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Abstract

The generation capacity of existing and currently planned power generators goes beyond the limits of a 2°C carbon budget. Some assets will have to be stranded unless carbon is sequestrated with retrofit CCS or the carbon budget is expanded by the large-scale deployment of negative emissions technologies (NETs), potentially including land-based approaches referred to as "natural climate solutions". In this paper, we show that NETs could reduce stranding by 26% to 46% over the course of the century, depending on the pursued climate goal. The bulk of the additional carbon budget is likely to go to efficient gas generators; the stranding of coal-fired power plants occurs irrespective of the availability of NETs.

Keywords: negative emissions technologies (NETs), carbon budget, stranded assets, climate policy, power generation

JEL: Q01; Q4; Q54; Q5

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1. Introduction

Geologists have long thought that there would not be enough fossil fuels in the ground to sustain economic growth past the 20th century (e.g. Hubbert, 1949). However, developments in extraction technologies and the discovery of new reserves show that the Earth still abounds with fossil fuels.[1] These additional resources have become a major threat for climate change mitigation because energy-intensive activities heavily rely on them. Assessments of currently installed and planned assets in the power sector show that, if existing installations were used at normal rates and for their entire lifetime, they could quickly exhaust the carbon budget consistent with limiting global warming below 2°C.[2] Investors seem to be implicitly betting that either no climate policy will prevent the continuing use of carbon-intensive assets or that the limitations of a carbon budget will not apply, perhaps thanks to the development of new technologies, in particular negative emissions technologies (NETs).[3]

In this paper, we assess the actual consequences that the development of NETs might have for the existing stock of generation capacity worldwide. NETs would create additional atmospheric space by actively removing carbon from the atmosphere (Humpenöder *et al.*, 2014), and include a large diversity of technologies, such as natural climate solutions (Griscom et al., 2017) including biochar, bioenergy or the enhancement of natural carbon sinks, e.g. by reforestation, along with direct air capture and ocean-based approaches

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[1] At 2010 production levels, known global reserves amount to approximatively 45 years of production for oil, 65 years for gas and 140 years for coal. This is our own calculation based on McGlade and Ekins (2015). These authors estimate that more than 80% of coal reserves are unburnable in order to attain the 2°C goal of the Paris agreement.

[2] See Davis and Socolow (2014), Johnson et al (2015), Rozenberg et al. (2015), Pfeiffer et al. (2016, 2017) and Shearer, Fofrich and Davis (2017).

[3] For an asset owner, a stranding of his investments can mean a financial loss and potentially cause him to default on his debt (Weyzig et al., 2014; Carney, 2015; Battiston et al., 2017). For a policy maker, the potential scale of asset stranding has important implications in respect to the choice of future environmental, climate and energy policies (Baldwin, Cai and Kuralbayeva, 2016; Rozenberg, Vogt-Schilb and Hallegatte, 2017).

(Anderson and Peters, 2016; Buck, 2016; Fuss *et al.*, 2016; Heck *et al.*, 2016).[4] Their potential for removal of carbon dioxide from the atmosphere appears high. For example, a recent assessment of land-based carbon sequestration initiatives estimates they have the potential to provide over one third of the cost-effective climate mitigation needed between now and 2030 to stabilize warming to below 2 °C (Griscom et al., 2017). The question of the impact of NETs on asset stranding is important for investors in the energy sector: are decisions to invest in new long-lived fossil fuel plants potentially profit maximizing if NETs succeed? The question is also very relevant to policy-makers. Existing infrastructure already increases the difficulties of achieving a climate policy consistent with the Paris goals (Johnson *et al.*, 2015; Baldwin, Cai and Kuralbayeva, 2016). Weak near-term energy policies that allow the building of even more polluting capital stock will make it even harder for climate policies to succeed in the future as the amount of asset stranding required to meet the climate goals increases (McJeon, 2015; Caldecott, Bouveret, *et al.*, 2017; Rozenberg, Vogt-Schilb and Hallegatte, 2017).

