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Effects of Direct Air Capture Technology Availability on Stranded Assets and Committed Emissions in the Power Sector

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We examine the effects of negative emission technologies availability on fossil fuel-based electricity generating assets under deep decarbonization trajectories. Our study focuses on potential premature retirements (stranding) and committed emissions of existing power plants globally and the effects of deploying direct air carbon capture and biomass-based carbon capture and sequestration technologies. We use the Global Change Analysis Model (GCAM), an integrated assessment model, to simulate the global supply of electricity under a climate mitigation scenario that limits global warming to 1.5–2°C temperature increase over the century. Our results show that the availability of direct air capture (DAC) technologies reduces the stranding of existing coal and gas based conventional power plants and delays any stranding further into the future. DAC deployment under the climate mitigation goal of limiting the end-of-century warming to 1.5–2°C would reduce the stranding of power generation from 250 to 350 GW peaking during 2035-2040 to 130-150 GW in years 2050-2060. With the availability of direct air capture and carbon storage technologies, the carbon budget to meet the climate goal of limiting end-of-century warming to 1.5–2°C would require abating 28–33% of 564 Gt CO_2 -the total committed CO_2 emissions from the existing power plants vs. a 46–57% reduction in the scenario without direct air capture and carbon storage technologies.

Keywords: integrated assessment model, direct air capture, negative emissions, power sector, committed emissions, stranded assets

INTRODUCTION

Limiting global warming to +1.5°to 2°C by the end of this century requires substantial reduction in global CO_2 emissions (IPCC, 2014, 2018). In the absence of actively removing greenhouse gases from the atmosphere, achieving the internationally agreed upon limits on temperature increase will require that large quantities of economically recoverable fossil fuel reserves be left unexploited (McGlade and Ekins, 2014, 2015). Along with the fuel, economically significant stocks of fossil fuel infrastructure in mining, transportation, refining and electricity generation will also be at risk of premature retirement, or stranding. The magnitude of assets subject to potential stranding is sufficient to warrant concerns over macroeconomic stability, especially in countries with the greatest fossil asset exposure (Leaton et al., 2015; Battiston et al., 2017).

Near-term climate mitigation policy signals from countries with the greatest emissions imply a large emissions gap from the emission level required to achieve climate goals (UNEP, 2018). At the same time, even countries promising substantial efforts to reduce emissions continue to invest in fossil-fuel infrastructure. As a result, there is a growing concern over the potential economic effects of impending lock-in and later stranding of fossil fuel infrastructure assets due to future climate mitigation policies (Carney, 2015; UNEP, 2018; González-Mahecha et al., 2019; Rep. Casten, 2019; Tong et al., 2019). Much of these infrastructures have multiple decades of design life. Near-term lock-in of fossil fuel capacity makes future mitigation costly and less politically palatable, since most future policy scenarios for achieving the well-below 2°C temperature target will require the premature decommissioning of large stocks of valuable assets.

Several recent reports by the Intergovernmental Panel on Climate Change (IPCC) including the Fifth Assessment Report highlight the need to deploy large-scale negative emission technologies (NETs) in order to meet the stringent climate mitigation scenarios like 2°C (IPCC, 2014, 2018). Given the significant role NETs are likely to play in the future strategies to mitigate climate change, several studies have appeared highlighting the need for a careful assessment of NETs role in climate mitigation (Fuss et al., 2018; Fuhrman et al., 2019; Hilaire et al., 2019). For example, the land area required for using only biomass energy-based carbon capture and sequestration (BECCS) for carbon removal is estimated to be one billion hectares (roughly equivalent to the area of the lower 48 US states).

In the integrated assessment modeling literature, BECCS and Afforestation (AR) are the most studied of the NETs (Rao and Riahi, 2006; Calvin et al., 2009; Wise et al., 2009; Edmonds et al., 2013; Humpenöder et al., 2014; Bertram et al., 2018; Grubler et al., 2018; van Vuuren et al., 2018), and even fewer include direct air capture technologies (DAC) in the portfolio of NETs (Chen and Tavoni, 2013; Marcucci et al., 2017; Realmonte et al., 2019) or enhanced weathering (EW) (Strefler et al., 2020). A key finding in these studies is that additional NETs deployment makes emission reductions in the near-term less attractive (Hilaire et al., 2019). This has important implication on climate mitigation led stranding of assets and the effects on the stranded assets associated with the NET deployment.

We examine how the availability of NETs affects the early retirement of fossil fuel generation assets under a 2°C climate stabilization goal. Using the Global Change Analysis Model (GCAM-5.3v), an integrated assessment model, we investigate the effects on power generation capacity stranding attributable to the availability of a suite of NETs technologies including DAC, BECCS and AR. In the absence of a climate policy, irreversible investments are made in relatively carbon-intensive capital stock, which, in turn, implies a set of anticipated resulting emissions, referred to as "committed emissions." Under a stringent long-term climate mitigation goal that requires a substantial reduction in CO_2 emissions in the near-term, these irreversible investments cannot be divested above the natural rate of depreciation and thus profits become negative. As the profits become negative at the margin, power plants will be increasingly idled, which would eventually lead to premature retirements.

NETs slow or reverse the climate change by removing CO_2 emissions from the atmosphere. Deployment of NETs like BECCS and AR requires land-based resources. A large-scale deployment of these NETs, under a warming target of 2°C, would require substituting substantial land and water resources away from other potential uses like food and timber production, leading to a significant increase in the cost of CO_2 reduction through these NETs. Although per unit investment in direct air capture is costlier than BECCS and AR, the marginal cost of additional CO_2 emissions reduction through DAC will be lower than BECCS and AR in later periods when BECCS and AR will face larger trade-offs with the land-based resources. As a result, we find that the availability of DAC would provide an opportunity to reduce additional CO_2 emissions at much lower cost than BECCS later in the century. Limiting the warming to 2°C by the end of century, having DAC or not having DAC, both paths should lead to the same cumulative emissions. So, the path having DAC must begin with higher emissions than the path without DAC. Thus, the availability of DAC in the NETs portfolio reduces near-term CO_2 abatement and this implies less stranding of power plant capacity when compared to the NETs portfolio that only includes BECCS and AR.

