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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

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[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**

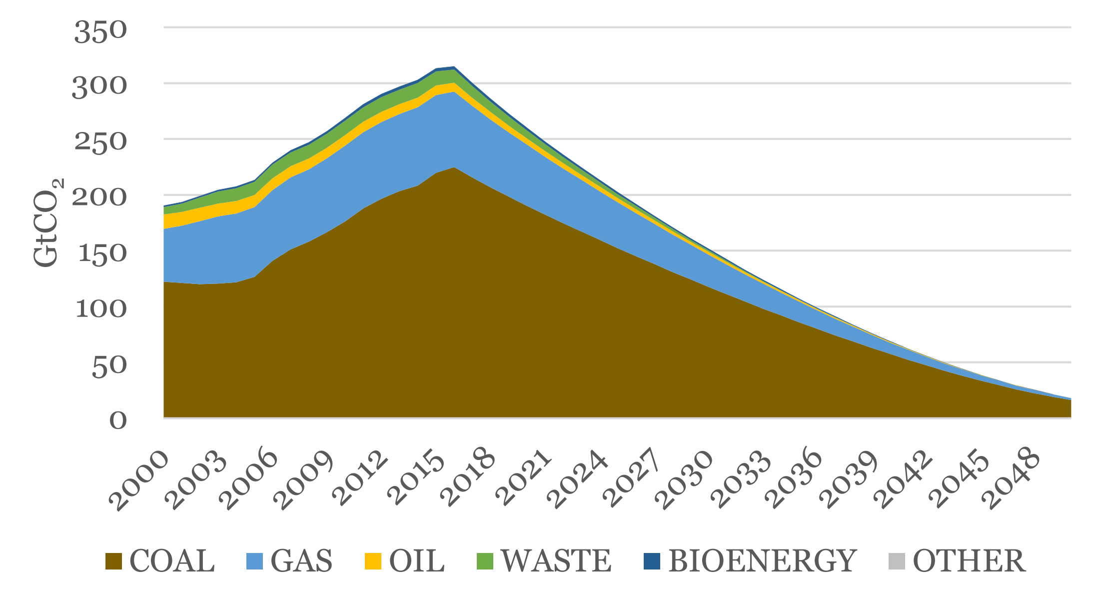
** Renewables include hydro, solar and wind, and do not result in committed emissions. ** Other includes nuclear and geothermal; the non-zero committed emissions associated with these generators stems from a small amount of fugitive emissions from geothermal power generation.*

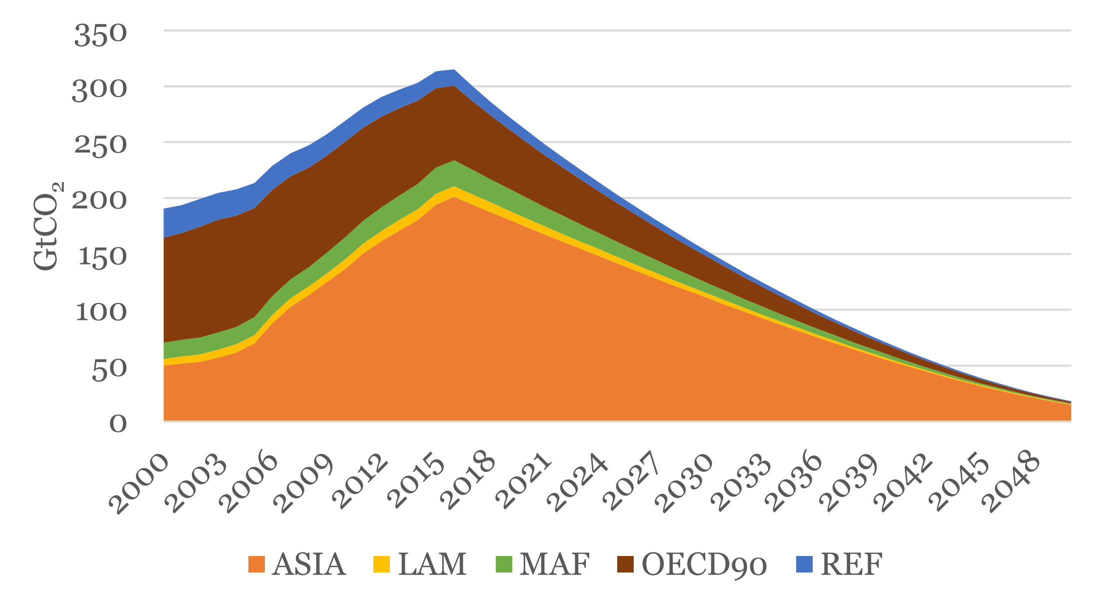
Overall, this capacity, if operated over its full remaining lifetime at current utilization rates, could generate ~537k TWh (~23 years of generation at current levels)[9] and would emit ~300 $GtCO_2$ over the coming decades (i.e. ~7 years-worth

[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)

[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).