We approach this question by relying on the output of a wide set of Integrated Assessment Models (IAMs), as appended in the AMPERE database and the IPCC's AR5 database. IAMs compute likely pathways for electricity generation for a wide range of 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). As such, these models come up with a likely level of power generation from fossil fuels (oil, gas and coal). On the other side, we can evaluate the total amount of

[4] Such efforts should not be confused with carbon capture and storage (CCS), which describes the process of capturing carbon emissions at the point where they originate, i.e. where the fuel is burned, and then transporting them to a reservoir where they can be stored safely for hundreds or thousands of years (Smith, Fahrenkamp-Uppenbrink and Coontz, 2009). While CCS, as an add-on to fossil fuel powered processes, usually avoids the additional release of fossil carbon into the atmosphere, NETs actively remove carbon from the atmosphere. In fact, NETs and CCS could be combined. This would be the case with bio-energy with carbon capture and storage (BECCS). BECCS would integrate trees and crops to electricity production. The biomass would extract carbon dioxide from the atmosphere as it grows, then be used by power-plants, and the CO_2 released would be injected back into geological formations. BECCS is now considered as one option with relatively high potential to loosen the constraint imposed on the power sector by climate change mitigation (Campbell, Lobell and Field, 2009).

energy that existing assets will be able to provide over the course of their lifetime. We perform this evaluation by manually merging all power plants and generators from the most recent versions of the five databases: CoalSwarm; Platt's UDI World Electric Power Plants (WEPP) database; Greenpeace's database of planned coal generators in China; Sekitan's Japan coal-fired power plant database; and Kiko Network's Japan coal-fired power plant database. The merger of these databases increases data reliability and completeness. We assess asset stranding as the difference between the generation that existing assets will provide and the maximum amount of electricity that should be produced from fossil fuels according to the electricity pathways obtained from the IAMs. We then evaluate the impact of NETs on asset stranding by comparing the scenarios with and without NETs.

As per the previous literature (e.g. Pfeiffer et al., 2016 and 2017), we find that power plant capacity already exceeds the remaining carbon budget that can be devoted to power generation if we are to slow down global warming and reach the 2°C degree target. In a 430-480ppm scenario (roughly in line with limiting global warming to below 2°C), existing and recently planned capacity already overshoots the carbon budget since they could over-produce 640 EJ of electricity. 55% to 65% of required asset stranding would come from coal-fired power plants, and the remainder mostly from gas-fired power plants (30-40%). Required asset stranding represents 9 years of global electricity generation at 2005 levels. Over-commitments are substantial in China and in India, where they are equivalent to 265 and 95 EJ of electricity, or 28 and 37 years of electricity generation at 2005 levels.

Our main contribution is to show that NETs may impact asset stranding differently according to the fuel type of power plants, and the climate constraint imposed on power plants. In the 430-480 ppm scenario, NETs have the potential to reduce asset stranding for gas-fired power plants by half, whereas the reduction of asset stranding for coal-fired power plants is small (minus 7%). The likely explanation is that NET will come at a cost and that the atmospheric space created by NET will be allocated to the power generation that is carbon efficient. As gas emits approximately half the CO_2 per EJ generated than coal, it is understandable that capacity stranding would probably still affect coal in the presence of NETs. However, when the climate constraint is relaxed and higher carbon concentrations are allowed (480-530 and 530-580 ppm scenarios), then NETs start benefitting both, coal- and gas-fired power plants.

This paper extends from the previous literature analysing carbon stranding in the electricity sector. At present, the fuels consumed for electricity and heat generation represent around 40% of GHG emissions worldwide (Foster and Bedrosyan, 2014). In the future, decarbonized electricity will play a central role to combat climate change (Williams, 2012). Yet, electricity generation is still heavily polluting. Davis and Socolow (2014) have been the first to develop a methodology to account for the future CO_2 emissions committed in the power sector. They estimated that existing assets in the power sector are committed to about 307 $GtCO_2$ future emissions. They also estimated an annual 4% growth in committed emissions over the previous decade, due to the construction of new power plants. Pfeiffer et al. (2016) use a similar methodology and find that, as of today, the existing capital stock for electricity generation is already above the remaining power-generation-only carbon budget for a 50% chance for global warming below 2°C. Pfeiffer et al. (2017) further extends the accounting of committed emissions to include generators currently under construction or in different stages of the planning process. They confirm the finding that part of the electricity sector should be stranded in order to avoid global warming.

In this paper, we furthermore show that the stranding of coal-fired power plants will have to take place, with or without NETs, if global long-term emissions concentrations are limited to 430-480 ppm. This finding is important since a new strand of research has identified significant potential opportunities from NETs to create additional atmospheric space (e.g. Griscom et al., 2017). Many scientists believe that negative emissions technologies could or even have to play an important role in humanity's attempt to stay within its carbon budgets (Anderson and Peters, 2016). Yet, its current and future success is questionable (Kriegler et al., 2013; van Vuuren et al., 2013; Creutzig et al., 2015; Kreidenweis et al., 2016; Smith et al., 2016; Vaughan and Gough, 2016; Bhave et al., 2017). This paper shows that this high potential of NETs to mitigate climate change reduces the risk of asset stranding in priority for those investments that will be carbon efficient. Investors that finance carbon inefficient technologies such as coal-fired power plants will not be the primary benefiters of the availability of such technologies.