Several studies have shown that the effects of climate policies on stranding assets depend upon the stringency of the policies in the near-term. For example, Riahi et al. (2015), use a suite of models (AMPERE) to compare the costs of near-term climate policies that complement the long-term climate objectives. They show that the national pledges from the Copenhagen Accord and Cancun Agreements to achieve a 2030 emission target would result in a further "lock-in" of fossil fuel investments and would increase the risk of unattainable low GHG stabilization levels without large scale deployment of backstop technologies like traditional fossil fuel power-based CCS. In similar vein, Bertram et al. (2015) show that insufficient policy signals in the near-term result in the "lock-in" of coal-based electricity generation. As noted earlier, fossil fuel resources are also subject to stranding. Mercure et al. (2018) estimate that Canada and the United States stand to lose a combined $5 trillion ($2016) in fossil fuel resource value under a global 2°C policy scenario. Iyer et al. (2015) use GCAM to compare near and long-term implications for the global energy system of agreements based on nationally determined contributions (NDCs), such as those announced in COP21. They show that NDCs with more aggressive near-term mitigation policies tend to reduce premature retirements by reducing new fossil capacity deployment.

More recently, Binsted et al. (2020) find that for Latin American and the Caribbean (LAC), a region with one of the least carbon-intensive power sectors in the world, the Paris Agreement's near-term targets, the NDCs, and the long-term temperature target both result in premature retirement of carbon-intensive assets. Saygin et al. (2019) and Johnson et al. (2015) examine the phasing out of coal-based power plants in the near-term as an implication of climate policy and show that strengthening the policy reduces new capacities and thus the stranding of coal capacity and its associated costs. These assessments, however, only include BECCS and AR and thus ignore the trade-offs that may arise due to the availability of additional NETs like DAC (Hilaire et al., 2019).

We contribute to this literature by examining the effects of the availability of DAC on stranded capacities of existing fossil-based (coal, oil, and gas) power generation and the consequent reductions in their committed emissions under the well-below 2°C end-of-century climate goal. To do so, we model a climate mitigation scenario that limits radiative forcing to 2.3 W/m^2 by end-of-century. Since this is an aggressive pathway compared to a 2°C end-of-century warming target, we also include an additional scenario that limits radiative forcing to 2.6 W/m^2 by end-of-century. We compare these effects with the case when BECCS and AR are the only available NETs. Our findings suggest that achieving the climate goal would result in substantial premature retirements of existing power plants in the two decades from 2020 through 2040 even when BECCS and AR are available. Stranded capacity in the power sector would amount to 250–350 GW during 2035–2040, which would be largely coal-based power plants. The stranding of natural gas power plants would amount to nearly 80–100 GW in year 2025. The availability of DAC would both reduce total stranding and delay the stranding that would still occur. With DAC, the magnitude of stranded capacity would decline to about 130–150 GW during year 2050–2060 and mostly stranded capacities in the coal and gas-based power plants would be substantially reduced.

The effect on committed emissions is in line with the effect on the stranded power plant capacity. DAC availability would allow for a less stringent reduction in committed CO_2 emissions required to meet the climate goal. Out of the total committed 564 Gt CO_2 emissions from existing power plants over the century, the carbon budget required to meet the climate goal of 2°C would only require abating 28–33% of the total committed emissions from these power plants, which is lower by 17–24% than the case when BECCS and AR are the only available NETs.

The rest of the paper is organized as follows. Section Methods describes the methodology, our approach to modeling the availability of DAC in GCAM, the characteristics of DAC technology and climate stabilization scenarios. Section Results and Discussion describes the effects on climate, carbon sequestration, stranded assets and committed emissions. Section Conclusions concludes.

METHODS

To assess the effects from DAC deployment, we construct least cost climate policy scenarios in GCAM, where the different scenarios describe differing availability in NETs technology. We consider two climate mitigation goals that limit the total radiative forcing by the year 2100 to 2.3 and 2.6 W/m^2, respectively. The 2.3 W/m^2 total radiative forcing goal is set such that it yields global warming in each scenario to well-below 2°C from pre-industrial levels in all time periods between now and the year 2100 and thus the scenario is much stringent climate scenario. The scenario to limit end-of-century total radiative forcing to 2.6 W/m^2 is set to represent a less stringent climate scenario. These climate mitigation goals yield the end-of-century warming to 1.5°-2°C. The following subsections detail our implementation of the integrated assessment model, our DAC technology assumptions and our method for determining stranded assets and reductions in committed emissions.

Integrated Assessment Model–GCAM

GCAM is a global integrated assessment model (IAM) that links energy, economy, and land-use with a climate system model. GCAM is one of the six IAMs used for the development of the Shared Socioeconomic Pathways to be used in IPCC 5th assessment report. GCAM is an open source community model (Edmonds et al., 2004; Iyer et al., 2015; Riahi et al., 2015; JGCRI, 2020). The GCAM (5.3v) has detailed representation of 32 geographical regions, 384 land sub-regions and 235 water basins in the world. The model includes energy systems with detailed representations of extractions of fossil fuels such as coal, natural gas, oil, and uranium and renewable resources such as bioenergy, hydro, solar, and wind in each geographical region and also has rich representations of the transformation processes of these primary resources to final energy carriers that are used to meet final demand by end users (JGCRI, 2020).

GCAM is a dynamic recursive model that captures decisions in each period assuming agents do not have knowledge about the future. For long-lived investments like power plants, GCAM models investment decisions by assuming that agents base their decisions on expected future profit streams over the expected lifetime of the asset, given current period prices. These investments in each period are subject to the stock-turnover of power plant capacities from the last period. For example, the total capacity of power plant in operation in each period will be the sum of the stock-turnover of power plants from the last period and the investment in that period.

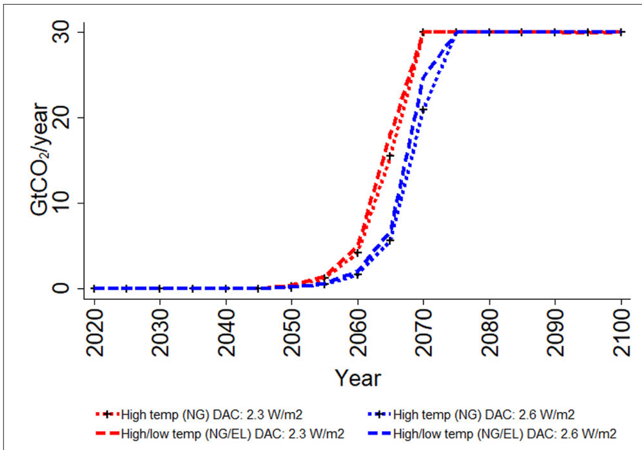

FIGURE 1 | The deployment of DAC under the least cost strategy scenarios that aim to achieve climate mitigation goal by limiting the total radiative forcing to 2.3 W/m^2 by year 2100 (shown in red color) and 2.6 W/m^2 by year 2100 (shown in blue color), respectively. The scenario "High temp (NG) DAC" shows deployment of high temperature natural gas-based DAC in addition to BECCS and AR, and the scenario "High/low temp (NG/EL) DAC" shows aggregate deployment of three types of DAC (high temperature natural gas-based DAC, high temperature electricity- based DAC and low temperature electricity-based DAC) in addition to BECCS and AR.