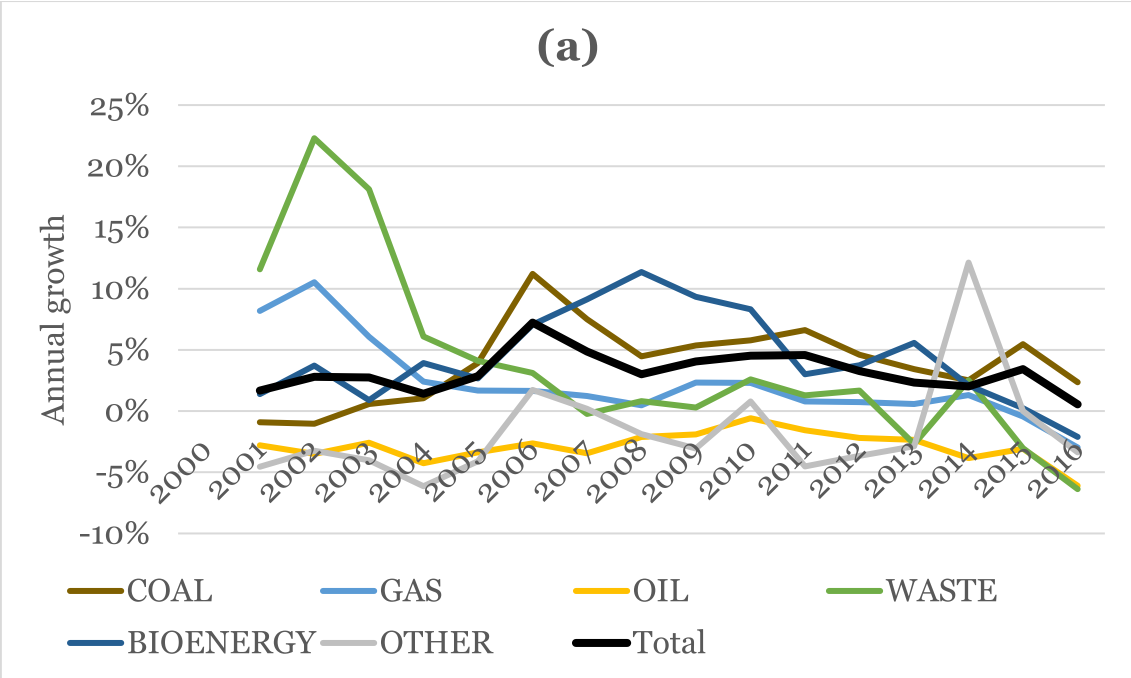
[11] See Appendix C.2 for the full regional split.

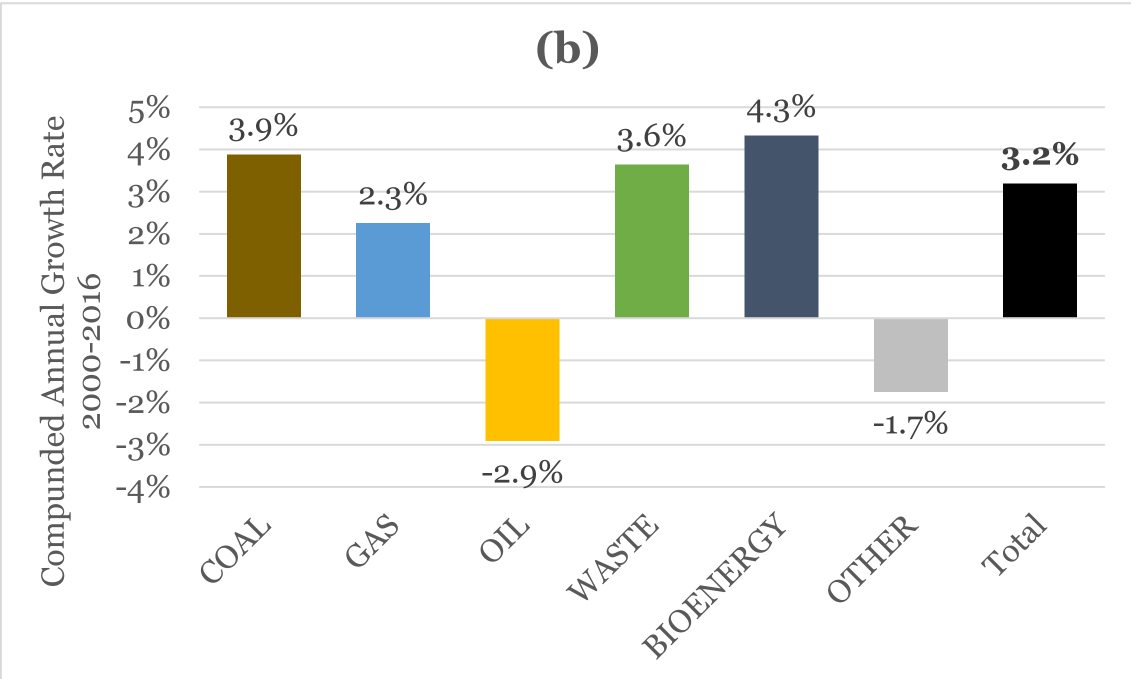
Figure 1: Historic development of committed emissions from electricity generators in operation in 2016, by technologies (panel a) and regions (panel b). *The strongest growth between 2005 and 2016 took place in Asia and comes from coal emission commitments. After 2016, emission commitments would decrease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