The rest of this paper is structured as follows: section 2 describes the datasets and method used, section 3 describes our results and section 4 concludes.

2. Data and methods

Our method consists in comparing two broad categories of data. First, power generator databases that contain and describe the global capital stock for electricity generation and its development over time on a granular level. Second, scenario databases that provide possible pathways for the development of the energy sector between now and 2100.

2.1 Power generator databases

Generation capacities were determined by manually merging all power plants and generators from the most recent versions of the following databases: (a) CoalSwarm (Feb 2017); (b) Platt's UDI World Electric Power Plants (WEPP) database (Q4 2016); (c) Greenpeace's database of planned coal generators in China; (d) Sekitan's Japan coal-fired power plant database (Q1 2016); and (e) Kiko Network's Japan coal-fired power plant database (Q1 2016). Several different databases are merged because all databases have individual known weaknesses and incomplete data. Platt's UDI WEPP database, for instance, is commonly known to have imperfect coverage of microgeneration and Chinese power generators.

By merging several databases, the quality of the estimate of the global generation capital stock can therefore be improved substantially. The sources are merged by manually confirming unique power plant names, locations, current statuses, online years[5] and capacity, and supplementing the result with internet research for individual power generators as required. The most recent data is used where

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

matched plants have conflicting fields (for example different operating statuses). The resulting database effectively defines the locations of all the world's power plants and generators, their ownership, age, fuel type, technology, and capacity. It is particularly current and comprehensive for coal-fired power stations but comparisons with other similar approached suggests that also gas- and oil-fired generation estimates are robust (Davis and Socolow, 2014; IEA, 2016).

2.2 Scenario databases

This paper resorts to the output of Integrated Assessment (IAMs) model. These produce likely pathways on the energy mix for electricity generation, according to a wide subset of hypotheses, e.g. in terms of achieved CO_2 concentrations. 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.

Two databases of IAM output, the AMPERE database and the IPCC's AR5 database, are used in this paper.[6] We exclusively rely on the IPCC's AR5 database to assess the impact of carbon stranding on NETs, since the labelling of scenarios with and without NETs is not available in the AMPERE database. However, a limitation of the IPCC's AR5 database is that it only provides global electricity pathways. To produce disaggregated, regional level results on asset stranding, we therefore rely on the pathways of the AMPERE database, since it provides regional and, in some cases, even country-specific, model outputs. We produce disaggregated estimates of the impact of NETs on stranding at regional level by assuming that the reductions in asset stranding estimated with the IPCC's AR5 database would uniformly take place across regions, in proportion of their stranded assets as estimated with the AMPERE database.

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

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, 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).

Later on, we provide results for three different levels of CO_2 concentrations: 430-480 ppm, 480-530 ppm and 530-580 ppm. 430-480 ppm refers to the 2100 concentration of CO_2eq. in the atmosphere and scenarios from this category are typically connected to having a 'more likely than unlikely' chance of limiting global warming to below 2°C. 480-530 ppm scenarios would likely result in warming between 2-3°C, and 530-580 ppm probably closer to 3°C (Krey et al., 2014).

For these levels of CO_2 concentrations, the AMPERE database and the IPCC's AR5 database include a multiplicity of scenarios that lead to different electricity generation pathways. The full IPCC AR5 database consists of 1,184 pathways from a wide range of scenarios processed with 31 IAMs (Krey *et al.*, 2014). Scenarios processed in the AR5 database can be classified along five dimensions: (1) different climate targets, determined by 2100 CO_2eq. concentrations (e.g. 450-ppm, 500-ppm, etc.); (2) overshoot of these 2100 levels between 2005 and 2100; (3) scale of deployment of carbon dioxide removal (CDR) or NETs; (4) availability of mitigation technologies, especially CDR and NETs; and (5) policy category (e.g. immediate vs. delayed mitigation, etc.). When use the AMPERE database, we rely on a set of around 400 pathways to 2100. These pathways correspond to a variety of scenarios processed with eight different integrated assessment models[7] (see Riahi, Kriegler, *et al.*, 2015, for a recent IAM comparison study). They 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).

