Pipeline availability limits on the feasibility of global coal-to-gas switching in the power sector

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ABSTRACT

Coal-to-gas switching in the power sector, as happened in the US, has been a key driver of near-term greenhouse gas emissions reductions. Can this success be replicated around the world? Here, we explore the limits of a global, plant-level, coal-to-gas transition arising from pipeline availability constraints. Globally, only 43% of coal capacity is within 14 km of a nearby pipeline, the median distance for recent coal-to-gas conversions. Furthermore, plant-to-pipeline distance distributions vary widely – only 30% of coal capacity in India is within 14 km of a nearby pipeline. Most global coal fleets are in the intermediate space of balancing two competing interests – having a young coal fleet with high "avoided" emissions potential through coal-to-gas switching but without access to low-cost gas resources. A global stocktake based on coal fleet age, pipeline access, and natural gas supply security suggests that a coal-to-gas transition is unlikely to be a universal climate solution.

Keywords: coal-to-gas switching, gas pipeline, coal power plant, geographical constraints

Power sector decarbonization has emerged as a central part of system wide emissions reduction through electrification [1]. At a global level, coal is still the dominant fuel for power generation with a share of 35.2% in 2020 [2]. The share of renewables in power generation rose to record levels in 2020 (11.7%), with the combined share of natural gas-fired power and renewables equaling and soon surpassing coal for the first time [3]. Given the inertia associated with expanding renewable energy infrastructure and the outsized impact of coal-burning on both global GHG emissions as well as air quality, there is a potential benefit to coal-to-gas switching in parallel to the transition to low carbon alternatives [4]. Early opportunities from fuel switching between fossil fuels represent a potential quick win only if avoiding longer-term climate impacts through lock-in is prioritized.

Natural gas (NG) has served as a viable bridge away from coal-based generation in the short term, as demonstrated by success in the United States and Europe [5-9]. While there is wide variation in life-cycle emissions across different sources of coal and NG, an estimated 98% of gas consumed today has a lower lifecycle emissions intensity than coal when used for power [4, 6, 10-15]. Furthermore, the displacement of coal generation by NG has led to a decrease in pollutants, such as sulfur dioxide, nitrogen oxides, and mercury, particularly from older coal power plants [16]. Yet, effective coal-to-gas switching requires alterations in current technological regimes, infrastructure investments, and supportive energy policies, such as a carbon price [17-19]. Given the rollout of carbon neutrality goals in most countries and the Paris Agreement's 1.5 °C climate target, there is a need to rapidly shift away from unabated coal use.

There are three main ways in which NG can substitute for coal in power generation – (1) preferential dispatch of existing gas plants over coal plants, (2) retirement of coal plants and the construction of new NG plants in other locations within an electricity grid, and (3) repowering of existing coal plants by converting the boiler of a coal-fired steam plant to burn NG. In this work, we focus on repowering which reduces capex costs compared with retirement and new construction by making use of existing infrastructure.

Coal phaseout and the prioritization of plant retirement in the power sector have been investigated thoroughly based on environmental, economic, regulatory, and technical criteria [4, 20-30]. For coal-to-gas switching, there are also a variety of multidimensional factors that need to be considered when choosing to repower, rather than retire or continue to operate a coal-fired unit. Previous repowered coal-fired units seem to share many characteristics with retired units [31]. On average, units selected for retirement or repower were smaller, older, less fuel-efficient, and more likely to operate within a regulated electricity market. One of the most obvious differences between a power plant that repowers versus retires is the need for additional NG infrastructure, which can be one of the most significant costs in a coal-to-gas conversion project. For cost-effective operation, a power plant must receive NG via a pipeline spur from the main transmission line. If a spur does not currently exist, the plant will need to evaluate the costs and activities, including permits and land rights, associated with constructing a new spur [28]. Indeed, recent studies suggest that building pipeline infrastructure is one of the biggest costs associated with a potential coal-to-gas transition [32-34]. In many cases, existing coal plants lack sufficient infrastructure for gas delivery which would need to be newly constructed. Intuitively, the clearest case for switching from coal to gas comes when there is a possibility to use pre-existing infrastructure to provide similar energy services but with lower emissions. A significant NG transmission and distribution pipeline system and spare fuel supply-chain capacity must already exist to support the transition while avoiding further high-carbon infrastructure lock-in through the build-out of new pipelines [35, 36]. So, if both the relative price of coal vs NG and regulatory support for switching, then geographical constraint, in the form of gas pipeline availability, can be critical to the feasibility of coal-to-gas switching and has never been thoroughly discussed before.

This study focuses on investigating the feasibility of coal-to-gas switching across global coal power plants from a novel perspective - geographical infrastructure constraints, defined as the nearest distance of coal power plants to existing gas pipelines. This paper is structured as follows: we first review the global distribution of coal power plants and their proximity to gas transmission pipelines. Next, we analyze pipeline availability limits to coal-to-gas switching on regional and national scales. Then, we discuss how factors such as the age of the coal fleet and NG supply availability further limit the potential for coal-to-gas transition. We conclude with a discussion of the implications of global carbon emissions.