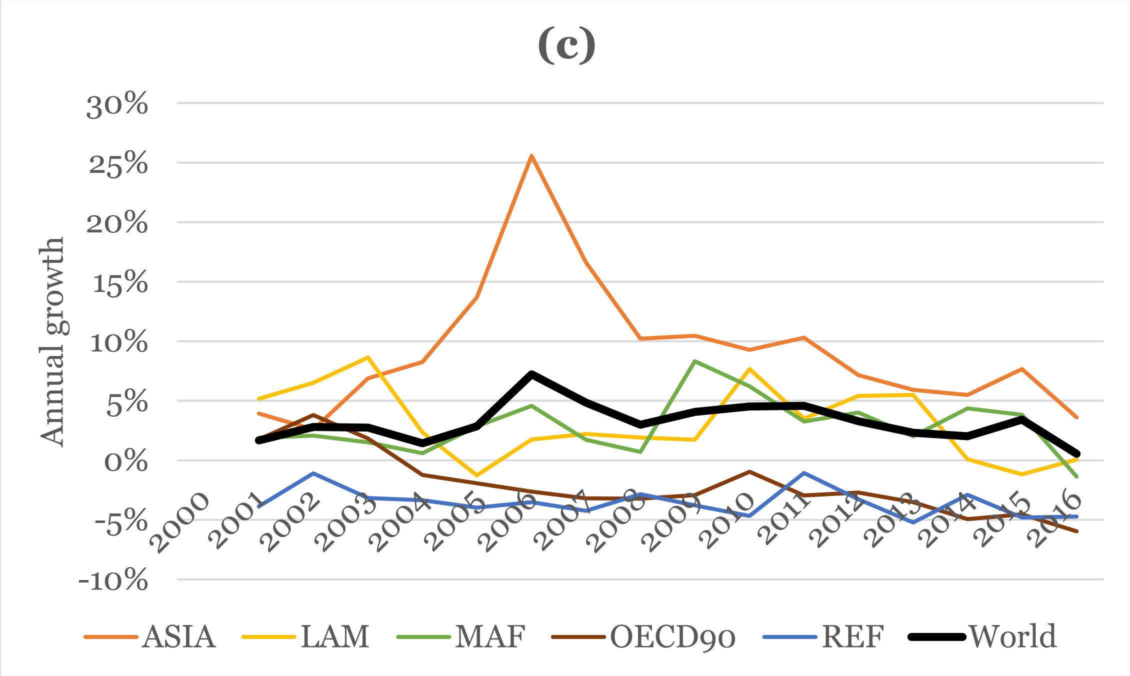
Figure 1 shows the development of committed emissions over time by technologies (panel a) and regions (panel b). After the present day, we show decreasing commitments as they 'realize' into actual emissions. Committed emissions from coal decreased by 1.4% between 2000 and 2003, presumably because coal 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



