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Climate Impacts of Hydropower: Enormous Differences among Facilities and over Time

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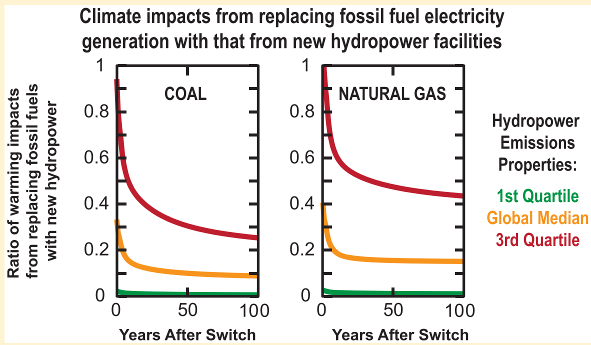
Supporting Information

ABSTRACT: To stabilize the climate, we must rapidly displace fossil fuels with clean energy technologies. Currently hydropower dominates renewable electricity generation, accounting for two-thirds globally, and is expected to grow by at least 45% by 2040. While it is broadly assumed that hydropower facilities emit greenhouse gases on par with wind, there is mounting evidence that emissions can be considerably greater, with some facilities even on par with fossil fuels. However, analyses of climate impacts of hydropower plants have been simplistic, emphasizing the aggregated 100-year impacts from a one-year pulse of emissions. Such analyses mask the near-term impacts of methane emissions central to many current policy regimes, have tended to omit carbon dioxide emissions associated with initial plant development, and have not considered the impact of the accumulation of gases in the atmosphere over time. We utilize an analytic approach that addresses these issues. By analyzing climate impacts of sustained hydropower emissions over time, we find that there are enormous differences in climate impacts among facilities and over time. If minimizing climate impacts are not a priority in the design and construction of new hydropower facilities, it could lead to limited or even no climate benefits.



1. INTRODUCTION

The urgency of climate change has made it clear that we need to drastically and rapidly reduce global emissions of greenhouse gases.[1] Reducing emissions while meeting growing energy demands involves scaling up renewable energy sources, such as hydropower, solar, and wind.

Hydropower is currently the leading renewable energy source, contributing two-thirds of global electricity generation from all renewable sources combined.[2] In fact, over a dozen countries use hydropower to produce more than 75% of their electricity requirements (such as Paraguay, Nepal, Norway, and Ethiopia),[3] and hydropower generation in China more than quadrupled from 2000 to 2017.[2] Electricity generation from hydropower is expected to grow by 45 to 70% by 2040 depending on future policies,[2] with 3700 new hydroelectric facilities either planned or under construction.[4]

The general perception among industry, governments, and the public, that is even written into children's books, is that hydropower is a low-carbon energy source and therefore an excellent alternative to fossil fuels; several assessments of greenhouse gas emissions from various energy technologies have previously classified hydropower on average as on par with wind and cleaner than solar.[5−9] However, a recent emphasis on data collection has revealed that average greenhouse gas emissions from hydropower are in fact much higher than wind and solar,[10−12] and individual plant emissions can even exceed those from fossil fuel plants.[11,13−19]

The anthropogenic carbon footprint of hydropower facilities is generally considered as the difference between the net carbon balance of the landscape before and after development of the plant.[20] Natural landscapes before they are transformed into hydropower sites range from carbon sinks (i.e., terrestrial landscapes) to carbon sources (i.e., peatlands and swamps).[21] Carbon cycling processes can then be altered dramatically as landscapes are flooded to create a reservoir, as endogenous and exogenous organic matter decomposes in the reservoir. Carbon dioxide (CO_2) is produced from oxidation of the organic matter, and when oxygen is limited (as is often the case in bottom waters), methane (CH_4) is produced. Emissions of CO_2 from reservoirs are also partially offset by the drawdown of CO_2 into the reservoir through photosynthesis. Nitrous oxide (N_2O) is also formed, but emissions have been shown to be low as compared with CO_2 and CH_4; however, emissions of N_2O do vary and depend on characteristics of the reservoir.[15,22]

The magnitude of greenhouse gas emissions from a hydroelectric reservoir depends on several factors, including meteorological conditions such as temperature and precipitation;[23,24] characteristics of the submerged vegetation and soil, and net primary productivity;[11,23] and features of the

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facility such as age, area, volume, and depth of the reservoir,[10−12] as well as the extent of reservoir drawdowns that lead to fluctuating water levels.[25]

Measuring net annual life cycle greenhouse gas emissions from individual hydropower facilities is challenging due to complex biogeochemistry, multiple emissions pathways, varying conditions across the reservoir seasonally and over a plant's lifetime, and commonly a lack of knowledge of the greenhouse gas emissions from the original landscape.[26] Estimating the aggregate emissions of hydropower globally is challenging due to the limited number of facilities that have been monitored as well as a lack of a standard methodology and thus inconsistent reporting metrics.[21] For example, some studies only report gross emissions,[15,19,20] while others omit parts of the life cycle such as methane bubbling, which has been found to double the methane flux.[10,11]

Acknowledging these uncertainties, studies to date show that individual hydropower plants have greenhouse gas emissions that vary across several orders of magnitude, some can even be a carbon sink,[12] while others can have emissions greater than those from coal-fired power plants on a per unit power generated basis.[11,13−19] Surface area of the reservoir per unit of electricity generated has been identified as a robust predictor of emissions of both CO_2 and methane; erosion rate, indicative of biomass transported to the reservoir, is a useful predictor of CO_2 emissions; and maximum temperature is a useful indicator of methane emissions (higher temperatures are associated with anoxic conditions as result of less mixing of the water column).[11,12] Latitude was once considered a proxy of emissions, with hydropower facilities in the tropics assumed to emit more greenhouse gases than those in temperate and boreal regions.[10] New measurements have shown that midlatitude reservoirs can emit as much as tropical reservoirs,[23] but the seasonal patterns of emissions are likely different (more temporally consistent emissions in the tropics and large springtime pulses of emissions in temperate and boreal zones).[27]

Another challenge beyond empirical measurements of emissions is translating observed emissions fluxes into climate impacts. Specifically, analyzing climate impacts of technologies that emit multiple climate pollutants with vastly different radiative properties and lifetimes, such as methane and CO_2, is difficult because each pollutant impacts the climate over different time scales. Methane, which is responsible for trapping over 100 times more heat than CO_2 kilogram for kilogram,[28,29] lasts for around a decade in the atmosphere, thereby only impacting the climate in the near-term after it is emitted. CO_2 can last for hundreds of years in the atmosphere, thereby impacting the climate as it builds in the atmosphere over time. (While methane does partially decay to CO_2, the resultant forcing is small.[28])

To analyze the climate impacts of hydropower, studies employ the traditional, and widely used, carbon dioxide equivalence (CO_2e) framework based on the Global Warming Potential (GWP) metric.[10−12,15,18−20,30] However, this metric requires the selection of a time scale in which to compare impacts, and studies almost always use impacts over 100 years of an annual pulse of emissions,[10,11,15,19,30] masking the near-term impacts of methane; further near-term impacts are overlooked due to studies omitting emissions from initial flooding of the reservoir. Studies that do consider a 20-year time horizon in addition to 100 years state that the impacts are much larger than for 100 years but focus their analyses on 100 years.[12,18,20] A further shortcoming of CO_2e is that the metric is based on emissions from one year and how they affect radiative forcing over the following t years, and does not include the accumulation of gases in the atmosphere from previous and future years.

It is important to consider both the near- and long-term climate impacts because each is associated with a specific set of damages.[31] Near-term impacts are important for the rate of warming, which impacts when we exceed tipping thresholds and is also critical for the survival of plants and animals.[32,33] Long-term impacts control shifts in biomes and the extent of ice melt and sea level rise.

In this work we analyze the integrated climate impacts of sustained emissions of hydropower over time, including the impact of creation of the reservoir, and compare them to those associated with the use of fossil fuels and other energy technologies. We use the most comprehensive database of net life cycle emissions available, with estimates for nearly 1500 plants currently in operation in over 100 countries, accounting for nearly half of global hydropower generation.[12] While uncertainties in this database exist, our approach provides key insights into the climate impacts of hydropower plants over time. We conduct a sensitivity analysis as to whether the large differences in hydropower plant climate impacts make a difference under future electricity generation policy scenarios. We conclude our analysis by providing recommendations for how to minimize climate impacts of future hydropower plant development.

2. METHODS

2.1. Hydropower Emissions Data. We use the hydropower greenhouse gas emissions data set developed by Scherer and Pfister (2016), based off of Barros et al. (2011) and Hertwich et al. (2013).[10−12] Scherer and Pfister (2016) estimated net steady-state CO_2 and methane emissions from 1473 hydroelectric facilities spanning 104 countries and covering 43% of global hydropower electricity generation in 2009. While caution must be applied to the use of this data set as it is a modeling study based on direct measurements from 100 plants, its broad global coverage and accounting of missing methane sources and multiple uses of the reservoir (such that greenhouse gas emissions are allocated proportionally for the different uses, and not all emissions are attributed to hydropower if the reservoir has other functions) makes it very useful.

