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 find 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. These generators would see average utilization rates drop from current levels of 39% (Gas) and 60% (Coal) to 33% and 29%, respectively, before 2050. Such underutilization 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. Our findings have implications for investors, who might want to re-assess current investment plans under lower future utilization rates, and for policy makers, who should consider extending the lifetimes of currently operating power generators to avoid further carbon lock-in by new investments.

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 1.5-2°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). This means that, in the future, all electricity generation will have to be (net-) zero-carbon, e.g. from renewables, fossil-powered generation with carbon capture and sequestration (CCS), or nuclear (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).

Notwithstanding this, currently 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). Despite the fact that 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. For instance, 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]

Despite the strong growth of renewable power generation, renewables alone are not yet sufficient to satisfy the rising energy demand in many regions around the world. Even in optimistic climate scenarios, which assume a continued

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

strong growth of renewables, and adherence to the 1.5-2°C target, coal and gas still play a significant role in the global energy mix over the coming decades (IPCC, 2013; IEA, 2016). While the current national GHG reduction pledges (NDCs[2]) are more ambitious than the previous Copenhagen pledges, they set objectives that allow countries to keep adding fossil fuel generation in the short term (Bertram, Johnson, *et al.*, 2015; Johnson *et al.*, 2015; McJeon, 2015). This means that, in years to come, phased-out fossil-fuel power generation will probably still be replaced with fossil fuel capacity and, in some regions, the installed fossil-fuelled capacity is even likely to expand.

One problem with that development is that power generators, especially fossil-fuels, tend to have a long lifetime. A 2014 study found that the median lifetime of coal and gas generators is 37 and 35 years respectively (Davis and Socolow, 2014), with some coal generators already operating for more than 70 years. This means that the amount of *committed emissions* over this lifetime is comparatively high for fossil-fuel generators. Davis and Socolow find that, as of 2012, an average of 23 GW of new fossil fuel capacity was added to the global capital stock every year, which would, over its lifetime, emit about 19 billion tons of CO_2 ($GtCO_2$). 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, Johnson, *et al.*, 2015; Erickson *et al.*, 2015; Pfeiffer *et al.*, 2016).

The long lifetime of fossil-fuel power infrastructure, and the implied large amount of committed generation and emissions stands in stark contrast to the change of the global generation mix that is required in the energy transition scenarios that would bring us to 1.5-2°C (van Breevort *et al.*, 2015). In almost all scenarios that meet this goal, coal-fired power generation (without carbon capture and sequestration, CCS) is being phased-out by mid-century, and gas (without CCS) soon thereafter. While CCS seems to play a role for gas generation in some pathways, coal-CCS does not play a mentionable role in

[2] NDC: Nationally Determined Contribution, also known as Intended Nationally Determined Contribution (INDC).

most of the scenarios.[3] Even for gas-CCS, it is still unclear to what extent the projected generation will come from new generators and how much of this will be through retrofitting.

Hence, cost-effective transition pathways towards a decarbonized electricity sector are likely to require some amount of stranded assets (Bertram, Johnson, *et al.*, 2015; McJeon, 2015; Rozenberg, Vogt-Schilb and Hallegatte, 2017). Such stranded assets can materialize in different ways, such as underutilization or early retirement (Caldecott and McDaniels, 2014; Caldecott *et al.*, 2016). The previously cited Carbon Tracker Initiative study, for example, finds that, as of July 2016, China had 895 GW of coal capacity that was running with a capacity factor of <50%. Also in other regions, the increasing share of renewables in the energy mix leads to low overall electricity retail prices. The marginal cost of producing renewable electricity are low compared to fossil fuels. Such lower retail prices distress gas- and coal-generators, which need a certain annual generation at 'high-enough' prices to be profitable (Caldecott *et al.*, 2017).

It is increasingly acknowledged that the financial and economic cost of the stranding of infrastructure assets affects utilities, the power sector in general, and, via higher energy prices, eventually also the consumer. In addition, when outstanding loans for fossil-fuel infrastructure or exploration and extraction projects default, the stability of the financial sector could also be affected (CTI, 2011, 2013; Weyzig *et al.*, 2014; Carney, 2015). The global economy is based on, and built around, the consumption of energy, most of it from fossil fuels. Around the world, communities and sectors are often built around a power plant or coal mine. When energy infrastructure strands, these jobs are at risk. The sociological effects of stranding may even be larger than the financial or economic risks (Newell and Mulvaney, 2013; Nelson *et al.*, 2014; Stern, 2014; Healy, 2017). An expected large-scale stranding of power generators may therefore jeopardize the political feasibility of environmental and climate

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3 Adding CCS to a power generator usually reduces plant efficiency (BTU/kWh). CCS, therefore, is usually only considered for highly efficient generators (IEA, 2008). Coal typically has a lower efficiency than gas (EIA, 2017). Many scenarios that include CCS, therefore, typically include it only for gas and some highly efficient coal generators.

focussed energy policies (Jenkins, 2014; Bertram, Luderer, *et al.*, 2015; Rozenberg, Vogt-Schilb and Hallegatte, 2017). Existing numerical estimates of stranded assets in emission-reduction pathways, however, are limited to only a few exercises, and often require a fully integrated assessment model or similar energy-economic model.

A growing body of academic research, therefore, aims to quantify the extent of asset stranding in leading scenarios and to investigate options for how to minimize this. As part of the AMPERE cross-comparison study, Bertram et al. (2015) explore how different climate policies affect capital stock additions and stranded assets. They find that, on a global level, weak near-term policies allow for larger coal additions, and hence lead to an increased amount of asset-stranding, renewable capacity additions, and the need for large-scale carbon-dioxide removal from the atmosphere in the medium- and long-term (2030-2050). Based on the same set of findings, Riahi et al. (2015) analyze whether the Paris pledges (NDCs) will be sufficient to avoid large scale asset stranding (Riahi, Kriegler, *et al.*, 2015). They find that NDCs are not strong enough to avoid further carbon lock-in "*and thus impede the required energy transformation to reach low greenhouse-gas stabilization levels*". Luderer, et al. (2016) assess the implications of current climate policies on long-term mitigation targets in three integrated assessment models (IAMs). They also find that weak near-term policies require faster and more aggressive transformations of energy systems in the medium term as well as more stranded investments in fossil-based capacities if climate targets are to be achieved. They conclude that such weak near-term policies lead to higher long-term mitigation costs and carbon prices, and to stronger transitional economic impacts, rendering the political feasibility of such pathways questionable.

Johnson et al. (2015) use the MESSAGE-MACRO integrated assessment model together with different climate policy scenarios to assess the magnitude and cost of stranded coal capacity. They find that in the least stringent (short-term) policy scenario, the implied coal capacity stranded globally would be equivalent to the premature retirement of almost three 500-MW power plants per month between 2031 and 2050, and amount totalling about 500 bn. USD in stranded investments. They also find that minimizing new construction of coal capacity without CCS is an effective strategy for reducing stranded capacity. This can be achieved by energy intensity improvements, and/or by lifetime extensions for existing plants.

McJeon et al. (2015) use a different IAM (the global change assessment model, GCAM) to assess the near versus long-term energy and economic-cost implications of the national pledges. They find that scenarios that delay action to after 2030 could require up to 2,300 GW of premature retirements of fossil fuel power plants, and up to 2,900 GW of additional low-carbon power capacity installations between 2031 and 2035. The NDCs, in their current form, could reduce these numbers by 50% and 34%, respectively; and increased ambition in the next round of NDCs could further reduce capacity stranding.