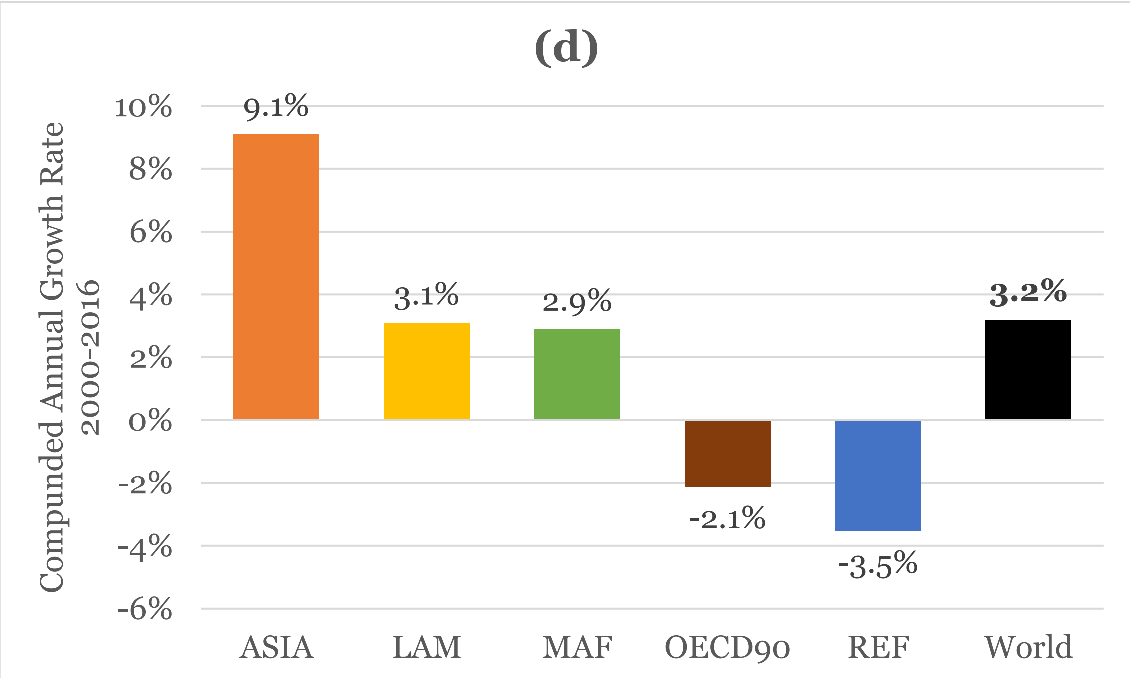


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Figure 2: Historic annual growth rates and compounded annual growth rates (CAGR) between 2000 and 2016 of emission commitments from electricity generators in operation in 2016, by technologies (panels a and b) and regions (panels c and d). *Countries 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.

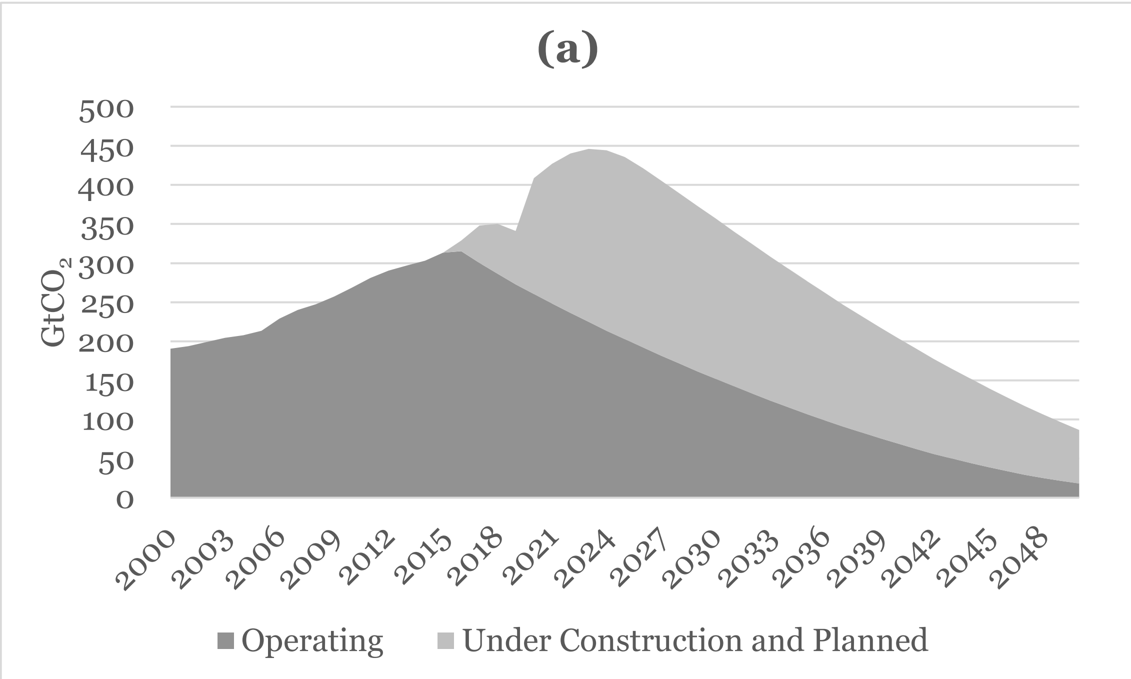
Table 2: Cumulative emissions of electricity generators under construction or planned in early 2017, by technologies and regions.

[$GtCO_2$]	**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.