Direct Air Capture and Carbon Storage Technology and Its Deployment

Direct air capture technology is still in the early development stage and has yet to be deployed at scale. Among the several variants of potential DAC technology, we consider the most prominent forms of the technology that are at different development stages (Fuhrman et al., 2020): (a) High temperature DAC that relies on process heat from natural gas combustion and (b) High and low temperature DAC that rely on electricity for the process heat. The electricity-based

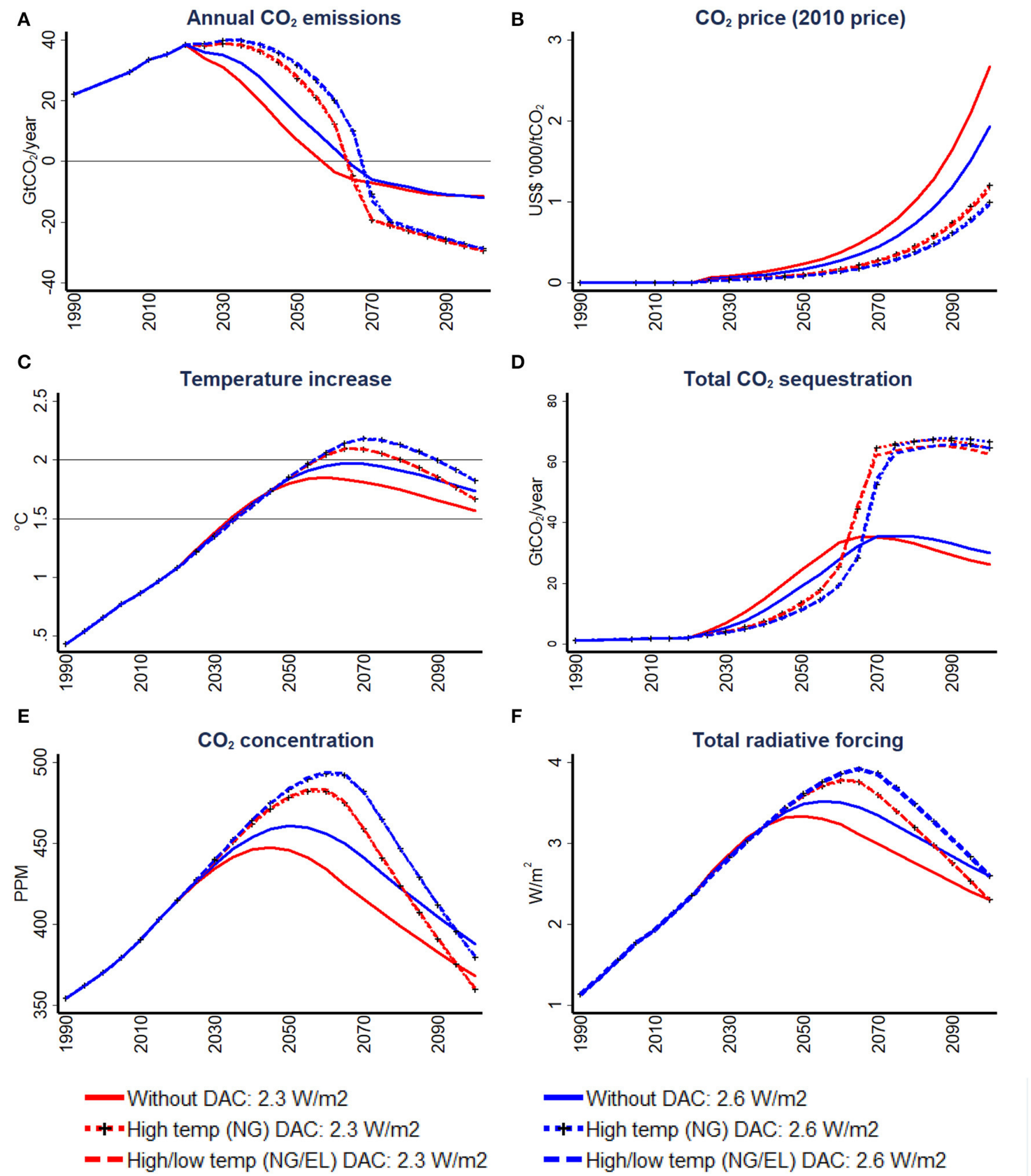

FIGURE 2 | Effects on the global CO_2 emissions path **(A)**, CO_2 prices **(B)**, global mean temperature **(C)**, the total CO_2 sequestration **(D)**, CO_2 concentration **(E)**, and the total radiative forcing **(F)** under the least cost strategy scenarios that aim to achieve climate mitigation goal by limiting the total radiative forcing to 2.3 W/m^2 by year 2100 (shown in red color) and 2.6 W/m^2 by year 2100 (shown in blue color), respectively. The scenario "Without DAC" includes only BECCS and AR, the scenario "High temp (NG) DAC" includes a high temperature natural gas-based DAC in addition to BECCS and AR, and the scenario "High/low temp (NG/EL) DAC" includes three types of DAC (high temperature natural gas-based DAC, high temperature electricity-based DAC and low temperature electricity-based DAC) in addition to BECCS and AR. "High/low temp (NG/EL) DAC" scenario, expanding the portfolio of DAC, by including two additional high and low temperature electricity-based DAC, does not significantly differ much from High/low temp (NG) DAC since the major share of the DAC deployment is high temperature natural gas-based.