It is important to note that the model deployed by Scherer and Pfister (2016) applies very large discounts to emissions from reservoirs that have multiple uses and preflooding net emissions are assumed negligible, both conservative assumptions. Given that most terrestrial ecosystems are net sinks of carbon, the carbon balance of terrestrial ecosystems that will be or have been flooded will almost always be negative in the absence of flooding (except for rare situations such as wildfires), resulting in net sequestration of carbon. Therefore, we treat the carbon dioxide emissions from hydropower plants as additional emissions to the atmosphere that otherwise would not have occurred. Even though some biogenic carbon in source waters might have been released otherwise, this is still a conservative approach as we do not include the avoided sequestration of carbon dioxide from the development of the reservoir.

Figure S1 shows the distribution in greenhouse gas emissions per facility in the database, per unit electricity

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generation and per year.[12] The global median emissions are 55 $kgCO_2$ MWh^{-1} and 0.43 $kgCH_4$ MWh^{-1}, and the global weighted average emissions are 170 $kgCO_2$ MWh^{-1} and 3 $kgCH_4$ MWh^{-1}.[12] Both CO_2 and methane emissions distributions are skewed toward higher emissions, with maximum emissions of 63000 $kgCO_2$ MWh^{-1} and 5000 $kgCH_4$ MWh^{-1}. Compared to emissions data reported in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), the global median estimate for CO_2 emissions in the database is twice as high, although the "typical" methane emissions from hydropower in the IPCC is comparable to the global weighted average rather than the global median.[9]

We assign regions to each facility using a modified United Nations (UN) geoscheme; North America is split into Canada and the United States due to the large amount of facilities in each (note that in the UN geoscheme Mexico is considered part of Central America, which works for our purposes due to similar climate zones and a limited number of facilities in the database), and Australia, New Zealand, and Papua New Guinea are combined as Oceania.[34] Figure S2 shows the geographical distribution of hydropower plants in the database based on energy generation; more than half of the energy generation is from 242 plants located in Asia (27% of generating capacity) and 73 plants located in South America (26% of generating capacity). Europe has the largest number of plants in the database with 545, accounting for 18% of energy generation, followed by the U.S. with 341 but only accounting for 7% of energy generation.

To analyze emissions from new, rather than steady-state hydropower plants, we adjust the data to account for initial emissions from flooding the reservoir, which accounts for large fluxes of CO_2 into the atmosphere for the first few years—available data suggests four years. We use the measurements in Teodoru et al. (2012) to develop a multiplier function for CO_2[17] and note that the amplified emissions in early years are proportionally consistent with Abril et al. (2005).[13] Emissions data for new plants were determined by multiplying steady state emissions by 5, 3, 2.5, and 2 for years one through four, respectively. CO_2 emissions from construction of the plant are found to be small compared to emissions from flooding and are included in the lifecycle annual emissions.[7]

2.2. Emissions Data from Other Energy Sources. We use global median estimates of greenhouse gas emissions per unit of energy generation for existing infrastructure for coal, natural gas, nuclear, solar rooftop, solar utilities, onshore wind, and offshore wind as reported by IPCC AR5 Working Group III (2014).[9] The data can be found in Table S1. Life cycle greenhouse gas emissions include emissions from all stages, from manufacturing of components to operations to transportation to decommissioning. Emissions estimates in IPCC AR5 Working Group III (2014) are derived from two main efforts: one in which emissions from dozens of studies for each technology have been harmonized to be as consistent and comparable as possible and one in which data were collected under uniform conditions.

Emissions from coal and natural gas include CO_2 emissions directly emitted from the plant and from the infrastructure, supplies, transport, etc. and methane emissions from the fuel production and delivery system. Emissions from nuclear, solar, and wind technologies include CO_2 emissions from upstream, operational, and downstream processes. There is no distinction between second and third generation nuclear power plants, and newer thin-film technologies for solar photovoltaics are included. Emissions intensities used in this analysis aggregate cradle-to-grave emissions, and therefore we do not consider the impact of varying emissions at different stages of life as well as technology replacements at the end of a technology's lifespan.

Emissions associated with building and installing equipment are included in the annual emissions for all technologies including hydropower. We note that the majority of greenhouse gas emissions from wind and solar are associated with construction. Therefore, we expect a pulse of emissions initially with lower emissions throughout the lifetime of the technology and another pulse when the technology is replaced 15 to 25 years later. However, this emissions pattern is not considered in this analysis because we do not look at technology/infrastructure turnover. This leads to an overestimate of solar and wind emissions annually and thus an underestimate in hydropower's climate impact compared to these technologies. We include the high emissions from reservoir flooding for a new hydropower facility because it is an important one-time phenomenon unparalleled by other technologies.

Although individual facilities and units of each technology exhibit their own range in emissions, we restrict our analysis to comparisons against the global medians because (i) hydropower arguably has the scarcest data available and the variability appears more extreme than among other technologies,[12] and (ii) there is an apparent lack of awareness of the variability among hydropower facilities by government stakeholders and the public. We do note, however, that there is a lack of data on global methane emissions from the oil and natural gas supply chain; recent studies have shown these emissions can greatly impact the net climate impact of facilities dependent on these supply chains in the U.S.[35,36]

2.3. Climate Impacts. To assess the climate impacts of greenhouse gas emissions over time, we use the Technology Warming Potential (TWP) metric as described in Alvarez et al. (2012).[37] TWP calculates the annual warming impact (via radiative forcing) of continuous emissions from one technology and compares this impact to that from a different technology. The metric builds on GWP and carbon dioxide equivalence but greatly enhances their utility as it does not rely on integrating climate impacts over a fixed time frame, which is very important as the influence of different technologies on the climate tends to shift over time, and it allows for characterizing the impact of continuous, rather than pulse, emissions as they occur in the real world. It is important to note that the TWP metric does not account for benefits/disbenefits other than radiative forcing, e.g., air quality, ocean acidification, land conversion. We use radiative and lifetime properties of methane and CO_2 from Myhre et al. (2013) and Etminan et al. (2016);[28,29] the values and calculations are outlined in the Supporting Information (Table S2).

2.4. Future Hydropower Use. To gain insight into the climate implications from anticipated hydropower growth, we consider three future policy scenarios developed in IEA (2017), along with information on under construction or planned hydropower dams collected by Zarfl et al. (2014).[4,38]

The three policy scenarios estimate electricity generation from various sources, including hydropower, from 2015 to 2040: current policies, new policies that are planned but not yet enacted as of 2016, and sustainable development policies that are consistent with the goals in the Paris Agreement (Table S3). In the current policies scenario, global electricity

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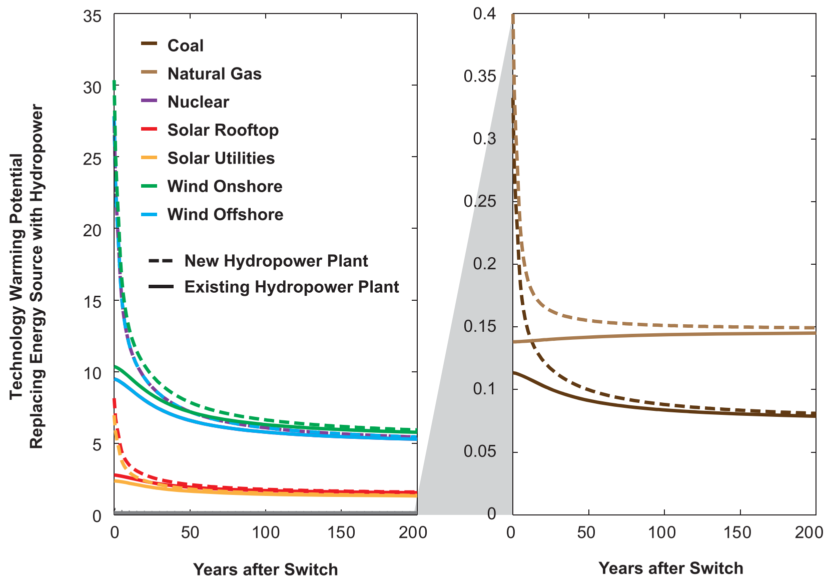

Figure 1. Ratio of climate impacts (using radiative forcing as a proxy) over time from replacing global median emissions from each energy technology (coal, natural gas, nuclear, solar, or wind) with global median hydropower emissions for existing (solid line) and new facilities (dashed line). Emissions from all technologies are per unit energy generation and are continuous throughout the 200 year period, assuming these facilities will last that long. A value greater than one means that hydropower has climate impacts greater than the respective energy technology, and a value less than one means that hydropower has climate impacts less than the respective energy technology.

generation from hydropower grows by 53% from 2015 to 2040, accounting for 14% of total electricity generation and 45% of renewable electricity generation (note that the totals here include all energy technologies in IEA (2017) and not just the six we analyze). In the new policies scenario (policies in development but not enacted yet), hydropower generation grows by 59% from 2015 to 2040, accounting for 16% of total electricity generation and 40% of renewable electricity generation. In the sustainable development scenario (pathway consistent with Paris Agreement goals), hydropower generation grows by 78% from 2015 to 2040, accounting for 19% of total electricity generation and 31% of renewable electricity generation. These scenarios were used to simulate the cumulative radiative forcing from total electricity generation from 2015 to 2040 for cases with different levels of greenhouse gas emissions for new hydropower facilities (Figure S6).