Our paper adds to this existing body of literature by systematically exploring the extent of stranded assets in the electricity generation sector implied by the IPCC's global decarbonization scenarios and the findings of the 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 in every year to the global electricity generation capital stock in any given scenario. The derived structure, and remaining lifetime of this capital stock, allows us to calculate the amount of capacity that would need to be stranded in each year, either via early retirement or lower utilization, for the scenario to be in line with its annual emissions and electricity generation.

This proposed 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. IEA, BP, EIA, IPCC), and power generation technology (e.g. coal, gas, oil, and biomass, but also solar, wind, etc.). Importantly, to work, it does not require a fully-fledged integrated assessment model (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 in detail, for the first time, in which regions and years 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[4]), 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.[5] 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

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

5 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.

additions to the capital stock in some regions and scenarios, but that the potential impact of this policy action has decreased during the last decade.

The rest of this paper is structured as follows: Section 2 describes the data (2.1) and scenarios (2.2) used as well as the simulation method (2.3); section 3 presents the results of the simulation for different technologies (3.1), regions (3.2), under different assumptions for currently planned generators (3.3), the development between 2005 and 2015 (3.4), and for different lifetime extensions (3.5). Section 4 discusses the findings and their implications in the wider context. Section 5 concludes.

2. 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).

2.1 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, Oil and Biomass) and regions: Latin America (LAM), Middle East and Africa (MAF), the OECD countries (OECD90), the Reforming Economies (REF) of the former Soviet Union,[6] and Asia.

2.2 Generation pathways

We use two different sets of pathways for electricity generation between 2005 and 2100, created by integrated assessment models (IAMs):[7] the AMPERE database and the IPCC's AR5 database.[8] From each of the analyzed scenarios, the model output for power generation from different technologies is used (e.g. coal, with and without CCS, bioenergy, 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[9] 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).

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6 Also known as 'Economies in Transition' (EIT).

7 See Appendix A.1 for more information about IAMs.

8 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).

9 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.

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, 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.).

2.3 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[10]) 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

[10] 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.

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 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[11] (EJ) of ‘unproduced’ electricity.

For illustrative purposes, Figure 1 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[12] (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[13]) 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).

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

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

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

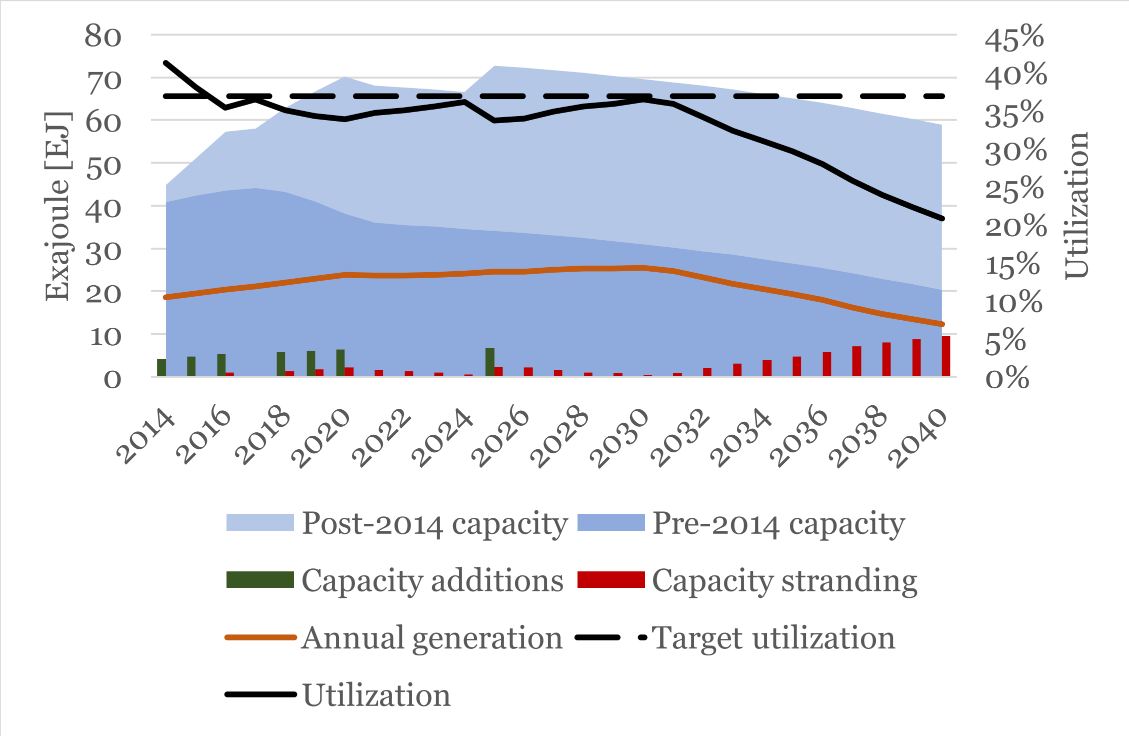


Figure 1: Schematic diagram of the simulation approach. *As currently operating capital stock retires (dark blue area) new capacity (green columns) is added to the total capital stock (light blue area). When annual generation (orange line) decreases, however, the utilization rate (black line) drops below target (dashed line) and stranding occurs (red columns).*

