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Early retirement of power plants in climate mitigation scenarios

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Supplementary material for this article is available online

Abstract

International efforts to avoid dangerous climate change aim for large and rapid reductions of fossil fuel CO_2 emissions worldwide, including nearly complete decarbonization of the electric power sector. However, achieving such rapid reductions may depend on early retirement of coal- and natural gas-fired power plants. Here, we analyze future fossil fuel electricity demand in 171 energy-emissions scenarios from Integrated Assessment Models (IAMs), evaluating the implicit retirements and/or reduced operation of generating infrastructure. Although IAMs calculate retirements endogenously, the structure and methods of each model differ; we use a standard approach to infer retirements in outputs from all six major IAMs and—unlike the IAMs themselves—we begin with the age distribution and region-specific operating capacities of the existing power fleet. We find that coal-fired power plants in scenarios consistent with international climate targets (i.e. keeping global warming well-below 2 °C or 1.5 °C) retire one to three decades earlier than historically has been the case. If plants are built to meet projected fossil electricity demand and instead allowed to operate at the level and over the lifetimes they have historically, the roughly 200 Gt CO_2 of additional emissions this century would be incompatible with keeping global warming well-below 2 °C. Thus, ambitious climate mitigation scenarios entail drastic, and perhaps un-appreciated, changes in the operating and/or retirement schedules of power infrastructure.

Introduction

Among scenarios that succeed in stabilizing global mean temperatures at less than 2 °C warmer than the preindustrial era, CO_2 emissions from the power sector decrease rapidly in the coming decades, in almost all cases reaching net-zero before mid-century [1–5]. Such rapid and complete decarbonization entails similarly rapid turnover of historically long-lived electricity-generating infrastructure. Coal- and gas-fired power plants have historically operated for 39 and 36 years (s.d.14 and 13 years), respectively [6]. However, in Integrated Assessment Models (IAMs), the decision of when to retire a generator is primarily economic, e.g. based on marginal operating costs, revenues, and the levelized costs of

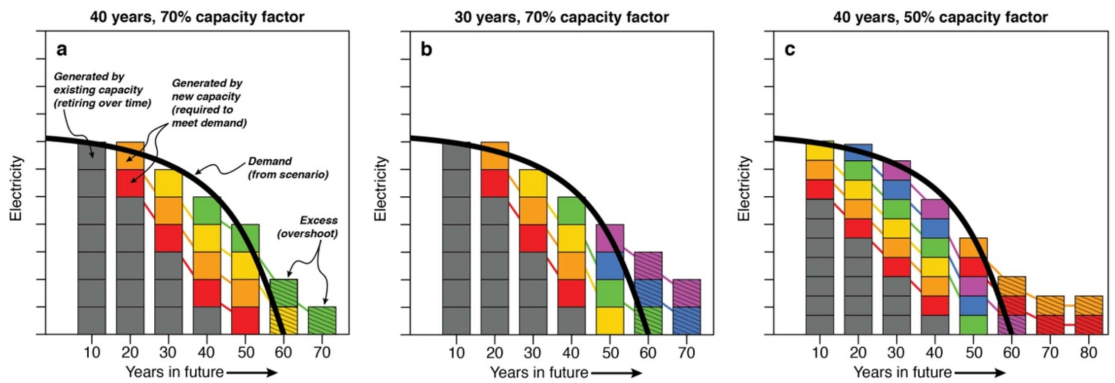

Figure 1. Schematic of modelling approach. Figure shows a hypothetical scenario to illustrate our methodological approach and is not representative of any specific integrated assessment model or shared socioeconomic pathway. Here we see, given a future electricity demand from coal- and gas-fired power plants in an integrated assessment model scenario (black curves), it may be necessary to build additional generating capacity (colored squares), whose operation may eventually exceed demand with corresponding 'overshoot' of emissions (hatched squares). Nonetheless, this schematic represents the model in its simplest form and does not capture the full extent of model ensembles.

new generating infrastructure [7–9]. IAM mitigation scenarios reconcile these economics with swift decarbonization of the electricity sector by modeling both policy-driven increases in the operational costs of CO_2-emitting power plants and rapidly decreasing costs of non-emitting sources of electricity [10, 11]. In reality, lawmakers may follow a similar approach, incentivizing the early closure of plants or severely reducing their operating hours by imposing strict regulations that increase their operating costs relative to non-emitting competitors. Examples of specific policies include setting a price on carbon, disallowing major maintenance (e.g. New Source Review in the United States), or subsidizing non-emitting technologies (e.g. renewable production tax credits). However, economics are not the sole determinant of power plant retirements, as there are numerous examples of fossil power plants now operating at a loss [12–14]. This suggests that more direct regulations such as an outright ban of a given fossil technology or mandating the early closure of certain power plants may be necessary. Nonetheless, given the initial capital costs of fossil fuel electricity generating capacity are typically \$200–5000 per kW and installed fossil capacity worldwide is today ~4000 GW [9, 15, 16], the premature retirement of power generating infrastructure could result in the loss of trillions of dollars of capital investment and future returns, and perhaps even jeopardize the stability of financial systems if not adequately managed and anticipated [17–20]. Moreover, losses from early retirement of fossil electricity generating assets may ultimately be borne by the rate- and tax-paying populace. For these reasons, the socioeconomic and political repercussions that arise from very early retirement of coal- and gas-fired power plants may be challenging to overcome.

