 2016 and early 2017, many previously planned coal-fired generators were cancelled (Shearer *et al.*, 2017). Most prominently, in January 2017, China announced the cancellation of 103 planned coal power plants with a combined capacity of 130 GW (Forsythe, 2017). Based on our analysis, this capacity alone would have added an additional ~23 $GtCO_2$ to the capital stock (~9% of planned committed emissions). Despite these recent cancellations, however, our analysis suggests that currently planned power generators would add a very significant amount of emission commitments to the already existing global capital stock. Much of this would still be left in 2050 when most economies around the world will already have to be widely decarbonized if the world were to reach its 1.5-2°C target (panel c).

3.3 Compatibility of the capital stock with remaining carbon budgets

To improve on the previous estimates of the currently remaining generation-only carbon budget we use all scenarios, assessed by the *Intergovernmental Panel on Climate Change* (IPCC) for its *5th Assessment Report* (AR5) (IPCC, 2013; IIASA, 2014b) combined with the results from a further climate modelling effort from a recent cross-comparison IAM[15] study: AMPERE[16] (IIASA, 2014a; Kriegler *et al.*, 2015). The analysis of the scenario outputs from these two databases suggests that the median remaining carbon budget available in 2005 for a good chance for 1.5-2°C warming (430-480 ppm scenarios), was 1,333 $GtCO_2$. According to the same scenarios ~14% of that budget in 2005 was earmarked for electricity generation, leaving a net generation-only carbon budget in 2005 of ~187 $GtCO_2$. In addition to this net budget, the median 2005-2100 cumulative electricity generation from bioenergy with carbon capture and storage (BECCS) in these scenarios was ~1,330 EJ (~ 370,000 TWh). This amount of BECCS generation would remove ~110 $GtCO_2$ from the atmosphere by the end of the 21st century,[17] thereby increasing the carbon budget for electricity production.

Using the same calculation method for 480-530 ppm and 530-580 ppm scenarios, respectively, and updating these numbers over time with realized annual emissions (Le Quéré *et al.*, 2016), results in the annual remaining generation-only carbon budgets illustrated in Figure 4. For better comparison, we also include carbon budget estimates from a recently published study which finds that the remaining post-2015 carbon budgets for a 50% chance for 1.5°C or 2°C warming were 817 $GtCO_2$ and 1,524 $GtCO_2$, respectively (Millar *et al.*, 2017).[18]

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[14] See Appendix A.2 for limitations with respect of the global generator pipeline.

[15] IAM: Integrated Assessment Model.

[16] AMPERE: Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates.

[17] 83 $MtCO_2/EJ$ (Kriegler *et al.*, 2013).

[18] To calculate generation-only carbon budgets we also multiply these total carbon budgets with 14% and add 110 $GtCO_2$ BECCS carbon removal.

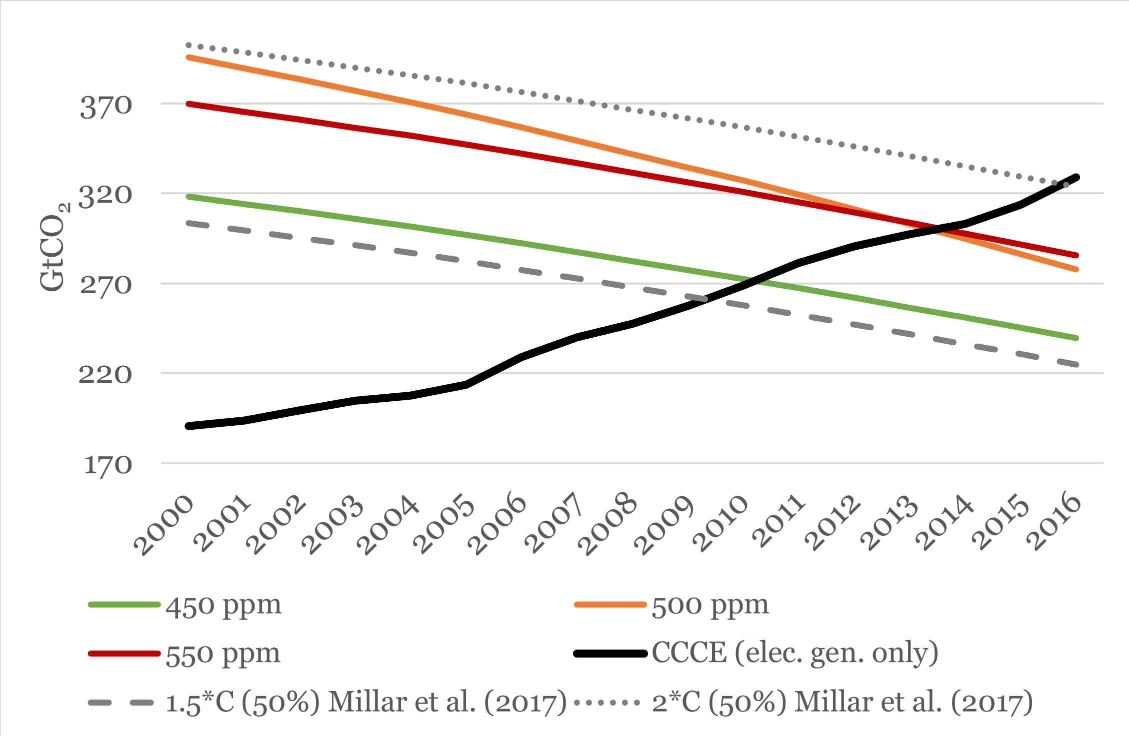

Figure 4: Development of remaining generation-only carbon budget in different climate scenarios (median) and committed emissions from generation capacity. *In 2011, committed emissions from electricity generators reached the remaining total generation-only budget for the median 430-480 ppm scenario (good chance for only 1.5-2 ℃ warming). In 2014, the remaining budget for the 480-530 and 530-580 ppm scenarios was reached. Following Millar et al. (2017), the generation-only budget for a 50% chance for warming of less than 2 ℃ was reached in 2016.*

We compare these remaining generation-only carbon budgets over time with the development of commitments from operating generators and find that the year in which built infrastructure committed us to enough emissions to reach the 1.5-2°C budget was in 2011, and hence six years earlier than previously estimated (Pfeiffer *et al.*, 2016). In 2014, emission commitments exceeded the remaining carbon budget for 480-530 and 530-580 ppm scenarios.

The above suggests that, if the climate goals set out in the Paris Agreement (UNFCCC, 2015) are to be reached, some of the existing and planned power plants will need to be underutilized, retired early, or retrofitted with expensive CCS or efficiency upgrades, or – in short – stranded. Figure 5 illustrates, for different climate goals, all combinations of stranding (in percent of normal utilization) between *old* (currently operating) and *new* (planned or under construction) power generators.

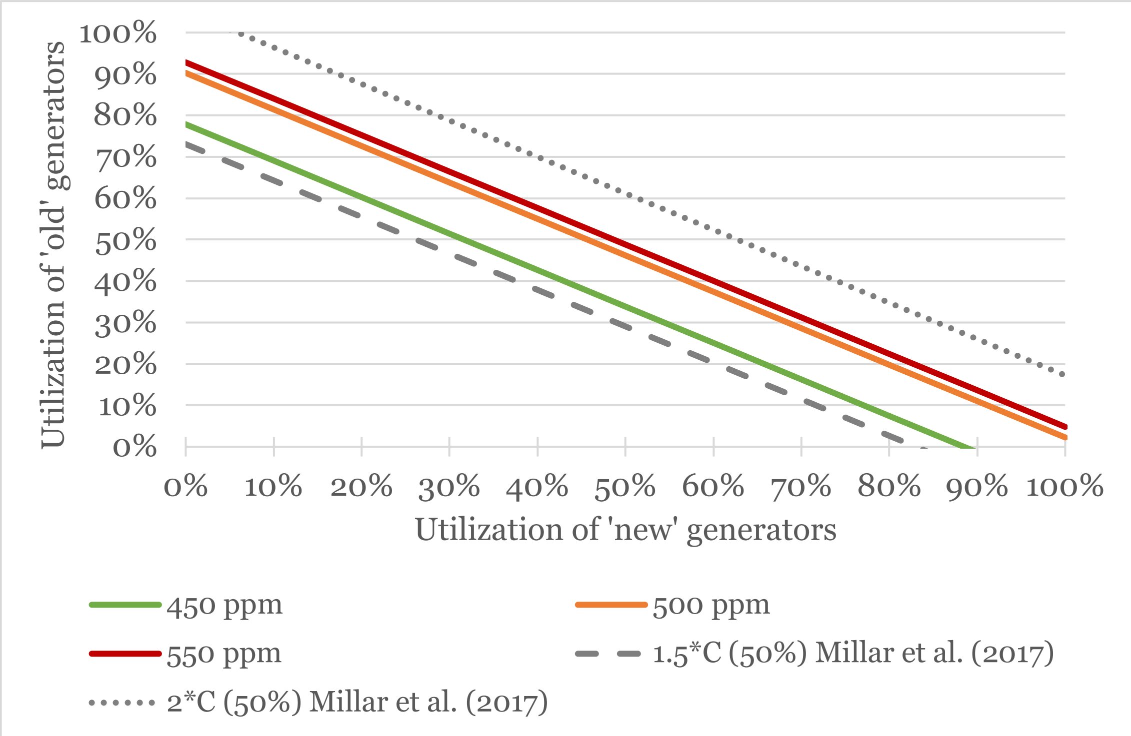

Figure 5: Different combinations of maximum possible utilizations of currently operating and pipeline electricity generators under different carbon budgets. *Even if plans for all new generators were to be cancelled, and current constructions halted (i.e. 0% utilization of new generators), already operating power generators could still only be utilized with ~80% (430-480 ppm) to ~90% (530-580 ppm) of their normal utilization to meet the respective climate goals.*

We find that, in different combinations, only 42% (430-480 ppm) to 49% (530-580 ppm) of the total capital stock of both operating and planned generators can be utilized. Even if every single currently planned project was cancelled, the generators that are already operating now would still have to see reduced utilization resulting in~20% of capacity becoming stranded (~80% of normal utilization) to meet the 430-480 ppm climate target.

Taking the remaining total global carbon budget as exogenous, the two most important factors in this analysis are the share of this budget that can be allocated to power generation (~14%) and the additional generation-only budget that is added by BECCS generation. Changing these numbers would change the results of this analysis considerably. Should the share of generation-only budget be one percentage point smaller (~13%) or bigger (~15%) the stranding estimates for the 430-480 ppm scenario would change by 1.6 percentage points. In a scenario in which power generation would have only 13% of remaining total carbon budget left (under unchanged future BECCS generation) the 1.5-2°C compatible average utilization for currently operating and under construction or planned generators would drop from ~42% to ~39%. Should generation-only budget be 15% of total instead of 14% possible utilization would increase to ~44%. The total amount of GHG captured by BECCS is also important. If BECCs turns out to be entirely unable to remove carbon from the atmosphere, the utilization rate of power generators compatible with 1.5-2°C would drop from 42% to 22%.

3.4 Sensitivity of findings

Our findings regarding the committed emissions of currently operating and under construction or planned power generators are particularly sensitive towards simulated lifetimes and target utilization rates.

Realised lifetimes of power generators depend on a variety of factors that affect the economic viability of the generator, such as electricity, fuel, and carbon prices, regulation, and technological change (see Appendix A.1). At the same time, the future lifetime for a currently operating (or planned) generator has a considerable effect on its remaining emission commitments. Based on a 42-year lifetime for coal generators, every additional year of lifetime would increase the original emission commitments of currently planned coal generators (210 $GtCO_2$ commitments) by 5 $GtCO_2$ (+2.4%). For currently operating coal generators (220 $GtCO_2$ commitments remaining in 2016), each additional year of lifetime increases committed emissions by 10 GtCO2 (+4.6%).[19] For gas-fired generators currently operating (emission commitments of 66 $GtCO_2$ in 2016) every additional year increases emission commitments by 3.3 GtCO2 (+5%).[20] For new gas generators each year would increase the emission commitments from 49 $GtCO_2$ to 50 $GtCO_2$ (+2%).

Utilization rates, as well, have a significant impact on our results. For instance for coal we apply a global average utilization rate of 61%. Reducing (or increasing) this utilization rate by one percentage point would result in a reduction (or increase) of committed emissions by 4 $GtCO_2$ (1.6%). For gas the applied utilization rate is 39% and every percentage point change hence a 2.6% increase or decrease in committed emissions. For a further discussion of utilization rates please see Appendix A.1.