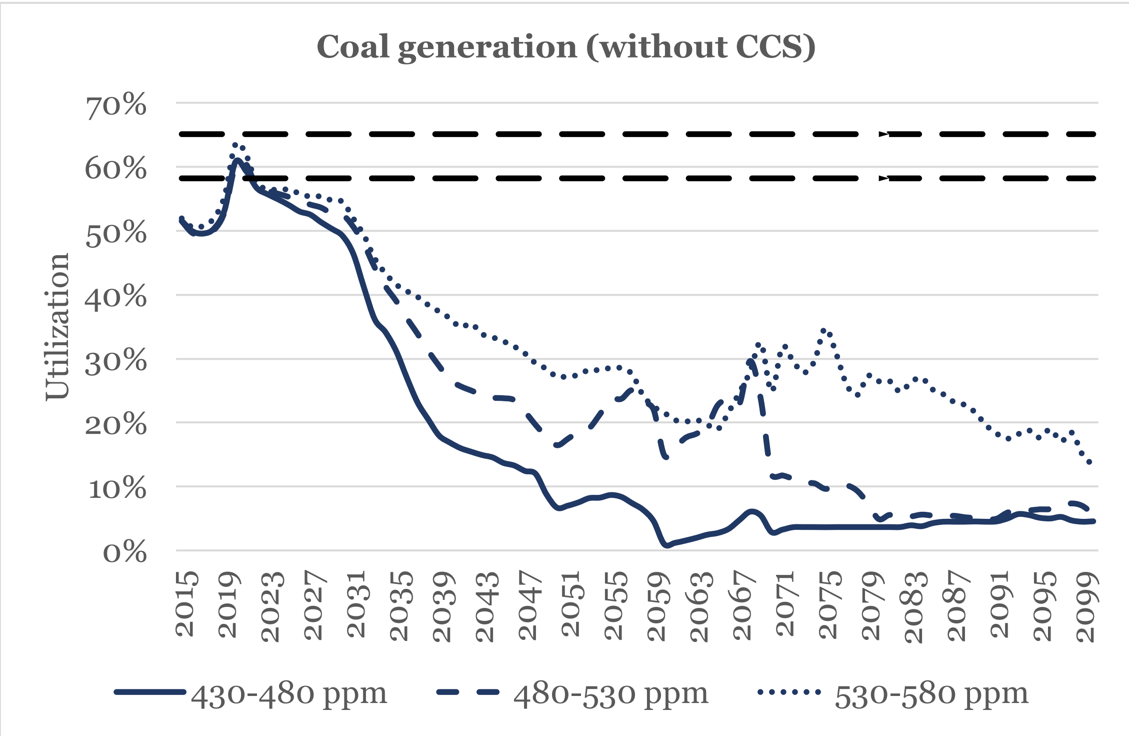
3. Findings

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 we assume a phase-out period of five years. We only analyze carbon emitting generation capacity, i.e. coal, gas, oil and biomass – all without CCS. In the analyzed scenarios, other forms of power generation – namely fossil fuels with CCS, renewables, nuclear, and hydro – play a role and affect the output of those scenarios. These other forms of generation are, however, not the subject of this analysis and hence are not mentioned in the following.

3.1 Utilization rates and stranded capacity

Utilization rates of different fossil fuels in the base case develop quite differently. Biomass utilization rates start from a relatively low level (around 20%) in 2015. Strongly increasing generation in almost all climate-mitigation scenarios increases the utilization of capacity to its target band of ~55% from around 2040 onwards. These results are relatively consistent among the analyzed scenarios, even with different temperature goals (see Appendix B.1.b for biomass results). For coal, the results are different (see Figure 2, panel a). 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

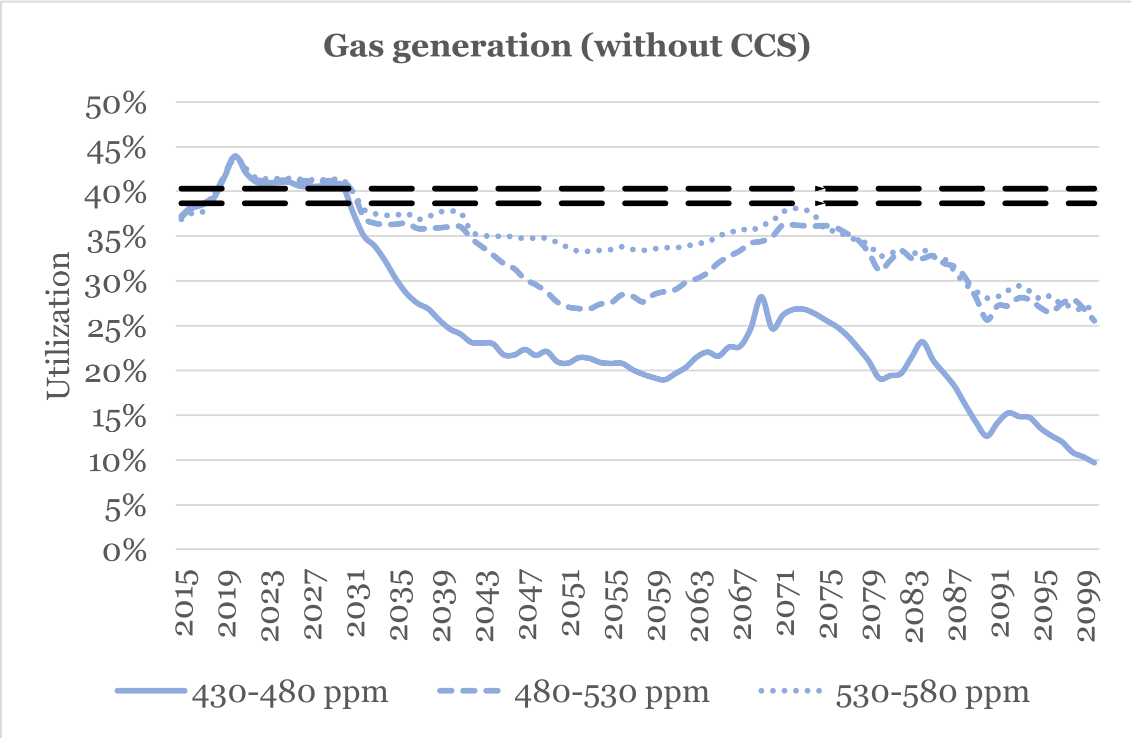


Figure 2: Simulation results for coal- and gas-fired capacity utilization. *(a) coal utilization drops rapidly after 2030 in almost all analyzed climate scenarios. (b) gas utilization drops considerably after 2030 in the 430-480 ppm scenario but remains relatively stable in 480-530 and 530-580 ppm scenarios.*

For gas and oil generation, the results are similar to coal but on a lesser scale (see Figure 2, panel b for gas and Appendix B.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 3 shows the amount of stranded generation for coal, gas, oil and biomass for each of the analyzed climate scenarios.[14] Coal will experience by far the most stranding of all analyzed technologies, and could see up to ~310 EJ (86,000 TWh) 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

[14] See Appendix C.1 for results table.

TWh). Gas and biomass come second and third, respectively, with ~140 EJ (39,000 TWh) for gas and ~40 EJ (11,000 TWh) for biomass in 1.5-2°C consistent scenarios.

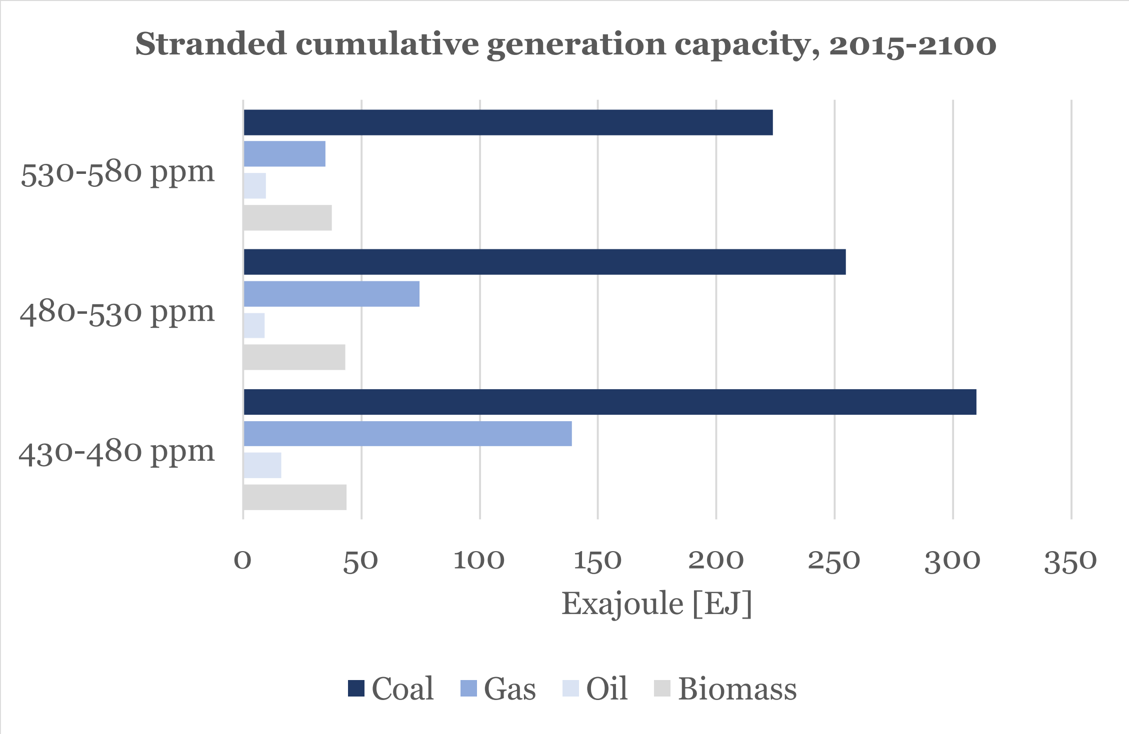


Figure 3: Total stranded cumulative generation capacity, 2015-2100. *In the base case, without including currently planned generators, and with a phase-out period of five years for 'overaged' generators, over 300 EJ would need to be stranded in the 430-480 ppm scenario for coal alone.*