Several previous studies have estimated the CO_2 that will be emitted by existing and proposed energy infrastructure if it is operated for historical average lifetimes [6, 8, 16]. Others have used IAMs in various ways: using scenarios as a guide to future fossil capacity [21], adding plant lifetime as an exogenous constraint within a model [22], or evaluating the infrastructural inertia of emissions in a designed multi-model experiment [23]. However, prior work has generally focused on differences in emissions related to the lifetime, operation, or commissioning of generating infrastructure. Here, we also take the opposite perspective: what do the rapid emissions reductions in mitigation scenarios imply for the lifetime, operation, and commissioning of generating infrastructure? Specifically, how severely must the lifetime or operation of power plants be abbreviated or curtailed, respectively, in order to achieve the emissions decreases (i.e. mitigation rates) in different scenarios and regions? Although the answers to these questions can be explicitly calculated by some IAMs, modeling approaches between IAM vary, retirements are endogenous to the models, and retirement rates are not reported—or even tracked—by all modeling groups.

Here, using detailed data of currently existing power plants worldwide [24] in addition to electricity and emissions outputs from six major integrated assessment models, we analyze coal- and natural gas-fired power plant utilization rates and lifetimes as embedded in 171 recent scenarios, spanning three levels of emissions mitigation (1.9, 2.6, and 4.5 W m^{-2} of radiative forcing; i.e. trajectories likely to avoid 1.5 °C, 2 °C, and 3 °C of mean warming this century), and five different socioeconomic trajectories (SSPs) [25]. We explicitly exclude oil-fired power generators from our analysis since they compose less than 5% of global electricity generating capacity [26]. Further details of our analytic approach are in the *Methods* and *supplementary information* (available online

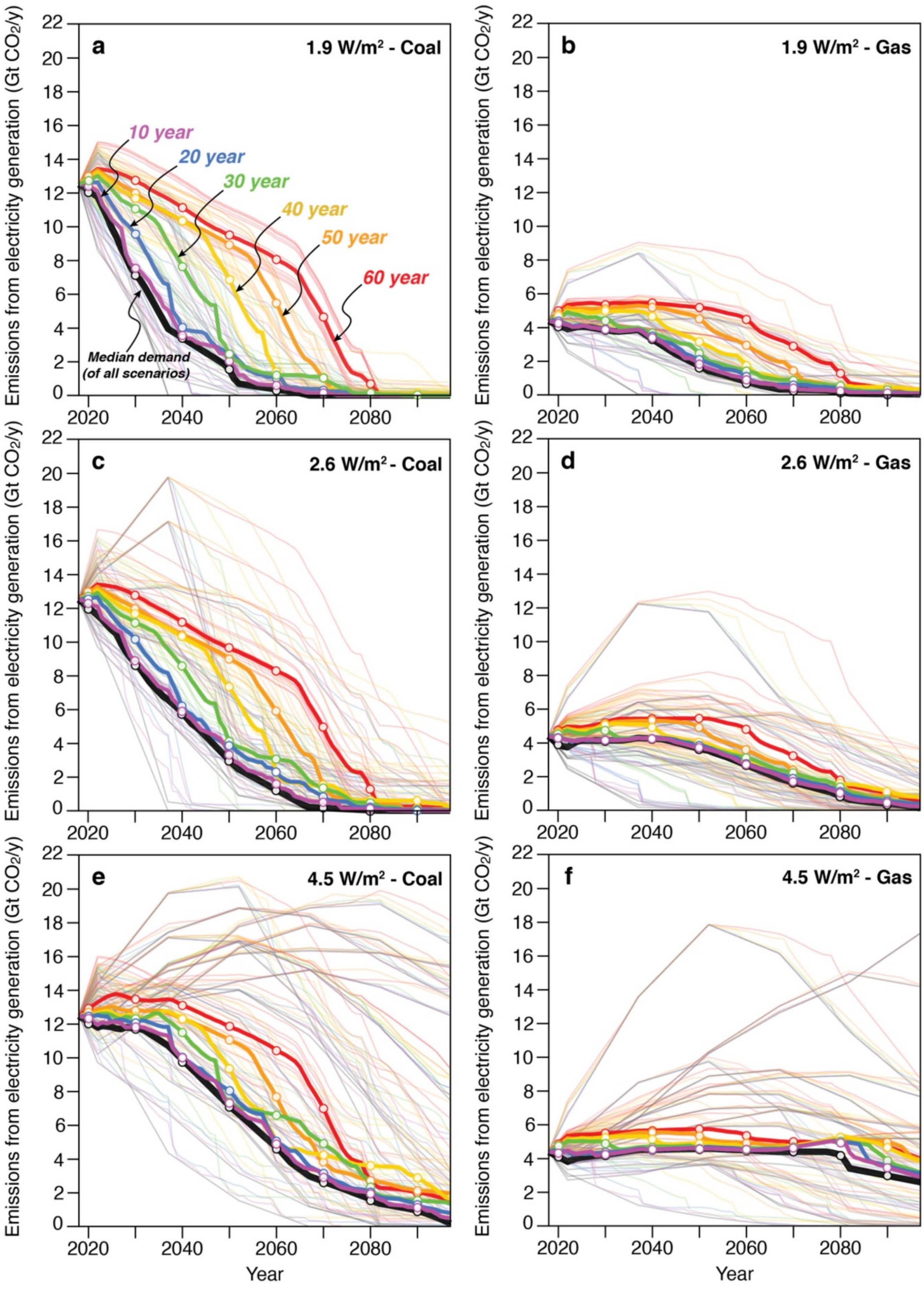

Figure 2. Inertia in power sector emissions. Future emissions from coal- and gas-fired power plants in the 1.9, 2.6, and 4.5 W m^{-2} radiative forcing scenarios (black curves) often decrease more rapidly than emissions from power plants which at region-specific mean capacity factors and power plant lifetimes ranging from 10 years to 60 years (colored curves). The thin lines show each IAM-SSP combination, and the bold lines show the median value of all IAM-SSP projections. Given the age structure of now-existing energy infrastructure, ambitious mitigation pathways such as 1.9 and 2.6 W m^{-2} imply very short power plant lifetimes, particularly for coal-fired units.