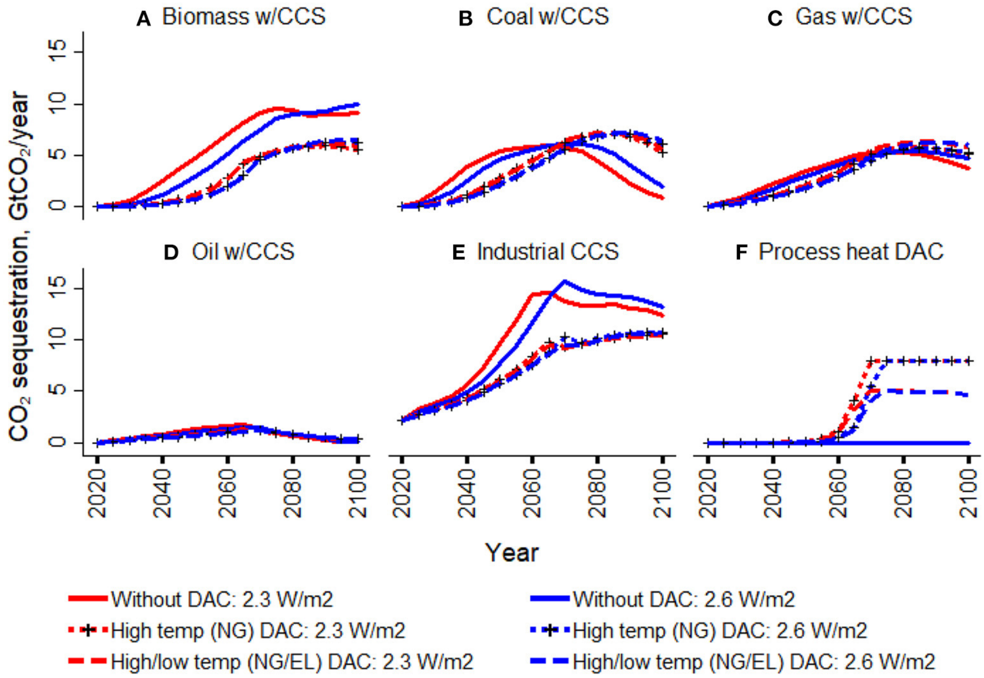

FIGURE 3 | CO_2 sequestration under the least cost strategy scenarios that aim to achieve climate mitigation goal by limiting the total radiative forcing to 2.3 W/m^2 by year 2100 (shown in red color) and 2.6 W/m^2 by year 2100 (shown in blue color), respectively. The scenario "Without DAC" includes only BECCS and AR, the scenario "High temp (NG) DAC" includes a high temperature natural gas-based DAC in addition to BECCS and AR, and the scenario "High/low temp (NG/EL) DAC" includes three types of DAC (high temperature natural gas-based DAC, high temperature electricity-based DAC and low temperature electricity-based DAC) in addition to BECCS and AR.

DAC can be powered by low or zero carbon electricity if it is available. High temperature DAC is solvent-based, relying on aqueous reactions and therefore requires water inputs to replace evaporative losses at the air contactor (Keith et al., 2018). Low temperature DAC is solid sorbent-based and does not require water input (Fasihi et al., 2019). The energy and water inputs for DAC, as well as storage costs for the captured carbon are determined endogenously at the regional level within GCAM. Our technical parameters and cost assumptions for DAC are shown in Appendix (**Supplementary Table 1**).

We include three distinct technologies to provide a more complete picture of the balance of different DAC technologies. To capture the potential cost variation and the role of technological improvement, we parametrize the future improvements of all three DAC technologies conservatively relative to some literature estimates. Note that our study does not account for the costs that might arise from feedbacks in non-energy sectors because the GCAM model is a partial equilibrium model and accounting these general equilibrium effects in the model is beyond the scope of this study. Abstracting from these general equilibrium effects, we focus on scenario analysis comparing technology substitutions, fuel-switching, investments, and their impact on the climate system. To consider these model limitations and assuming a backstop technology, we limit the deployment of DAC to an upper limit of 30 Gt of CO_2/yr following Realmonte et al. (2019).

Determination of Stranded Capacities

Our approach to determining the stranded capacity in the power sector under climate mitigation policy stems from Binsted et al. (2020) who define profit-based capacity retirements as stranded capacity. To explore the effects of DAC availability, in addition to BECCS and AR, we extend the method by constructing least-cost climate mitigation strategy scenarios in GCAM. Such approaches, but in different applications, are illustrated in Johnson et al. (2015) and Chen and Tavoni (2013). In the absence of a climate policy, existing carbon-intensive capital stocks operate at their full capacity subject to the natural depreciation. If a stringent climate policy is implemented the return to these carbon-intensive existing investments will fall, but the assets cannot be divested above the natural rate of depreciation, so profits become negative, which will lead to idling of power plants and, hence, premature retirement.

We simulate regional electricity supply with an optimal generation mix in the 32 sub-regions in the GCAM model. Each region has an endogenously determined generation mix of power plants, which depends on a variety of factors including electricity demand, plant load factor and pre-existing capacity. We track these existing power plant vintages over time and compute gross retirements of each vintage based on plant expected life-time.

We model the natural retirement of the power plants (retirement not due to climate policy) following Davis and Socolow (2014), where a fraction of existing power plants