The stranding of biomass generation mostly takes place before 2030, whereas the main stranding of coal, and almost all stranding of gas and oil happens after 2030 (Figure 4). 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.

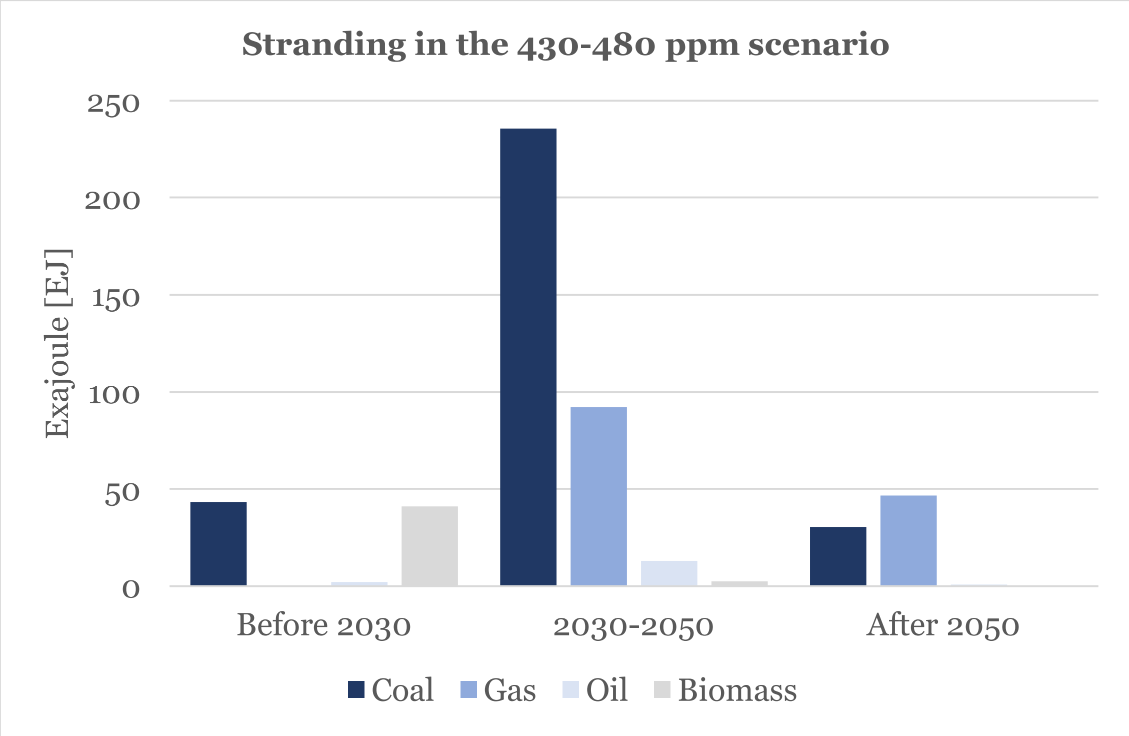


Figure 4: Stranding over time. *By far most the stranding for all fossil fuels would happen between 2030 and 2050.*

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).

3.2 Regional results

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 the 'REF' countries of the former Soviet Union (Figure 5). Non-OECD Latin America and the Middle-East and Africa region see much less overall stranding and more gas than coal stranding. In REF countries, coal and gas stranding is relatively equal.

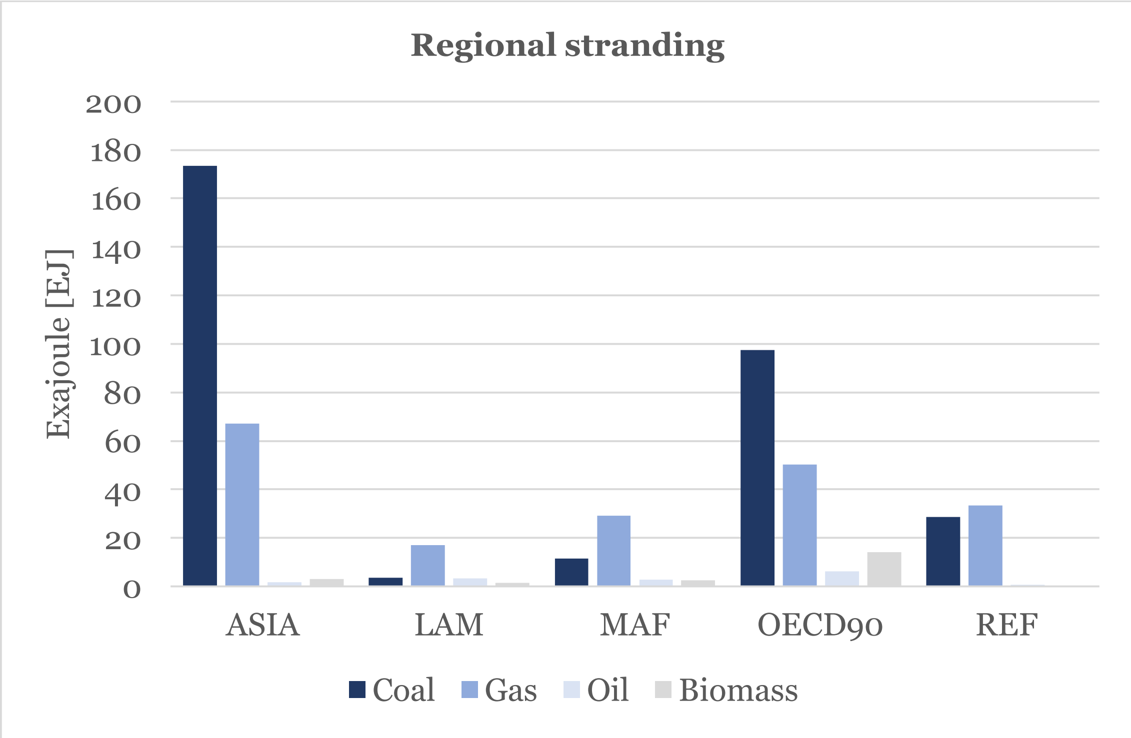


Figure 5: Regional stranding in the 430-480 ppm scenarios. *Asia would be affected most, followed by the OECD countries.*

Within these regions, China and the United States of America experience most stranding, both mostly driven by coal stranding (Figure 6). 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 the Europe region, these figures amount to only ~20% (coal) and ~30% (gas).