at (stacks.iop.org/ERL/15/094064/mmedia). Figure 1 summarizes how our analyses were conducted schematically. In this figure we only show the simplest approach to facilitate the readers understanding of our methodology. Here we assume a uniform operating lifetime (e.g. 40 years in figure 1(a)) and capacity factor (e.g. 70% in figure 1(a)). In addition, we evaluate whether and when fossil fuel- and

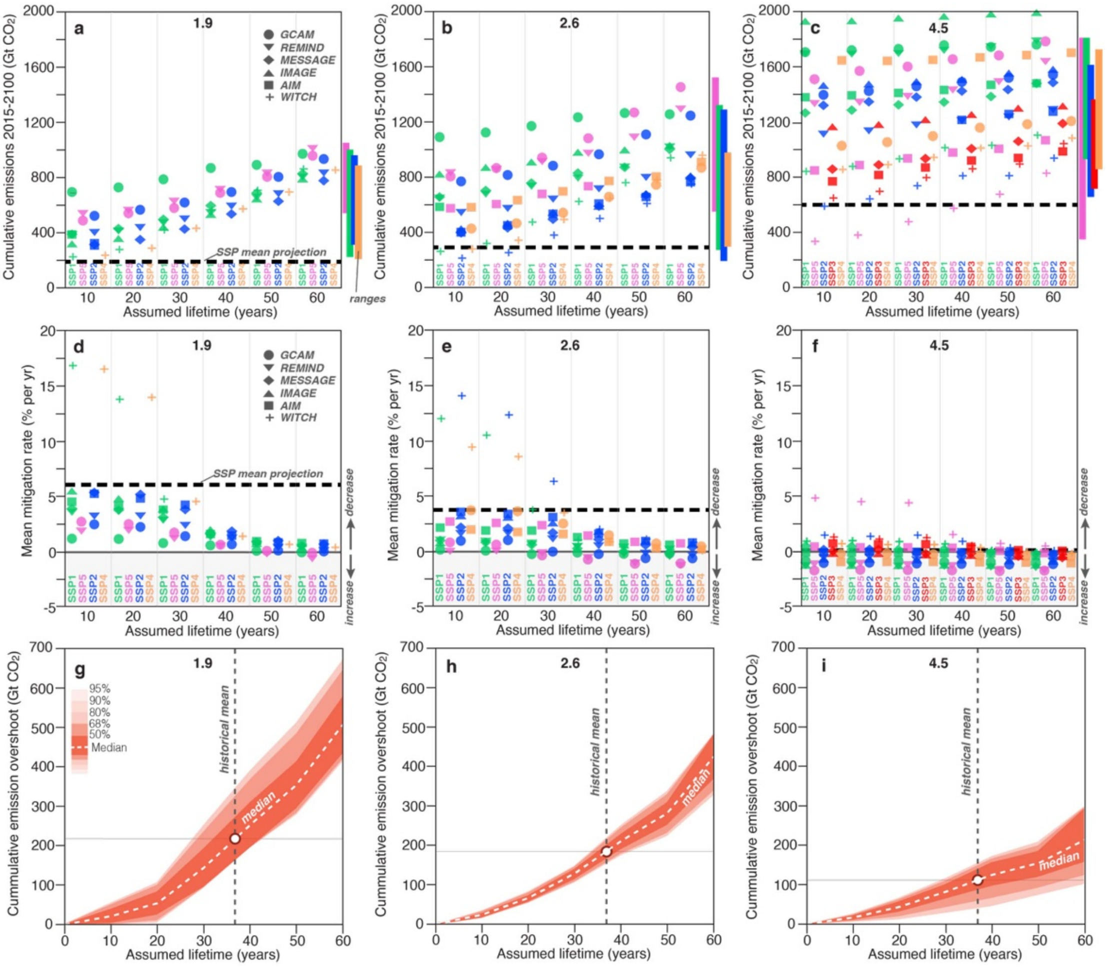

Figure 3. Annual mean emission mitigation rates, cumulative emissions and emission overshoot in energy-emission scenarios. Cumulative CO_2 emissions from coal- and gas-fired power plants in the 1.9, 2.6, and 4.5 W m^{-2} radiative forcing trajectories over the 21st century (a–c). Cumulative emissions increase as power plants lifetimes are prolonged and as climate mitigation goals wane. Annual emission reductions from coal and gas electrical generators decline with an increase in assumed power plant lifetime and with increased inertia from electricity production (d–f). Differences between SSP emissions projections and emissions under different lifetime assumptions (g–i). Dashed vertical line indicates the historical mean lifetime whereas the white dashed line is the cumulative emission mean across all IAM-SSPs for each of the forcing scenarios. Color intensity indicates the 50th—95th percentile cumulative emissions for all of the IAM-SSPs. The light horizontal line represents the median cumulative emission overshoot value, if power plants follow historical mean lifetime trends. The cumulative emission overshoot under different lifetime assumptions decreases as the radiative imbalance increases.