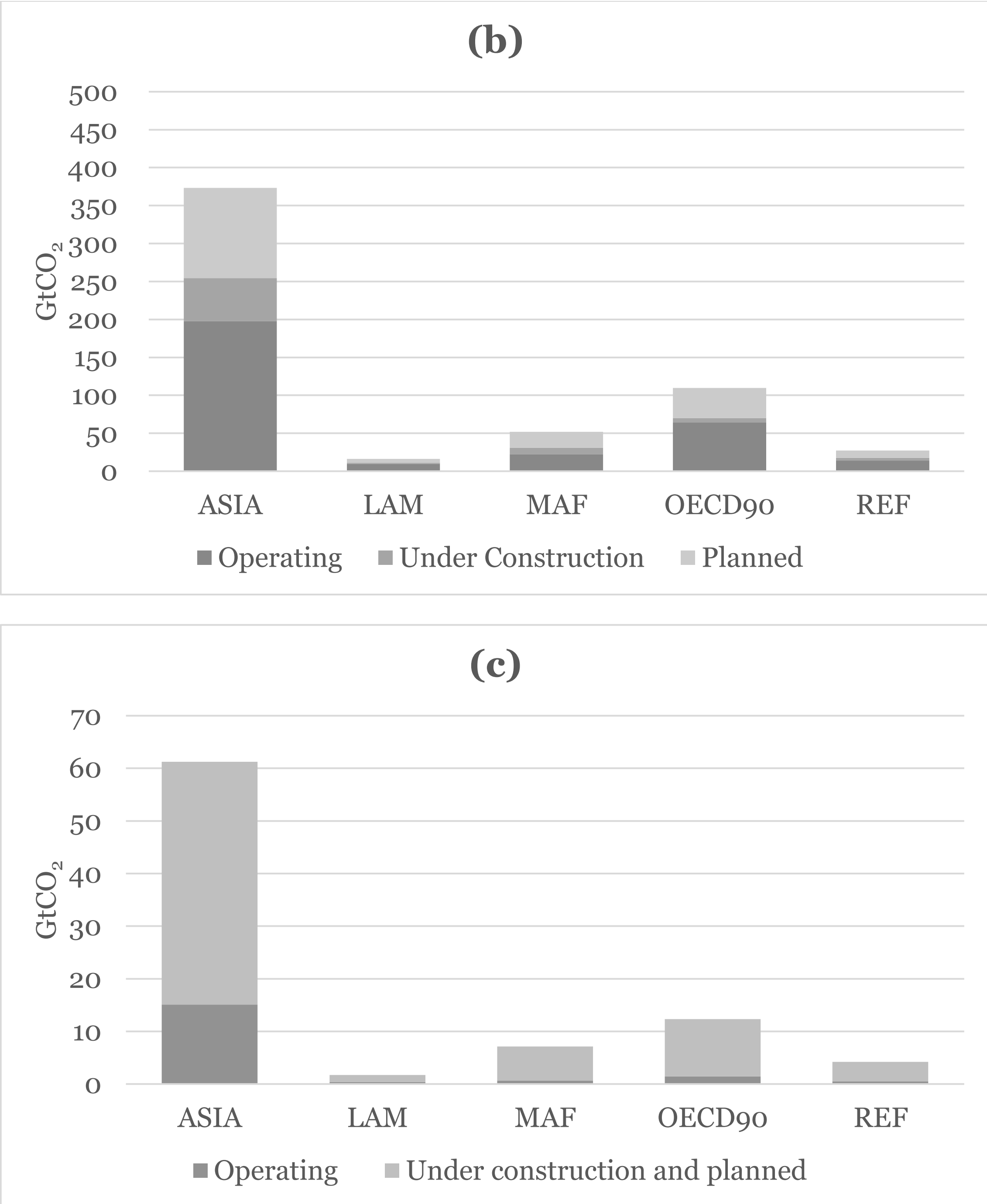


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Figure 3: Historic (until 2016) and expected (thereafter) development of committed emissions from electricity generators in operation, under construction, or planned in 2016, by status (panel a), 2016 committed emissions by regions (panel b), and remaining 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.