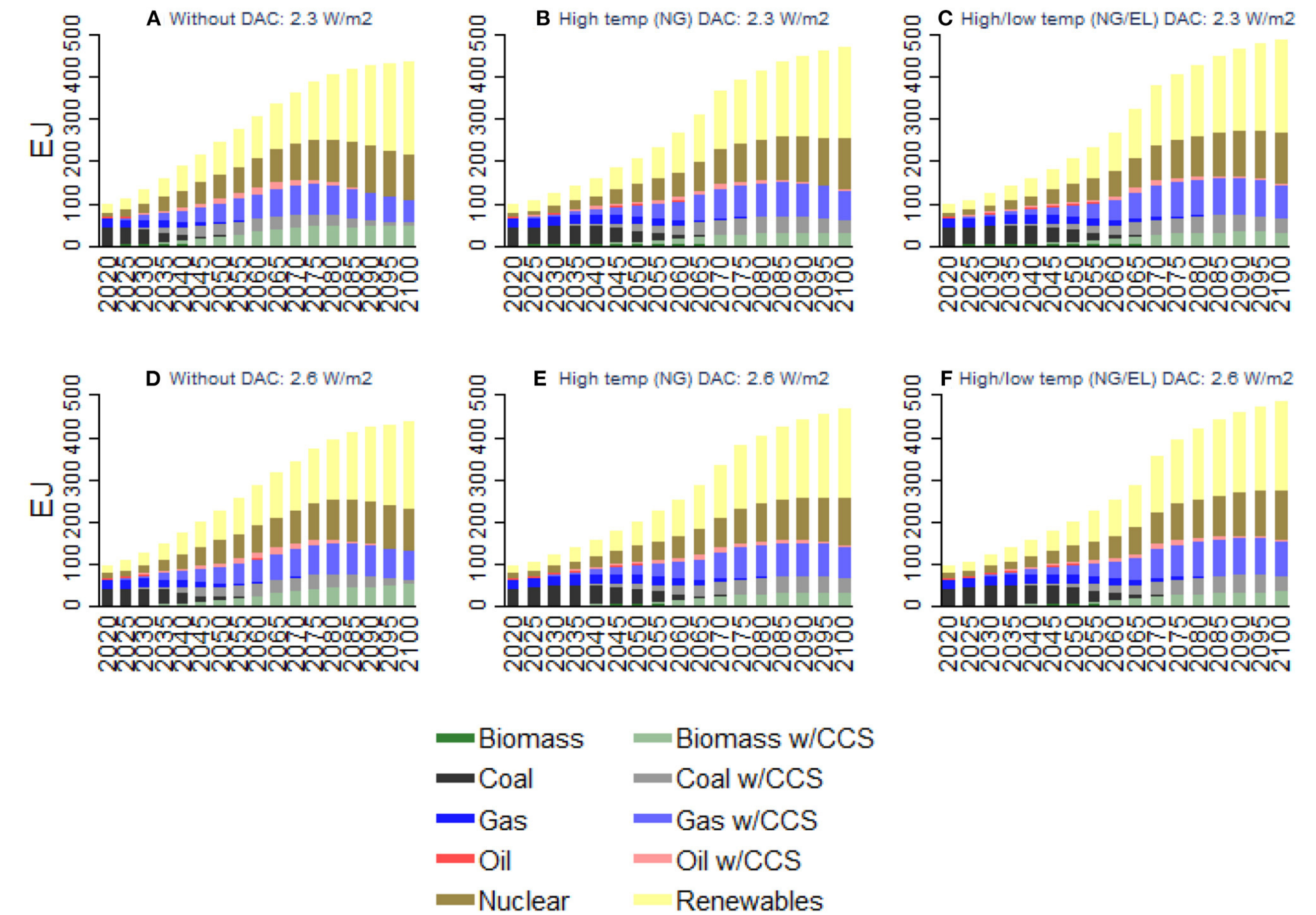

FIGURE 4 | Supply of electricity and generation mix in the global power sector under the least cost climate mitigation scenarios that aim to achieve climate mitigation goal by limiting the total radiative forcing to 2.3 and 2.6 W/m^2 by year 2100, respectively. The three panels in the top row shows the electricity generation mix under the 2.3 W/m^2 by year 2100 and the three panels in the bottom row shows the electricity generation mix under the 2.6 W/m^2 by year 2100. The scenario "Without DAC" includes only BECCS and AR, the scenario "High temp (NG) DAC" includes a high temperature natural gas-based DAC in addition to BECCS and AR, and the scenario "High/low temp (NG/EL) DAC" includes three types of DAC (high temperature natural gas-based DAC, high temperature electricity-based DAC and low temperature electricity-based DAC) in addition to BECCS and AR.

naturally retire, depending upon plants' expected lifetime and current age (see **Supplementary Tables 2**, **3**). As in Binsted et al. (2020), to determine natural retirements of existing power plants, we use a logistic retirement curve given by $sfrac_t = \frac{1}{1+ exp(a^*(t-b))}$, where, "*sfrac*" is a fraction of existing power plants with half-life "*b*" that would survive in a time-period "*t*". The coefficient "*a*" specifies the steepness of the logistic retirement curve. The value of the coefficient a = 0.1 for all existing power plants globally (see **Supplementary Table 2**). Note that the steepness coefficient is an input parameter to GCAM and the value to this coefficient comes from GCAM input assumptions on how existing technologies would naturally retire.

We define stranding as the early retirement of an existing power plant when it can no longer earn its variable operating costs (Binsted et al., 2020). Climate mitigation policies such as a carbon tax will push variable costs of some plants above the market prices of electricity, which would lead to early shutdown of the generator leading to its premature retirement. We compute stranded capacity as the difference between gross retirements and natural retirements. In this paper, we consider implication on stranding of existing fossil fuel-based (coal, natural gas, and oil) power plants.

Although we include the existing nuclear and renewables in our model, these power plants would not be stranded under the climate mitigation scenarios and these plants would naturally retire. After their natural retirement, these power plants would be replaced by the respective advanced technologies and thus the DAC's deployment may affect the planned investments in the future. We do not consider the effect on the planned investments as stranding and thus exclude nuclear and renewables in computing stranded capacities.

Scenario Description

We construct least-cost climate policy scenarios by imposing two limits on the end-of-century total radiative forcing to 2.3 and 2.6 W/m^2 while allowing an overshoot in years before the target year.

Both scenarios limit end-of-century warming to 1.5–2°C but the 2.3 W/m^2 total radiative forcing would result in warming well below 2°C in all years even though temperature is not explicitly constrained and thus is a much more stringent scenario. The 2.6 W/m^2 total radiative forcing scenario is selected to consider a less stringent climate goal. To formulate these scenarios, we first run the model by choosing an arbitrary initial carbon price in 2025 and increasing it by the discount rate of 5% each year until 2100. The carbon price path mimics the hoteling price path (Nordhaus, 1982). The model is then run several times, increasing the initial carbon price by a small increment in each run until the model solution converges to the total radiative forcing target in year 2100. We describe below these scenarios:

(a) **Business as usual scenario**: This scenario assumes there would be no climate policy implementation. The business-as-usual scenario follows the central shared socioeconomic pathway (SSP2) described in Calvin et al. (2017).

(b) **Without DAC:** In this scenario, we assume that the climate policy would limit the targeted end-of-century total radiative forcing (2.3 and 2.6 W/m^2) but with a portfolio of NETs that includes a zero-upper limit on DAC and no deployment limit on BECCS and AR. The implementation of climate mitigation policy is assumed to begin from year 2025.

(c) **High temp (NG) DAC scenario:** In this alternative scenario, we keep everything else the same as in the "Without DAC" scenario but we include high temperature, natural gas-based DAC in the portfolio of NETs. Also, we replace the zero-upper limit by an upper limit on DAC deployment to 30 Gt of CO_2/yr, following Realmonte et al. (2019).

(d) **High/low temp (NG/EL) DAC scenario:** In this alternative scenario, we keep everything else the same as in the "High temp (NG) DAC" scenario but in the portfolio of NETs, we include two additional DAC technologies: a high temperature, electricity-based DAC and a low temperature, electricity-based DAC. As before we impose an upper limit on DAC deployment to 30 Gt of CO_2/yr following Realmonte et al. (2019).