4. Discussion of findings

We analyze the expected (business as usual) cumulative carbon emissions from currently operating and planned power generators around the world and find that this capital stock would likely emit more CO_2 than compatible with the median scenarios that would meet current climate goals. Moreover, we estimate that commitments reached the remaining carbon budget for 1.5-2°C warming in 2011; with the carbon budget for 2-3°C warming being breached in 2014. Despite making similarly conservative assumptions with regards to decarbonization in other sectors, this finding updates an earlier estimate in which we identified 2017 as the year in which operating capital stock would commit us to 2°C (Pfeiffer *et al.*, 2016). The changes compared to the previous finding come from updated, and more accurate, carbon budget figures as well as an update of the previously used power generator database. Supplemental databases add power generators (especially in China) and close known gaps, thereby improving the representation of the global generation capital stock.

The updated findings suggest that much of the global electricity generation capital stock would need to become stranded if the world were to meet its climate

[19] Current global average age of coal generators is 20 years with remaining lifetime of 22 years.

[20] Current global average age of gas generators is 18 years with remaining lifetime of 20 years.

goals. This result postulates that power generation is assigned the same share of the overall carbon budget as in the median pathway and that future BECCS generation can add the expected atmospheric space. Under these conditions, some stranding would occur (~10 to 20% of operating capacity) even if all current plans and construction projects for additional power generators would be suspended. This stranding would likely have the strongest impact on the coal sector in Asia, where 64% of current and 65% of planned committed emissions are located, most of it in coal-fired generators.

Committed emissions depend on future lifetimes and utilization rates of existing and newly build power plants. Shorter realised lifetimes or lower utilization rates would reduce remaining emission commitments of operating and planned generators considerably. Indeed, developments in recent years point towards decreasing utilization rates, at least for coal-fired power generators. In the context of this analysis lower utilization rates would constitute stranding.

The stranding of power generation assets can have several causes and materializes in different ways (Caldecott and McDaniels, 2014; Caldecott, Tilbury and Carey, 2014; Caldecott, Kruitwagen, *et al.*, 2016). Among the most important causes for stranding in power generation are changing regulations (e.g. emission standards), higher input costs (e.g. rising prices for coal, gas and CO_2 permits), and changing market conditions (e.g. falling wholesale prices). Regulatory and technological efforts to keep within carbon budgets compatible with the Paris Agreement will result in significant stranding of both operational and planned fossil fuel power generation. The extent to which this affects existing assets, or those currently in planning, is largely a market and policy question. Regardless of where the stranding occurs, however, it will generate significant social and political economy impacts. Power plant owners, operators, connected communities and investors will be affected, but so too will producers of coal and gas upstream. These different groups, whether directly or indirectly, might have the political power to block policy reforms (Caldecott, Elizabeth, *et al.*, 2016; Vogt-Schilb and Hallegatte, 2017).

Options to avoid stranding if carbon budgets are inflexible are limited: the carbon budget 'allocated' to the power sector could in principle be expanded, but the power sector appears to be the one that is technically easiest to decarbonize (Clarke *et al.*, 2014; Audoly *et al.*, 2017). Another radical solution around the issue of stranding coal power plants could be to relax climate goals (Guivarch and Hallegatte, 2013), but that would be at odds with the Paris Agreement and result in elevated climate risk for the most vulnerable countries (Stern, 2007; IPCC, 2014).

Our findings may help investors and companies to consider stranding risks and materialization scenarios in their capital allocation decisions. In recent years, the interest within the financial community for such evaluation frameworks and scenario assessments has increased (CTI, 2013; Caldecott, Dericks and Mitchell, 2015; Carney, 2015). Some recent developments in the global power generation sector, such as the cancellation of ~130 GW of planned coal-fired generators in China, might have been motivated in part by the realization that said capacity could be at risk of becoming stranded if renewables continue to grow at high rates (Mason, 2017). The substantial pipeline of fossil-fuel powered generators, however, suggests that these risks are still not sufficiently considered (or considered sufficient). Furthermore, the trade-off between the stranding of currently operating and yet to be built generators imposes challenges for investors with broader generation portfolios. Under the constraint of a carbon budget, the optimization of such portfolios might include the stranding of *old* in favour of *new*, more efficient, generators, extended lifetimes for *old* instead of building *new* generators, the retrofit of some generators with efficiency enhancing or CCS technology, and the shifting of future capacity additions towards low-carbon technologies (such as renewables and, maybe, gas).

Our findings may also help policymakers improve the set of economic incentives for different types of generation infrastructure. Any further additions to the polluting generation capital stock increase the cost that will need to be paid to achieve the agreed climate goals in the. Efficient and effective policies would incentivize investors to optimize their portfolios to meet carbon budgets, and shift current and future investments towards low-carbon technologies. In the meantime, regulation, such as emission standards, coal moratoriums, and emission levies could help to avoid any further carbon lock-in in the electricity sector and to un-commit some of the budget by decommissioning old and, particularly, dirty generators. Longer lifetimes, and maybe even subsidies for existing and relatively clean generators, on the other hand, could also help reduce the need for additional dirty infrastructure.

5. Conclusion

Current carbon emission commitments exceed the remaining carbon budget for the electricity generation sector if the world is to meet its climate goals. Nonetheless, the sector will see large amounts of carbon emitting infrastructure being added to its capital stock over the next few years. Investors should re-assess their investment decisions in dirty infrastructure, and policy makers should design their policies to avoid any further carbon lock-in that will prove costly in the future when emissions must decrease to meet climate targets. While long-term policies are not yet in place, some short-term measures, such as emission standards, coal levies and moratoriums, and even lifetime extensions for relatively clean fossil-fuel powered generators could help to avoid further dirty investments.

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Appendix

Appendix A: Additional information

A.1 Additional information and discussion of the methodology

To calculate the total and remaining committed emissions, the described databases and sources are merged at the generator level. For oil, gas and biomass generators, the decisive factor for the heat rate is, in addition to fuel, the turbine type. For coal, the approach is more granular, and considers, in addition to the turbine type, the capacity, fuel type (e.g. lignite, bituminous, sub-bituminous, etc.), and steam type (e.g. critical, sub-critical, super-critical, etc.). For all generators, year-specific heat rates are assigned based on the online year of the generator, to adjust for advances in technology over time. Annual maximum emissions of a given generator are then calculated with the information about its maximum capacity (MWh), heat rate (mbtu/MWh) and the emission factor of the fuel used (gCO_2/mbtu).

The committed emissions of the generator are calculated by multiplying this annual maximum emission level (applying historic average load factors) with the expected, or simulated, lifetime of that generator. Missing information about online years and expected lifetimes of generators in the database can be estimated by using the information available from similar clusters within the database.[21]

Utilization rates depend on many different factors – often the same factors that also affect lifetimes – and can experience regionally very different developments. In the U.S., for instance, the strong growth of natural gas fired power generation in recent years has decreased utilization rates from 65% in 2014 to 53% in 2016 (IEA, 2017). In China, overcapacities have decreased coal utilization even from 57% in 2013 to 49% in 2016. Even on a global average level in recent years coal utilization rates have decreased from 59% in 2013 and 2014 to 52% in 2016.

Globally, the development in recent years points towards a trend of decreasing utilization rates for coal-fired generators. Using long-term average historic utilization rates we capture a possible definition of the desired or 'target' utilization rates of the power generator operators. Applying this utilization rate going forward results in the committed emissions under normal economic conditions. Any lower utilization rate would constitute stranding as defined in section 3.3.

Finally, lifetimes are simulated by applying random numbers from a *Poisson* distribution with the expected lifetime of that generator as the mean. The simulation accounts for the fact that generators are rarely retired exactly after their expected lifetime, but are rather retired some years around their expected

[21] E.g. median lifetime of generators from the same country, year, manufacturer, fuel, type, etc.

retirement date. Within the database, many of the generators are still in operation long after, while others retire long before their expected retirement.[22]

Applying Poisson distributions around expected economic lifetimes rather than applying these lifetimes directly helps balancing the effects of periods in which many generators were added to the capital stock (e.g. after 2005). By using a distribution rather than a point estimate the development and especially phase-out of the capital stock can be smoothened. This represents a more realistic phase-out profile of generators than a sudden simultaneous retirement of all generators that came online in the same year. Actual retirement of individual power generators depends on a number of global (e.g. fuel prices, technological change, etc.), regional (e.g. wholesale electricity price, carbon price, regulation, etc.) and even local (e.g. taxes, levies, pollution control, etc.) factors. These factors are not foreseeable but operators in most cases will try to operate their generators as close to the 'normal' economic lifetime as possible. Where this is profitable under then existing economic conditions, generators will be operated longer, while in other cases generators will be retired 'early', e.g. because of technological change or changing market conditions which could make a continued operation unprofitable.[23]

The strong growth of renewable power generation and natural gas should also be mentioned. Both have the potential to replace coal-fired power generation, thereby significantly shortening realized lifetimes of coal-fired power generators. Vice versa an early retirement of coal generators would increase the available carbon budget for gas generators, thereby decreasing stranding for these assets. In the context of our analysis shorter economic lifetimes for any class of generators constitutes stranding for these generators, independently of what happens to other generators.

A.2 Main limitations

The databases used are unlikely to be complete or flawless. The UDI WEPP data base includes electric power plants in every country in the world (including operating, projected, deactivated, retired, and cancelled generators). It's coverage is comprehensive for medium- and large-sized generators. However, it's coverage for wind turbines, diesel and gas engines, photovoltaic (PV) solar systems, fuel cells, and mini- and micro-hydroelectric units is only considered representative, but not exhaustive. Approximately one quarter of the data base consists of units of <1 MW nameplate capacity. Generators of <1 kW are not included and coverage

[22] For generators that are still in operation in 2016 but with a simulated retirement year before 2016, a 10-year phase-out period is used in which every year the then oldest decile of generators is retired.

[23] Alternatively, an empirical distribution based on historic retirements could have been applied. While this may yield more realistic results, in many cases not enough historical data for a particular class of generators was available to yield a sufficiently robust distribution. In these cases, we had to decide between estimating a realistic expected (median) lifetime for a particular technology and aggregating over many different technologies and fuels to retrieve a sufficiently robust distribution.

of generators with <25 kW nameplate capacity is limited.[24] Known gaps within the database (e.g. in China and Japan, and for micro-generation) have been addressed by merging several different databases and the resulting database is believed to be representative for the global oil-, gas- and especially coal-fired generation capital stock. Comparison with other data sources (e.g. IEA) confirms this.

The UDI WEPP database contains many generators for which the 2016 status is unknown, or for which important data, such as online or retirement year, is missing. Furthermore, the heat rate data retrieved from the EIA and EPA is more accurate for U.S. generators, and is likely to misrepresent technology in e.g. Asia, Middle-East and Africa, and countries of the former Soviet Union. Moreover, the methodology used to estimate historic heat rates, especially of generators installed in the last century, will occasionally over- or underestimate actual heat rates, since technological development and advancements in efficiency have not always been the same for all technologies.

Completing missing information regarding online year and expected lifetimes with averages from similar generators carries several risks. Within a given country, technologies often remain relatively constant over several years and, hence, using technology as an estimator for the year in which a generator came online can yield misleading results. Furthermore, retirement years are not only dependent on the lifetime of the underlying technology, but are also heavily affected by management decisions, regulation and the economic situation. While simulating retirement instead of using point estimates can account for such uncertainties to some degree, it will only yield satisfactory results on an aggregate level, i.e. when applied to many generators.

Despite these limitations, it is believed that the applied data sources and methodology yield a good representation of the global electricity generation capital stock. While lifetime, retirement and committed emissions calculations on an asset level can be inaccurate, robustness checks and comparisons with other peer-reviewed results, suggest that these inaccuracies cancel out on the aggregate level.

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24 https://www.platts.com/im.platts.content/downloads/udi/wepp/descmeth.pdf (retrieved February 25, 2018).

Appendix B: Additional figures

Figure B.1: Committed emissions from electricity generators in operation, under construction or planned in 2016, by technologies. *By far the most committed emissions currently under operation and in the pipeline stem from coal-powered generation.*

Appendix C: Additional tables

Table C.1: Global power generators operating in 2016, by technology.

	Capacity [GW]	**Mean current age** [Years]	**Mean remaining lifetime** [Years]	**Mean utilization** [2004-14 average]
SUN	68	5.4	31.2	10%
BIOGAS	16	13.5	20.3	58%
BIOMASS	32	12.1	22.6	58%
BIOOIL	9	17.1	18.0	58%
COAL	2,136	20.2	21.9	61%
GAS	1,385	18.1	20.2	39%
GEOTHERMAL	13	17.0	14.6	71%
NUCLEAR	371	26.0	7.5	79%
OIL	428	26.6	10.4	28%
WASTE	296	10.7	9.1	58%
WATER	1,156	28.2	37.0	38%
WIND	298	9.6	6.0	21%
Total	**6,207**	**18.8**	**18.0**	**48%**

Table C.2: Committed emissions from power generators operating in 2016, by region and technology.