region-specific electricity demand in each IAM scenario (black curves) will require new capacity to be commissioned (colored squares) if existing capacity (gray squares) is not able to meet the projected fossil electricity need. As fossil electricity demand declines within the IAMs in the future, we quantify the extent to which there would be excess generating capacity given the assumed lifetime and capacity factor of operating power plants (black-hatched squares). By further assuming a carbon emissions factor (CO_2 per unit electricity generated) in line with historical estimates, we can in turn quantify the potential emissions associated with such excess capacity. Assumed lifetime, capacity factor, and carbon emission factors are varied in repeated analyses (e.g. figures 1(b) and (c)). We analyze model projections using fixed lifetimes and capacity factors to project all plausible values of future emissions. Additionally, we vary power plant operating conditions in each subsequent annual time step as a sensitivity test for our results. However, this added flexibility to the initial operational conditions of power generating infrastructure had very little impact on our overall results. For context, table 1 compares operating conditions and constraints on infrastructure retirements within each of the six IAMs.

In figure 2, the black curves show the annual CO_2 emissions from coal- and gas-fired electricity generation, as projected by the integrated assessment models, for all SSPs under different levels of future warming used in this study (i.e. radiative forcing of 1.9, 2.6, and 4.5 W m^{-2}). In comparison, colored curves show our calculated emissions if power plant lifetimes are assumed to be 10, 20, 30, 40, 50, or 60 years (purple, blue, green, yellow, orange, and red, respectively). Here we also assume historical mean capacity

Table 1. Integrated Assessment Model Assumptions. Regional averaged values for each of the integrated assessment models used within this study. However, as the IAMs continue to evolve so do the underlying parameters. Thus, values represented in this table may change over time as newer versions of IAMs are released.

	Lifetime (years)	Capacity factor (maximum/minimum)	Depreciation of capital rate (average percent per year)	Carbon intensity (range across technologies, regions, years, and SSPs)
Coal				
AIM/CGE	35	60%	4%	Different across regions
GCAM	60	80%–85% depending on type of plant		643 to 1233 gCO2 per kWh, depending on technology, region, year
IMAGE	40	Depending on relative operational costs ($\sim$85% till 0%)	Capacity gets retired after 40 ± 5 years of operation	Different per region, year, technology
MESSAGE-GLOBIOM	30	67%–85%	5%	724–1302 gCO2 per kWh
REMIND-MAGPIE	40	75%–80%	Non-linear	Different per region, year, technology; regional fleet averages of 738–1140 g kWh^{-1} in 2015
WITCH-GLOBIOM	40	85%	2.8%	699 to 1390 gCO2 kWh^{-1}, depending on technology, region, year
Gas				
AIM/CGE	30	70%	4%	Different across regions
GCAM	60 for existing gas plants, 45 for new plants	80%–85% depending on type of plant		274 to 720 gCO2 per kWh, depending on technology, region, year
IMAGE	40	Depending on relative operational costs ($\sim$90% till 0%)	Capacity gets retired after 40 ± 5 years of operation or via early retirement in case of relatively high operational costs	Different per region, year, technology
MESSAGE-GLOBIOM	30	58%–85%	5%	260–850 gCO2 kWh^{-1}
REMIND-MAGPIE	35	55%–65%	Non-linear	Different per region, year, technology; regional fleet averages of 328–547 g kWh^{-1} in 2015
WITCH-GLOBIOM	25	70%	4.4%	354 to 1000 gCO2 kWh^{-1}, depending on technology, region, year