In the results section, we report average stranding figures corresponding to either 430-480 ppm, 480-530 ppm or 530-580 ppm concentrations. These figures have been obtained by averaging out the values found across all the available scenarios / pathways from either the AMPERE or IPCC's AR5 databases.

2.3 Estimating asset stranding

In order to forecast capital stock additions and stranding post-2025, we apply the approach described extensively in Pfeiffer *et al.* (2017). First, we evaluate the assets still in operation at time *t* by depreciating the then operating generation capacity according to its likely lifetime. We then compute the generation capacity of all these assets at time *t* based on their historical utilisation rates. For any given scenario of the AMPERE or IPCC's AR5 databases, we compare the predicted generation levels of operating capital stock at time *t* with the electricity that should be generated with fossil energy (oil, gas or coal) for this year. We evaluate the remaining portion of the energy demand that should be met with additional assets (in the absence of stranding) or determine the level of stranding required in the scenario. The amount of stranding that takes place in a given year is defined as an underutilization rate of operating capacity for currently existing assets that should still be active at time *t*. Underutilization in this case is defined by utilization rates below historical averages. Stranding is computed separately for

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

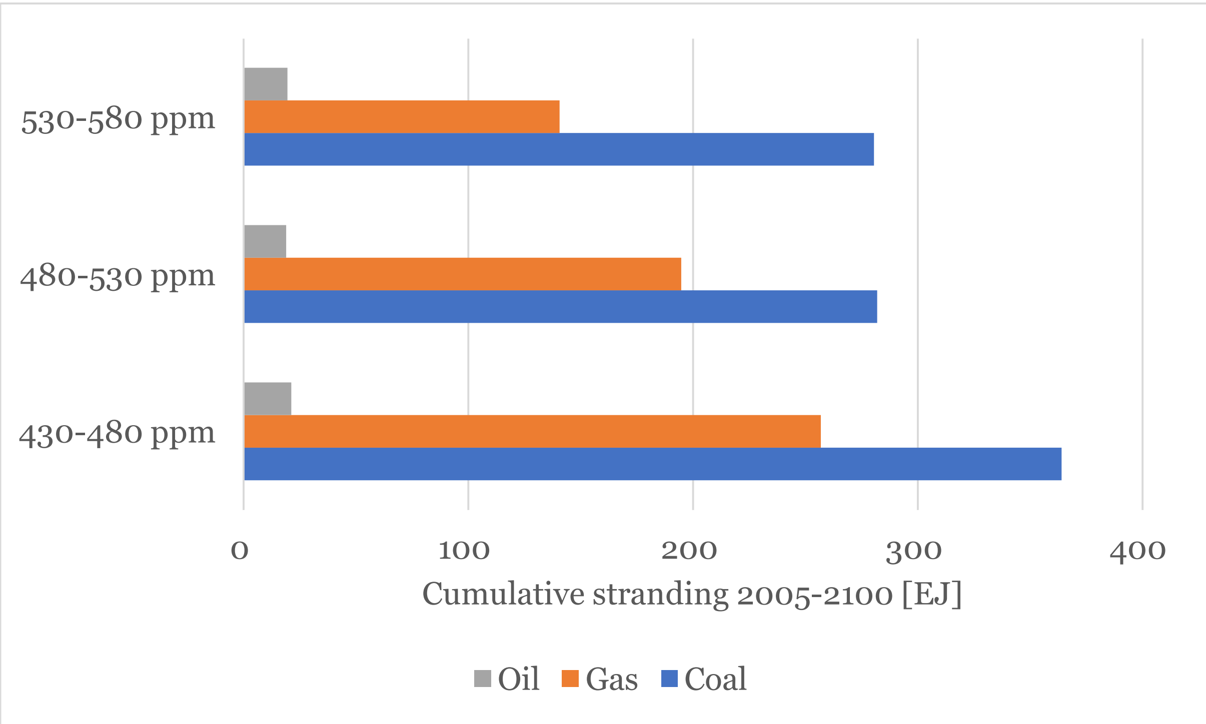
coal-, oil- and gas-fired power plants. We express it in Exajoule (EJ) of 'unproduced' electricity, and also in years of electricity generation at 2005 levels, to allow for cross-country comparisons. Since the reference year of the scenarios from the IAMs is 2005, our results are for asset stranding between 2005 and 2100.