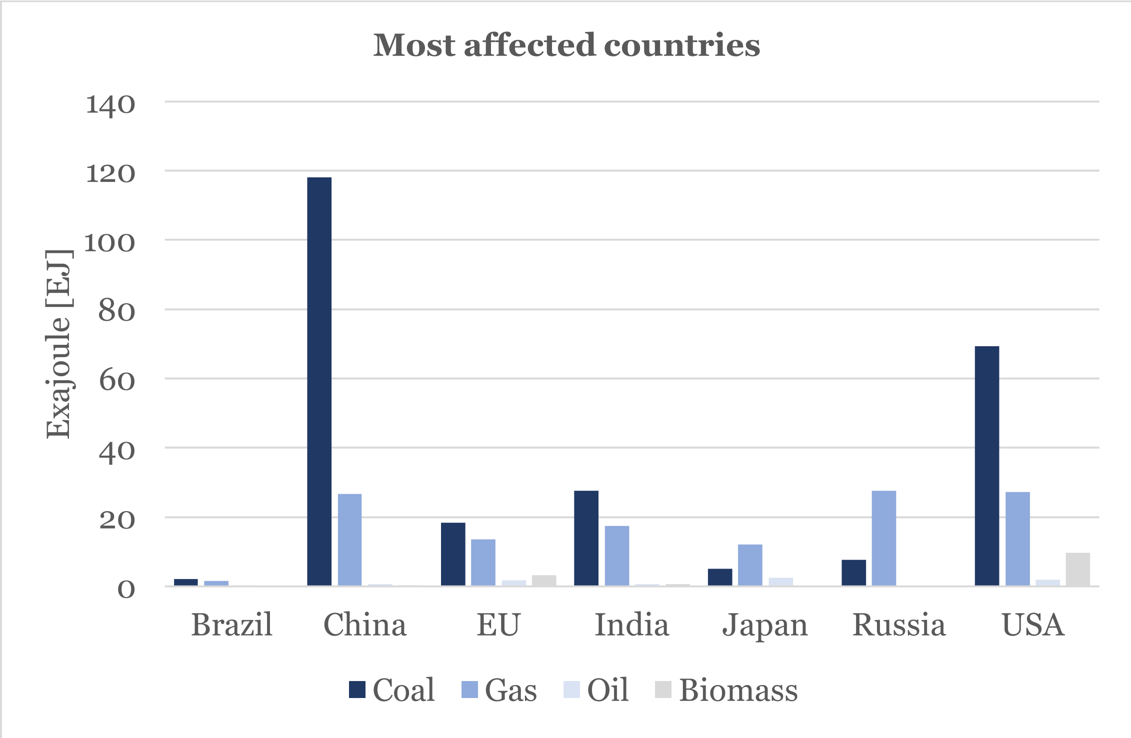


Figure 6: Country-level stranding in the 430-480 ppm scenarios. *On a country-level, China and the USA would be most affected while other countries, such as Japan and Brazil, would be mostly spared.*

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.

3.3 The fossil fuel pipeline

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. Based on our analysis of the Platt's UDI WEPP dataset, a total of ~460 EJ (~12,800 TWh) of future cumulative generation capacity from coal, gas, oil and biomass is currently at some stage of the planning process.[15]

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15 Assuming a 100% utilization rate. While 100% utilization is not a valid assumption for any technology (coal had maximum historic utilization of all fossil fuels with ~60%) it does not affect results. 100% utilization is a technical assumption for simulation purposes and is later on replaced with target utilization to compare stranding (defined as difference between actual and target utilization).

Figure 7 shows how 2015-2100 capacity stranding would change if all that capacity came online.[16]

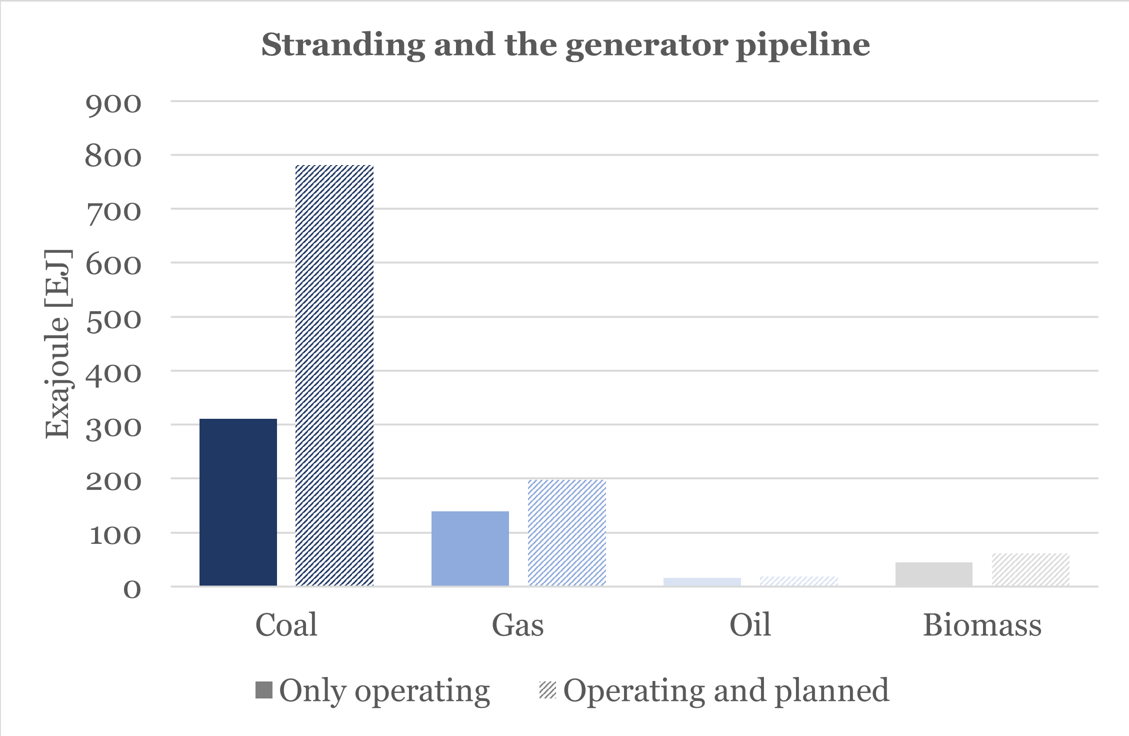

Figure 7: Stranding and the current pipeline of planned power generators in the 430-480 ppm scenarios. *If currently planned power generators are in fact built, the amount of stranding required would increase dramatically, mostly for coal.*

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 biomass 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

[16] See Appendix C.2 for results table.

ppm scenario from ~140 to ~200 EJ (+43%) and biomass from ~44 to ~61 EJ (+38%). Oil would see the smallest increase from ~16 to ~19 EJ (+16%).

3.4 Development between 2005 and 2015

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 8 shows that this increase comes mainly from newly built coal generators (+32%), while asset stranding in gas capital stock has decreased (-12%).[17] 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 and biomass each increase by more than 100%, this occurs from a much lower initial base and hence only adds a little to the overall increase in stranding.

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[17] See Appendix C.3 for results table.