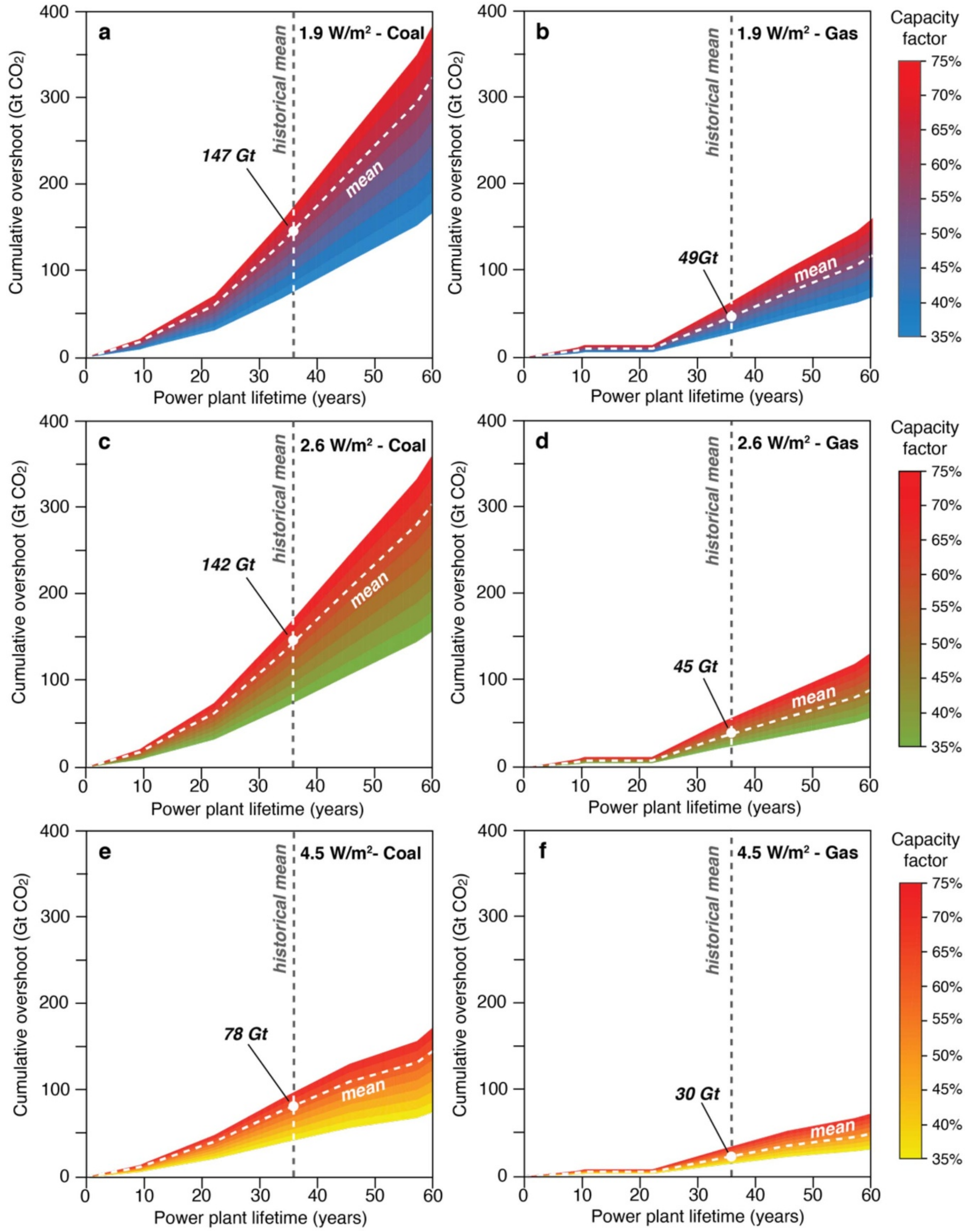

Figure 4. Excess CO_2 emissions from coal and gas-fired power plants. Differences between mean IAM emissions projections and mean estimated CO_2 emissions under different capacity factor and lifetime assumptions. The panel rows represent the three different levels of radiative forcing (1.9, 2.6, and 4.5 W m^{-2}) while the panel columns show the difference between coal- and gas-fired power plants. Color shading indicate a range of capacity factors ranging from 35%–75%. Dashed vertical line represents the historical mean power generator lifetime of 37 years whereas the white dashed line moving along the x-axis represents the historical mean capacity factor.

and carbon emissions factors, see tables S1–6, however we vary power plant operational conditions in subsequent calculations to test impacts on our results. In all cases, bold curves represent the median of all global integrated assessment model scenarios ($n = 171$).

We see the median IAM emissions (black curves) generally decrease more quickly than the emissions we estimate if plants were to operate for more than 30 years (green curves), especially in the case of coal-fired plants and under the more ambitious (lower warming) scenarios (figure 2). For example, figure 2(a) shows that median emissions, assuming coal-fired generator lifetimes greater than 30 years, do not decline as rapidly as the median IAM projections (bold black curve) for the 1.9 W m^{-2} scenario. The

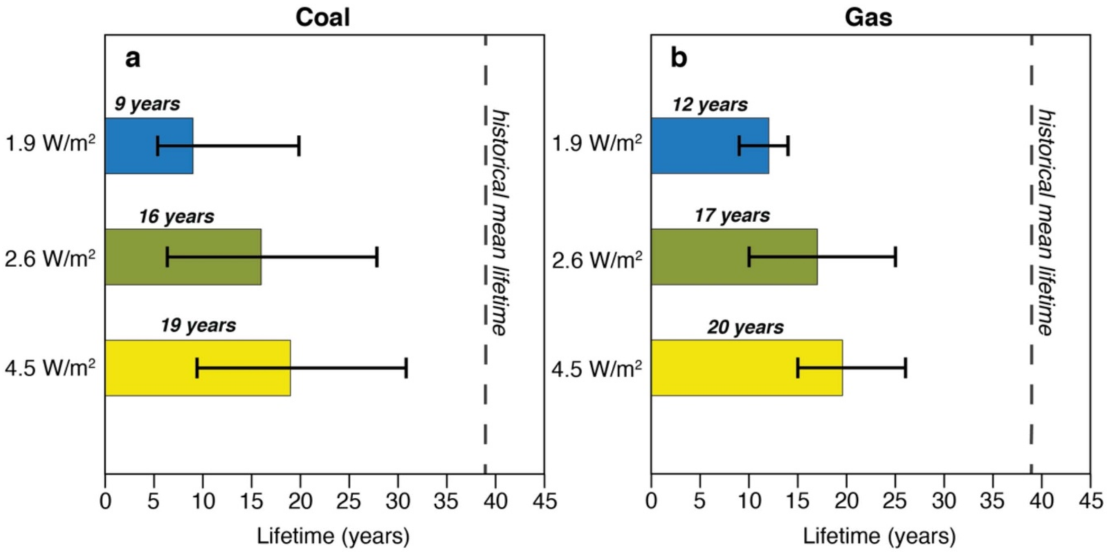

Figure 5. Maximum power plant lifetime under different electricity-emission scenarios. Under ambitious climate change scenarios, fossil powered electricity generating infrastructure retire much earlier than they have historically. Here we present the maximum obtainable lifetime under different electricity demand scenarios for three levels of radiative forcing (radiative forcing 1.9, 2.6, and 4.5 W m^{-2}). Error bars show the full range of power retirements under different capacity factor assumptions.

differences between the black IAM curves and our calculated curves reflects the magnitude of such excess emissions, which consistently increase as longer lifetimes are considered. However, the scenarios from different IAMs and SSPs can result in considerably different cumulative emissions, with greater model spread under higher warming scenarios (from left to right in figures 3(a)–(c)). For instance, in the lower warming (i.e. likely to avoid 1.5 °C and 2 °C) scenarios, cumulative emissions averaged across models and assumed lifetimes are greatest for SSP2 ('middle-of-the-road'; blue), followed by SSP5 ('fossil-fueled development'; pink) and least for SSP1 ('sustainability'; green) and SSP4 ('inequality'; pale orange). See *Methods* or ref [27] for further discussion on how the SSPs differ. Averaging across models, for a given lifetime, cumulative emissions vary by 27%, 30%, and 36% across SSPs in the different warming scenarios, respectively. In comparison, the average variation in cumulative emissions among models for a given SSP and lifetime are 31%, 45%, and 48% in the different warming scenarios, respectively.