3. Results

3.1 Asset stranding by emissions scenario, fuel type and region

Our model results for global asset stranding, as measured by cumulative underutilized power generation capacity between 2005 and 2100, are provided in Figure 1, for the three different scenario categories (430-480 ppm, 480-530 ppm, and 530-580 ppm) mentioned earlier, and separately for oil-, gas- and coal-powered generation capacity.

Figure 1: Average global generation stranding (in EJ un- or underutilized capacity between 2005 and 2100), by type of fuel and climate scenario

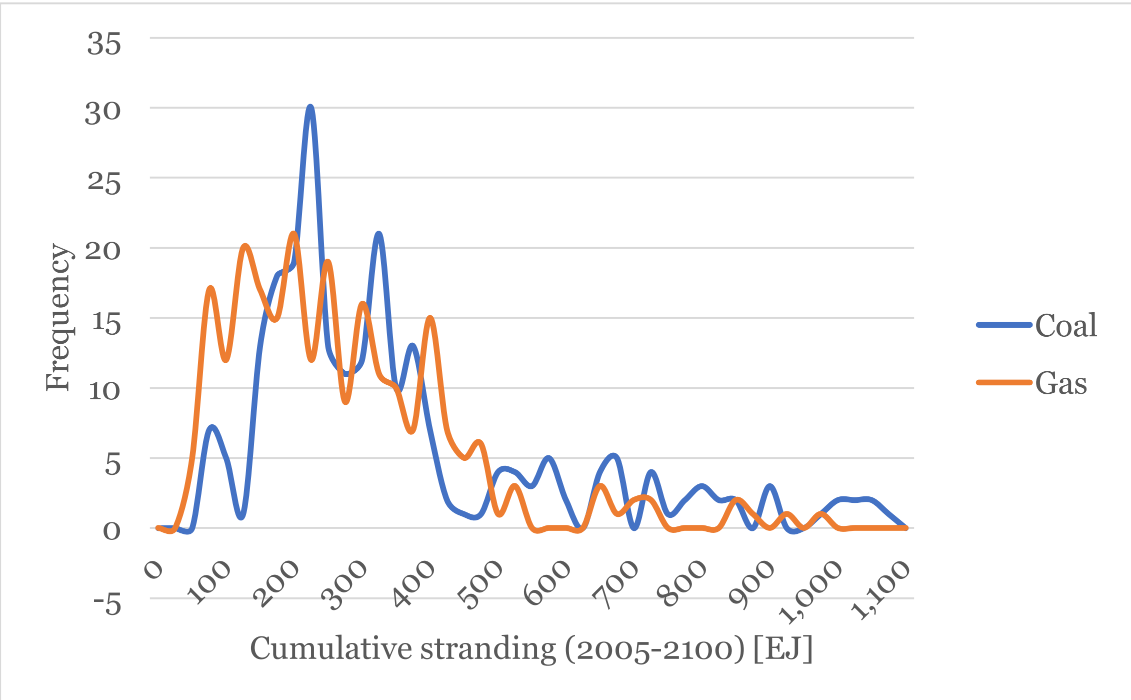


Note: Analysis contains all applicable model-scenario combinations in the respective climate categories from the IPCC's AR5 and the AMPERE databases.

We find that, depending on the climate scenario, global asset stranding for fossil fuel powered generation could amount to 440-640 EJ (about 10-15 years of global electricity generation at 2005 levels). 55% to 65% of asset stranding comes from coal-fired power plants and the remainder would mostly stem from gas-fired power plants (30-40%).

The average estimates of Figure 1 have been obtained from the distribution of the average stranding across all the scenarios within each scenario group. As an example, Figure 2 shows the variation for coal and gas stranding within the 430-480 ppm scenario group (241 scenarios).

Figure 2: Frequency of the estimates for global coal and gas stranding in the 430-480 ppm scenario group



Note: Analysis contains all applicable model-scenario combinations in the 430-480ppm climate category from the IPCC's AR5 and the AMPERE databases.

The global average estimate of 440-640 EJ hides important regional disparities. Table 1 breaks down estimated stranding across a set of regions and selected countries for the 430-480 ppm scenario.[8]

[8] The results for the 480-530 ppm and 530-580 ppm scenarios are reported in Appendix A.3.