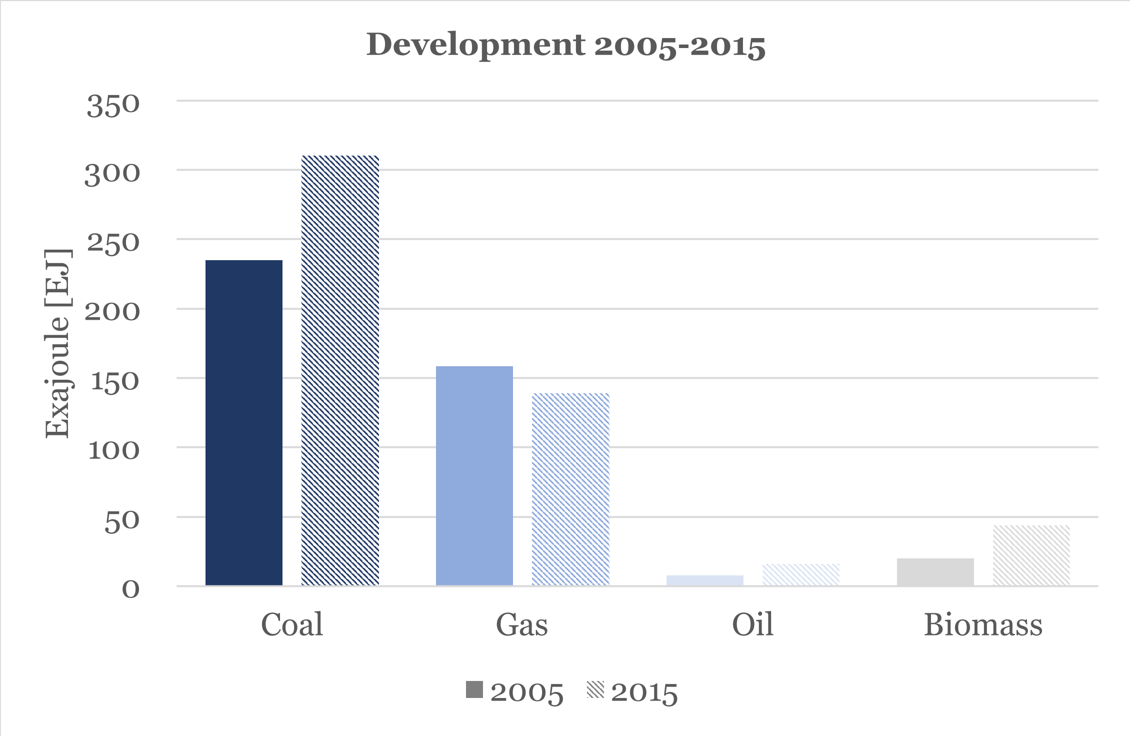


Figure 8: Development over the past decade in the 430-480 ppm scenarios. *The required amount of stranding to achieve 430-480 ppm scenarios has increased considerably over the past decade, mostly for coal.*

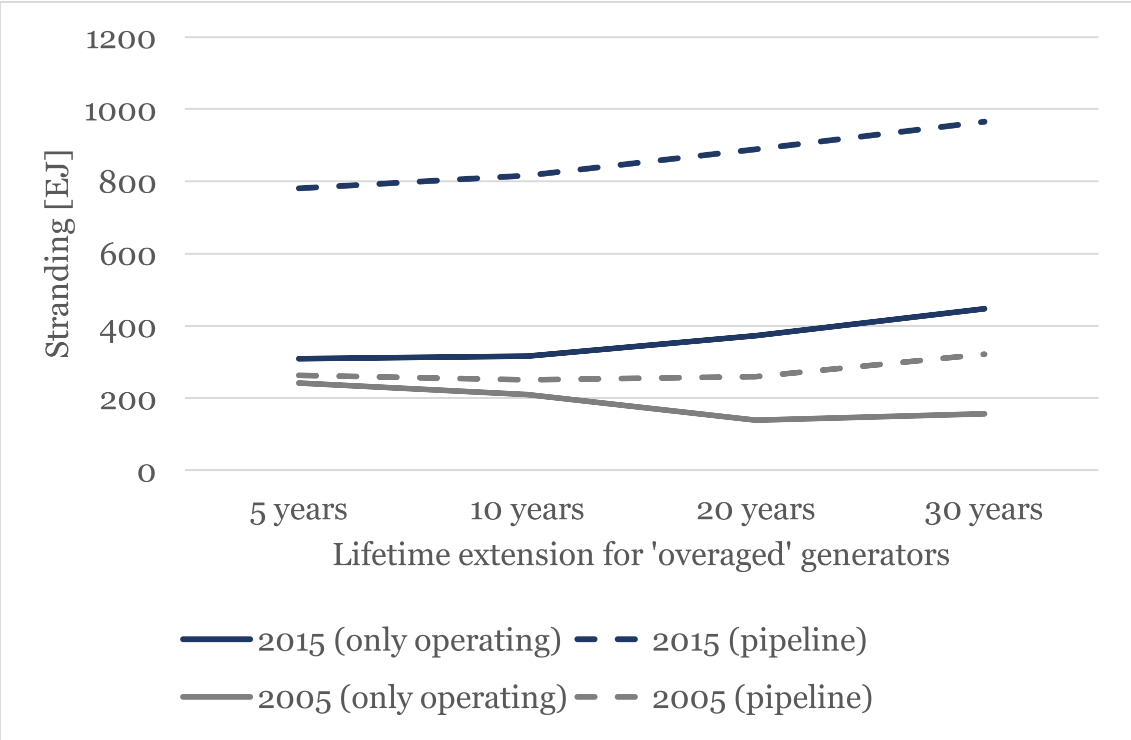
3.5 Lifetime extensions

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 9 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