The projections for hydropower growth in each region for the new policies scenario provided by IEA (2017) were combined with data collected by Zarfl et al. (2014) to identify regions with the largest projected growth in hydropower electricity generation and capacity. Both sources highlight Africa, Brazil, China, India, and Southeastern Asia as hotspots of anticipated hydropower growth;[2,4] these regions are responsible for nearly 70% of the anticipated hydropower growth based on capacity.[4] To further look at the importance of future hydropower plant greenhouse gas emissions properties, we consider the climate impacts (per energy generation) of new hydropower facilities in each of these regions where new plants are likely to be built. We calculate median and first and third quartile emissions properties of existing hydropower facilities within each region based on the Scherer and Pfister (2016) database,[12] supplement with additional emissions from reservoir creation, and compare the climate impacts of new facilities with regional emissions profiles to that from median emissions from fossil fuel plants. The assumption that future plants are similar to existing plants is a limitation of this analysis, and changes to technologies and current practices could modulate or enhance emissions.

3. RESULTS

3.1. Climate Impacts of Average Hydropower. For most of our analysis, though not all, we use global median emissions of greenhouse gases from hydropower rather than a weighted average (where emissions of CO_2 are three times higher and emissions of methane are seven times higher in the weighted average). This is both to be statistically conservative as well as consistent with emissions estimates we use of other technology sources, which are provided as global medians. Further, due to the high skewness of the greenhouse gas emissions distributions among facilities in the database, a median can be more appropriate than a mean in representing "average" hydropower emissions. However, we note that hydropower studies often emphasize the weighted average and not the median emissions[11,12] and throughout our analysis we compare our median-derived results to that from a weighted average.

Figure 1 compares the climate impacts (using radiative forcing as a proxy) of continuous global median emissions of new and existing hydropower to that from other electricity sources. The comparison is a ratio between the annual radiative forcing from hydropower emissions per electrical generation to that from the other electricity sources and can be considered the relative climate impacts of replacing another electricity technology with hydropower. A value greater than one means that hydropower has climate impacts greater than the other electricity source, and a value less than one means that hydropower has climate impacts less than the alternative electricity source (i.e., switching from the alternative electricity source to hydropower produces a climate benefit).

Overall, global median hydropower emissions are greater and thus worse for the climate than nuclear, solar, and wind but better for the climate than coal and natural gas. However, the relative climate impact of hydropower is far greater in the

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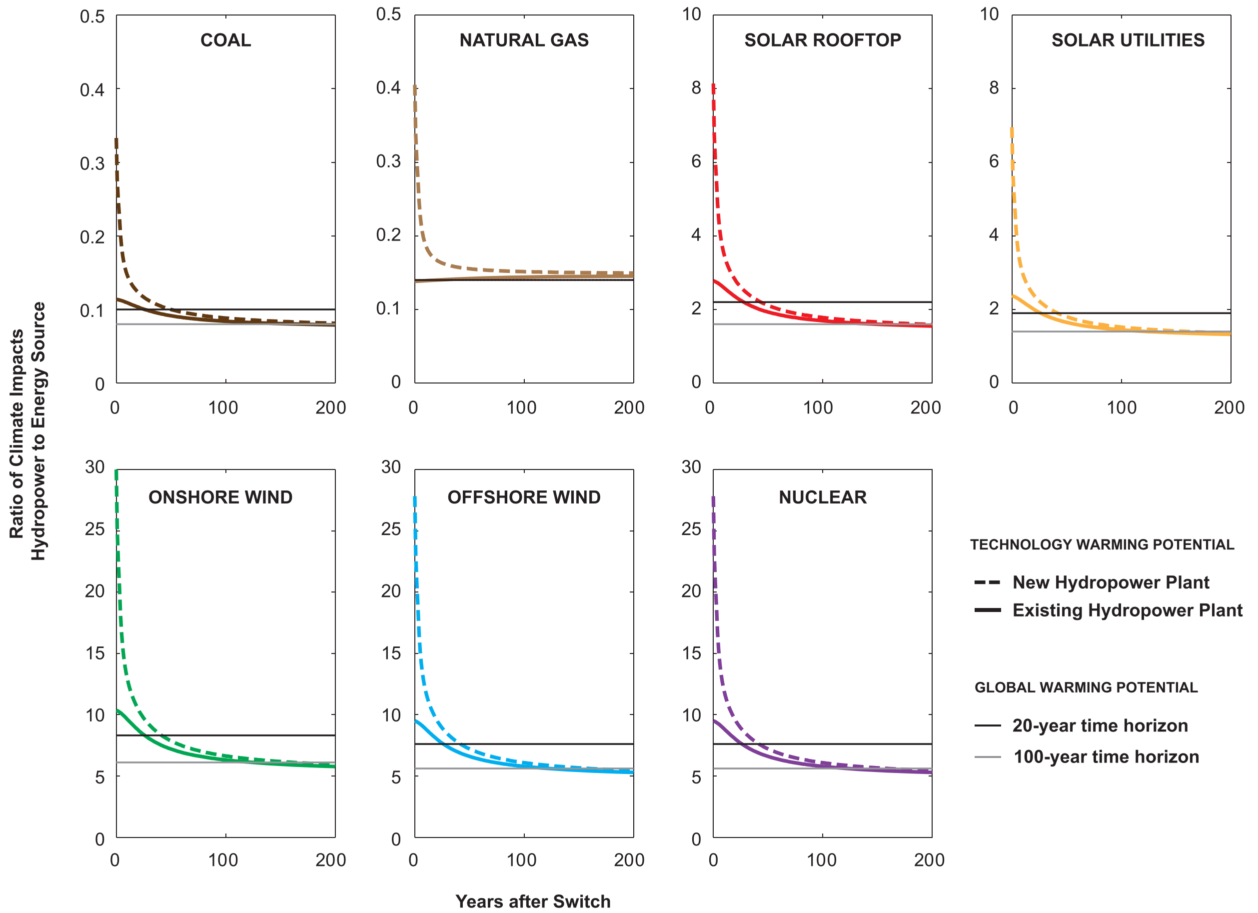

Figure 2. Ratio of climate impacts comparing global median hydropower emissions per unit energy generation to global median emissions from each energy technology (coal, natural gas, nuclear, solar, or wind) per unit energy generation. Thick colored lines show ratios of climate impacts (using radiative forcing as a proxy) over time for continuous emissions that are allowed to accumulate in the atmosphere until they decay; this is the Technology Warming Potential metric. Thin lines show ratios of climate impacts (using radiative forcing as a proxy) of a pulse of emissions integrated over a specified time horizon (black line: 20 years; gray line: 100 years); this calculation uses the Global Warming Potential metric derived from IPCC AR5 (2013)[28] and Etminan et al. (2016)[29] with values of methane GWP20 = 96 and GWP100 = 33. For both metrics, a value greater than one means that hydropower has climate impacts greater than the respective energy technology, and a value less than one means that hydropower has climate impacts less than the respective energy technology.

near-term than the long-term, especially for a new hydropower plant. The use of new hydropower plants (with median emissions properties, would be even greater using weighted average characteristics) instead of solar or wind yields climate impacts that are initially 8 or 30 times greater, respectively. While, in the long term, hydropower median emissions yield climate impacts that are about 10% and 15% that of coal and natural gas, respectively, the initial percentages are 35% and 40% when a new hydropower plant is constructed. Construction emissions can more than double the climate impact from a hydropower plant for the first few years (Figure S4).

However, even for existing hydropower plants, impacts are greater in the near-term. For example, hydropower climate impacts are initially an order of magnitude greater than onshore and offshore wind and nuclear but drop to five times worse after 200 years. The reason for this temporal shift is that methane emitted from the reservoir does not accumulate in the atmosphere the way that CO_2 does; of all considered alternative technologies, only coal and natural gas have associated methane emissions. Methane's impact can account for half of hydropower's climate impact in the near-term but only 15% in the long term (Figure S5). Because the natural gas supply chain also emits a considerable amount of methane (the coal supply chain also emits methane but a proportionally smaller role in net radiative forcing), we find that switching from natural gas to existing hydropower yields a nearly constant impact across the time horizon, in contrast to the larger near-term impact of hydropower compared to all other electricity technologies.

To show the benefit of this analysis method (i.e., Technology Warming Potential) and provide context for how our results compare to previous analyses, we compare the ratio of the climate impacts over time to the values derived using Global Warming Potential (Figure 2). It takes around 100 years of sustained hydropower emissions to arrive at a ratio calculated using GWP with a 100-year time horizon (such as hydropower climate impacts are 5 times higher than that from offshore wind). Before these 100 years, climate impacts from hydropower are much greater than the GWP metric suggests, especially in the near-term (hydropower climate impacts can be 10 to 25 times higher than offshore wind in the first several years). Given that most policies aimed at reducing global warming have much shorter time horizons than 100 years, the use of GWP with a 100-year time horizon to meet those policy objectives can provide spurious understandings.