RESULTS AND DISCUSSION

Our findings confirm previous results that adopting an ambitious climate mitigation target to limit warming to below 2°C requires substantial investment in removing CO_2 from the atmosphere. Given current best estimates for technological development, we find that DAC will be deployed only after the mid-century (**Figure 1**). The large-scale deployment of DAC, mainly high temperature natural gas-based DAC, is expected to have a significant effect on the optimal CO_2 mitigation path (**Figure 2A**). The deployment of DAC would result in removing nearly 0.5–1.5 $GtCO_2$/yr in year 2055, with DAC capacity increasing to the maximum capacity 30 $GtCO_2$/yr during 2065–2070, the limit we imposed in the model. This amounts to nearly half of the combined CO_2 sequestered in total during the period (**Figures 1**, **2D**).

DAC deployment would lower the total CO_2 mitigation cost compared to the scenario with no direct air capture technologies

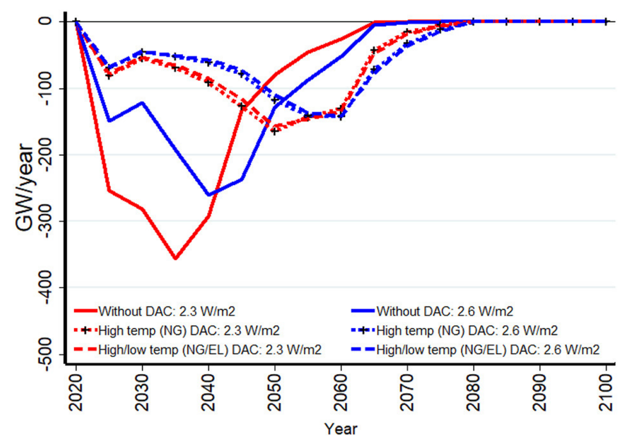

FIGURE 5 | Stranded capacities of existing generation in the global power sector under the least cost strategy scenarios that aim to achieve climate mitigation by limiting total radiative forcing to 2.3 and 2.6 W/m^2 by year 2100, respectively. The scenario "Without DAC" includes only BECCS and AR, the scenario "High temp (NG) DAC" includes a high temperature natural gas-based DAC in addition to BECCS and AR, and the scenario "High/low temp (NG/EL) DAC" includes three types of DAC (high temperature natural gas-based DAC, high temperature electricity-based DAC and low temperature electricity-based DAC) in addition to BECCS and AR.

(**Figure 2B**), in-line with the findings by Chen and Tavoni (2013). The removal of CO_2 using DAC has lower resource trade-offs when compared to BECCS and AR. Deployment of BECCS and AR requires land-based resources, and a large-scale deployment of these NETs significantly increases the CO_2 removal cost due to competition for the use of land in the production of food and water. DAC thus would significantly reduce net CO_2 emissions later in the century (**Figure 2A**). Since, to achieve the same radiative forcing by the end of century (**Figure 2F**), having DAC or not having DAC, both paths should lead to nearly the same cumulative emissions, the path having DAC begins with higher CO_2 emissions than the path without DAC (**Figures 2A,E**). We also note that the global mean temperature would increase more than in the case without DAC (**Figure 2C**) during the transition, because of higher CO_2 emissions.

CO_2 Sequestration

Our results suggest that availability of DAC would significantly affect the CO_2 sequestration path for other CCS technologies under the climate mitigation goals. Under end-of-century total radiative forcing to 2.3 W/m^2 goal, in the "Without DAC" scenario, a cumulative total 1,086 Gt of CO_2 would be sequestered over the century using fossil-fuel CCS technologies and BECCS, with BECCS delivering over 42% (454 Gt). In the less stringent 2.6 W/m^2 total radiative forcing climate goal, the cumulative total sequestration over the century would be 1,012 Gt of CO_2 and the share of BECCS would be 38%. With DAC deployment, the cumulative total CO_2 sequestration would increase to 1,873 Gt and 2,232 Gt in the "High temp (NG) DAC" and "High/Low (NG/EL) DAC" scenarios, respectively. The share of DAC would be over 55 and 47% of the cumulative total CO_2