The longer the assumed lifetime of power plants, the lower mean mitigation rates (defined here as the annual percent reduction in CO_2 emissions from 2017–2050) will be, figures 3(d)–(f). Since mean mitigation rates are inversely related to future warming, this relationship illustrates the temporal constraints imposed by infrastructural inertia. For example, in the scenarios likely to bring back warming to below 1.5 °C by 2100 (SSPx-1.9 scenarios from ref. [11]), integrated assessment model outputs average 6% per year reductions in emissions from coal- and gas-fired power plants (dotted gray line), but mean mitigation rates when assuming plant lifetimes of 30 or more years decrease to <3% per year (figure 3(d)). Similarly, model outputs average 3.7% per year reductions in scenarios likely to avoid 2 °C (SSPx-2.6, dotted gray line), but mean mitigation rates when assuming plant lifetimes of 30 or more years decrease to <2% per year (figure 3(e)). Thus, allowing fossil-fired power infrastructure to operate for more than 30 years from initial commissioning is incompatible with the rapid mitigation rates achieved in the IAMs.

Since climate change is proportional to society's cumulative emissions, we were interested in quantifying the amount of emissions over the IAMs (hereby 'cumulative overshoot') when power generators are operated for different periods of time. We find the cumulative overshoot increase along with assumed lifetimes but are also substantially greater in the lower warming scenarios (figures 3(g)–(i)). For instance, if we assume power generators will follow historical operating norms, a lifetime of 37 years and mean capacity factor (dashed lines), the cumulative overshoot rises from a median 112 Gt CO_2 in 4.5 W m^{-2} scenarios, to 188 Gt CO_2 in 2.6 W m^{-2} scenarios, to 220 Gt CO_2 in 1.9 W m^{-2} scenarios. Given that total cumulative emissions averages just 182.5 Gt CO_2 in 1.9 W m^{-2} scenarios, an additional 220 Gt CO_2 represents an overshoot of 220.5% and is roughly equivalent to the entire fossil electricity CO_2 budget in the 2.6 W m^{-2} scenario. We find the similarity between the 1.9 and 2.6 W m^{-2} scenarios (figure 4) largely result from the age distribution of the existing power fleet. In both cases, the IAM scenarios result in immediate reductions to global CO_2 emissions but do not consider the power infrastructure lifetimes of operating plants. Using our methods, but following the 2.6 W m^{-2} scenario requires modest deployment of new fossil capacity resulting in a similar overshoot. Nonetheless, these findings indicate the extent to which the low cumulative emissions in ambitious mitigation scenarios are the result of early retirement of coal- and gas-fired power plants. In addition, the similarity of the IAM electricity pathways while achieving different levels of radiative forcing indicate that a substantial reduction of annual CO_2 emissions from other industries is required to reach the 1.9 W m^{-2} pathway. Figure 5 highlights the full range of power plant retirements under a range of capacity factor assumptions. If coal and gas power plant operations are severely curtailed, and climate mitigation targets are relaxed, then these plants may operate at similar lifetimes as they have historically. In contrast, these plants would have to retire decades earlier than they have in the past if we are to meet more ambitious climate warming trajectories.

In turn, supplementary figure 1 shows how key regions contribute to the cumulative overshoot in lower warming scenarios (averaging across the values for 1.9 and 2.6 W m^{-2} shown in figures 3(g) and (h)). In comparison to the other regions shown, overshoots increase most dramatically in China when longer lifetimes of power plants are assumed. This is consistent with previous unit-level inventories of emissions which have shown that half of now-existing coal-fired generating capacity is in China, and mostly <15 years old [28]. Supplementary figure S1(a) reveals the extent to which model scenarios anticipate the retirement of these Chinese plants before they reach 20 years of age. Similarly, early retirements are required to avoid substantial overshoots in other regions, but the magnitude of overshoot when an historical lifetime of 37 years is assumed are roughly 53%, 26% and 87% less in India, the U.S. and Western Europe than in China, respectively.

Supplementary figure 2 acts as sensitivity test to our projected emissions from allowing additional flexibility in initial power plant operational conditions. For example, varying assumptions of plant lifetime and capacity factor by 25% has a similar effect on estimated cumulative emissions, regardless of radiative forcing or SSP (Supplementary figure S2). However, both lifetime and capacity factor become less important in higher warming scenarios, and the assumed carbon intensity of electricity becomes a dominant factor (Supplementary figure S2).