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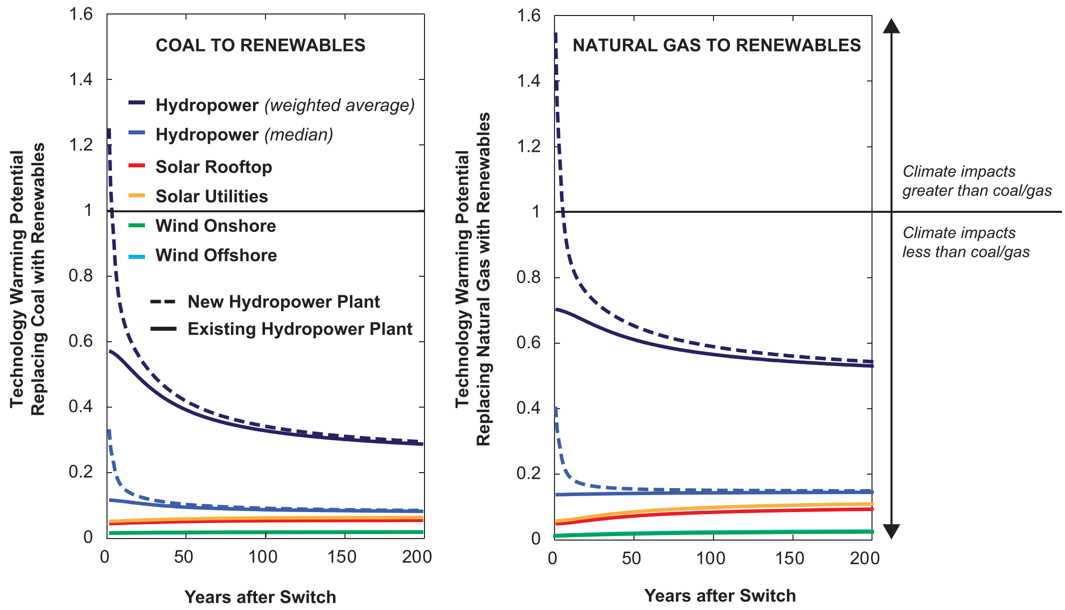

Figure 3. Ratio of climate impacts (using radiative forcing as a proxy) over time from replacing global median emissions from fossil fuels (left: coal; right: natural gas) with global median emissions from renewable energy sources (hydropower, solar, wind). Global weighted average hydropower properties also included, as are hydropower emissions for existing (solid line) and new (dashed line) facilities. Emissions from all technologies are per unit energy generation and are continuous throughout the 200 year period.

While using a time horizon of 20 years better captures near-term impacts, it overestimates the impacts in the long term. This is why a metric that resolves climate impacts over time is so valuable.

Given that most strategies to address climate change involve switching from fossil fuels to renewables, we compare the relative climate impacts of switching from coal and natural gas to hydropower, solar, and wind, respectively (Figure 3). We account for both new and existing plants and consider the global weighted average for hydropower emissions in addition to the global median to show the climate impacts of a range of average hydropower emissions. The global weighted average is most often reported in studies.[12] We find that for the global weighted average, while long-term climate impacts are less than coal and natural gas (30% and 60% respectively), compounding effects from plant development (i.e., reservoir flooding) and methane yield climate impacts that are initially greater than that from fossil fuel based electricity generation.

Whereas the ratio of the climate impacts of hydropower go down over time relative to fossil fuels, owing to the strong near-term impacts of methane emissions before CO_2 has sufficiently built up in the atmosphere to dominate climate impacts, the ratios of solar and wind grow over time. This is because both coal-fired power plants and natural gas plants emit methane, whereas solar and wind do not, and therefore solar and wind's most minimal impact on climate compared to coal and natural gas will be in the near-term when methane plays an outsized role in the climate impact of coal and natural gas. Over time, methane's role is diminished as CO_2 accumulates.

Overall, we find that near-term climate impacts of hydropower are much larger than in the long term, especially for new plant development. It is important that these near-term impacts are considered when replacing fossil fuels with hydropower, as near-term warming yields various consequences, such as exceeding tipping point thresholds and preventing species from adapting to changes.[32,33]

3.2. Climate Impacts of Existing Sites. While analyzing the global median and weighted average hydropower emissions are useful for broad comparisons between hydropower and other energy sources over time, it is important to analyze individual plant emissions as there exists a tremendous range in climate impacts (Figure S1). For example, 23% of hydroelectric facilities in the database are estimated as net CO_2 sinks, whereas 3% and 7% of the facilities have CO_2 emissions per unit of electricity generated that are above median coal and natural gas electrical plants, respectively.

Evaluating the climate impacts over time from switching from coal or natural gas to each of these existing hydropower facilities clearly shows that some sites are far better for the climate than fossil fuel based generation, while some sites are far worse (Figure 4). In the near term, within 20 years, 15% and 17% of all hydropower plants in the database have greater climate impacts than median coal and natural gas emissions, respectively, accounting for 6% and 12% of electrical generation in the database, respectively (Table 1). Over the entire 200-year period that we analyze, 7% and 12% of hydropower facilities have climate impacts greater than the average coal and natural gas generating station. These long-term percentages are similar to the results derived when using GWP100/CO_2e100 (9% and 13%, respectively) and underscore the issues with using simplified metrics, such as underestimating the amount of plants with climate impacts greater than fossil fuels at some point in time. On the other hand, 44% and 40% of hydropower facilities have impacts less than 10% of coal and natural gas initially, accounting for 24% and 20% of electrical generation in the database, respectively.

It is important to note that every geographic region has hydropower facilities that have climate impacts greater than coal and natural gas generated electricity (Table S4). Western Africa has the largest percentage of plants that fall into this category (71% of their facilities that account for 86% of their hydropower generation); however, the overall energy generation from Western Africa accounts for less than one percent

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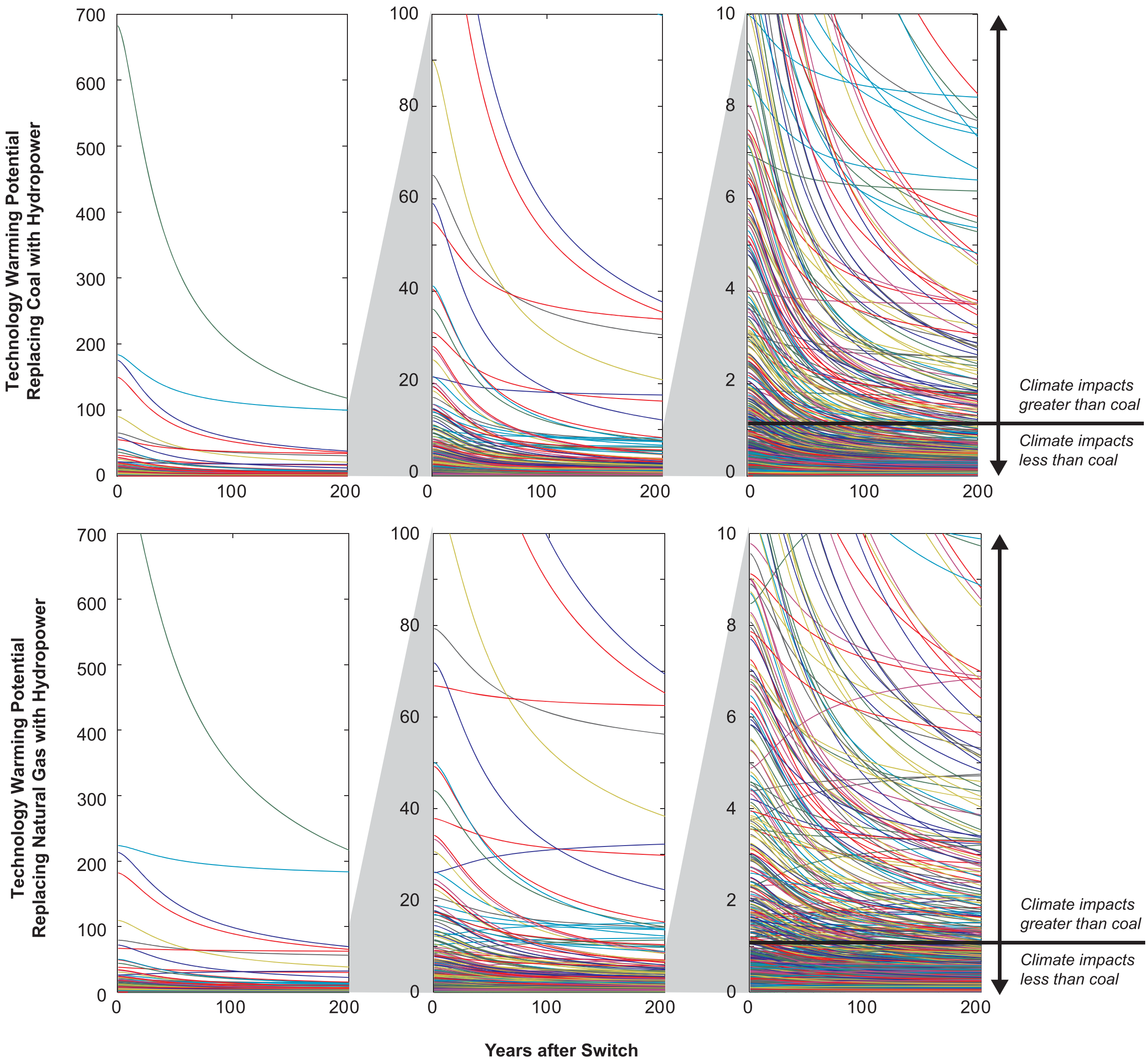