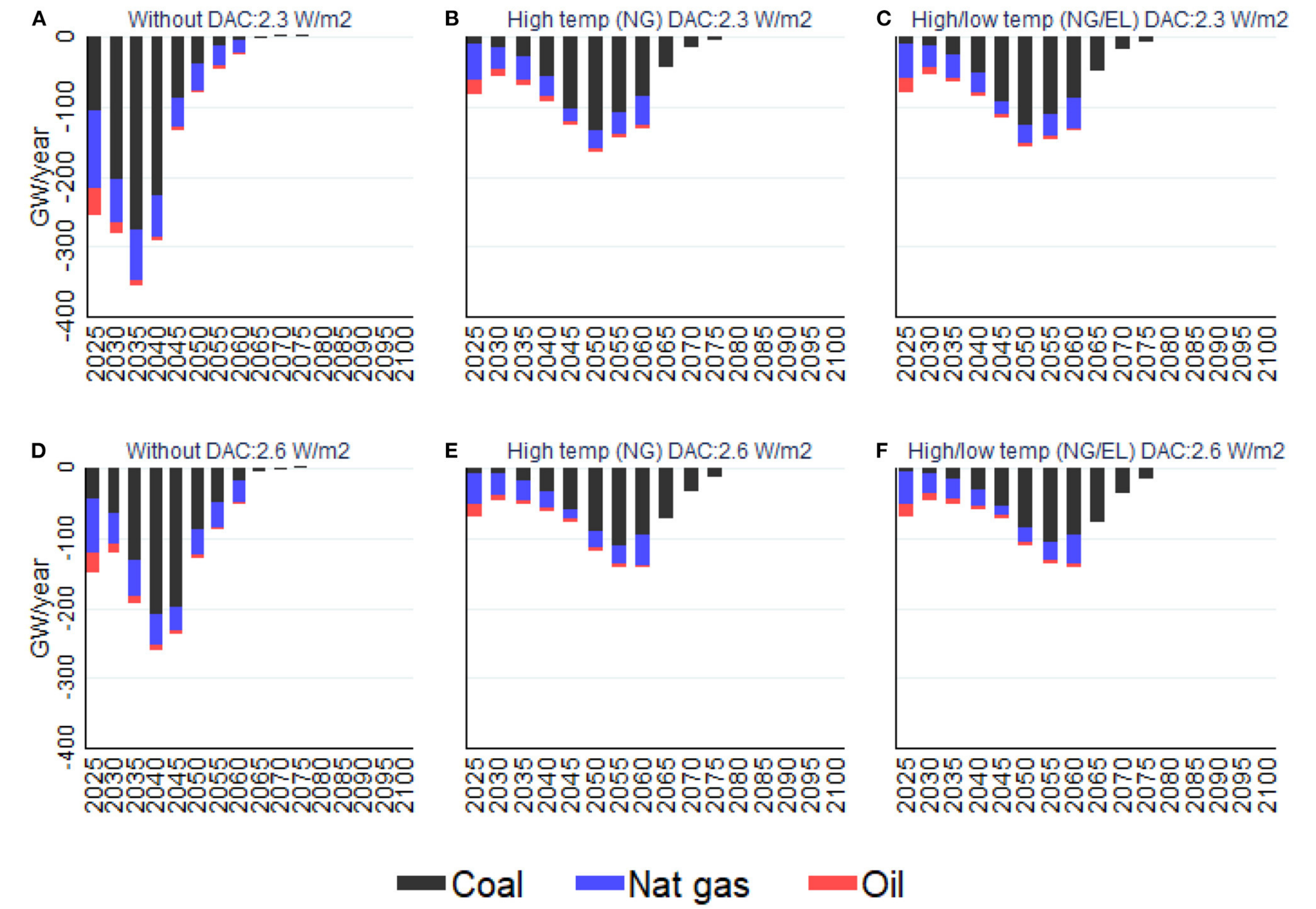

FIGURE 6 | Stranded capacities in the existing power plant types in the global power sector under the least cost strategy scenarios that aim to achieve climate mitigation by limiting total radiative forcing to 2.3 and 2.6 W/m^2 by year 2100, respectively. The scenario "Without DAC" includes only BECCS and AR, the scenario "High temp (NG) DAC" includes a high temperature natural gas-based DAC in addition to BECCS and AR, and the scenario "High/low temp (NG/EL) DAC" includes three types of DAC (high temperature natural gas-based DAC, high temperature electricity-based DAC and low temperature electricity-based DAC) in addition to BECCS and AR.

sequestered, respectively, while the sequestration by BECCS falls to 12 and 10%. Under the end-of-century total radiative forcing to 2.6 W/m^2 goal, the total cumulative CO_2 sequestration would increase to 1,709 and 1,757 Gt in the "High temp (NG) DAC" and "High/Low (NG/EL) DAC," respectively. In both scenarios, the DAC deployment would still amount to over 54% while the share of BECCS falls to about 12% of the cumulative total CO_2 sequestered.

The availability of DAC would reduce biomass-based CCS throughout the century. The near-term increase in opportunity cost of CO_2 removal due to the prospect of future DAC deployment reduces the biomass-based CCS to a greater extent than the fossil fuel CCS technologies. We find that the marginal cost of CO_2 reduction using BECCS is higher than for fossil fuel CCS technologies, the higher costs largely due to BECCS intensive use of scarce land resources. Interestingly, as BECCS decreases later in the century, DAC availability increases the use of CCS in coal and natural gas power generation, suggesting that CO_2 emissions reduction from fossil CCS would be less costly than BECCS during that period (**Figure 3**).

Supply of Electricity and Generation Mix

With no climate policy in place, the supply of electricity is expected to be dominated by conventional coal and natural gas-based electricity generation technologies. To achieve the 2°C climate goal, much of these conventional electricity generation technologies would need to be either replaced or equipped with CCS technologies (**Figures 4A,D**). DAC deployment would have two significant effects: the near-term supply of electricity from conventional coal and natural gas power plants would increase and the long-term supply of electricity from BECCS would decrease (**Figures 4B,C,E,F**). Non-emitting electricity generation from nuclear, solar and wind would be used consistently across the climate policy scenarios.

Stranded Capacity

Fossil fuel generators built prior to the implementation of a climate policy are subject to stranding as their variable costs rise above the price of electricity. In fact, under a 2°C climate goal most existing conventional coal and natural gas power plants would be stranded, if they are not equipped with CCS