Table 1: Average total fossil fuel generation stranding (coal, gas and oil) in the 430-480 ppm scenario, global and by region and selected countries

Region	Total fossil gen. stranding (2005-2100) [EJ]	Total gen. (2005) [EJ]	Cumulative asset stranding (2005-2100) [years of total 2005 gen.]
World	642.2	65.5	9.8
Asia	404.8	14.9	27.1
- China	265.5	9.2	28.9
- India	95.1	2.5	37.7
OECD	230.2	37.4	6.1
- USA	163.9	15.4	10.6
- EU	67.6	11.8	5.7

Note 1: Analysis contains all applicable model-scenario combinations in the 430-480ppm climate category from the IPCC's AR5 and the AMPERE databases.

Note 2: Our scenario analysis has three levels: (1) global, (2) regional, and (3) country-level. Therefore, the sum of all countries within a region does not sum up to the amount for the region and the sum of all regions does not sum up to the global level of asset stranding. The reason is that aggregation assumes inter-regional exchanges of energy and may mask required regional stranding. E.g. the global level estimated for stranding might be lower than the sum of all regions because, while e.g. coal generation in OECD goes down, it goes up in Asia. On a global level analysis, this reduced demand in OECD countries is offset by increased demand in Asia. Generation capacity in the OECD would not be stranded if it fed the Asian market (as assumed with aggregated values). On a regional or country level analysis, however, this capacity would become stranded.

In absolute terms, China alone would encompass more fossil fuel stranding than all OECD countries together. In column 3, we report the level of electricity generation by region for the reference year of the computations (2005).[9] We normalize the total level of asset stranding by the current level of electricity generation in column 4 to allow for cross-country comparisons. Indian and Chinese electricity generation appears to be disproportionately at risk of

[9] We use numbers from the 2017 *World Energy Outlook* of the IEA rather than the 2005 base level in the IPCC's scenarios.

stranding: the level of production that will be stranded represent about 37 years of total 2005 electricity generation in India and 28 years of 2005 generation in China. A more granular analysis shows that India and China above all suffer from a risk of asset stranding for their coal-fired power plants (see Table 2). Coal stranding would represent 25 years of 2005 electricity production in India and gas stranding only 12 years; in China, these figures amount to 21 years for coal and 7 years for gas. OECD countries display much smaller but equal levels of stranding for coal and gas-fired power plants (each 3 years). The U.S. (coal and gas stranding each 5 years of total generation) seem to be more at risk of stranding than the E.U. (each ~3 years).

Table 2: Total fossil fuel generation stranding by fuel type in the 430-480 ppm scenario, expressed in EJ and in years of total 2005 generation[10] (in brackets)

Region	Coal stranding (2005-2100) [EJ] (years of total 2005 gen.)	Gas stranding (2005-2100) [EJ] (years of total 2005 gen.)	Oil stranding (2005-2100) [EJ] (years of total 2005 gen.)	Total fossil gen. stranding (2005-2100) [EJ] (years of total 2005 gen.)
World	364 (5.5)	256.9 (3.9)	21.1 (0.3)	642.1 (9.8)
Asia	274.9 (18.4)	118.2 (7.9)	11.4 (0.7)	404.7 (27.1)
- China	195.5 (21.3)	65.6 (7.1)	4.2 (0.4)	265.4 (28.9)
- India	62.2 (24.7)	30.6 (12.1)	2.1 (0.8)	95 (37.7)
OECD	110.2 (2.9)	110.4 (2.9)	9.4 (0.2)	230.2 (6.1)
- USA	81.2 (5.2)	77 (5)	5.5 (0.3)	163.8 (10.6)
- EU	31.3 (2.6)	32.3 (2.7)	3.9 (0.3)	67.6 (5.7)

Note 1: Analysis contains all applicable model-scenario combinations in the 430-480ppm climate category from the IPCC's AR5 and the AMPERE databases.

Note 2: The generation stranding as estimated in EJ in the 430-480 ppm scenario is divided by the 2005 total national (or regional) electricity generation level. For instance, we have reported

[10] IEA World Energy Outlook 2007

~5.5 years of generation stranding globally for coal since the global estimated stranding for coal is 364 EJ and the 2005 electricity generation (from all fossil fuel sources) was around 65.5 EJ.

However, the share of assets at risk of stranding will go down in these countries, in proportion to the growth in energy demand that they are likely to experience. Table 3 reproduces the results of table 2, but expresses stranding in years of 2040 electricity generation. Expected stranding goes down to 8 years of electricity generation at 2040 levels in China, and 6 years in India. The country with the highest levels of stranding in relation to forecasted energy production at 2040 levels is the United States (9 years).