Figure 4. Ratio of climate impacts (using radiative forcing as a proxy) over time from replacing fossil fuels (global median emissions from coal (top) and natural gas (bottom)) with each existing hydropower plant in the database (1473 facilities). Emissions from all technologies are per unit energy generation and are continuous throughout the 200 year period; 15% of plants have climate impacts initially greater than coal (TWP > 1) and 17% of plants have climate impacts initially greater than natural gas (TWP > 1). Using CO_2e with a 100-year time horizon, 9% and 14% of plants have climate impacts greater than coal and natural gas, respectively.

Table 1. Number of Hydropower Facilities with Climate Impacts Greater than Fossil Fuels

	Climate impacts greater than coal			Climate impacts greater than natural gas		
Length of time after switch[a]	Number of plants in database	Share of total plants in database	Share of hydro energy generation in database[b]	Number of plants in database	Share of total plants in database	Share of hydro energy generation in database[b]
0+ years	216	15%	6%	248	17%	12%
10+ years	210	14%	6%	245	17%	12%
25+ years	189	13%	6%	232	16%	11%
50+ years	158	11%	5%	218	15%	10%
100+ years	126	9%	3%	198	13%	10%
200+ years	105	7%	3%	179	12%	10%

[a]This column refers to the time period in which the hydropower facility has climate impacts greater than coal and/or natural gas, such that "0+" means that a facility has climate impacts worse than coal/natural gas at least initially and "200+" means that a facility has climate impacts worse than coal/natural gas for at least 200 years. [b]This column represents the percent of global energy generation from hydropower in the database that these individual plants account for. For example, the 216 hydropower facilities with climate impacts greater than coal initially account for 6% of the energy generation in the database.

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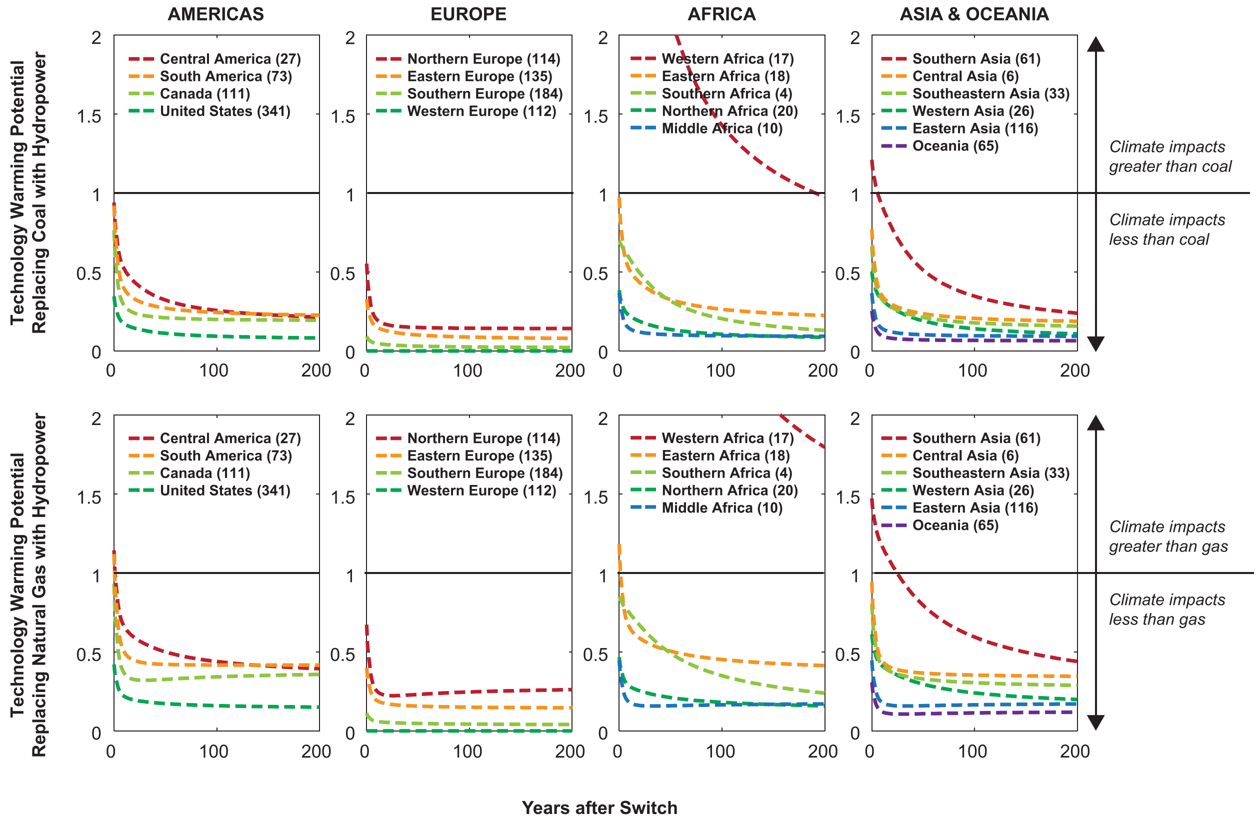

Figure 5. Ratio of climate impacts (using radiative forcing as a proxy) over time from replacing fossil fuels (global median emissions from coal (top) and natural gas (bottom)) with a new hydropower plant based on regional hydropower median emissions. Number of plants in the database for each region are noted in the parentheses in the legend. Emissions from all technologies are per unit energy generation and are continuous throughout the 200 year period.

of global generation in the database (based on 2009 generation levels); 19% of South America's facilities (20% of capacity) have greater climate impacts than natural gas generated electricity initially, these facilities account for 5% of generation capacity in the global database. Eastern Asia and Western Europe have the lowest percentage of plants with greater climate impacts than fossil fuel generated electricity.

Figure S3 shows the median hydropower emissions in the database binned by region. The 17 facilities in Western Africa have near-term climate impacts per unit energy generation that are triple that of global coal-fired power plants; this is mostly due to high methane emissions. Near-term impacts of median emissions in Southern Asia (61 facilities) are on par with that of natural gas. Median emissions of the 112 facilities in Western Europe are near zero.

Identifying why certain regions have more facilities with large climate impacts compared to others is not straightforward due to the complexity of factors that control greenhouse gas emissions from reservoirs and within region variability. However, regions with more plants with high climate impact (Western Africa, Southern Africa, and Southern Asia) have higher ratios of reservoir surface area to electricity generated, and regions with fewer high-emitting hydropower plants have ratios that are low (Eastern Asia and Western Europe). The correlation between percentage of high emitting facilities and ratio of surface area to electricity generation is $r = 0.82$. Other characteristics with correlations include the surface area of the reservoir ($r = 0.7$), the erosion rate in the reservoir ($r = 0.57$), and the maximum temperature ($r = 0.59$) — indicative of the climate zone. The volume of the reservoir and the age of the facility explained relatively less of the variation.

3.3. Climate Impacts of Future Hydropower Development. The database of existing facilities can be used to provide insight into regions that are targets for low-carbon hydropower development and where such development can be expected to lead to higher impacts; however, we caution that emissions properties can range tremendously even within a region. Figure 5 shows the climate impacts over time from replacing fossil fuels with new hydropower facilities based on median emissions in 19 regions.

New hydropower facilities in Western Europe have near-zero climate impacts, whereas new facilities in Western Africa yield climate impacts greater than coal and natural gas over all time scales. New facilities in Southern Asia yield climate impacts that are greater than coal and natural gas in the near-term, with many regions (Central and South America; Eastern and Southern Africa; and Central, Southeastern, and Western Asia) at risk of climate impacts on par with fossil fuels in the near-term following the development of new facilities. On the basis of this assessment, Europe can be targeted for low-carbon hydropower development, whereas caution should be used for developing hydropower in several parts of Africa and Asia if reducing climate impacts is of concern.