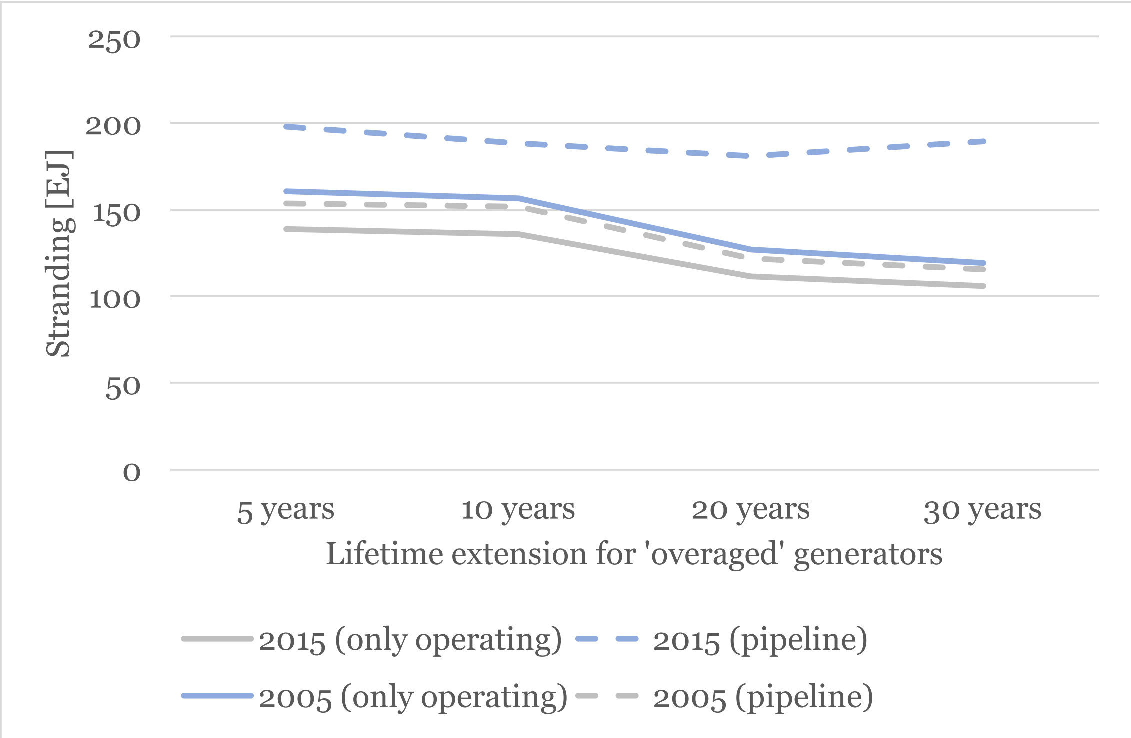


Figure 9: Lifetime extensions for operating 'overaged' capacity in the 430-480 ppm scenarios. *(a) Lifetime extensions for coal (instead of new capacity) would have reduced asset stranding a decade ago but will no longer do so today. (b) Lifetime extensions for operating gas capacity, however, might still be helpful to reduce asset stranding.*

For oil and biomass capital stock the results are clear (see Appendix B.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. For biomass, any lifetime extension would increase the amount of asset stranding in all cases. Because currently existing biomass capacity in our model is not fully utilized and only starts to experience full utilization towards 2040 (see Appendix B.1.b), an extension of the lifetime of current generators would only increase the amount of underutilized 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.

4. 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 NDCs. Even in a world in which concerted climate action fails, the economics of renewable energies will likely 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 adds to and confirms 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. The results show that 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.

5. 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: Additional Information

A.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).

A.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.[18] 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.[19]

A.3 Limitations

A.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.

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

19 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.

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 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.