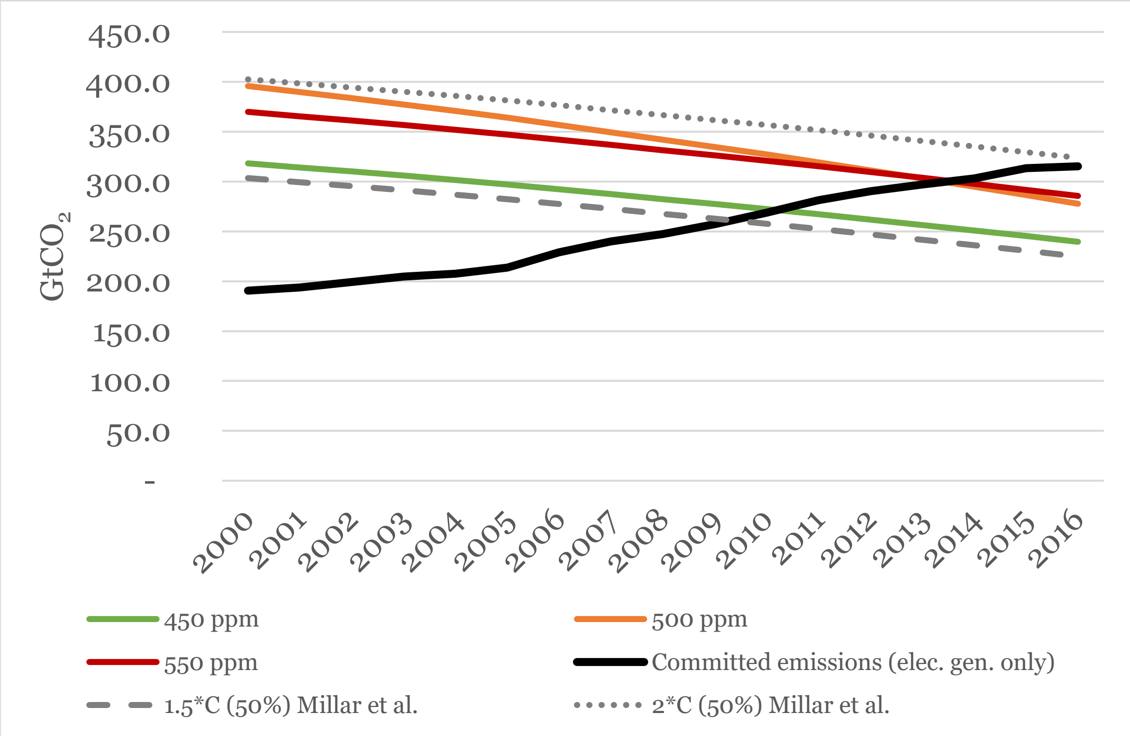

Figure 4: Development of remaining generation-only carbon budget in different climate scenarios (median) and committed emissions from generation capacity. *In 2011, committed emissions from electricity generators reached the remaining total generation-only budget for the median 430-480 ppm scenario (good 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.*[19]

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.

[19] Remaining generation-only budgets for 480-530 and 530-580 ppm scenarios cross around 2012 due to different assumptions regarding the generation emissions share of overall budget and the cumulative emissions sequestered by BECCS in the 21st century.

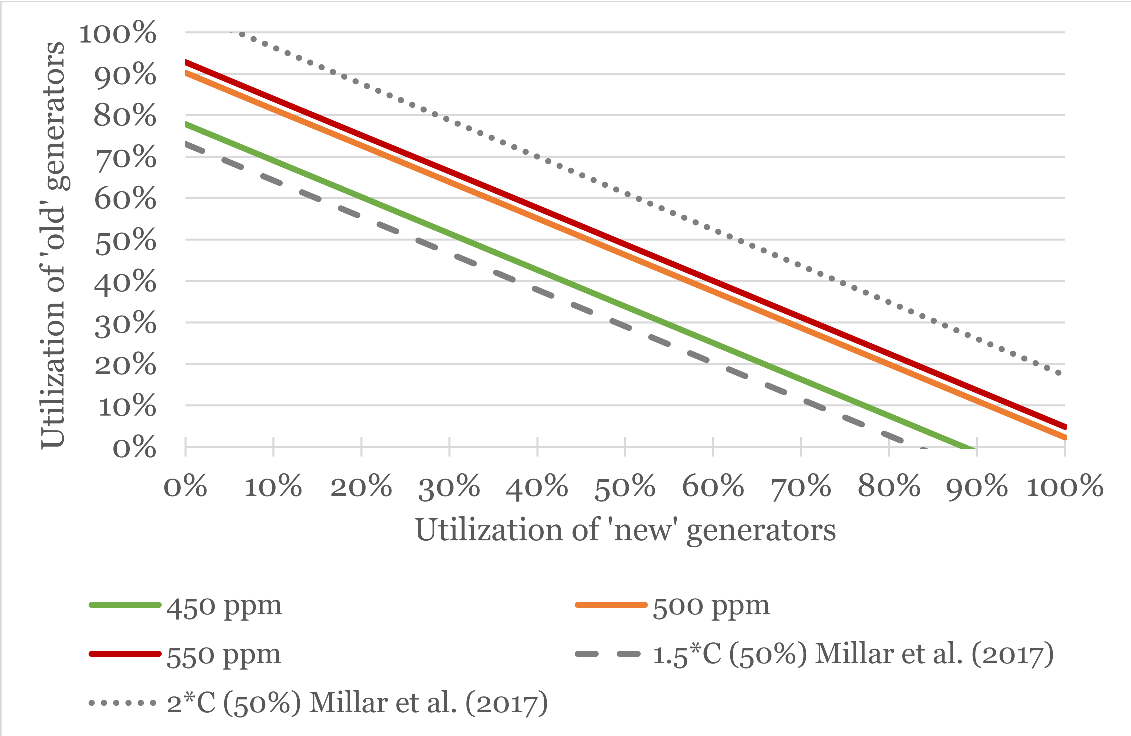

Figure 5: Different combinations of maximum possible utilizations of currently operating and pipeline electricity generators under different carbon budgets. *Even if plans for all new generators were to be cancelled, and current constructions halted (i.e. 0% utilization of new generators), already operating 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%).[20] For gas-fired generators, and based on an expected lifetime of 38 years, every additional year of lifetime for new gas generators would increase the emission commitments from 49 GtCO_2 to 50 GtCO_2 (+2%). The same one-year increase in the lifetime of currently operating generators (emission commitments of 66 GtCO_2 in 2016) would increase emission commitments by 3.3 GtCO2 (+5%).[21]

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.

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

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

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 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.