[$GtCO_2$]	**Asia**	**Latin America**	**Middle East & Africa**	**OECD 90 countries**	**Reforming Economies (former USSR)**	**Global**
COAL	183.0	2.5	2.8	24.4	7.4	220.1
GAS	10.6	4.0	13.9	31.9	5.5	65.9
OIL	1.2	1.4	3.4	1.4	0.3	7.6
WASTE	2.3	0.8	2.4	5.0	0.7	11.2
BIOENERGY	0.7	0.8	0.1	1.2	0.1	2.9
RENEWABLES*	-	-	-	-	-	-
OTHER**	0.0	0.0	0.0	0.0	0.0	0.1
Total	**197.8**	**9.4**	**22.5**	**64.0**	**14.0**	**307.7**

** Renewables include hydro, solar, and wind and do not result in committed emissions. ** Other includes nuclear and geothermal; the non-zero committed emissions associated with these generators stems from a small amount of fugitive emissions from geothermal power generation.*

Dead on arrival? Implicit stranded assets in leading IAM scenarios

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Abstract

While it is acknowledged that asset stranding could jeopardize the political feasibility of climate policies, the amount of stranded assets is rarely made explicit in most decarbonization pathways. This paper introduces a novel method that extracts, for every given energy sector transition scenario, the implicit amount of new power generation capacity that is added every year, and the required amount of stranding if this scenario is to be in line with its projected generation mix. We show that most scenarios that stabilize warming to below 1.5-2°C require a high level of asset stranding, not only for future capacity additions, but also for already existing and currently planned generators. Such stranding affects China and the U.S. most. The amount of future fossil fuel capacity stranding required, in line with 1.5-2°C warming, has increased by 21% between 2005 and 2015. We discuss implications for investors and policy makers.

Keywords: climate change mitigation; stranded assets; electricity generation; climate policy; energy policy *JEL:* Q01; Q4; Q54; Q5

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1. Decarbonization and carbon lock-in

To stop climate change, and stabilize global temperatures below 2°C, and as close to 1.5°C as possible (UNFCCC, 2015), humanity needs to reach net-zero carbon emissions before the end of the century (IPCC, 2013; Fay *et al.*, 2015; Rogelj, Luderer, *et al.*, 2015; Rogelj, Schaeffer, *et al.*, 2015). In the future, electricity generation will thus have to be (net-) zero-carbon, relying on renewable energy, fossil-powered generation with carbon capture and storage (CCS), or nuclear power (Luderer *et al.*, 2012; Sugiyama, 2012; Williams *et al.*, 2012; Clarke *et al.*, 2014; IEA, 2014). Even under less stringent climate targets (such as 3°C) and even if some technologies, such as nuclear power or CCS, turn out to be unavailable or limited, all economies are expected to have to decarbonize their electricity sectors before the end of the century (Rozenberg *et al.*, 2015; Audoly *et al.*, 2017).

On the other hand, existing power generation is mainly based on fossil fuels that emit greenhouse gases (GHGs). Globally, in 2016 67% of electricity generation came from either coal- (41%), gas- (22%), or oil-powered (4%) generators, and this is responsible for one third of global total CO_2 emissions (IEA, 2016). While most of the global capacity additions (62% in 2016) are now renewable power plants (Sawin J., Seyboth K., 2017), the current pipeline of power generation projects would still add a significant amount of fossil fuel power generation to this capital stock over the coming decade. A recent report by the Carbon Tracker Initiative found that 205 GW of coal capacity is under construction in China with an additional 405 GW at some stage of the planning process, for a total cost of up to 500 bn. USD (CTI, 2016).[1]

One problem with that development is that power generators, especially fossil-fuels, tend to have a long lifetime. The median lifetimes of coal and gas generators have been estimated at 37 and 35 years respectively, with some coal generators already operating for more than 70 years (Davis and Socolow, 2014). This means

[1] For India these figures amount to 65 GW under construction and an additional 178 GW proposed (Shearer, Fofrich and Davis, 2017).

that the amount of *committed emissions* over this lifetime is comparatively high for fossil-fuel generators. These 'baked-in' carbon emissions from existing infrastructure are commonly referred to as carbon lock-in (Unruh, 2000; Davis, Caldeira and Matthews, 2010; Kalkuhl, Edenhofer and Lessmann, 2012; Bertram *et al.*, 2015; Erickson *et al.*, 2015; Pfeiffer *et al.*, 2016). Due to this long lifetime, cost-effective transition pathways towards a decarbonized electricity sector are likely to require some amount of stranded assets, i.e. the early retirement or underutilization of power generators without CCS. A growing body of academic research quantifies the extent of asset stranding in emission reduction pathways and investigate options to minimize stranding (Bertram *et al.*, 2015; Johnson *et al.*, 2015; Kriegler *et al.*, 2015; McJeon, 2015; Riahi, Kriegler, *et al.*, 2015; Luderer *et al.*, 2016).

This paper systematically explores the extent of stranded assets in the electricity generation sector implied by the Intergovernmental Panel on Climate Change, IPCC's global decarbonization scenarios and the findings of a recent Integrated Assessment Model (IAM) comparison study: AMPERE (Riahi, Kriegler, *et al.*, 2015). It introduces a simple method that extracts the implicit amount of new fossil-fuel capacity that is added or stranded in every year in any given scenario, by comparing existing generation capacity, expected utilization, and electricity generation. In every year, in which scenario electricity generation would lead to a higher-than-expected utilization of existing capacity, new capacity is added and changes the capital stock going forward. In other years in which generation is lower than utilized capacity stranding occurs. This method itself is novel. It is simple to understand and replicate, works with only a few assumptions, and can be applied to any global or regional pathway (e.g. from the International Energy Agency IEA, the Energy Information Agency EIA, or the IPCC), and power generation technology (e.g. coal, gas, oil, and biomass, but also solar, wind, etc.). Importantly, this method does not require a fully-fledged IAM or similar energy-economic model. It is therefore suitable for policy makers, investors and corporate decision makers, and other stakeholders who might not have access to or sufficient knowledge about IAMs.

Our application of this method to the output of a wide range of global and regional peer-reviewed scenarios enables us to analyze at an unprecedented level of detail where and when stranding will occur, and how it will vary under different climate policies. The timing of stranding is particularly relevant to policy makers since early and targeted social policies can help to reduce the adverse social effects of asset stranding and thus smooth the transition. We add to previous findings regarding the influence of weak near-term policies by analyzing how the weak policies of the last decade have increased the required amount of future capacity stranding. Finally, our findings on whether an extension in the lifetimes of existing generators could reduce stranded assets add further detail to this policy option by analyzing different technologies and lifetime extensions and how the impact of this policy option has changed in the past ten years.

We find that, in all analyzed climate stabilization scenarios, a high level of asset stranding will be required. This finding applies to the scenarios that permit a chance for global warming below 1.5-2°C (430-480 ppm[2]), but also to less stringent scenarios (480-530 and 530-580 ppm). Most stranding takes place between 2030 and 2050, such that future additions to the power generation capital stock will be affected, as well as already operating or currently planned generators. Coal and gas generators could see average utilization rates drop from current levels of 39% (Gas) and 60% (Coal) to 29% and 23% in 2030-2050, respectively. Such underutilization especially affects China and the U.S., while other regions, such as Brazil and Japan, are relatively unaffected.[3] The amount of future global capacity stranding, in line with 1.5-2°C warming, has increased by 21% between 2005 and 2015, a period in which the global electricity generation capital stock has seen significant fossil-fuel additions. Finally, we find that extending the lifetimes of currently existing infrastructure could reduce the amount of future capacity stranding by reducing future additions to the capital stock in some regions and scenarios, but that the potential impact of this policy

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[2] ppm scenarios refer to the 2100 concentration of CO_2eq. in the atmosphere (ppm = parts per million).

[3] This can be explained by the fact that China and the U.S. generate much of their electricity from coal and gas while Brazil and Japan rely more on hydro and nuclear, respectively.

action has decreased during the last decade.

2. Findings

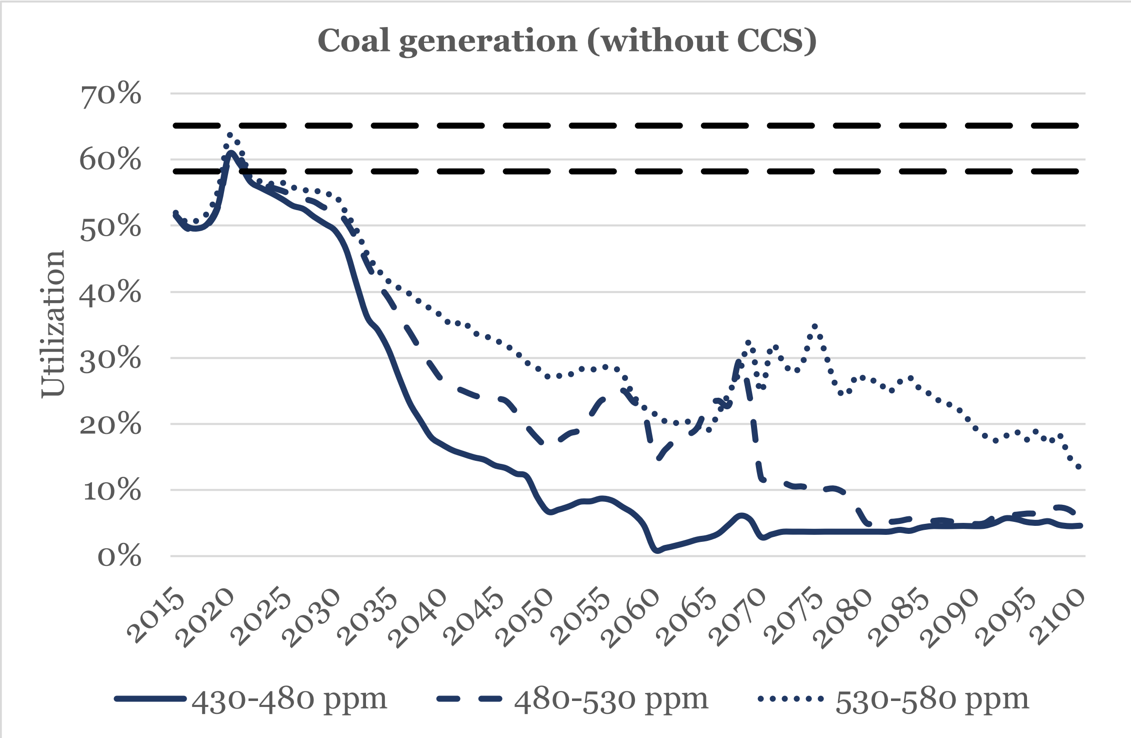
In our base case, we analyze the development of the global electricity generation capital stock under different climate scenarios starting in 2015, including generators that are currently under construction, and excluding generators that are currently in the planning process. Furthermore, for generators that are already 'overaged' in 2015, i.e. past their expected lifetime but still operating, we assume a phase-out period of five years. We only analyze carbon emitting generation capacity, i.e. coal, gas, and oil – all without CCS. These variables are extracted from scenarios in which the entire energy sector including all other technologies are modelled – namely fossil fuels with CCS, renewables, nuclear, and hydro. These other forms of generation are, however, not the subject of this analysis and hence are not mentioned in the following. Information regarding data and methods can be found in Appendices A and B, additional figures and tables in Appendices C and D.

2.1 Coal and gas see large-scale stranding after 2030

In the first step, we compare simulated utilization rates in the three climate stabilization scenarios (430-480 ppm, 480-530 ppm, and 530-580 ppm) to target utilization bands for each technology. The 430-480 ppm and 480-530 ppm scenarios are typically associated with pathways in which global warming below 2°C is likely (430-480 ppm) or at least about as likely as unlikely (480-530 ppm). The 530-580 ppm scenarios imply global warming between 2-3°C. Target utilization bands are defined by the historical minimum and maximum of the global average utilization rate of that technology between 2004 and 2014 (IEA, 2016).

The utilization rates of different fossil fuels in the base case develop differently. Figure 1 (panel a) shows the results for coal. Initially, high utilization rates (close to its target band) start decreasing shortly after 2020 and accelerate their downturn after around 2030 to near zero by 2060 (in the 430-480 ppm case) and 2080 (in the 480-530 ppm case), respectively.