Table 3: Total fossil fuel generation stranding by fuel type in the 430-480 ppm scenario, expressed in EJ and in years of 2040 generation in the IEA's *Sustainable Development Scenario*[11] (in brackets)

Region	Coal stranding (2005-2100) [EJ] (years of total SDS 2040e gen.)	Gas stranding (2005-2100) [EJ] (years of total SDS 2040e gen.)	Oil stranding (2005-2100) [EJ] (years of total SDS 2040e gen.)	Total fossil gen. stranding (2005-2100) [EJ] (years of total SDS 2040e gen.)
World	364 (2.8)	256.9 (1.9)	21.1 (0.1)	642.1 (4.9)
Asia	274.9 (n/a)	118.2 (n/a)	11.4 (n/a)	404.7 (n/a)
- China	195.5 (6)	65.6 (2)	4.2 (0.1)	265.4 (8.2)
- India	62.2 (4.2)	30.6 (2)	2.1 (0.1)	95 (6.4)
OECD	110.2 (2.5)	110.4 (2.5)	9.4 (0.2)	230.2 (5.2)
- USA	81.2 (4.6)	77 (4.3)	5.5 (0.3)	163.8 (9.2)
- EU	31.3 (2.5)	32.3 (2.6)	3.9 (0.3)	67.6 (5.5)

Note 1: Analysis contains all applicable model-scenario combinations in the 430-480ppm climate category from the IPCC's AR5 and the AMPERE databases.

Note 2: The generation stranding as estimated in EJ in the 430-480 ppm scenario is divided by 2040 total national (or regional) electricity generation level.

[11] IEA World Energy Outlook 2007

3.2 Impact of negative emissions technologies

We now turn to analyzing the impact that the availability of negative emission technologies between 2005-2100 would have on asset stranding. In the IPCC's classification, NETs are assumed to be available if the maximum amount of net negative CO_2 emissions (incl. land use) in any given year over the 21[st] century is larger than 20 $GtCO_2$ (Krey *et al.*, 2014). NETs in this sense can be anything that captures CO_2 from the air and stores it, e.g. bioenergy with carbon capture and storage (BECCS), direct air capture, preservation and enhancement of natural carbon sinks, ocean fertilization, etc.

The results of our asset stranding analysis with and without the assumption of NET availability are presented in Table 3.

Table 3: Impact of availability of NETs in models on capacity stranding of different fuel types, by climate scenario

World	**Impact on coal stranding [EJ] (%in brackets)**	**Impact on gas stranding [EJ] (%in brackets)**	**Impact on oil stranding [EJ] (%in brackets)**	**Impact of NETs on stranding [EJ] (%in brackets)**
430-480 ppm	-22.3 (-7%)	-110.6 (-50%)	-0.8 (-3%)	-133.7 (-24%)
480-530 ppm	-109 (-38%)	-128.7 (-61%)	0.1 (0%)	-237.6 (-46%)
530-580 ppm	-118.9 (-41%)	-69.7 (-48%)	1.2 (6%)	-187.4 (-41%)

Note: The asset stranding analysis with and without NETs has been obtained solely with the IPCC's AR5 scenario databases.

Not surprisingly, in scenarios in which the availability of NETs in the 21[st] century is assumed, the asset stranding is 24-46% lower than in scenarios in which no such negative emissions are expected. NETs would increase the atmospheric space for CO_2 and hence available carbon budgets for constant climate goals. Therefore, less committed emissions have to be 'unlocked', i.e. stranded. On a more concrete level, the lower levels of capacity stranding can be explained such that currently operating (and perhaps yet to be built) power plants can operate much to the end of their useful life and at their planned load factor despite potentially overshooting the available carbon budgets. NETs later in the century would revert atmospheric concentrations back to permitted levels and help achieving the climate goals.

Our analysis shows that gas-fired power generation would strongly benefit from lower stranding in all concentration scenarios (by 48% to 61%). On the other side, asset stranding is barely reduced (by 7%) in the case of coal-fired power plants for the low concentrations scenarios (430-480 ppm). Hence, coal-fired power plants would barely benefit from NETs in this group of scenarios. The likely reason is that almost all the atmospheric space from NETs would be allocated to gas-fired power plants, which are less carbon intensive. The value added per CO_2 emissions is higher for gas-fired power plants, making them more ideal candidates to benefit from NETs. In the higher emissions scenarios, both coal-fired and gas-fired power plants benefit from NETs, very plausibly since the constraint on gas-fired power plants has been relaxed and some of the benefits from NETs are passed on to coal-fired power plants.