References

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M. and Meinshausen, N. (2009) 'Warming caused by cumulative carbon emissions towards the trillionth tonne', *Nature*, 458(7242), pp. 1163–1166.

Audoly, R., Vogt-Schilb, A., Pfeiffer, A. and Guivarch, C. (2017) *Pathways toward zero-carbon electricity required for climate stabilization*, *IDB Working Paper Series*.

Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M. and Eom, J. (2015) 'Carbon lock-in through capital stock inertia associated with weak near-term climate policies', *Technological Forecasting and Social Change*. Elsevier Inc., 90(PA), pp. 62–72. doi: 10.1016/j.techfore.2013.10.001.

Caldecott, B., Dericks, G. and Mitchell, J. (2015) 'Subcritical Coal in Australia: Risks to Investors and Implications for Policymakers', *Smith School of Enterprise and the Environment, University of Oxford*. Oxford, UK (Working Paper Series).

Caldecott, B., Elizabeth, H., Cojoianu, T., Kok, I. and Pfeiffer, A. (2016) 'Stranded Assets: A Climate Risk Challenge', pp. 1–6. doi: 10.18235/0000517.

Caldecott, B., Kruitwagen, L., Dericks, G., Tulloch, D. J., Kok, I. and Mitchell, J. (2016) *Stranded assets and Thermal coal - An analysis of environment-related risk exposure*, *Smith School of Enterprise and the Environment, University of Oxford*.

Caldecott, B. and McDaniels, J. (2014) 'Stranded generation assets : Implications for European capacity mechanisms , energy markets and climate policy', *Smith School of Enterprise and the Environment, University of Oxford*. Oxford, UK (Working Paper Series).

Caldecott, B., Tilbury, J. and Carey, C. (2014) 'Stranded Assets and Scenarios: Discussion Paper', *Smith School of Enterprise and the Environment, University of Oxford*, (January), pp. 1–22.

Caldecott, B., Tulloch, D. J., Bouveret, G., Pfeiffer, A., Kruitwagen, L., McDaniels, J. and Dericks, G. (2017) *The fate of European coal-fired power stations planned in the mid-2000s*. Oxford, UK.

CARMA (2010) *CARMA database*, *Carbon Monitoring for Action*. Available at: http://www.carma.org (Accessed: 1 September 2017).

Carney, M. (2015) 'Breaking the Tragedy of the Horizon – climate change and financial stability'. Bank of England.

Clarke, L. E., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Loschel, D., McCollum, S., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., van der Zwaan, B. C. C. and van Vuuren, D. P. (2014) 'Assessing transformation pathways', in *Climate Change 2014: Mitigation of Climate Change. ontribution of Working Group III to the Fifth Assessment*

Report of the Intergovernmental Panel on Climate Change.

CTI (2013) *Unburnable carbon 2013: wasted capital and stranded assets*, *Management of Environmental Quality: An International Journal*. doi: 10.1108/meq.2013.08324eaa.003.

Davis, S. J., Caldeira, K. and Matthews, H. D. (2010) 'Future CO2 emissions and climate change from existing energy infrastructure', *Science*, 329(5997), pp. 1330–1333. doi: 10.1126/science.1188566.

Davis, S. J. and Socolow, R. H. (2014) 'Commitment accounting of CO2 emissions', *Environmental Research Letters*, 9(8), p. 84018. doi: 10.1088/1748-9326/9/8/084018.

EIA (2011) *Age of electric power generators varies widely*, *U.S. Energy Information Administration*. Available at: Age of electric power generators varies widely (Accessed: 1 September 2017).

EIA (2016) *Carbon Dioxide Emissions Coefficients*, *U.S. Energy Information Administration*.

EIA (2017) *Approximate Heat Rates for Electricity, and Heat Content of Electricity*, *U.S. Energy Information Administration*. Available at: https://www.eia.gov/totalenergy/data/monthly/pdf/sec13_6.pdf (Accessed: 1 September 2017).

EPA (2009) 'New Coal-fired Power Plant Performance and Cost Estimates', *U.S. Environmental Protection Agency*, p. 82.

Forsythe, M. (2017) 'China Cancels 103 Coal Plants, Mindful of Smog and Wasted Capacity', *The New York Times*, 18 January.

Guivarch, C. and Hallegatte, S. (2011) 'Existing infrastructure and the 2* Celsius target', *Climatic Change*, 109(3–4), pp. 801–805.

Guivarch, C. and Hallegatte, S. (2013) '2C or not 2C?', *Global Environmental Change*, 23(1), pp. 179–192. doi: 10.1016/j.gloenvcha.2012.10.006.

IEA (2016) *World Energy Outlook 2016*. doi: http://www.iea.org/publications/freepublications/publication/WEB_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf.

IEA (2017) *World Energy Outlook 2017: Executive Summary*. doi: 10.1016/0301-4215(73)90024-4.

IIASA (2014a) 'AMPERE Public Database. International Institute for Applied Systems Analysis.'