(a) Coal generation utilization



(b) Gas generation utilization

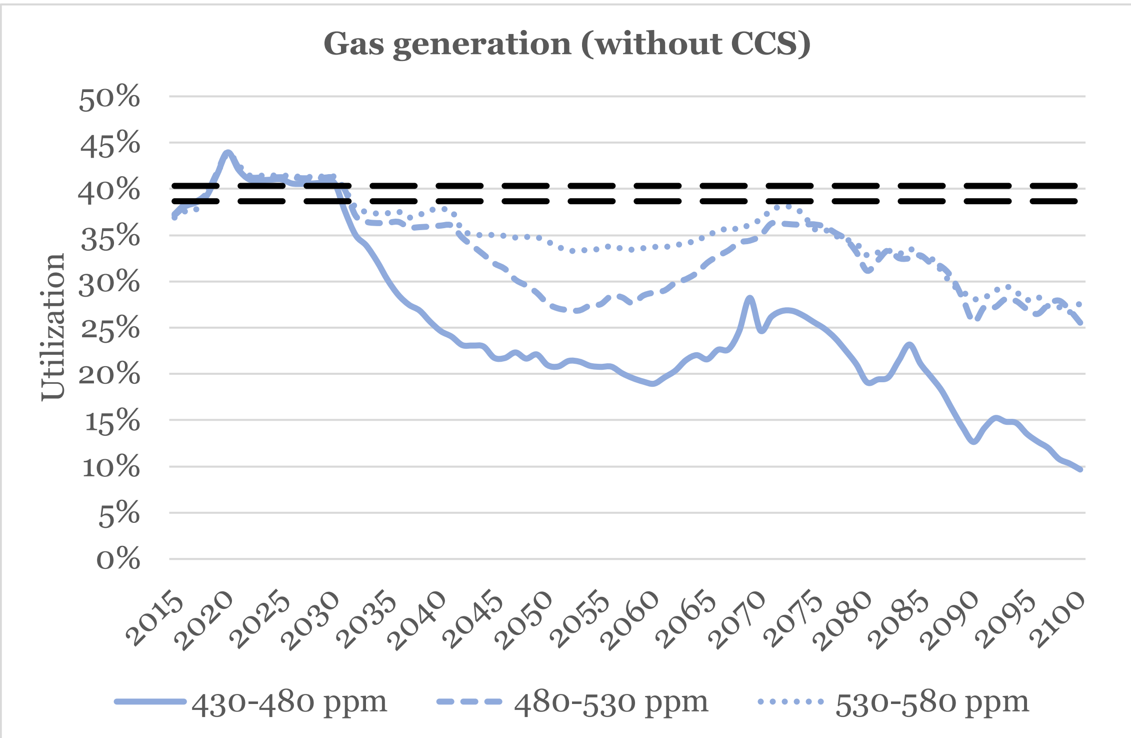


Figure 1: Simulation results for coal- and gas-fired capacity utilization. *(a) coal*

utilization drops rapidly after 2030 in almost all analyzed climate scenarios. (b) gas utilization drops considerably after 2030 in the 430-480 ppm scenario but remains relatively stable in 480-530 and 530-580 ppm scenarios. Dashed lines represent historic minimum and maximum of 2004-2014 average global utilization rate of that technology. Utilization peaks in the 2060s and 2070s are misleading as, by then, capacity and generation will be on such low levels that even the retirement of individual generators can lead to a much higher utilization for the remaining ones.

For gas and oil generation, the results are similar but on a lesser scale (see Figure 1, panel b for gas and Appendix C.1.a for oil results). Gas and oil both start with much lower utilization (and utilization targets) than coal in 2015 and hence also experience less utilization decline. Both fuels, however, see their utilization drop to below 10% by the end of the century.

Figure 2 shows the amount of stranded generation for coal, gas, and oil for each of the analyzed climate scenarios.[4] Coal will experience by far the most stranding of all analyzed technologies, and could see up to ~310 EJ (86,000 TWh[5]) of stranded generation between 2015 and 2100 if the world were to follow a path that leads to 1.5-2°C warming. Even under less stringent climate scenarios, coal would see significant stranding (220-260 EJ or 61,000-72,000 TWh). Gas and oil come second and third, respectively, with ~140 EJ (39,000 TWh) for gas and ~16 EJ (4,444 TWh) for oil in 1.5-2°C consistent scenarios.

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[4] See Appendix D.1 for results table.

[5] One Exajoule (EJ) is equivalent to ~277.78 Terawatt hours (TWh).

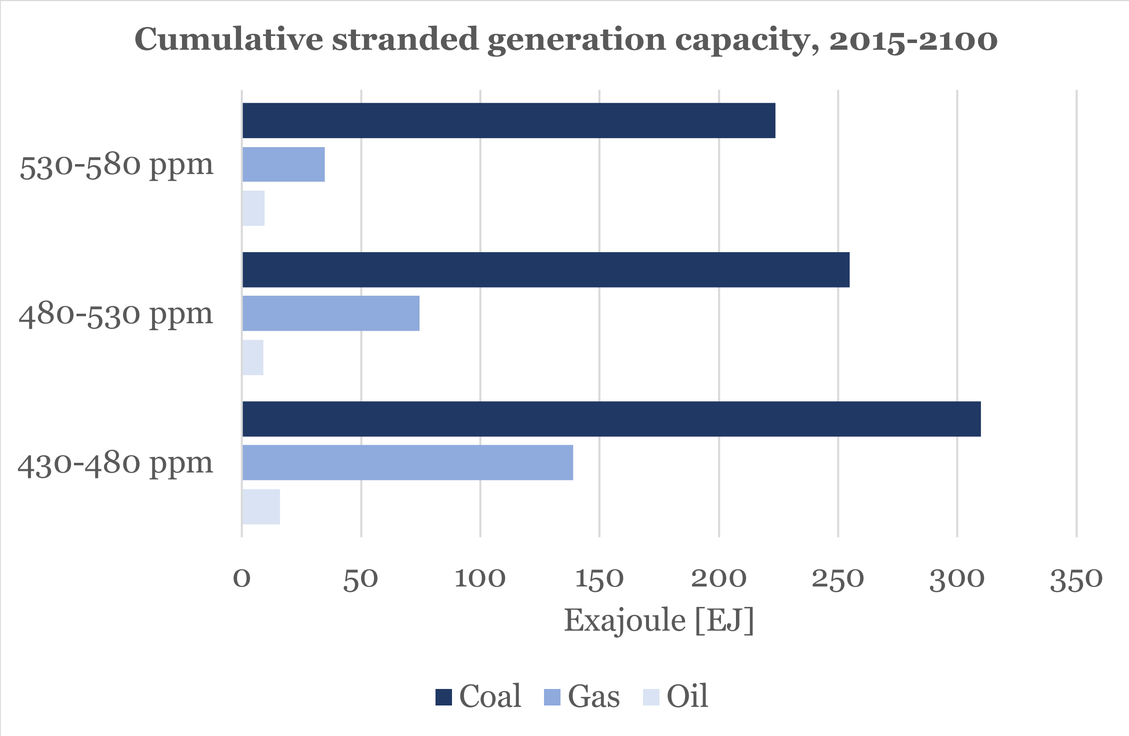


Figure 2: Total stranded cumulative generation capacity, 2015-2100. *In the base case, without including currently planned generators, and with a phase-out period of five years for 'overaged' generators, over 300 EJ would need to be stranded in the 430-480 ppm scenario for coal alone (~83,334 TWh).*

The main stranding of coal, and almost all stranding of gas and oil happens after 2030 (Figure 3). Perhaps surprisingly, even in less stringent climate scenarios, such as the 530-580 ppm scenario, gas experiences significant stranding. Even though gas is less emission intensive than coal, it still emits significant amounts of CO_2 when burned in a generator. Even under scenarios that allow for 2-3°C warming by 2100, gas-fired electricity generation (without CCS) will eventually have to be phased-out.

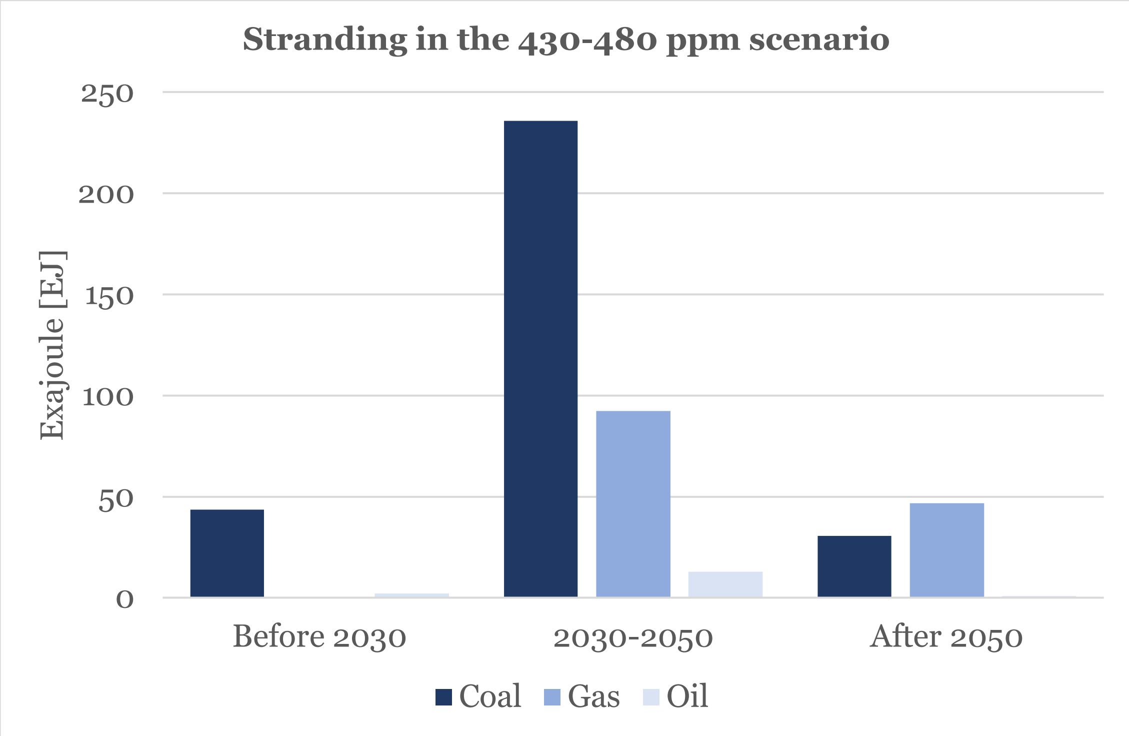


Figure 3: Stranding over time. *By far most the stranding for all fossil fuels would happen between 2030 and 2050.*

In the base case, average utilization rates for coal capacity would fall from 60% currently to 48% in 2015-30 and 23% in 2030-50 (430-480 ppm), or to 51% in 2015-30 and 33% in 2030-50 (530-580 ppm). Gas would see an increase in utilization from 39% currently to 42% in 2015-30, which would then be followed by a subsequent drop to 29% in 2030-50 and 21% thereafter (430-480 ppm).

2.2 China and the U.S. would be affected most

We find that, on a regional level, most stranding of capacity between 2015 and 2100 will take place in coal-fired generation in non-OECD Asia and the OECD countries, followed by countries of the former Soviet Union (Figure 4). Non-OECD Latin America and the Middle-East & Africa region see much less overall stranding and more gas than coal stranding. In former Soviet Union countries, coal and gas stranding is relatively equal.