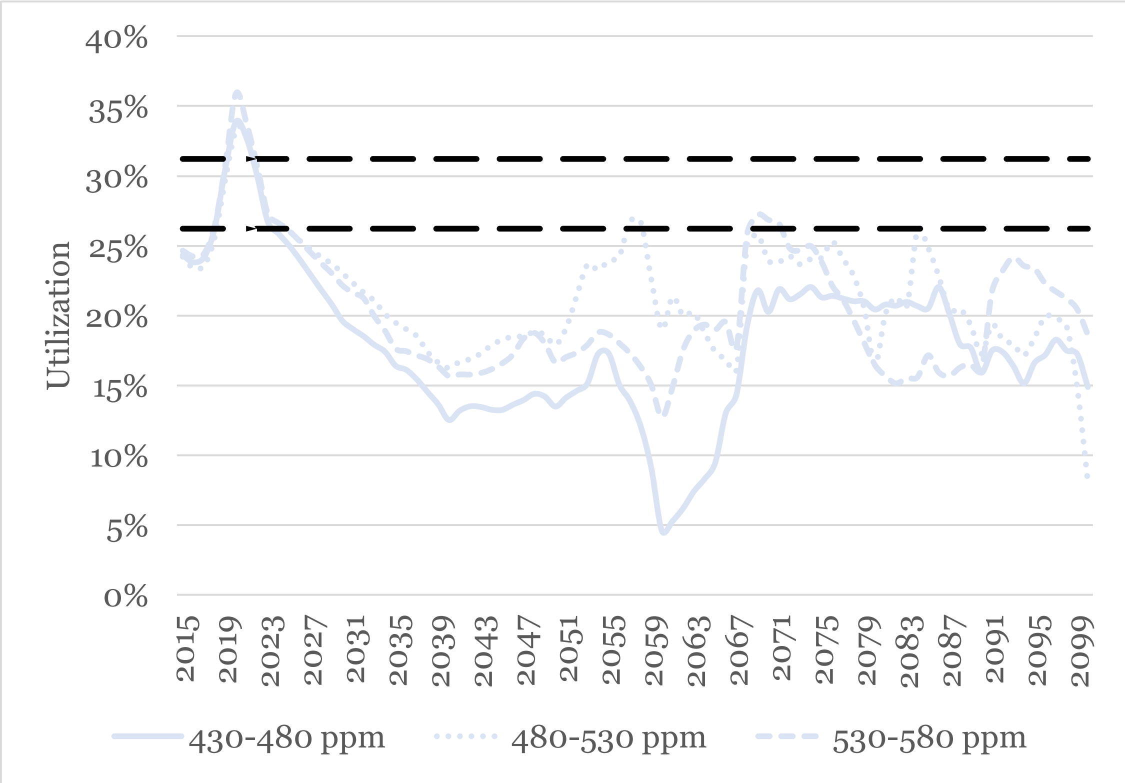
A.3.2 Scenario limitations

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 B: Additional figures

(a) Oil generation utilization



(b) Biomass generation utilization

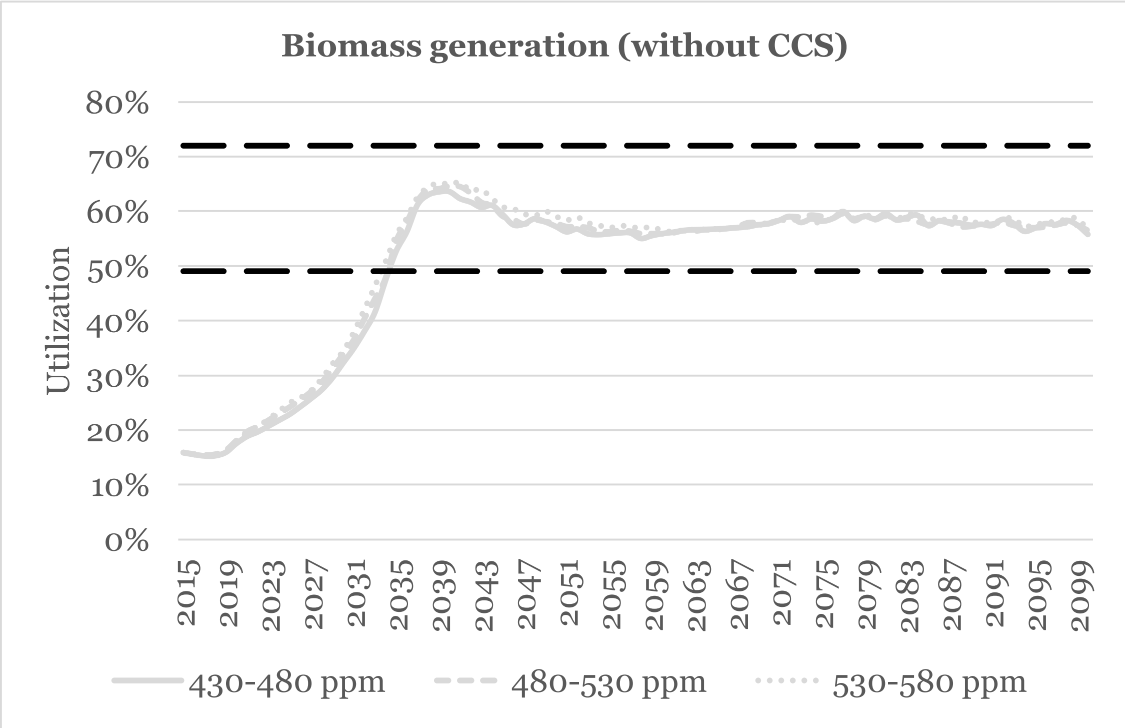
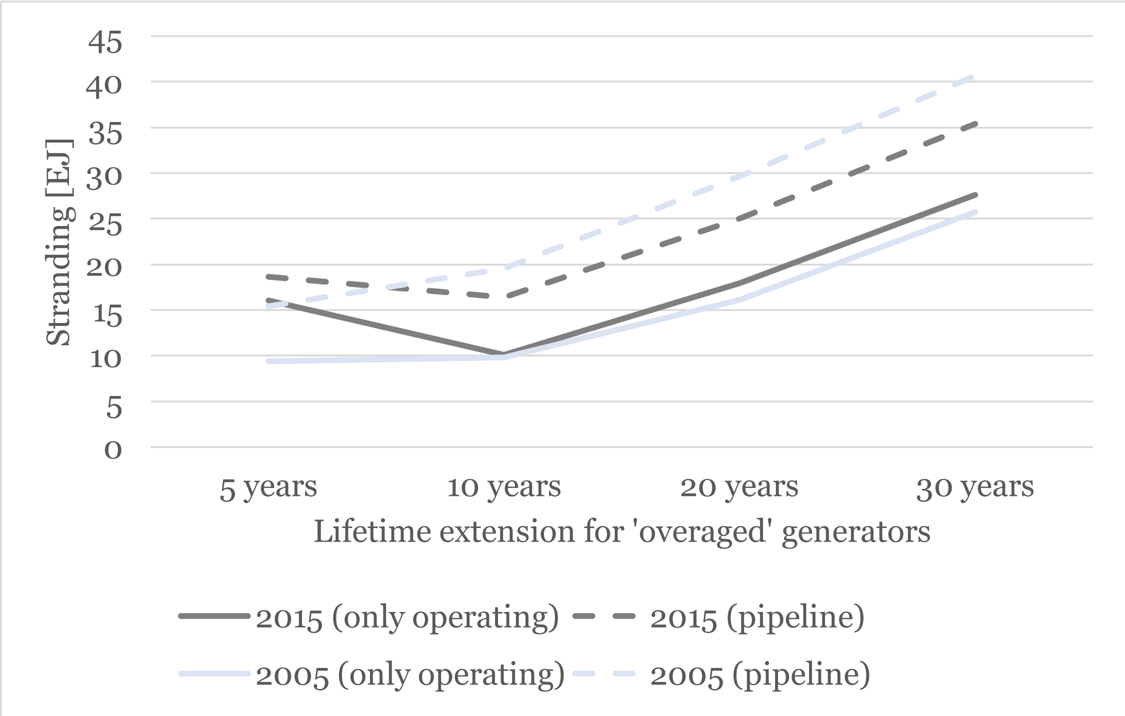


Figure B.1: Simulation results for oil- and biomass-fired capacity utilization. *(a) oil utilization drops after 2020 but then has strong variability after 2050. (b) biomass utilization rises to its target utilization band and stays within this band after 2035, an indicator that biomass will play a much more important role in power generation in the future than today.*

(a) Lifetime extension for oil capacity



(b) Lifetime extension for biomass capacity

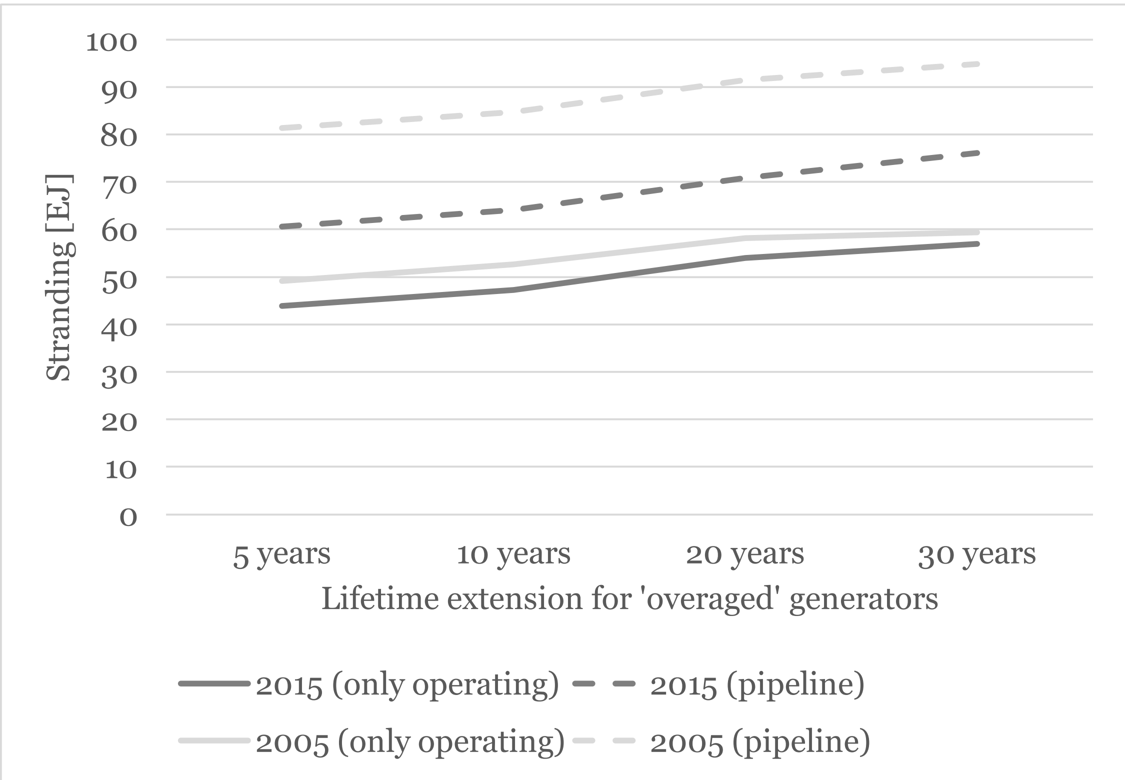


Figure B.2: Lifetime extensions for operating 'overaged' capacity in the 430-480

ppm scenarios. *(a) 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. (b) Lifetime extensions for currently operating biomass capacity, however, would increase stranding in all analyzed cases since biomass is currently underutilized.*

Appendix C: Additional tables

Table C.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
Biomass	44	43	37
Total	**509**	**381**	**306**

Table C.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%
	Biomass	44	61	+38%
480-530 ppm	**Coal**	255	680	+167%
	Gas	74	81	+9%
	Oil	9	13	+40%
	Biomass	43	60	+39%
530-580 ppm	**Coal**	224	603	+170%

	Gas	35	40	+14%
	Oil	10	15	+60%
	Biomass	37	50	+34%

Table C.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%
	Biomass	20	44	+117%
480-530 ppm	**Coal**	167	255	+53%
	Gas	80	74	-7%
	Oil	5	9	+68%
	Biomass	20	43	+118%
530-580 ppm	**Coal**	177	224	+26%
	Gas	39	35	-11%
	Oil	5	10	+87%
	Biomass	17	37	+122%