IIASA (2014b) *AR5 Scenario Database*, *About*. doi: 10.1142/S2010007813400083.

IPCC (2013) *IPCC Fifth Assessment Report (AR5) - The Physical Science Basis*, *IPCC*.

IPCC (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability Part. B: Regional Aspects*, *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. doi: 10.1007/s13398-014-0173-7.2.

Johnson, N., Krey, V., McCollum, D. L., Rao, S., Riahi, K. and Rogelj, J. (2015) 'Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants', *Technological Forecasting and Social Change*. Elsevier B.V., 90(PA), pp. 89–102. doi: 10.1016/j.techfore.2014.02.028.

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G. and Klein, D. (2013) 'Is atmospheric carbon dioxide removal a game changer for climate change mitigation?', *Climatic Change*, 118(1), pp. 45–57. doi: 10.1007/s10584-012-0681-4.

Kriegler, E., Riahi, K., Bosetti, V., Capros, P., Petermann, N., van Vuuren, D. P., Weyant, J. P. and Edenhofer, O. (2015) 'Introduction to the AMPERE model intercomparison studies on the economics of climate stabilization', *Technological Forecasting and Social Change*, 90(PA), pp. 1–7. doi: 10.1016/j.techfore.2014.10.012.

Mason, J. (2017) 'In latest move, China halts over 100 coal power projects', *Reuters*, 17 January.

Matthews, H. D. and Caldeira, K. (2008) 'Stabilizing climate requires near-zero emissions', *Geophysical Research Letters*, 35(4). doi: 10.1029/2007GL032388.

Matthews, H. D., Gillett, N. P., Stott, P. A. and Zickfeld, K. (2009) 'The proportionality of global warming to cumulative carbon emissions', *Nature*, 459(7248), pp. 829–832.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M. and Meinshausen, N. (2009) 'Greenhouse-gas emission targets for limiting global warming to 2-degree Celsius', *Nature*. Nature Publishing Group, 458(7242), pp. 1158–1162. doi: 10.1038/nature08017.

Millar, R., Allen, M., Rogelj, J. and Friedlingstein, P. (2016) 'The cumulative carbon budget and its implications', *Oxford Review of Economic Policy*, 32(2), pp. 323–342. doi: 10.1093/oxrep/grw009.

Millar, R. J., Fuglestvedt, J. S., Friedlingstein, P., Rogelj, J., Grubb, M. J., Matthews, H. D., Skeie, R. B., Forster, P. M., Frame, D. J. and Allen, M. R. (2017) 'Emission budgets and pathways consistent with limiting warming to 1.5 °C', *Nature Geoscience*, (September), pp. 1–8. doi: 10.1038/ngeo3031.

Millar, R., Otto, A., Hepburn, C. and Allen, M. (2015) 'Adaptive climate policy and the future of fossil fuels', *forthcoming*, pp. 1–20.

Pfeiffer, A., Millar, R., Hepburn, C. and Beinhocker, E. (2016) 'The 2-degree Celsius capital stock for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy', *Applied Energy*, 179, pp. 1395–1408. doi: 10.1016/j.apenergy.2016.02.093.

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S. and et al. (2016) 'Global Carbon Budget 2016', *Earth System Science Data*, 8(2), pp. 605–649. doi: 10.5194/essd-8-605-2016.

Rozenberg, J., Davis, S. J., Narloch, U. and Hallegatte, S. (2015) 'Climate constraints on the carbon intensity of economic growth', *Environmental Research Letters*. IOP Publishing, 10(9), p. 95006. doi: 10.1088/1748-9326/10/9/095006.

Sanchez, D. L., Nelson, J. H., Johnston, J., Mileva, A. and Kammen, D. M. (2015) 'Biomass enables the transition to a carbon-negative power system across western North America', *Nature Climate Change*, 5(February), pp. 3–7. doi: 10.1038/nclimate2488.

Shearer, C., Fofrich, R. and Davis, S. J. (2017) 'Future CO2 emissions and electricity generation from proposed coal-fired power plants in India'. doi: 10.1002/eft2.201.

Shearer, C., Ghio, N., Myllyvirta, L., Yu, A. and Nace, T. (2017) *Boom and Bust 2017*.

Stern, N. H. (2007) *Stern Review: The Economics of Climate Change*. Cambridge, UK: Cambridge University Press.

UNFCCC (2015) *Adoption of the Paris Agreement*. UNFCCC.

Vogt-Schilb, A. and Hallegatte, S. (2017) 'Climate Policies and Nationally Determined Contributions: Reconciling the Needed Ambition with the Political Economy', *WIREs Energy Environ*, e256. doi: 10.1002/wene.256.

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.[22]

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. Despite these recent drops it is reasonable to assume that investors in these assets had not expected these at the time of the investment decision and some might therefore struggle to recoup their investment.

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

[22] 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.[23]

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.[24]

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

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[23] 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.

[24] 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.[25] 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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25 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.*