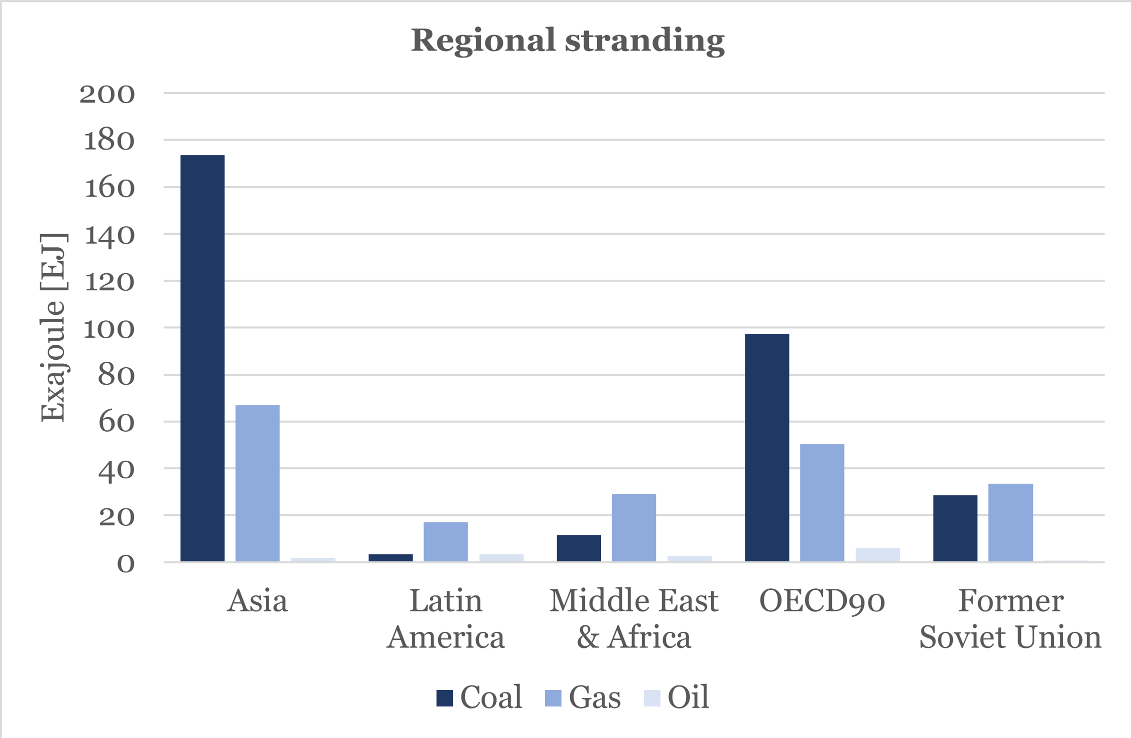


Figure 4: Regional stranding in the 430-480 ppm scenarios. *Asia would be affected most, followed by the OECD countries.*

Within these regions, China and the United States of America experience most stranding, both mostly driven by coal stranding (Figure 5). For coal stranding within Asia, China experiences ~65% and India only ~15%; for gas these numbers amount to ~40% (China) and ~25% (India). Within the OECD countries, the United States experiences ~70% of all coal stranding and ~60% of all gas stranding. For Europe, these figures amount to only ~20% (coal) and ~30% (gas).

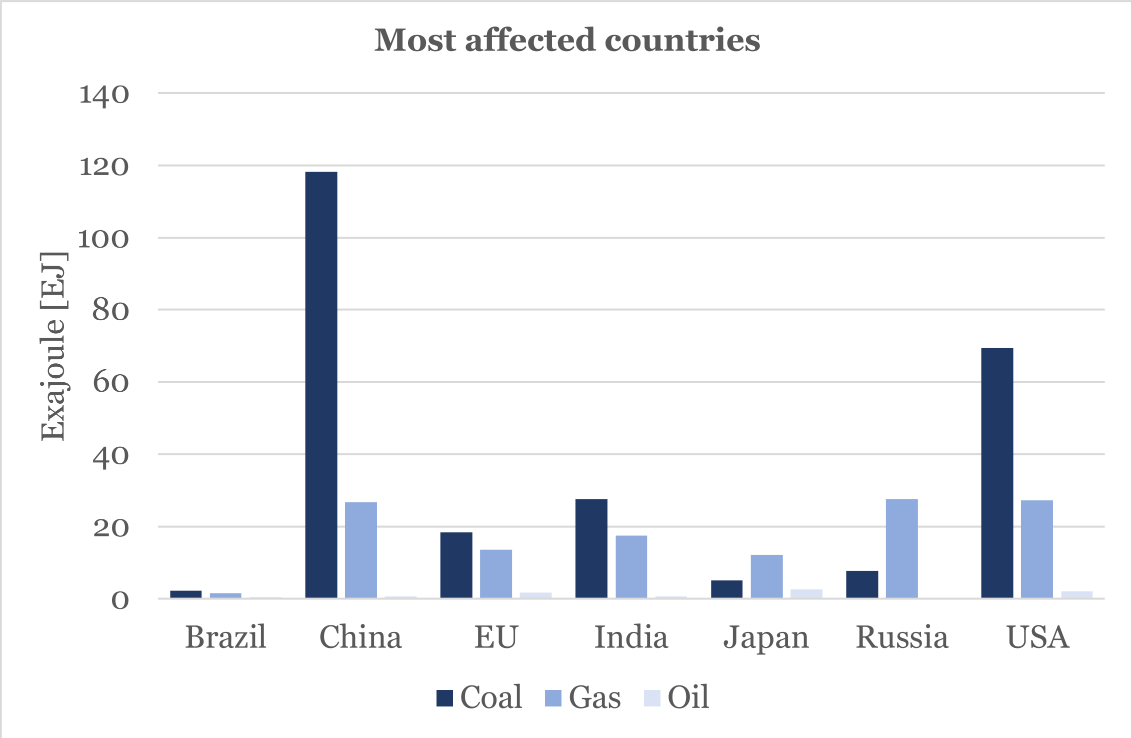


Figure 5: Country-level stranding in the 430-480 ppm scenarios. *On a country-level, China and the USA would be most affected while other countries, such as Japan and Brazil, would be mostly spared.*

Other countries such as Brazil, Japan, and even Russia, experience low levels of coal stranding (2-8 EJ) and, besides Russia (~25 EJ of gas stranding, similar to the U.S.), also relatively low levels of gas stranding.

2.3 The current power plant pipeline would increase stranding

While our base case analysis does not consider potential future capacity additions from currently planned power generators, we move on to analyze how the added capacity of these generators over the next few years would change future asset stranding.[6] Figure 6 shows how 2015-2100 capacity stranding would change if all the capacity came online that is currently some stage of the planning process.[7]

[6] Based on an analysis of the Platt's UDI WEPP dataset.

[7] See Appendix D.2 for results table.

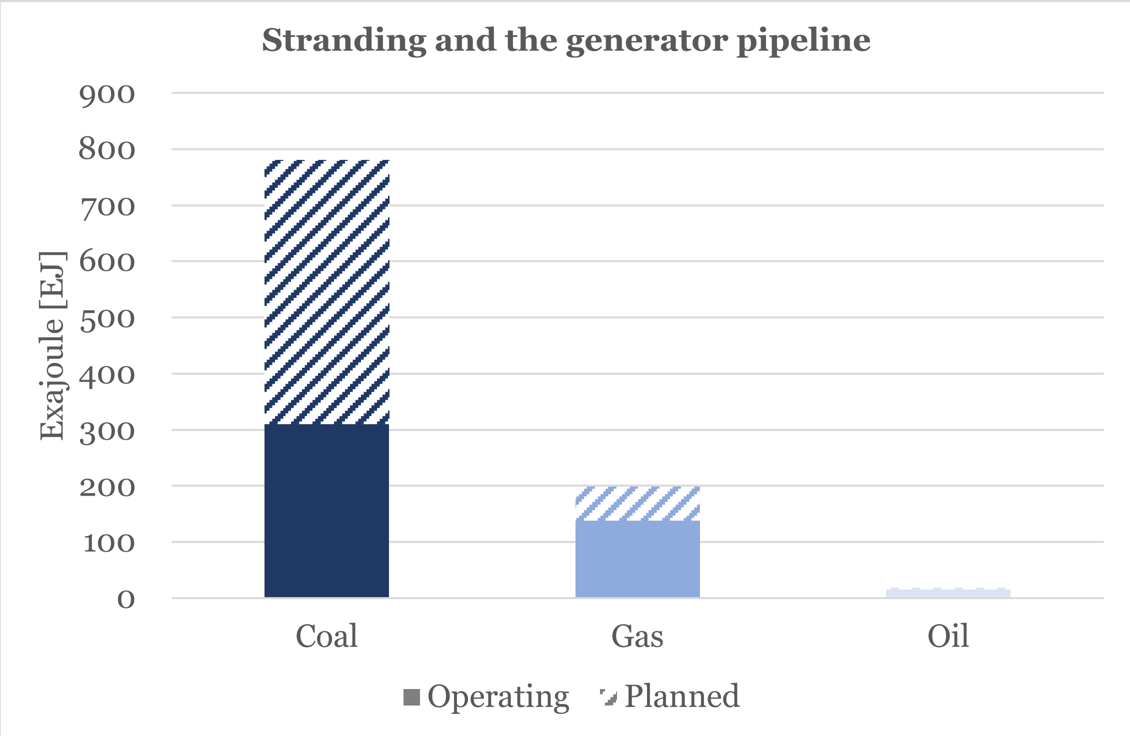


Figure 6: Stranding and the current pipeline of planned power generators in the 430-480 ppm scenarios. *If currently planned power generators are in fact built, the amount of stranding required would increase dramatically, mostly for coal.*

The largest increase in stranding can be observed for coal-fired power generation. The amount of future stranding increases by over 2.5 times, from ~310 to ~780 EJ. This development can be observed because a large share of the current generation pipeline consists of coal-fired power generation (mainly in Asian countries like India and China) and because coal-fired power generation will see the steepest decline in 1.5-2°C consistent scenarios.

While also gas and oil would see an increase in future stranding if all currently planned capacity is built, the increase is much smaller than for coal. Gas-fired generation would see an increase of future stranding in the 430-480 ppm scenario from ~140 to ~200 EJ (+43%) and oil would see the smallest increase from ~16 to ~19 EJ (+16%).

2.4 Future stranding has increased by 21% over the last decade

Over the past ten years, a large amount of capacity has been added to the global generation capital stock. While some of this was needed to satisfy rising energy demand, (especially in Asia) these generators will run for many years, and sometimes many decades, and hence could add to future stranding. Running the simulation for the base year 2005 (unharmonized scenarios and 2005 operating capital stock) and for 2015 (harmonized scenarios and 2015 operating capital stock), respectively, reveals that the amount of potentially stranded assets has increased by 21% in this period.

Figure 7 shows that this increase comes mainly from newly built coal generators (+32%), while asset stranding in gas capital stock has decreased (-12%).[8] This somewhat counter-intuitive finding can be interpreted such that over the past decade more gas was built than originally thought. The current gas operating capital stock will therefore already satisfy much of the demand over the next decades and less new capital stock must be built as a result. This will eventually reduce stranding. While stranding for oil increases by more than 100%, this occurs from a much lower initial base and hence only adds a little to the overall increase in stranding.

[8] See Appendix D.3 for results table.

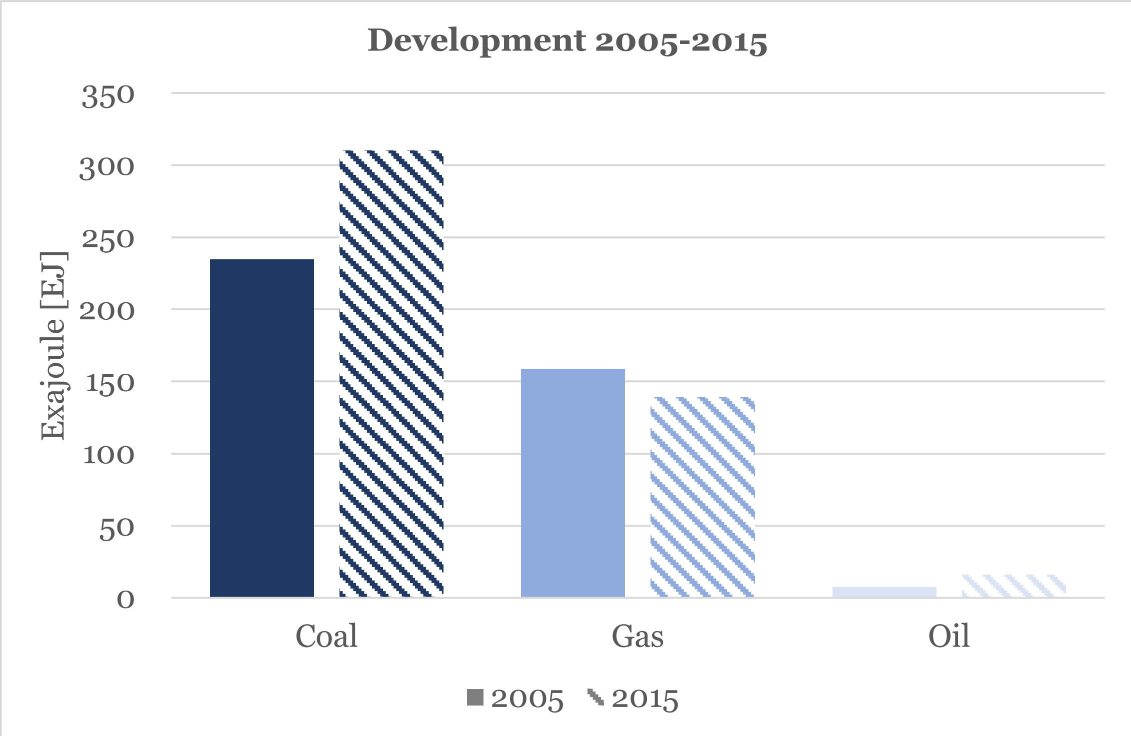


Figure 7: Development over the past decade in the 430-480 ppm scenarios. *The required amount of stranding to achieve 430-480 ppm scenarios has increased considerably over the past decade, mostly for coal.*