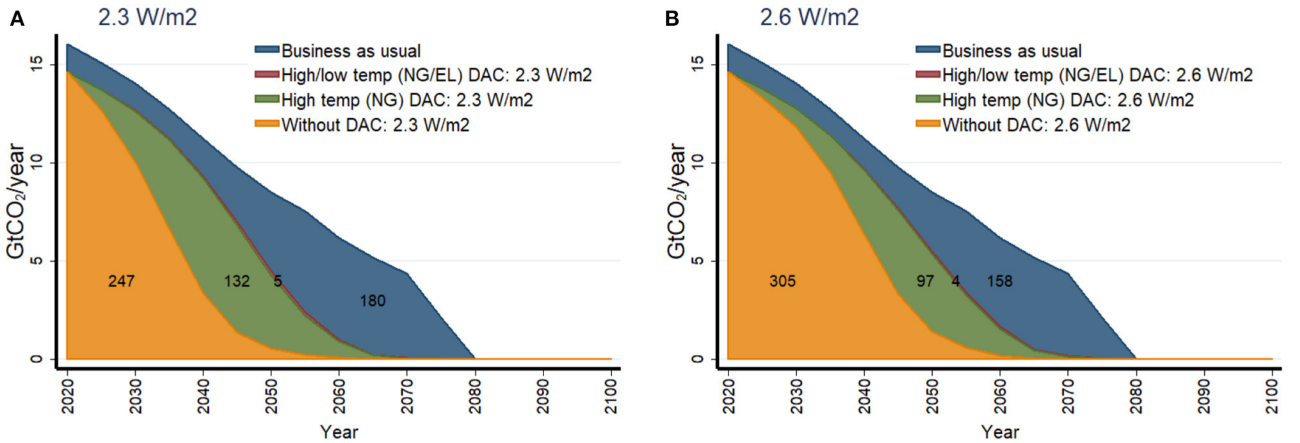

FIGURE 7 | The effects of DAC availability on the CO_2 emissions from the existing power plants in the global power sector. The emissions in the absence of climate policy is shown in "Business as usual" scenario. The scenario "Without DAC" includes only BECCS and AR, the scenario "High temp (NG) DAC" includes a high temperature natural gas-based DAC in addition to BECCS and AR, and the scenario "High/low temp (NG/EL) DAC" includes three types of DAC (high temperature natural gas-based DAC, high temperature electricity-based DAC and low temperature electricity-based DAC) in addition to BECCS and AR. The left panel **(A)** shows the climate mitigation goal of limiting the total radiative forcing to 2.3 W/m^2 by year 2100 and the right panel **(B)** shows the climate mitigation goal of limiting the total radiative forcing to 2.6 W/m^2 by year 2100. The cumulative CO_2 emissions from the existing power plants are 564 Gt in the "Business as Usual" scenario. In climate mitigation scenario of 2.3 W/m^2 total radiative forcing, the cumulative emissions are 247, 379, and 384 Gt in the "Without DAC," "High temp (NG) DAC" and "High/low temp (NG/EL) DAC" scenarios, respectively. In climate mitigation scenario of 2.6 W/m^2 total radiative forcing, the cumulative emissions are 305, 402, and 406 Gt in the "Without DAC," "High temp (NG) DAC" and "High/low temp (NG/EL) DAC" scenarios, respectively. The numbers on the plot denote the difference in cumulative emissions between adjacent scenarios.

technologies. In the absence of DAC deployment, the amount of generation stranded each year would peak in year 2035 and 2040 at nearly 350 and 250 GW in the 2.3 and 2.6 W/m^2 climate goal, respectively (**Figure 5**). Most of these stranded generation would be existing coal-fired power plants (**Figures 6A,D**). The subsequent two decades would see stranding of existing natural gas combined cycle power plants in addition to coal plants, although premature natural gas retirements are considerably smaller in magnitude.

The anticipated, future availability of DAC would delay the onset of asset stranding until year 2050–2060 (**Figures 5, 6B,C,E,F**). Under the "High temp (NG) DAC" scenario, the highest annual stranding would be approximately 150 GW peaking in year 2050 in the 2.3 W/m^2 climate goal. In 2.6 W/m^2 climate goal, the annual stranding is lower, approximately 130 GW and peaks in year 2060. In the "High/low temp (NG/EL) DAC" scenario, expanding the portfolio of DAC, by including two additional high and low temperature electricity-based DAC, does not significantly affect much since the major share of the DAC deployment is high temperature natural gas-based. The availability of DAC thus both delays the onset of stranding of existing power generation and limits its magnitude.

Committed Emissions

Next, we examine how the availability of DAC affects carbon "lock-in," that is the committed CO_2 emissions that would be emitted by the normal operation of the existing fleet of power plants. Since the committed emissions are linked to the existing power plant operations, the stranding of these power plants reduces the emissions from these plants. In the absence of climate policy, the existing power plants (constructed prior to the year 2020) in the global power sector would commit to CO_2 emissions of about 564 Gt over the remainder of the century. Although, there is uncertainty about the remaining carbon budget in the literature because of differences in model to model climate sensitivity, the committed emissions represent about 37–48% of the remaining carbon budget (from 2020 to 2100) which corresponds to approximately a 67% chance of remaining below 2°C warming by the end of century and the entire remaining carbon budget if the warming is to be limited to 1.5°C (Clarke et al., 2014; Rogelj et al., 2018a,b; Tong et al., 2019).

Our results show that, in the absence of DAC, the climate mitigation goal of keeping warming well below 2°C by limiting the total radiative forcing to 2.3 W/m^2 by year 2100 would require eliminating about 317 Gt (57%) of total committed CO_2 emissions from the existing power plants (**Figure 7A**). If we limit the total radiative forcing to 2.6 W/m^2, this would be about 259 Gt (46%) of total committed CO_2 emissions (**Figure 7B**). Most of the reduced emissions would come from stranding coal-based power plants (**Supplementary Figures 1A,D**). With the availability of DAC, the climate mitigation scenario of 2.3 W/m^2 would only require eliminating 180-185 Gt, or about 31–33% of total committed CO_2 emissions from the existing power plants, mostly coal power plants (**Supplementary Figures 1B,C**). Under the climate mitigation scenario of 2.6 W/m^2, the availability of DAC would require eliminating about 158–162 Gt (28–29%) of total committed CO_2 emissions (**Supplementary Figures 1E,F**). Thus, the availability of DAC would require relatively smaller reduction (17–24% less) in CO_2 emissions from the existing power plants and achieve the same climate goal.

CONCLUSIONS

There is a growing recognition that efforts to limit global warming to below 2°C will require the premature retirement of macroeconomically significant amounts of existing electricity generation infrastructure. The types and magnitude of asset stranding depend on the cost and availability of negative emission technologies, which serve as a substitute for near-term emission mitigation. We use the GCAM integrated assessment model to examine how climate policy affects the premature retirement of existing generation in the global power sector and how that stranding is affected by the expected future deployment of direct air capture and carbon storage.

The availability of DAC lowers stranding in the power sector while helping meet ambitious global temperature goals. The availability of DAC in the future reduces the stranding of coal and gas plants and delays the remaining stranding of these plants. The DAC deployment under the climate mitigation goal of limiting the warming to 1.5°-2°C would reduce the stranding of power generation from about 250–350 GW peaking during 2035–2040 to 130-150 GW in years 2050–2060.

The availability of direct air capture would reduce the need to eliminate already committed CO_2 emissions in order to achieve the climate goal. In the absence of climate policy, existing coal, natural gas and oil power plants would commit about 564 Gt CO_2 emissions between 2020 and the end of the century, which represents between 37 and 48% of the target carbon budget remaining to achieve global warming target of 2°C. Without the availability of DAC, 46–57% of the committed CO_2 emissions would need to be eliminated. If DAC is developed 28–33% of committed emissions would need to be eliminated.

This study shows how the availability of DAC affects generation asset stranding under the climate mitigation goal of limiting warming to 1.5°-2°C. Direct air capture technologies are in an early stage of technological development and the current cost estimates do not include the potential value from the use of captured CO_2 as a feedstock. For example, the pure stream of CO_2 generated from DAC could either be used either as a feedstock in catalytic processing to make synthetic hydrocarbons, such as liquid fuel or in building materials like plastic polymers or in the production of low carbon cements. These value additions can provide additional incentive for DAC deployment. Future research work in this area could be interesting.

DATA REFERENCE

GCAM is an open-source community-based integrated assessment model. The source code of the model to run the "business-as-usual" case is available at https://github.com/JGCRI/gcam-core.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SP, WS, HM, SD, and AC led the study design and the writing of the paper. SP and JF led the modeling activity. MB assisted with data processing and visualization. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.660787/full#supplementary-material

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