1. Discussion and conclusions

Our results suggest that climate scenarios which are stabilize global temperatures in the range of 1.5 °C to 2 °C or below, retire coal- and gas-fired plants decades before their technical or historical lifetimes have been reached. Although it is generally understood that CO_2 emitting infrastructure will need to be swiftly decommissioned in order to mitigate the most extreme consequences of climate change, the extent to which climate mitigation scenarios rely on the premature retirement of existing plants and the curtailment of future construction is not widely known. Since IAMs conduct power plant retirements endogenously, the rates and processes that dictate these retirements seem obscure to many who wish to interpret IAM results [29]. In addition, the IAM projections typically begin in 2005 and without incorporating information about the current installed fossil capacity or age distribution of fossil fuel-fired plants. Thus, climate mitigation scenarios may underestimate the inertia of emitting infrastructure. As a result of the IAM structure, the operating power capacity and projected mitigation rates in their scenarios can quickly diverge from the realities of the existing fossil fleet and can vary greatly between IAMs and SSPs.

The mitigation rates observed within IAMs are unprecedented and thus represent a potential challenge to society, particularly with the continued deployment of coal-fired power plants around the globe [30]. If coal-fired power generators are not retired early (or their capacity factors drastically reduced), then mitigation rates will fall behind IAM scenarios (figures 3(d) and (e)) and cumulative emissions will rise sharply (figures 3(a), (b), (g), and (h)), thus undermining the ability to achieve lower-warming targets without additional compensatory decreases in emissions from other sources [26, 27]. Although negative emissions are represented within the integrated assessment models, our results highlight that longer power plant lifetimes would require an even larger negative emissions than the prodigious quantities already present in some of the more ambitious mitigation scenarios (which are in some cases many Gt CO_2 per year) [31]. Moreover, the need for shortened infrastructure lifetimes is particularly critical in China, where coal-fired generating capacity is both young and large [16].

Given the established relationship of cumulative carbon budgets and climate warming [32–35], prior studies have estimated and compared 'committed' emissions over the expected lifetime of emitting infrastructure [6, 8, 16, 36]. Many climate mitigation scenarios thus optimize operating and retirement schedules of fossil-fueled infrastructure to lower their cumulative carbon emissions (hence attaining lower carbon budgets and establishing lower warming trajectories) by prioritizing economic conditions where costs of the power sector are equal to revenues from electrical generation rather than reflecting the inertia of the power fleet which is already in existence today. In actuality, decommissioning trillions of dollars' worth of privately-owned capital after only 25% of its anticipated life has elapsed will present enormous political and economic challenges. Indeed, it is these challenges, collectively, that represent the infrastructural inertia (i.e. carbon lock-in) [9, 16, 36].

While the IAMs serve as a powerful tool, allowing users to gain insight regarding a particular sector, the mechanisms behind endogenous calculations are often seen as black boxes by the broader scientific community leading some to question their methods as inscrutable [29]. Thus, by using a standardized method to quantify the implicit lifetimes of power plants within these climate mitigation scenarios, our analysis provides a transparent process while demonstrating the extent to which lower warming scenarios may be contingent upon the early retirement of power sector infrastructure. In many cases, deliberately planned retirement of coal- and gas-fired power plants are necessary in mitigation scenarios which project limited growth in demand for fossil-fuel electricity. If instead, the deployment of fossil fuel power capacity is continued in the upcoming years, stabilizing global mean temperatures at less than 2 °C relative to the preindustrial will require even shorter retirement ages than those achieved within climate mitigation scenarios. Nonetheless, our results suggest that these targets can only be achieved through a strategic manipulation of installed coal- and gas-fired power capacity, generator lifetimes, and capacity factors (e.g. retiring certain plants prematurely or severely curtailing their usage while extending the lifetime of others until renewable electricity generating technology is deployed locally at scale). Thus, if current power sector trends continue, this may necessitate economically costly options—e.g. stranding fossil electrical assets, retrofitting existing plants with CCS, or offsetting increased emissions through mass deployment of carbon dioxide removal technologies [5, 37], which ultimately may come at a higher expense than early retirement. While the value of such generating capital and the total cost to society are represented and depreciated within these scenarios, the distribution of these costs is not. Therefore, lost revenues and profitability for plant owners and local governments, or job losses for workers might prove prohibitively high.

It should be noted that some of our projections of future emissions reported here do not allow lifetimes and capacity factors to vary over time, across regions, or between different generating assets which is in contrast to the flexibility allowed in power plant operational conditions both in the integrated assessment models and the real world. Thus, insofar as capacity factors and lifetimes may in reality decrease over the lifetime, operation, and retirements may be strategically scheduled, and plants might be mothballed and re-operated. Thus, the overshoot we project should be interpreted to reflect the capacity-weighted average lifetime and may be overestimated. However, we find it crucial to demonstrate the incapability of continued investments in fossil fuel power infrastructure with more ambitious climate mitigation scenarios rather than focus on any one single lifetime trajectory. That is, because it is newly commissioned power plants that create the greatest inertia and scenario overshoot. While in some cases inertia and emissions could be avoided by extending the life of existing and due-to-retire plants, such that new plants will not have to be built (and the older plants can be more readily retired to rapidly decrease emissions), achieving such flexibility in reality would depend upon clear foresight of both regional electricity demand and global climate-energy policies, as well as rational economic behavior on the part of utilities and power plant owners whom historically have not been transparent in their decisions [38, 39]. Nonetheless, decarbonizing the global power sector is currently technically and economically feasible given proven technology but is contingent on the increased investment and construction of low-carbon technology and infrastructure as well as passing legislation regulating carbon emitting technologies [40]. While costly, the co-benefits to society often outweigh the overall financial burdens that result from a swift retirement of polluting plants [41]. Thus, policy makers should immediately begin to phase out fossil-fired power plants by supporting low-carbon energy infrastructure while simultaneously implementing legislation that's unfavorable for continued fossil fuel use. However, in reality, governments have been observed taking the opposite approach, choosing instead to prop up economically unstable power plants through subsidies and/or by passing industry favorable regulations in order to minimize the socioeconomic consequences of plant closures and ultimately prolonging the infrastructural inertia of these plants [39].