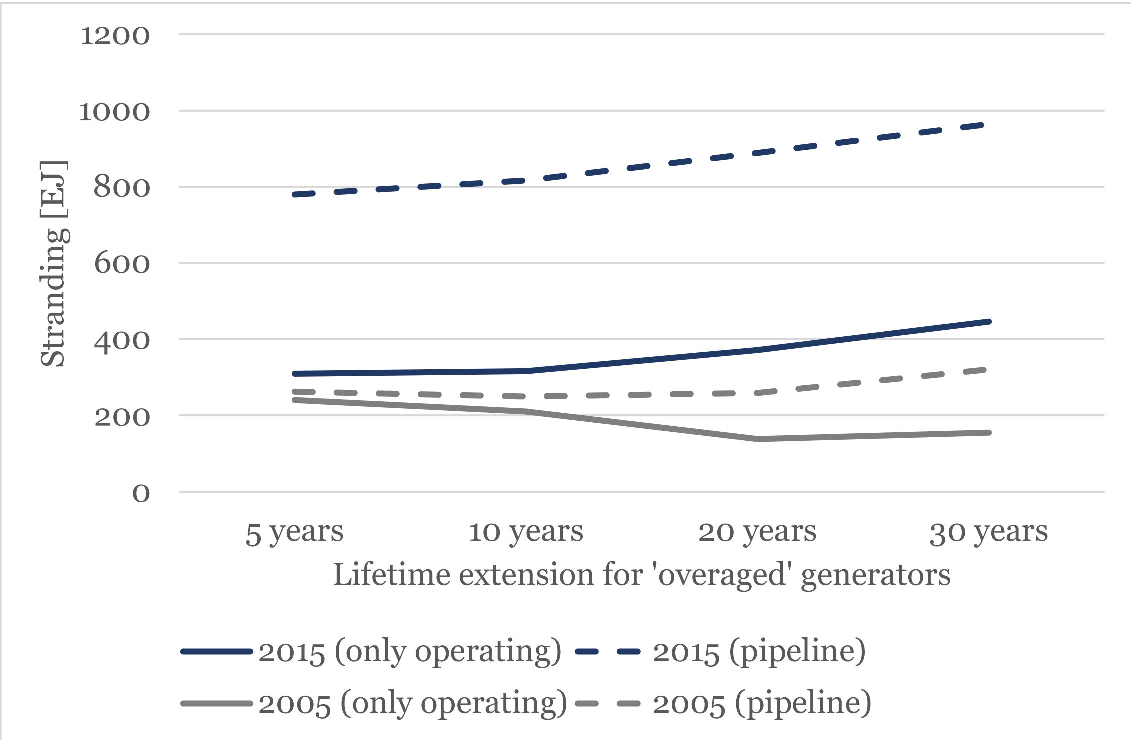
2.5 Longer lifetimes to reduce stranding are not an option (anymore)

One potential policy option to avoid the addition of new polluting capital stock is to extend the lifetimes of existing generators. Such a lifetime extension could help to satisfy energy demand without building new 'dirty' generators, thereby avoiding that these generators must be stranded in the future. To assess the impact of different lifetime extensions on future asset stranding, we vary the phase-out period for currently 'overaged' generators. We define an 'overaged' generator as one that should have been retired before 2015 but that is still in operation in 2015. In our simulation, such generators are being phased-out uniformly over a certain period starting with the oldest generators. To simulate the effect of lifetime extensions we vary this phase-out period between 5 and 30 years. Figure 8 shows the overall amount of cumulative asset stranding between 2015 and 2100 for coal and gas in the 430-480 ppm scenario and for different phase-out periods.

Our findings differ significantly between technologies. For coal, the level of asset stranding does not differ much for lifetime extensions of 1-10 years but increases for longer extensions. This finding indicates that most of the coal generation over the next decade or so in the median 430-480 ppm scenario could be met by varying utilization rates of currently existing infrastructure, largely within its target utilization band. We find that additional coal capacity is required in the future in almost none of the analyzed climate scenarios (largely independent of lifetime extensions). Extending lifetimes beyond 10 years, however, would lead to more asset stranding as such large amounts of coal capacity are simply not needed anymore after 2025-30 in the analyzed scenarios.

For gas, a lifetime extension of 1-10 years would see an almost constant level of asset stranding while extensions of 10-30 years would see asset stranding fall. Extending the lifetimes of currently operating gas capacity would avoid some of the otherwise required further capacity additions between 2030 and 2050 and hence subsequent stranding. Should the current gas pipeline be built, however, asset stranding would increase, with lifetime extension beyond 20 years. This indicates that for gas, currently operating and planned capacity (assuming longer lifetimes for currently overaged generators) is almost sufficient to satisfy total future demand in the 430-480 ppm scenario.

(a) Lifetime extension for coal capacity



(b) Lifetime extension for gas capacity

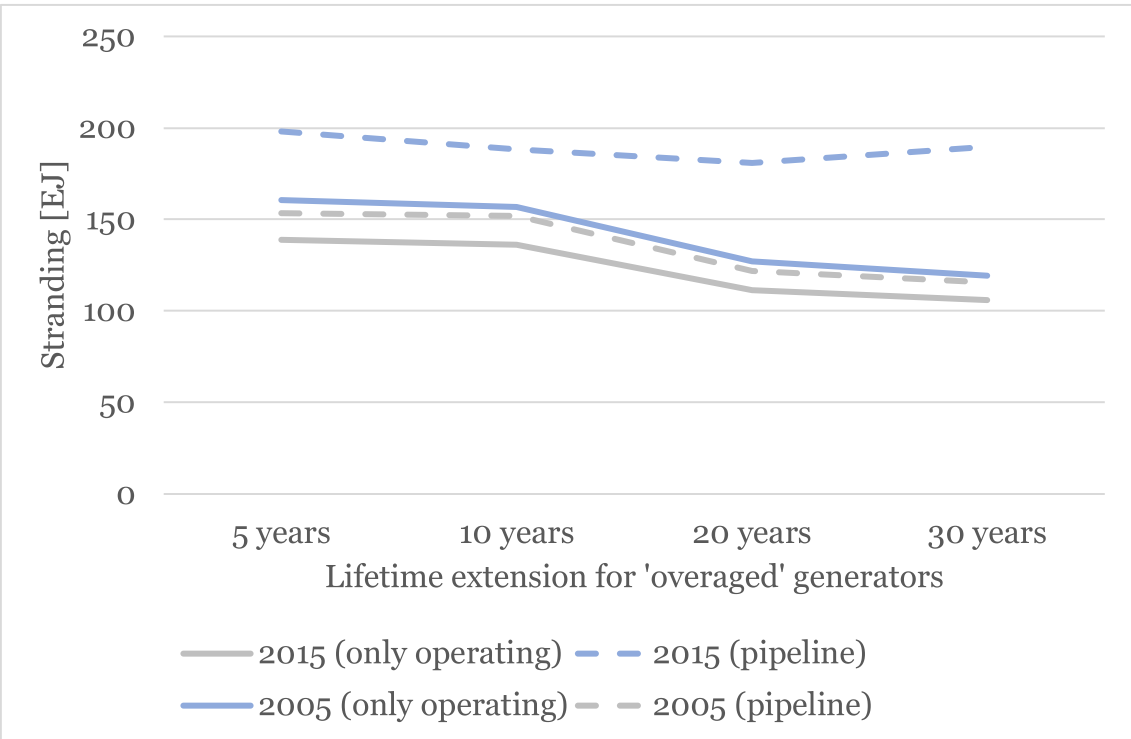


Figure 8: Lifetime extensions for operating 'overaged' capacity in the 430-480

ppm scenarios. *(a) Lifetime extensions for coal (instead of new capacity) would have reduced asset stranding a decade ago but will no longer do so today. (b) Lifetime extensions for operating gas capacity, however, might still be helpful to reduce asset stranding.*

For oil capital stock the results are clear (see Appendix C.2). For oil, a lifetime extension of up to 10 years would decrease, while anything beyond 10 years would then increase, future asset stranding. This result can be interpreted such that, over the next ten years, there will still be a certain amount of generation from oil in some regions. This will then decrease, however, such that the then existing capacity will become stranded. Avoiding new generators that replace phased-out generators over the coming ten years will reduce that amount of stranded capacity.

Comparing these results to the situation in 2005, we find that an extension of lifetimes would have significantly reduced asset stranding requirements for coal and gas capital stock. This indicates that much of the capacity that will see asset stranding in the future has been built over the last 10 years and could have been avoided by relying instead on longer lifetimes for coal and gas plants. This political choice, however, seems not to be on the table anymore.

3. Discussion of findings

Between 2005 and 2015, much fossil-fuel capacity has been installed. In some countries (e.g. India and China) this capacity mainly consists of coal, while in others (e.g. USA) it is to a large extent from gas. Either way, this has added a large amount of committed cumulative generation from fossil fuels to the global capital stock that is unlikely to be fully utilized if the global community follows through with the Paris climate goals or even only the current Nationally Determined Contributions (NDCs). Even in a world in which concerted climate action fails, the economics of renewable energies could lead to a total phase-out of fossil fuels by the end of this century (Audoly *et al.*, 2017) and hence to a certain level of asset stranding.

This paper details the findings of the existing literature, that weak near-term policies could increase future asset stranding, by showing that weak policies during the last decade have already increased the stranding required by one fifth.

Moreover, while ten years ago an extension of the lifetimes of existing generators could have been an effective strategy to reduce new capacity and hence future stranded assets, this policy option today seems to have lost its effect for coal, and largely also for gas on a global level. Policy makers are now in a situation in which it is not enough anymore to 'simply' avoid additional coal capacity, meaning that existing capacity must be stranded, either by underutilization or by early retirement.

Our findings have important implications for policy makers and investors. Most of the already existing electricity generation capacity cannot be fully utilized, even in the less-stringent policy scenarios, where global warming is likely to exceed 1.5-2°C or even reaches closer to 3°C. This underutilization will be much higher if even a small share of currently planned fossil fuel capacity comes online. In early-2017 Asian (mostly coal) and the OECD countries (mostly gas) are planning significant additions to the 'polluting' generation capital stock, i.e. their fossil fuel powered generation capacity (Pfeiffer *et al.*, 2017; Shearer *et al.*, 2017). These countries are already strongly affected by future asset stranding, even without these future additions. Policy makers in these countries should re-assess their energy policies to avoid further carbon lock-in.

Any addition to the current fossil fuel generation capital stock, be it coal or gas, could increase the amount of assets that need to be stranded in the future. While this was already true for coal in 2005 it seems now to be true for gas as well. Additions to the global polluting capital stock in the last decade have increased the amount of coal stranding required by 32% while they decreased gas stranding by 12%. Adding even more *dirty* capacity would increase coal stranding 2.5-fold and gas stranding by 43%. These findings indicate that no additional generation capacity is needed, for coal or gas, to meet projected generation in the 1.5-2°C scenarios. A sensible energy and climate policy could therefore be to focus on avoiding any additional dirty capacity to the fossil fuel capital stock instead of retiring existing capacities early.

Moreover, policy makers should carefully assess their environmental strategies with respect to planned generating capacity. Despite the lack of penalty for breaching the Paris agreement, there remains a potential economic cost to the industry through inaction, as excess generating capacity reduces overall utilization rates for the industry. Policy makers could assess capacity building in their electricity markets to ensure that the decision to build additional capacity is congruent with the long-term interest of their citizens and their own CO_2 reduction pledges.

For investors and corporate decision makers, our results could be used to adjust hurdle rates and assess investment decisions. The significant asset stranding observed in most scenarios means that investments in almost all fossil fuel generators around the world are likely to suffer from falling utilization rates. While these declining utilization rates come at different times (as early as 2020-30 for coal and as late as 2030-50 for gas) they could have impacts on investment portfolios today once climate policies reveal the likely future pathways. Asset stranding can happen in different ways (e.g. via early retirement or underutilization). Stress testing investment projects and portfolios of fossil fuel generation with low utilization rates at different times could reveal meaningful new information for investment decisions. The transparency and ease of use of our proposed simulation method, and the fact that no IAM is needed, allows investors and managers to apply this analysis to a wide range of different global, national, or even local, energy scenarios to assess what these scenarios would mean for individual investments on asset level. It hence acknowledges that electricity systems are not global and, in many cases, not even transnational and therefore require a different approach to that which most IAMs can provide.