Of course, targets for hydropower development largely depend on technical feasibility. Regions that have been identified as hydropower "hotspots" for new hydropower facilities include Brazil, China, India, Pakistan, the Democratic Republic of the Congo, and Mynamar.[4] Over a thousand new plants, a quarter of all major hydropower dams worldwide

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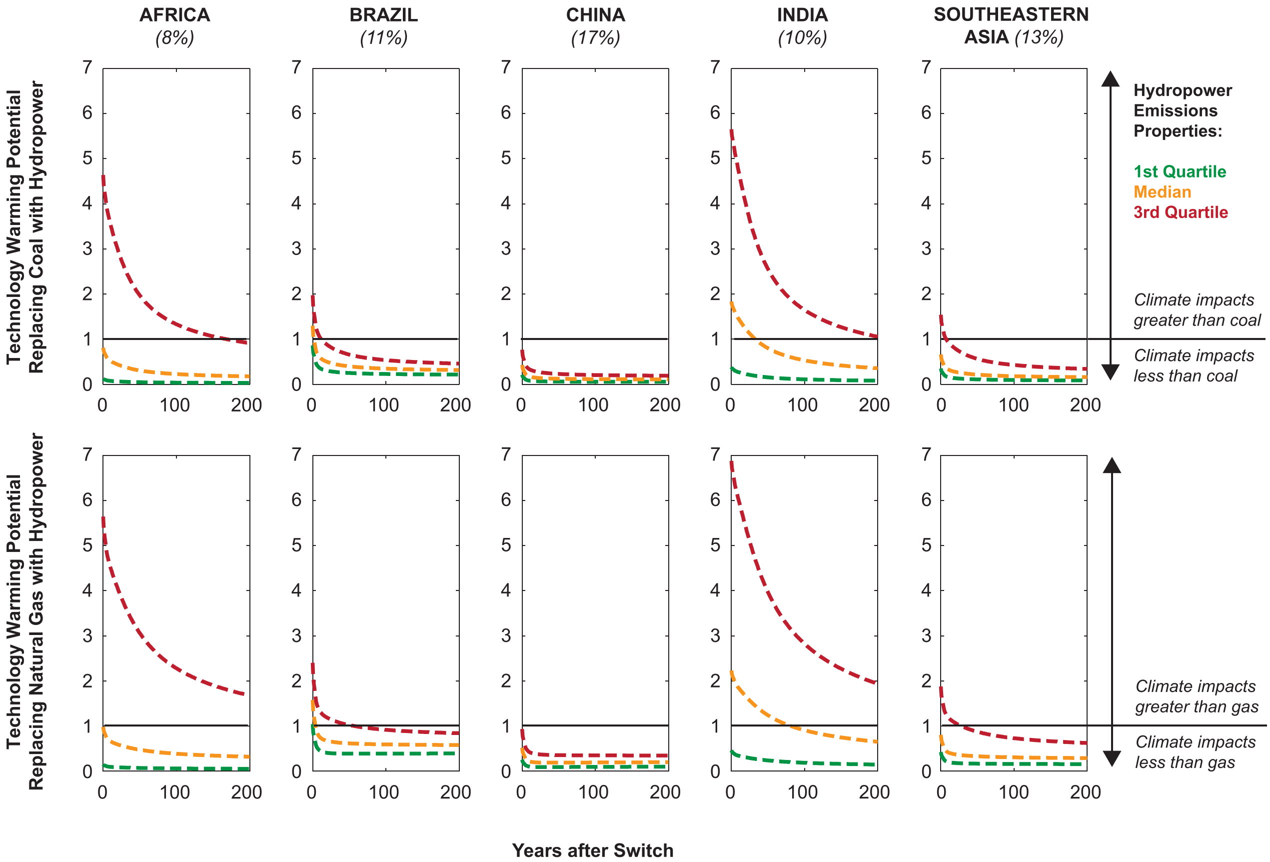

Figure 6. Ratio of climate impacts (using radiative forcing as a proxy) over time from replacing fossil fuels (global median emissions from coal (top) and natural gas (bottom)) with a new hydropower plant based on median and first and third quartile emissions in hotspot regions that are expected to incur the most growth in hydropower by 2040 (based on WEO (2017) Sustainable Development scenarios). Emissions from all technologies are per unit energy generation and are continuous throughout the 200 year period. Italicized number in parentheses is the hotspot's share of global growth in electricity generation from hydropower.

under construction or planned, are located in Brazil and are anticipated to have a capacity of nearly 90000 MW.[4] In China, about 200 anticipated hydropower facilities are expected to account for over 160000 MW in additional capacity, nearly a quarter of the global capacity from anticipated new hydropower.[4] In Africa, 5 new plants in the Democratic Republic of the Congo are expected to have 45000 MW in capacity.[4] In Southeast Asia, electricity generation from hydropower is projected to increase by 350% from 2015 to 2040, and in India, it is expected to increase by 230%.[38] How much of this capacity will actually be brought on line is hard to estimate.

Figure 6 shows the climate impacts of replacing fossil fuels with new hydropower facilities for the hotspot regions, for regional median emissions, and also for emissions at first and third quartiles. Given that we only have a few plants in the database each for the Democratic Republic of the Congo, Pakistan, and Myanmar, we utilize the entirety of data available for Africa and Southeastern Asia regions in considering the impacts.

In Africa and India, new facilities that exhibit third quartile greenhouse gas emissions properties are worse for the climate than coal and natural gas over all time scales. We note that weighted average emissions for Africa are slightly less than the third quartile emissions. In India, even facilities with median hydropower emissions properties have climate impacts greater than fossil fuels in the near-term, and weighted average emissions for India are similar to median emissions. Of around 50 hydropower facilities in India in the emissions database, half have climate impacts initially worse than coal. Given that electricity generation from hydropower in India is expected to more than triple from 2015 to 2040 it is important to consider the climate implications. New hydropower plants in China have the lowest climate impacts of these five regions with considerable anticipated hydropower growth. We note that weighted average emissions for China are in between the median and third quartile for CO_2 emissions, and similar to median emissions for emissions.

What remains unclear is whether or not the climate impacts of hydropower actually matter for climate change going forward. In order to determine whether or not hydropower emissions impact climate in the aggregate, we analyzed climate impacts from three future policy scenarios for electricity generation from 2015 to 2040 (described in the Methods section and displayed in Table S3).[38] We restricted our analysis to the electricity generating technologies that account for over 90% of total global electricity generation currently (coal, natural gas, nuclear, hydropower, wind, and solar).

Figure S6 shows the aggregate radiative forcing from electricity generation from 2015 to 2040 for the six major electricity generation technologies (coal, natural gas, nuclear, hydropower, wind, and solar). On the basis of global median emissions properties, hydropower's share of 2040 radiative forcing from electricity generation is 3%, 4%, and 6% for the current policies, new policies, and sustainable development

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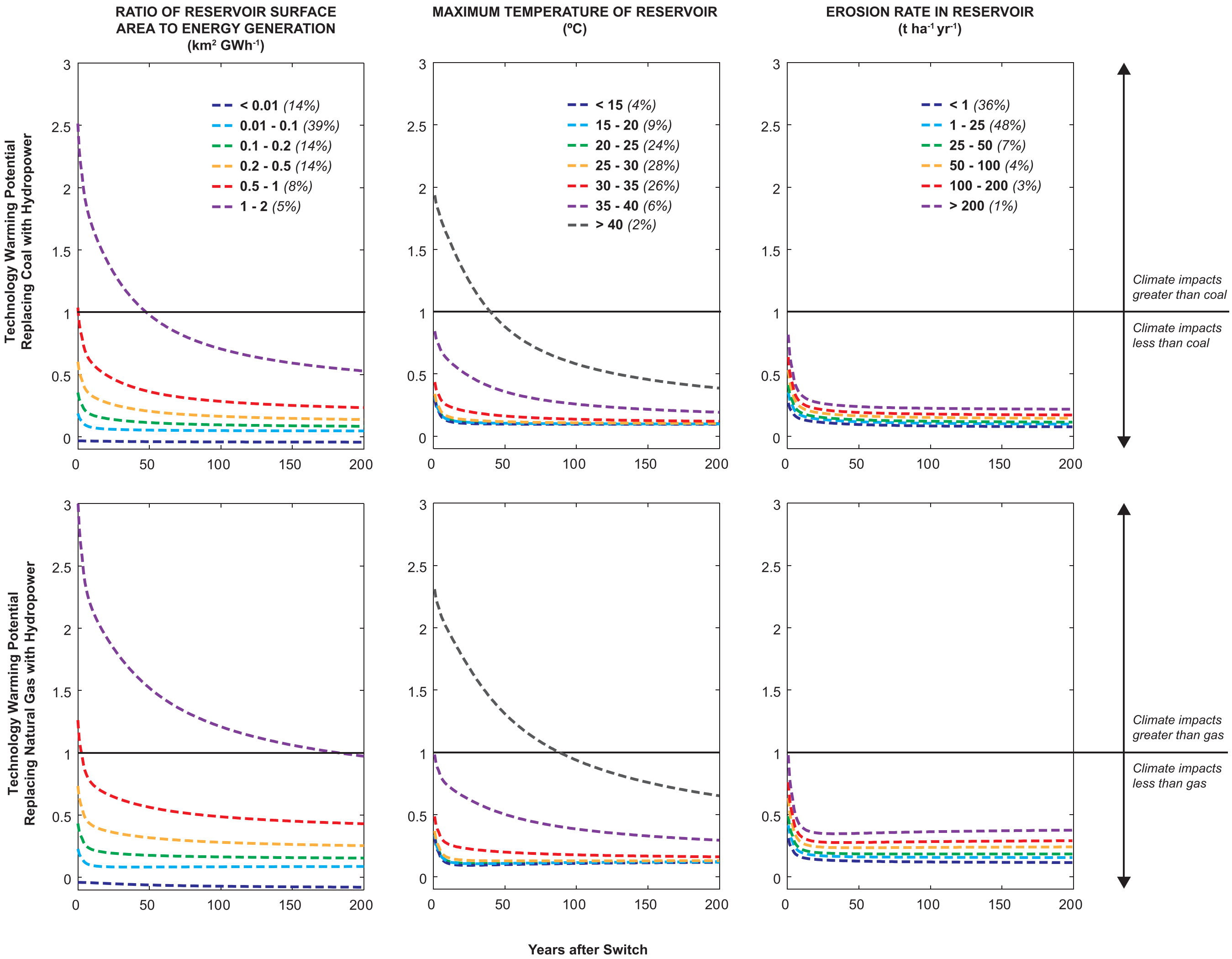