Thus, in conclusion, power sector capital that is amassed over decades will also take decades to retire unless its value is sacrificed, and lower-warming scenarios often demand such sacrifice. Which policy mechanisms force early retirements may ultimately determine who will bear the economic losses. In jurisdictions with strict climate policies, proactively limiting the time period that new coal- and gas-fired plants will be allowed to operate might forestall investments that would otherwise either contribute to emissions overshoot or else be forced to retire early at great expense. In the future, operating lifetimes and economic implications of CO_2 emitting-infrastructure should be considered when formulating future energy investments that are consistent with existing climate policies so that investors may determine the compatibility of their planned energy infrastructure investments with different scenarios of climate change and fully understand the risks of their monetary investments [18, 38].

2. Methods

2.1. Existing and historical infrastructure

We use the Global Power Plant Emissions Database (GPED) to analyze historical coal and gas power plants that are currently operating. We quantify the annual electrical generation, installed nameplate capacity, yearly averaged emission intensities, and annual mean capacity factor of all existing and past power plants. For currently operating generators, we identify current installed capacity in each region and the year each was commissioned, and project the expected year of retirement based on an assumed lifetime.

2.2. Power infrastructure commissioned in future

Regional scenarios of future electricity projections were produced for each of the Shared Socioeconomic Pathways (SSPs) by the Asia-pacific Integrated Model/Computable General Equilibrium (AIM/CGE), Global Change Assessment Model (GCAM), Integrated Model to Assess the Global Environment (IMAGE), the Model of Energy Supply Strategy Alternatives and their General Environmental impacts—Global Biosphere Management (MESSAGE-GLOBIOM), Regional Model of Investments and Development—Model of Agricultural Production and its Impact on the Environment (REMIND-MAGPIE), and World Induced Technical Change Hybrid—Global Biosphere Management (WITCH-GLOBIOM) integrated assessment models (IAMs). Each IAM uses different number of regions to represent global society and classifies these regions based on their socioeconomics, geopolitics, and stage in economic development of the nations represented. A full list of IAM regions and associated historical mean capacity factors and carbon intensities is provided within the *supplementary information, tables 2–7*. We quantify existing power generating infrastructure, electricity demand, and generator operating conditions using the same regional classifications as represented in each IAM. We then project the need for new electricity generating capacity by estimating the difference between IAM projections and existing electrical capacity in each world region and SSP-model-radiative forcing trajectories.

Repeated analyses vary the assumed lifetimes of coal- and gas-fired power plants 10–60 years and capacity factors from 35%–75%, applicable to both existing generators and any infrastructure commissioned in the future. In our standardized approach, power generators are phased out once their expected operational lifetime has elapsed. New power generators are only built if the annual power supply dips below annual power demand, which can occur when existing power infrastructure is retired or if there is a sustained increase in power demand projected by the IAMs. Newly constructed generators are assumed to have the same operating conditions as the corresponding model run. Nonetheless, we calculate the 1.9 and 2.6 W m^{-2} radiative forcing scenarios required very little deployment of new coal-fired power plants, instead most of the overshoot observed in our results come from existing power infrastructure with the exemptions of a few regions globally.

2.3. Emissions

We convert our estimates of electricity generation to carbon dioxide emissions using IAM electricity projections, our energy calculations under different lifetime assumptions, and IAM regional mean historical carbon intensities ranging from 387–1381.4 gCO_2 kWh^{-1}. Here we analyze 18 810 of individual IAM regional coal and gas electricity scenarios and categorically applied the corresponding carbon intensity. A detailed list of IAM regional mean carbon intensities can be found in the *supplementary information, tables 2–7*. Additionally, we use a linear regression approach and looked at the annual emission reductions 2017 to 2050, to determine the annual emission mitigation rates of each IAM-SSP included in this study. For each radiative forcing pathway, cumulative emissions overshoot was determined by taking the difference between the cumulative emission projection and the cumulative emissions trajectories under the various power plant lifetime assumptions used for this study. In each RF, cumulative emissions are calculated by model, SSP, and lifetime assumption individually then separated by their statistical distribution thus identifying the probability of the emissions trajectory.

2.4. Regional analysis

We analyze regional emissions under each of the IAMs included in this study using the mean IAM regional capacity factors and carbon emissions intensities. In each case, we calculate the cumulative emission overshoot for both coal-fired and natural gas electricity generation individually by RF, IAM, and SSP. We separate the cumulative emission overshoot by their statistical distribution to quantify the likelihood of this emission projection and plot the median cumulative carbon dioxide emissions in each case. Additionally, we identify the magnitude of CO_2 emission overshoot for each region based on historical median power plant lifetimes of 37 years. Regional calculations are based on IAM regional classifications and are aggregated to quantify global energy and emissions. In each case, we analyze global emissions overshoot for each of the radiative forcing trajectories included in this study. Here we calculated the overshoot and again vary the historical capacity factors by 35%–75% and vary the power plant lifetimes from 10–60 years. Using the GPED database, we estimate the historical capacity factors to be ∼65% and ∼55% for coal and gas power plants, respectively.

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Contributions

RF and SJD designed the study; RF led the analysis with additional input and data support from SJD, DT, KC, HSB, JE, OF, SF, GL, and JR; RF led the writing with input and revisions from all coauthors.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request

Conflict of interest

The authors declare no competing interests.

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