More research also needs to be undertaken on a regional and local level to assess the potential impact of lifetime extensions on asset stranding. We only analyze the impact of such extensions on asset stranding for 'overaged' generators, in the same fuel class and on a global level. Nevertheless, we find that, in some cases, an extension of the lifetimes of currently operating generators can reduce future asset stranding by reducing future additions to the capital stock. This result complements findings by Lecuyer & Vogt-Schilb (2014), who suggested that investing today in new gas power plants with shorter-than-normal lifetimes could be a way to reduce mid-term asset stranding. Here, we show that investments made to extend the lifetime of *existing* fossil fuelled power plants could be a way to achieve this result. Further research could apply our method to regional capital stocks and to sectors other than power generation. This could reveal in which regions, for which fuels, and under which assumptions, an extension of lifetimes is a sensible policy choice.

4. Conclusion

Using a simple and transparent method to simulate the development of the global electricity generation capital stock in several hundred global and regional scenarios, we analyze the amount of stranded capacity required in scenarios consistent with 1.5-2°C global warming by 2100. We find that, not only has this amount increased by 21% in the past decade, but that it also seems to have shut the door to some policy options that might have been pursued to reduce stranded assets. We hence derive four implications for policy makers and investors alike; (1) the focus of policy makers should be on avoiding additions to the global fossil-fuelled electricity generation capital stock instead of retiring existing ('dirty') infrastructure early; (2) investors and managers alike may reassess investment decisions and stress-test portfolios of power generators with much lower capacity factors than is currently the case; (3) more focus should be put on local and differentiated assessments where an extension of lifetimes could reduce asset stranding by avoiding new fossil investments; and (4) a global moratorium on any further coal development (capacity and resources) is needed to avoid further investments that will almost certainly become stranded in the near- and medium term if the global community follows through with the Paris goals.

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Appendix

Appendix A: Data and Methods

We use a four-step approach to calculate the stranded capacity: (1) we simulate the depreciation of currently operating global generation capacity (existing capital stock) over the coming decades; (2) we compare the remaining portion of that capacity in any given year in the future with the generation in that year in the respective pathway; (3) by employing target utilization bands (based on historical utilization rates), we assess, for any given year, the amount of capacity that would need to be added to the capital stock; and finally (4) we calculate the amount of stranding that takes place in a given year as defined by the underutilization of operating capacity. Underutilization in this case is defined by utilization rates below their historical bands. Since we rely on several external databases, limitations apply, and our findings should be interpreted with caution (see Appendix A.3 for a discussion of the limitations).

A.1 The global electricity generation capital stock

We use two different sources of data for the calculation of committed CO_2 emissions: Platt's *UDI World Electric Power Producer* (WEPP) database, as of June 2016, and the International Energy Agency's (IEA) *World Energy Outlook 2016* (WEO). Platt's WEPP database is a proprietary database that contains generator-level data of electric power generating units. It contains data for plants of all sizes and technologies operated by regulated utilities, private power companies, and industrial auto-producers (captive power). The IEA's WEO is an annual publication providing regional insights in capacity, generation, investments and utilization rates.

In addition to these two sources, we use the IPCC's and AMPERE's definitions for generation technology (Coal, Gas, and Oil) and regions: Latin America (LAM), Middle East and Africa (MAF), the OECD countries (OECD90), the Reforming

Economies (REF) of the former Soviet Union,[9] and Asia.

A.2 Generation pathways

We use two different sets of pathways for electricity generation between 2005 and 2100, created by integrated assessment models (IAMs):[10] the AMPERE database and the IPCC's AR5 database.[11] From each of the analyzed scenarios, the model output for power generation from different technologies is used (e.g. coal, with and without CCS, gas, with and without CCS, nuclear, etc.). The AMPERE database provides regional and, in some cases, even country-specific model outputs, while the IPCC's AR5 database provides only global results for the required outputs.

First, for insights on a global and local level, we use a set of ~400 pathways to 2100 generated by a variety of scenarios processed with eight different IAMs[12] for a recent IAM comparison study: AMPERE (Riahi, Kriegler, *et al.*, 2015). The different scenarios cover a wide range of different technology scenarios (e.g. 'No CCS', 'No new nuclear', etc.), long-term concentration targets (e.g. 450-ppm, 500-ppm, etc.), and short-term targets for 2030 (e.g. low or high short-term target vs. optimal policy short-term target).

Second, for further insights on a global and regional level, we analyze the full IPCC AR5 database, consisting of 1,184 pathways from a wide range of scenarios processed with 31 IAMs (Krey *et al.*, 2014). Scenarios processed in the AR5 database can be classified along five dimensions: (1) different climate targets,

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[9] Also known as 'Economies in Transition' (EIT).

[10] See Appendix B.1 for more information about IAMs.

[11] These data sets are chosen since they are freely available online (IIASA, 2014a, 2014b). Other recent studies such as EMF27 (Kriegler *et al.*, 2014) or the SSP dataset (Riahi, van Vuuren, *et al.*, 2015) are of similar scope, use a broader variety of models and assumptions, and reach qualitatively and quantitatively similar results, but are unfortunately currently not publicly available online (at least not in the required granularity).

[12] GCAM, IMACLIM, IMAGE, MERGE-ETL, MESSAGE-MACRO, POLES, REMIND, and WITCH. The database also includes the DNE21+ model. This has been excluded, however, since it only models the period through to 2050.

determined by 2100 CO_2-eq. concentrations (e.g. 450-ppm, 500-ppm, etc.); (2) overshoot of these 2100 levels between 2005 and 2100; (3) scale of deployment of carbon dioxide removal (CDR) or negative emissions technologies (NETs); (4) availability of mitigation technologies, especially CDR and NETs; and (5) policy category (e.g. immediate vs. delayed mitigation, etc.).

A.3 Simulation approach

In the first step, we simulate the development of currently operating global generation capacity. We calculate the expected lifetimes for each generator, and simulate their expected lifespan to derive the expected future annual generation profile of the total capital stock (see Appendix A.2 for more details). In cases where the simulated lifespan is shorter than the observed lifespan (i.e. overaged generators that 'should' have been retired but are observably still in operation today), we assume a phase-out period over the subsequent years (starting with the oldest generators in year 1 and so on). In section 3.5 we present our results for different phase-out times.

Second, we use the AR5 and AMPERE pathway databases (both harmonized to 2015[13]) to calculate the median generation profiles for different global warming scenarios. We then compare these scenarios with the annual remaining generation of today's capital stock.

Third, to assess the amount of fossil fuel capacity that would need to be added in any given year for it to match that scenario's generation profile, we compare the then operating capital stock with realistic utilization assumptions (historic 10-year average utilization rates, 2004-14). If utilization would be higher than the historic average, new capacity is added to the capital stock.

Finally, we calculate the amount of stranding that takes place in each year. In many scenarios, the decrease of fossil-fuel powered generation in later years is

[13] Pathways in the AR5 and AMPERE databases are based and harmonized on the years 2005 and 2000, respectively. We use historical generation data (IEA, 2016) and a peer-reviewed harmonization approach (Rogelj *et al.*, 2011) to harmonize scenarios with historic observations.

steeper than the 'natural' decrease of generation capacity (retirements). This leads to decreasing utilization rates. We define stranding as the difference between the historic minimum utilization rate (over the period 2004-2014) and actual utilization, and express it in Exajoule[14] (EJ) of 'unproduced' electricity.

For illustrative purposes, Figure 9 provides an example of the global capital stock, utilization, and stranding of generation capacity. The installed capacity (dark blue area) continues to increase after 2015 as generators that are currently already under construction come online. The sharp decrease after 2018 (through 2020-21) is due to generators that are currently overaged being phased-out in the years after 2015. In other cases, in which a longer phase-out period is assumed, this decline is less steep. Generation[15] (orange line) must be met without pushing the utilization of capacity (black line) beyond its target utilization (black dashed line). Therefore, additional capacity (green columns) is added to the capital stock over time (light blue area[16]) as old capacity retires. This new (and old) capacity then experiences underutilization after 2030 when generation starts to decline faster than the natural decline of capital stock without further additions. This leads to considerable amounts of stranded (i.e. underutilized) generation capacity between 2025 and 2060 (red columns).

[14] One Exajoule is equal to 10^{18} (one quintillion) joules or ~278 terawatt hours (TWh).

[15] Generation profile as modelled by IAM in this scenario (e.g. 430-480 ppm scenario).

[16] Light blue area is the result of the inertia (lifetimes) of added new capacity (green columns).

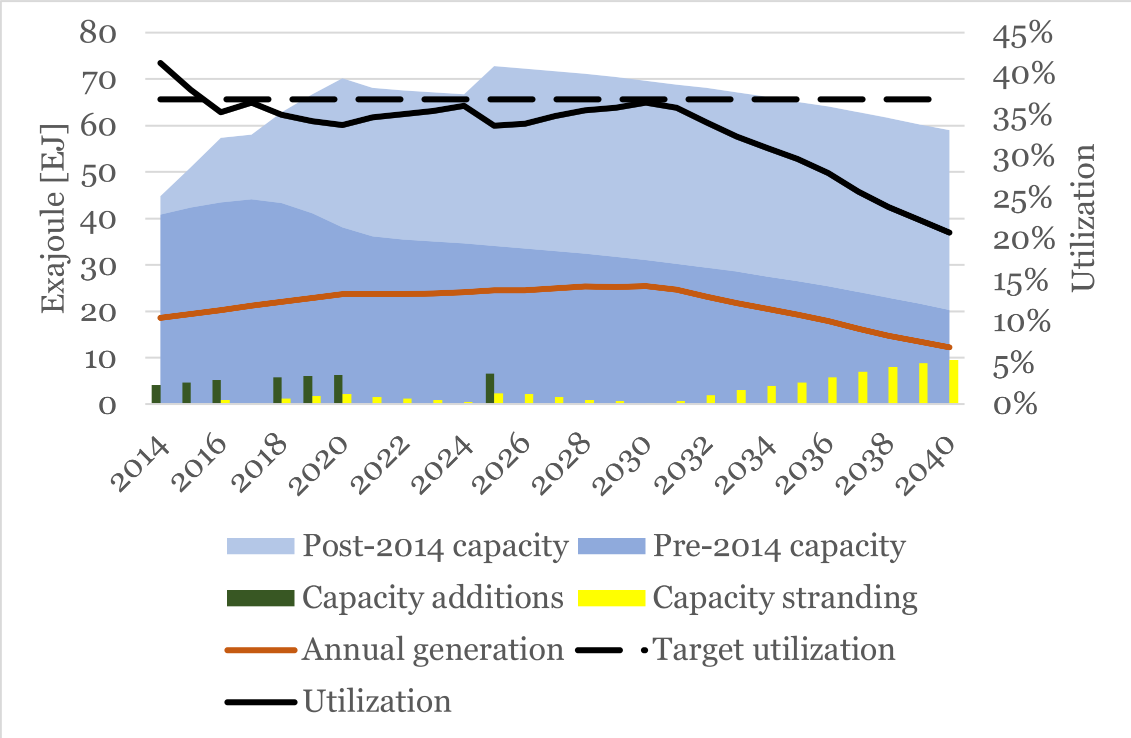

Figure 9: Schematic diagram of the simulation approach. *As currently operating capital stock retires (dark blue area) new capacity (green columns) is added to the total capital stock (light blue area). When annual generation (orange line) decreases, however, the utilization rate (black line) drops below target (dashed line) and stranding occurs (red columns).*

Appendix B: Additional Information

B.1 Additional information about databases and sources

IAMs have been the key tools for the analysis of climate change impacts since the foundation of the IPCC (Clarke *et al.*, 2009). They are now used for the economic assessment of climate change policies in the IPCC's ARs, and by governments around the world. IAMs can be classified either as policy optimization models (POMs) or policy evaluation models (PEMs) (IPCC, 2001). POMs include a 'damage function' and focus on a full cost-benefit analysis of climate change mitigation action and optimal policy. PEMs, on the other hand, look at the cost-effectiveness of achieving an exogenous mitigation target by means of a specific policy (Farmer *et al.*, 2015). The databases used in this paper focus on PEMs (IPCC, 2014), which compute cost-effective pathways and energy system transitions under different socio-economic and policy assumptions and constraints set by climate targets. They factor in a wide range of parameters, such as long-term demographic evolution, the availability of natural resources, and countries' participation in emission-reduction efforts. Technology costs and maximum penetration rates are calibrated using a mix of historical uptake rates and assumptions on learning by doing and autonomous technical progress (Wilson *et al.*, 2013; Iyer *et al.*, 2014). IAMs are regularly peer-reviewed in comparison exercises (Clarke *et al.*, 2009; van Vuuren *et al.*, 2009; Edenhofer *et al.*, 2010; Kriegler *et al.*, 2014, 2015) and occasionally evaluated against historical data (Guivarch, Hallegatte and Crassous, 2009; Wilson *et al.*, 2013).