Figure 7. Ratio of climate impacts (using radiative forcing as a proxy) over time from replacing global median emissions from fossil fuels (top: coal; bottom: natural gas) with new hydropower plants based on reservoir surface area to electricity generation ratios, maximum temperature of the reservoir, and annual erosion rate in the reservoir. Emissions from all technologies are per unit energy generation and are continuous throughout the 200 year period. The surface area to electricity generation ratios are for annual energy production in the year 2009.

scenarios. To determine whether or not the emissions properties matter for the new plants, we considered emissions properties at 10th, 25th, 75th, and 90th percentiles of the emissions from the facilities in the database. Because the distribution of emissions in the database are skewed toward higher emissions, the changes in emissions at each of these percentiles are not linear. We see this in the impacts to radiative forcing, where 75th and 90th percentile emissions have major impacts to the overall radiative forcing, but 10th and 25th percentiles only moderately lower the overall radiative forcing.

If all new hydropower plants had emissions properties at the 75th percentile in the database, radiative forcing from total electricity generation (including coal, natural gas, nuclear, hydropower, wind, and solar) would increase by 5%, 6%, and 12% for the current policies, new policies, and sustainable development scenarios, respectively. If all new hydropower plants had emissions properties of the 90th percentile in the database, radiative forcing from total electricity generation would increase by 34%, 40%, and 67% for the current policies, new policies, and sustainable development scenarios, respectively. It is therefore critical to ensure that new hydropower plant facilities do not emit greenhouse gases at these higher levels.

3.4. Hydropower Development Guidance. Given our findings that emissions properties matter for future hydropower plants, it is important to develop guidance for new development. Considering that one cannot measure postflooding and plant emissions before creation of the reservoir, a proxy is needed. Here, we analyze three proxies for greenhouse gas emissions: the ratio of reservoir surface area to electricity generation, maximum temperature of the reservoir, and erosion rate in the reservoir.

The ratio of reservoir surface area to electricity generation has been found to be the best indicator of greenhouse gas emissions to date.[11] In the Scherer and Pfister (2016) database, this ratio (based on electricity generation in the year 2009) has a correlation coefficient of 0.9 with carbon dioxide emissions and 0.5 with methane emissions. The smaller the ratio, the less the greenhouse gas emissions. Maximum temperature is a proxy of the climate zone and therefore can also be indicative of methane emissions; the warmer the temperature, the less likely of mixing in the water column and thereby anoxic conditions that favor methane production.[23]

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Erosion rate is indicative of organic matter transported to the river and has been linked to CO_2 fluxes.[12]

Using these proxies, we binned emissions in the database (both CO_2 and methane emissions for ratio of surface area to electricity generation, methane for maximum temperature with CO_2 median emissions, and CO_2 for erosion rate with methane median emissions) and analyzed resulting climate impacts of new facilities with these sets of properties compared to that from fossil fuels (Figure 7).

For surface area to electricity generation ratios, 6% of plants had ratios above 2 km^2 GWh^{-1}, and climate impacts for new plants with these properties are worse than fossil fuels over all time scales (not shown in Figure 7). A ratio between 1 and 2 km^2 GWh^{-1} (represents 5% of database) has climate impacts greater than coal generated electricity for the first 50 years (climate impacts of a new hydropower plant are initially double that from a coal plant) and greater than those from a natural gas plant over all time scales. A ratio between 0.5 and 1 km^2 GWh^{-1} (represents 8% of the database) has climate impacts less than coal and natural gas generated electricity after the first few years for a new facility. However, 81% of the database has ratios that are less than 0.5 GWh^{-1}, which is promising for future development. In fact, 39% of facilities have ratios between 0.01 and 0.1 GWh^{-1}, which yield climate impacts that are around 10% of that from coal and natural gas generated electricity.

New hydropower reservoirs with a maximum temperature estimated to be above 40 °C (2% of the database, half of which are in India) have greater climate impacts than coal over 50 years and greater climate impacts than natural gas over 100 years. These plants are mostly located in Asia and Africa. Maximum temperatures between 35 and 40 °C (6% of the database) are initially on par with fossil fuel impacts but, in the long term, have climate impacts less than 30% that of fossil fuels. Hydropower facilities with maximum reservoir temperatures below 35 °C (92% of the database) have initial climate impacts less than 50% that of fossil fuels and around 10% in the long term.

Variations in erosion rate did not yield large differences among climate impacts. Higher erosion rates (greater than 200 t ha^{-1} yr^{-1}) had climate impacts only marginally larger than the lowest erosion rates (less than 1 t ha^{-1} yr^{-1}), and all categories had climate impacts less than fossil fuels over all time scales.

Overall, in order to minimize climate impacts of new hydropower facilities, reservoir surface area to electricity generation ratios above 2 km^2 GWh^{-1} should be avoided, and ratios below 1 km^2 GWh^{-1} are desirable. Given that the electrical output from a reservoir is positively correlated with dam height, targeting mountainous regions will reduce climate impacts.[12] Further, hydropower development in regions where the reservoir might reach above 40 °C at its peak should be limited or at least carefully planned to minimize emissions via other governing factors (such as smaller surface areas). We note that the majority of the maximum temperatures estimated in the Scherer and Pfister (2016) database are based on model algorithms and are not empirical measurements. However, the insight remains that potential reservoirs with high temperatures may have larger greenhouse gas emissions that are on par, at least initially, with fossil fuels.

4. DISCUSSION

While decisions about shifting technologies are based on more than just the climate impact parameter, involving all sorts of economic, environmental and social impacts, this analysis provides a framework through which to consider the climate impacts of hydropower as compared to other energy technologies; the differences that emerge are not consistent with the well-established narrative.

Climate impacts of hydropower vary considerably over time, especially for newly developed plants. There are major differences between the impacts of individual hydropower facilities and also over time. The specific characteristics of future hydropower plants matter greatly if efforts to address climate change in both the near- and long-term are to be effective. Storage is also a factor in creating a reliable electrical system, and as such, this is a useful potential attribute of hydropower. However, it too needs to be low impact to be useful in meeting global deep decarbonization goals.

Given the limited data on the annual cycle of direct hydropower emissions globally and its potential importance in impacting climate change, there is a need for collecting more comprehensive data on greenhouse gas emissions from hydropower reservoirs to reduce uncertainty and fully understand the climate implications of hydropower. The underlying message that hydropower is not universally beneficial to the climate needs to be more widely understood if the global commitment to reduce global warming rates are to be met.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b05083.

More detailed information on data used in this study and the emissions in the database, as well as additional figures and tables with further results (PDF)

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■ REFERENCES

(1) IPCC. *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*; Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.

B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T., Eds.; 2018.

(2) IEA. *World Energy Outlook*. 2018.

(3) The World Bank. Electricity production from hydroelectric sources. https://data.worldbank.org/indicator/EG.ELC.HYRO.ZS. Last access date: 17 December 2018.

(4) Zarfl, C.; Lumsdon, A. E.; Berlekamp, J.; Tydecks, L.; Tockner, K. A global boom in hydropower dam construction. *Aquat. Sci.* **2015**, *77* (1), 161−170.

(5) World Nuclear Association. *Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources*. 2011.

(6) Steinhurst, W.; Knight, P.; Schultz, M. Hydropower Greenhouse Gas Emissions, State of the Research. Synapse Energy Economics, Inc. 2012.

(7) National Energy Technology Laboratory. Power Generation Technology Comparison from a Life Cycle Perspective. 2013.

(8) Amponsah, N. Y.; Troldborg, M.; Kington, B.; Aalders, I.; Hough, R. L. Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. *Renewable Sustainable Energy Rev.* **2014**, *39*, 461−475.