In table 4, the impact of NETs on carbon stranding has been distributed across all regions in proportion to their share of total stranding (as estimated in Table 2). Table 4 illustrates that, in absolute terms, Chinese generation infrastructure could benefit most from NETs. In scenarios in which NETs are available in the 21st century, overall fossil fuel asset stranding in China could be up to 47 EJ smaller than in a world without NETs. The second biggest beneficiary would be the U.S. with an asset stranding reduction of 44 EJ. However, because of the previously described difference on NETs on coal- and gas-stranding, the Chinese and U.S. gas-infrastructure would benefit most of the availability of NETs.

Table 4: Regional impacts of availability of NETs in models on capacity stranding of different fuel types in the 430-480 ppm scenario

Region	Impact on coal stranding [EJ]	Impact on gas stranding [EJ]	Impact on oil stranding [EJ]	Impact of NETs on stranding [EJ]
World	-22.3	-110.6	-0.8	-133.7
Asia	-19.2	-59.1	-0.3	-78.7
- China	-13.7	-32.8	-0.1	-46.7
- India	-4.4	-15.3	-0.1	-19.8
OECD	-7.7	-55.2	-0.3	-63.2
- USA	-5.7	-38.5	-0.2	-44.4
- EU	-2.2	-16.2	-0.1	-18.5

Note: The estimation of asset stranding with and without NETs has been obtained solely with the IPCC's AR5 scenario database but the distribution across regions with the AMPERE database.

4. Conclusion

Previous research has shown that existing coal-fired and gas-fired power plants can burn more fossil fuels than what would be consistent with the Paris agreement. However, such studies have not yet fully accounted for potential technologies that could remove carbon dioxide from the atmosphere at scale. The availability of negative emissions technologies could be game changing if they could substantially expand the carbon budget.

In this paper, we show that the development of negative emissions technologies, as forecasted with the best forecasting models available, could indeed expand the carbon budget allocated to the electricity sector and reduce required asset stranding in the electricity generation sector by 24% to 46%. However, it is unlikely that the benefits from NETs would be equally shared across sectors or even regions. The reason is simple: because NETs come at a cost, it is only optimal to stretch the carbon budget for activities that display high value added per ton of CO_2 emissions. In the power sector, we find that the beneficiaries from NETs are predominantly gas-fired power plants.

Our results provide little comfort for investors in long-lived fossil-intensive assets, especially coal. Even in optimistic scenarios in which negative emissions technologies exist and are scaled up, NETs may still be too expensive to allow the most carbon-intensive processes and in particular coal-fired power generation to remain.

This research primarily draws from very long-run forecasts. It also depends on the underlying assumptions used in the IAM models whose output is stored in the IPCC's AR5 database and the AMPERE database. The figures provided all throughout should be considered with caution. While they may only be indicative of the levels of stranding likely to happen, we still expect them to pinpoint with accuracy the risk of stranding for coal-fired and gas-fired power plants, particularly in Asia, and the fact that NETs may only increase the carbon budget for the less carbon-intensive power plants.

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Appendix

Table A.1: Average total fossil fuel generation stranding (coal, gas and oil) in the 480-530 ppm scenario, global and by region and selected countries

Region	Total fossil gen. stranding (2005-2100) [EJ]	Total gen. (2005) [EJ]	Cumulative asset stranding (2005-2100) [years of total 2005 gen.]
World	495.9	65.5	7.5
Asia	236.2	14.9	15.8
- China	160.8	9.2	17.5
- India	63.9	2.5	25.3
OECD	184.6	37.4	4.9
- USA	144.2	15.4	9.3
- EU	63.7	11.8	5.4

Note: Analysis contains all applicable model-scenario combinations in the 480-530ppm climate category from the IPCC's AR5 and the AMPERE database.

Table A.2: Average total fossil fuel generation stranding (coal, gas and oil) in the 530-580 ppm scenario, global and by region and selected countries

Region	Total fossil gen. stranding (2005-2100) [EJ]	Total gen. (2005) [EJ]	Cumulative asset stranding (2005-2100) [years of total 2005 gen.]
World	440.8	65.5	6.7
Asia	319.3	14.9	21.4
- China	207.7	9.2	22.6
- India	70.8	2.5	28.1
OECD	288.2	37.4	7.7
- USA	162.6	15.4	10.5
- EU	96.7	11.8	8.2

Note: Analysis contains all applicable model-scenario combinations in the 530-580ppm climate category from the IPCC's AR5 and the AMPERE database.