B.2 Additional information about methodology

To calculate total and remaining capacity the described databases and sources are merged on a generator level. The remaining capacity of each generator in each year is calculated by multiplying the annual maximum generation with the expected or simulated lifetime of that generator. Missing information about online years and expected lifetimes of generators in the database can be estimated by using the information available from similar clusters within the database.[17] Finally, lifetimes are simulated by applying random numbers from a *Poisson* distribution with the expected lifetime of that generator as the mean. The simulation accounts for the fact that generators are rarely retired exactly after their expected lifetime but are rather retired some years around their expected retirement date. Within the database, many of the generators are still in operation long after, while others retire long before, their expected retirement.[18]

B.3 Limitations

B.3.1 Technical limitations

The calculations and estimations throughout this paper depend on a variety of databases, sources and assumptions, most notably in respect to the asset-level database containing the generators (Platt's WEPP UDI), the IPCC AR5 and AMPERE scenario databases, and the historical data containing energy insights (IEA World Energy Outlooks). It should not be assumed that these databases and sources are 100% exhaustive or perfectly accurate. In some cases, important information is missing in the databases. For instance, the online years of many power generators, an important input to the calculation of committed emissions, are missing in the WEPP UDI database and must be estimated. The same applies to fuel-type, generator and turbine technology, and even the countries of some generators. Moreover, the status of generators in the database is often missing or must be presumed to be wrong: some generators that came online in the early 20th century, are still included as "*operating*" or "*stand-by*" in the database, while others, that came online just a few years ago, are already "*retired*". It remains possible, however, that the database does not contain all power generators, or contains some power generators that are not operating anymore.

The estimation of the current generator pipeline is based on the same sources.

[17] E.g. median lifetime of generators from the same country, year, manufacturer, fuel, type, etc.

[18] For generators that are still in operation in 2016 but have a simulated retirement year before 2016 a 10-year phase-out period is used in which every year the then oldest decile of generators is being retired.

Many of the generators included in the pipeline have the status "*delayed*", "*deferred*", "*under construction*", or "*planned*". Generators that are "*cancelled*" are explicitly excluded from this pipeline. It is possible, however, that our current estimate of the pipeline still includes generators that were once planned but are now not planned anymore. Often it is not even clear whether a plant is (still) planned or not. For instance, the database includes eight planned coal-generators (~2.5 GW in total) in Australia, five of which are in Queensland. Closer research, however, reveals that the local government strongly opposes the addition of new coal capacity while the national government proposes such move (Murphy, 2017). The company that would oversee the extension, CS Energy, is on record as being opposed to the idea but does not rule it out entirely (Cooper, 2017). It is often not clear what the likelihood is that some of the planned power generators in the database will ever operate, it is, however, clear that plans exist for each of these generators, and there is high probability that at least some will eventually be built.

In addition to these database limitations several other technical limitations can be identified: (a) online years and generator status are often estimated; (b) the total and remaining lifetimes of currently operating power generators are either estimated or simulated; (c) the future utilization of generators is estimated based on global historic average utilization rates of a certain fuel type; and finally (d) the decision to add or strand generators in the long-term simulation method does not include any foresight of the agents in the model.

B.3.2 Scenario limitations

The applied scenario databases (IPCC AR5 and AMPERE) also have several limitations. All the scenarios used in this paper are the outputs of integrated assessment models. IAMs have recently come under increasing criticism (Revesz *et al.*, 2014) among prominent mainstream economists (Pindyck, 2013; Stern, 2013; Weitzman, 2013) even going so far as to call their outputs "*close to useless*" (Pindyck, 2013). Criticism of IAMs can broadly be categorized into five categories (Farmer *et al.*, 2015): (1) the way they handle uncertainty and especially 'fat tail events' in economic and physical climate systems (Pindyck, 2013; Stern, 2013); (2) aggregation and distributional issues, i.e. the 'representative agent' (Stern, 2013; Iyer *et al.*, 2015); (3) technological change and how innovation is modelled (Farmer and Lafond, 2016); (4) the damage functions (Pindyck, 2013, 2015; Burke *et al.*, 2015); and (5) other issues such as behavioural assumptions (Tversky and Kahneman, 1974; Kahneman and Tversky, 1979) and the equilibrium assumption (Arent *et al.*, 2014). While these limitations play a decisive role when it comes to the evaluation of policy options, they affect the results of this paper to a lesser extent. The objective of this paper is not to evaluate policy options but rather to model how different climate goals and scenario assumptions will affect asset stranding. The model outputs of scenarios are therefore sufficient if they appropriately model the interaction of different generation technologies with each other, with overall energy demand, and with carbon budgets.

In addition to the inherent limitations of IAM scenario outputs, in the context of this paper, the main limitation is that they are mostly harmonized to either 2000 or 2005. Most model outputs (such as annual electricity generation or carbon emissions) start around 2005. Since then, over a decade has passed, however, and global emissions have so far developed along the upper end of scenarios, close to a business-as-usual paradigm, as modelled by RCP8.5. Several emission pathways that appeared realistic, or at least possible, just ten years ago appear now outlandish. On the other hand, the deployment of renewables has been much faster than deemed realistic in many scenarios in 2005. It is now much more realistic that renewables will provide a significant share of global electricity supply by 2020, 2030 or 2050. Using scenarios harmonized to 2000 or 2005 will therefore distort the pathways that are likely today.

Appendix C: Additional figures

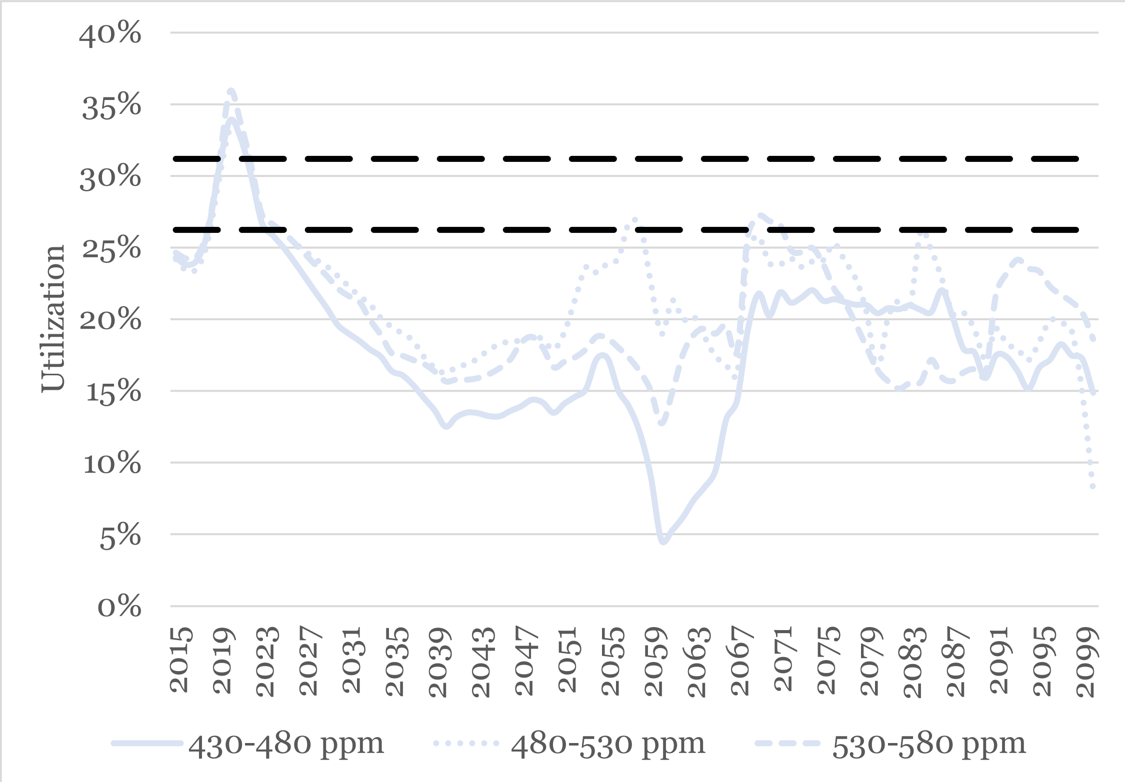

Figure C.1: Simulation results for oil-fired capacity utilization. *Oil utilization drops after 2020 but then has strong variability after 2050.*

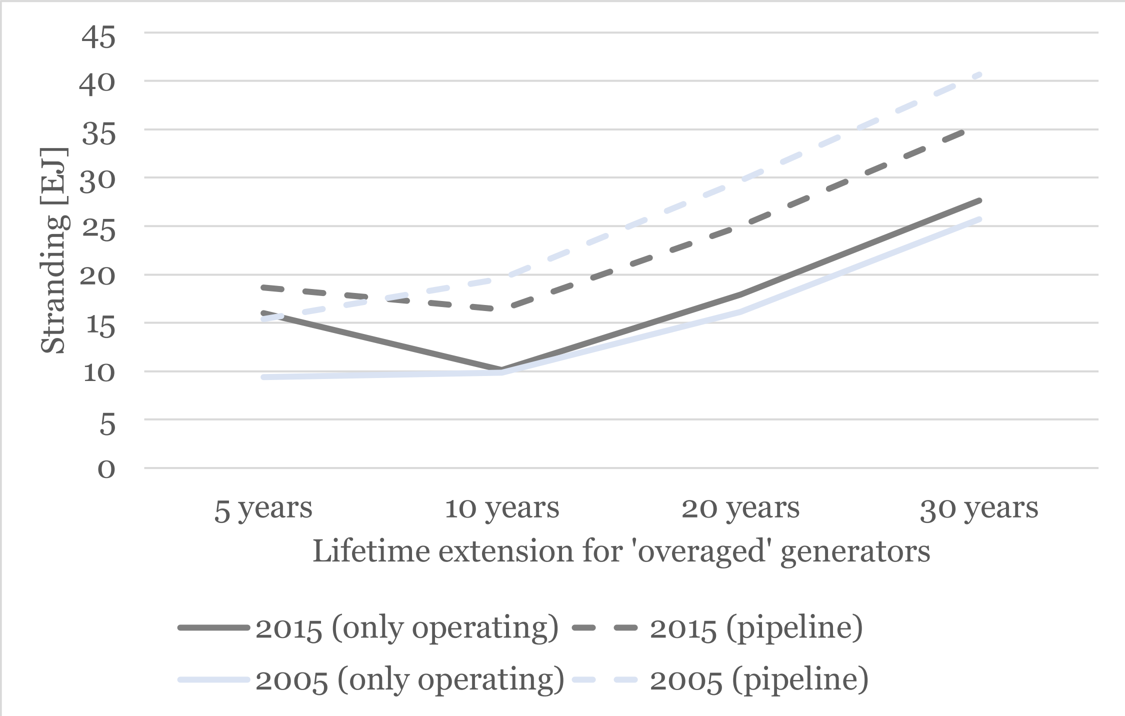

Figure C.2: Lifetime extensions for operating 'overaged' oil capacity in the 430-480 ppm scenarios. *Lifetime extensions of up to ten years for oil (instead of new capacity) could reduce future asset stranding, even if the pipeline was to be built.*

Appendix D: Additional tables

Table D.1: Total asset stranding by scenario and technology.

[Exajoule]	**430-480 ppm**	**480-530 ppm**	**530-580 ppm**
Coal	310	255	224
Gas	139	74	35
Oil	16	9	10
Total	**509**	**381**	**306**

Table D.2: Total asset stranding for currently operating generators and including the current pipeline, by scenario and technology.

[Exajoule]		**Only currently operating**	**Including pipeline**	**Change**
430-480 ppm	**Coal**	310	780	+152%
	Gas	139	198	+43%
	Oil	16	19	+16%
480-530 ppm	**Coal**	255	680	+167%
	Gas	74	81	+9%
	Oil	9	13	+40%
530-580 ppm	**Coal**	224	603	+170%
	Gas	35	40	+14%
	Oil	10	15	+60%

Table D.3: Total asset stranding until 2100 in 2005 and 2015, by scenario and

technology.

[Exajoule]		2005	2015	Change
430-480 ppm	**Coal**	235	310	+32%
	Gas	159	139	-12%
	Oil	7	16	+114%
480-530 ppm	**Coal**	167	255	+53%
	Gas	80	74	-7%
	Oil	5	9	+68%
530-580 ppm	**Coal**	177	224	+26%
	Gas	39	35	-11%
	Oil	5	10	+87%

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  - Provided substantial edits and comments to all sections
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  - Provided input to introduction, results, and discussion sections
  - Provided substantial input to literature review section
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  - Overall comments and small edits
  - Provided input to introduction and discussion sections