(9) Schlömer, S.; Bruckner, T.; Fulton, L.; Hertwich, E.; McKinnon, A.; Perczyk, D.; Roy, J.; Schaeffer, R.; Sims, R.; Smith, P.; Wiser, R. *Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R., Pichs-Madruga, Sokona, Y.; Farahani, E.; Kadner, S.; Seyboth, K.; Adler, A.; Baum, I.; Brunner, S.; Eickemeier, P.; Kriemann, B.; Savolainen, J.; S., Schlömer, C., von Stechow, Zwickel, T., J. C., Minx, Eds.; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2014.

(10) Barros, N.; Cole, J. J.; Tranvik, L. J.; Prairie, Y. T.; Bastviken, D.; Huszar, V. L.; Del Giorgio, P.; Roland, F. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nat. Geosci.* **2011**, *4* (9), 593.

(11) Hertwich, E. G. Addressing biogenic greenhouse gas emissions from hydropower in LCA. *Environ. Sci. Technol.* **2013**, *47* (17), 9604−9611.

(12) Scherer, L.; Pfister, S. Hydropower's biogenic carbon footprint. *PLoS One* **2016**, *11* (9), No. e0161947.

(13) Abril, G.; Guérin, F.; Richard, S.; Delmas, R.; Galy-Lacaux, C.; Gosse, P.; Tremblay, A.; Varfalvy, L.; Dos Santos, M. A.; Matvienko, B. Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). *Global Biogeochem. Cyc.* **2005**, *19* (4), 2457 DOI: 10.1029/2005GB002457.

(14) Santos, J. M.; Ferreira, M. T.; Pinheiro, A. N.; Bochechas, J. H. Effects of small hydropower plants on fish assemblages in medium-sized streams in central and northern Portugal. *Aquatic Conservation: Marine and Freshwater Ecosystems* **2006**, *16* (4), 373−388.

(15) Demarty, M.; Bastien, J. GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH4 emission measurements. *Energy Policy* **2011**, *39* (7), 4197−4206.

(16) Kemenes, A.; Forsberg, B. R.; Melack, J. M. CO2 emissions from a tropical hydroelectric reservoir (Balbina, Brazil). *J. Geophys. Res.* **2011**, *116* (G3), 1465 DOI: 10.1029/2010JG001465.

(17) Teodoru, C. R.; Bastien, J.; Bonneville, M. C.; del Giorgio, P. A.; Demarty, M.; Garneau, M.; Hélie, J. F.; Pelletier, L.; Prairie, Y. T.; Roulet, N. T.; Strachan, I. B. The net carbon footprint of a newly created boreal hydroelectric reservoir. *Global Biogeochem. Cyc.* **2012**, *26* (2), 4187 DOI: 10.1029/2011GB004187.

(18) De Faria, F. A.; Jaramillo, P.; Sawakuchi, H. O.; Richey, J. E.; Barros, N. Estimating greenhouse gas emissions from future Amazonian hydroelectric reservoirs. *Environ. Res. Lett.* **2015**, *10* (12), 124019.

(19) Räsänen, T. A.; Someth, P.; Lauri, H.; Koponen, J.; Sarkkula, J.; Kummu, M. Observed river discharge changes due to hydropower operations in the Upper Mekong Basin. *J. Hydrol.* **2017**, *545*, 28−41.

(20) IEA. Guidelines for quantitative analysis of net GHG emissions from reservoirs−Volume 1: measurement programs and data analysis, Annex XII. 2012.

(21) Prairie, Y. T.; Alm, J.; Beaulieu, J.; Barros, N.; Battin, T.; Cole, J.; del Giorgio, P.; DelSontro, T.; Guerin, F.; Harby, A.; Harrison, J.; Mercier-Blais, S.; Serca, D.; Sobek, S.; Vachon, D. Greenhouse gas emissions from freshwater reservoirs: what does the atmosphere see? *Ecosystems* **2018**, *21* (5), 1058−1071.

(22) Tremblay, A.; Therrien, J.; Hamlin, B.; Wichmann, E.; LeDrew, L. J. Synthesis. In *Greenhouse Gas Emissions: Fluxes and Processes, Hydroelectric Reservoirs and Natural Environments*; Tremblay, A., Varfalvy, L., Roehm, C., Garneau, M., Eds.; Springer: Berlin, Germany, 2005; 637−659.

(23) Deemer, B. R.; Harrison, J. A.; Li, S.; Beaulieu, J. J.; DelSontro, T.; Barros, N.; Bezerra-Neto, J. F.; Powers, S. M.; dos Santos, M. A.; Vonk, J. A. Greenhouse gas emissions from reservoir water surfaces: a new global synthesis. *BioScience* **2016**, *66* (11), 949−964.

(24) DelSontro, T.; McGinnis, D. F.; Sobek, S.; Ostrovsky, I.; Wehrli, B. Extreme methane emissions from a Swiss hydropower reservoir: contribution from bubbling sediments. *Environ. Sci. Technol.* **2010**, *44* (7), 2419−2425.

(25) Harrison, J. A.; Deemer, B. R.; Birchfield, M. K.; O'Malley, M. T. Reservoir water-level drawdowns accelerate and amplify methane emission. *Environ. Sci. Technol.* **2017**, *51* (3), 1267−1277.

(26) Teodoru, C. R.; Prairie, Y. T.; Del Giorgio, P. A. Spatial heterogeneity of surface CO2 fluxes in a newly created Eastmain-1 reservoir in northern Quebec, Canada. *Ecosystems* **2011**, *14* (1), 28−46.

(27) Miller, B. L.; Arntzen, E. V.; Goldman, A. E.; Richmond, M. C. Methane ebullition in temperate hydropower reservoirs and implications for US policy on Greenhouse Gas emissions. *Environ. Manage.* **2017**, *60* (4), 615−629.

(28) Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; Nakajima, T.; Robock, A.; Stephens, G.; Takemura, T.; Zhang, H. Anthropogenic and Natural Radiative Forcing. In: *Climate Change* 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A.; Xia, Y.; Bex, V., Midgley, P. M., Eds.; Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

(29) Etminan, M.; Myhre, G.; Highwood, E. J.; Shine, K. P. Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophys. Res. Lett.* **2016**, *43* (24); DOI 12614.

(30) Tremblay, A. Measuring Net Emissions from Eastmain 1 Reservoir. *Hydro-Review* **2011**.

(31) Ocko, I. B.; Hamburg, S. P.; Jacob, D. J.; Keith, D. W.; Keohane, N. O.; Oppenheimer, M.; Roy-Mayhew, J. D.; Schrag, D. P.; Pacala, S. W. Unmask temporal trade-offs in climate policy debates. *Science* **2017**, *356* (6337), 492−493.

(32) Lenton, T. M. Early warning of climate tipping points. *Nat. Clim. Change* **2011**, *1* (4), 201.

(33) Settele, J.; Scholes, R.; Betts, R.; Bunn, S.; Leadley, P.; Nepstad, D.; Overpeck, J. T.; Taboada, M. A. Terrestrial and inland water systems. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C. B., V. R. Barros, D. J., Dokken, K. J., Mach, M. D., Mastrandrea, T. E., Bilir, M., Chatterjee, K. L., Ebi, Y. O., Estrada, R. C., Genova, B., Girma, E. S., Kissel, A. N., Levy, S., MacCracken, P. R., Mastrandrea, White, L. L., Eds.; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2014; 271−359.

(34) United Nations. Standard Country or Area Codes for Statistical Use (M49). https://unstats.un.org/unsd/methodology/m49/ (Last Access Date: August 22 2019).

DOI: 10.1021/acs.est.9b05083
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

(35) Zavala-Araiza, D.; Alvarez, R. A.; Lyon, D. R.; Allen, D. T.; Marchese, A. J.; Zimmerle, D. J.; Hamburg, S. P. Super-emitters in natural gas infrastructure are caused by abnormal process conditions. *Nat. Commun.* **2017**, *8*, 14012.

(36) Alvarez, R. A.; Zavala-Araiza, D.; Lyon, D. R.; Allen, D. T.; Barkley, Z. R.; Brandt, A. R.; Davis, K. J.; Herndon, S. C.; Jacob, D. J.; Karion, A.; Kort, E. A.; Lamb, B. K.; Lauvaux, T.; Maasakkers, J. D.; Marchese, A. J.; Omara, M.; Pacala, S. W.; Peischl, J.; Robinson, A. L.; Shepson, P. B.; Sweeney, C.; Townsend-Small, A.; Wofsy, S. C.; Hamburg, S. P. Assessment of methane emissions from the US oil and gas supply chain. *Science* **2018**, 7204.

(37) Alvarez, R. A.; Pacala, S. W.; Winebrake, J. J.; Chameides, W. L.; Hamburg, S. P. Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure. *Proc. Natl. Acad. Sci. U. S. A.* **2012**, *109* (17), 6435−6440.

(38) IEA. *World Energy Outlook*. 2017.

DOI: 10.1021/acs.est.9b05083
Environ. Sci. Technol. XXXX, XXX, XXX−XXX