Results

Global coal plants and gas transmission pipelines

Figure 1 shows the network of global coal power plants and gas transmission pipelines based on data as of August 2021. Coal plants mostly concentrate in East and South Asia, Eastern Europe, and North America. 1610 GW or about 78% of total global coal generation capacity is concentrated in just 5 countries: China, the United States, India, Japan, and Germany. Meanwhile, China, Europe, and North America also have more densely distributed gas pipelines compared to other regions. Coal plants that have access to nearby gas pipeline infrastructure have fewer barriers and lower costs in the near-term transition from coal to gas. Recent research has demonstrated that barriers to new pipeline construction including costs, local opposition, and regulatory delays can be considerable [37]. Thus, the coal-to-gas transition is likely more feasible in regions that have more dense gas pipeline networks. Conversely, isolated coal plants are the most unlikely candidates for coal-to-gas conversion.

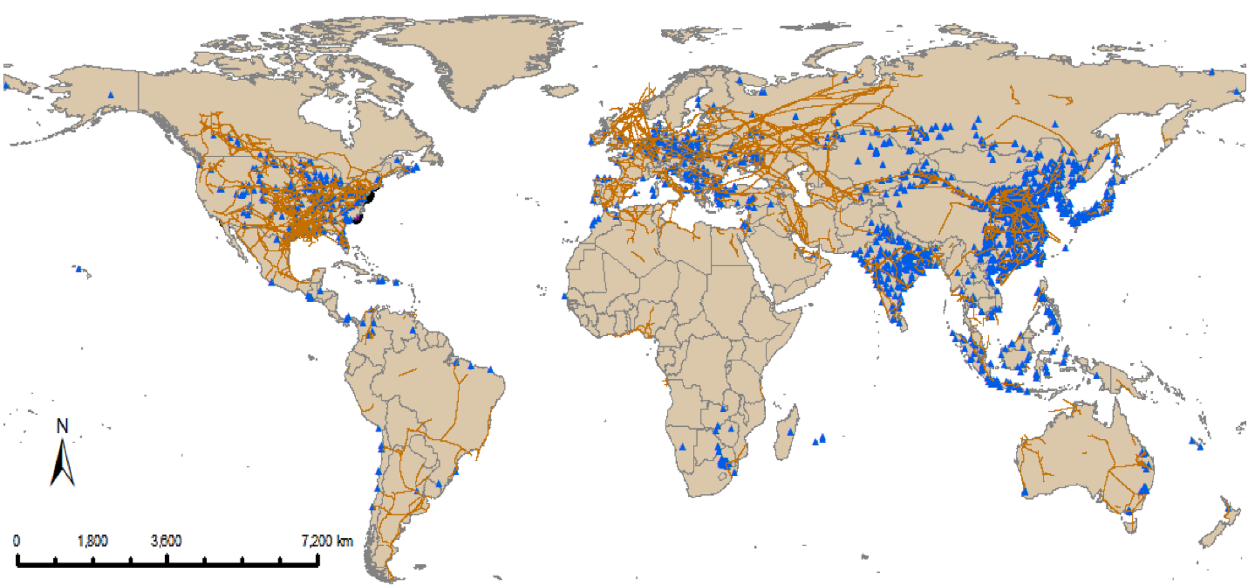

Figure 1. The network of global coal power plants (blue triangles) and gas transmission pipelines (orange lines). India, China, the US, and Eastern Europe represent around 82% of

total coal power generation capacity. China, Europe, and the US also have dense gas transmission networks.

Figure 2(a) shows the cumulative global coal capacity as a function of the distance of coal plant to nearest gas pipeline. Globally, half of the total coal power plant capacity is located within 18.5 km to the nearest gas pipeline. Comparing this to the median US coal-to-gas pipeline distance of 14 km, nearly 43% of global coal-powered capacity will not be constrained by pipeline availability for coal-to-gas switching. However, coal plants where coal-to-gas switching is feasible because of nearby pipeline access, are not uniformly distributed around the world.

Figure 2(b) shows the cumulative global coal capacity as a function of the distance of coal plant to the nearest gas pipeline disaggregated by age of the plant. The global coal-based generation fleet is young – 50% of global capacity is younger than 13.2 years. However, the plants that are closer to a nearby gas pipeline are generally older. For example, nearly 50% of coal plants older than 50 years are within 14 km of a gas pipeline. However, for plants that are 21 – 30 years old, less than 40% have a gas pipeline within the 14 km empirical US-median distance. Thus, the feasibility of coal-to-gas transition based on pipeline availability is higher for coal plants over 40 years than coal plants younger than 30 years. Given that older plants are near the end of their operational lifetimes and may require significant investments to extend their usable lifetimes for NG conversion, it might make more environmental sense to replace them with zero-carbon alternatives, especially in countries with more stringent environmental regulations or ambitious climate targets. Except for plants over 40 years old, the coal plant cohort in the 11 – 20 year age has the next largest percentage, 43.4% of capacity, that are within 14 km to the nearest gas pipeline. Coal plants in the 31 – 40, 0 – 10, and 21 – 30 age groups have 42.9%, 40.3%, and 37.3%, respectively, of coal capacity located within 14 km of a nearby pipeline.

Figure 2(c) presents the cumulative capacity of global coal power plants as a function of distance of coal plant to nearest gas pipeline across individual countries. The distribution varies significantly across countries, with implications for the feasibility and cost of coal-to-gas transitions. Countries like India, where only 30% of existing coal capacity is within 14 km of a gas pipeline, have limited potential for a large-scale coal-to-gas transition without major investments in expanding domestic pipeline infrastructure. Conversely, countries where the coal-to-gas transition has successfully reduced power sector carbon emissions like the US, have over 60% of existing coal capacity within 14 km of a gas pipeline. Based on total coal fleet capacity, China has the largest potential for coal to gas substitution with 480 GW, followed by the US (146 GW) and India (69 GW).

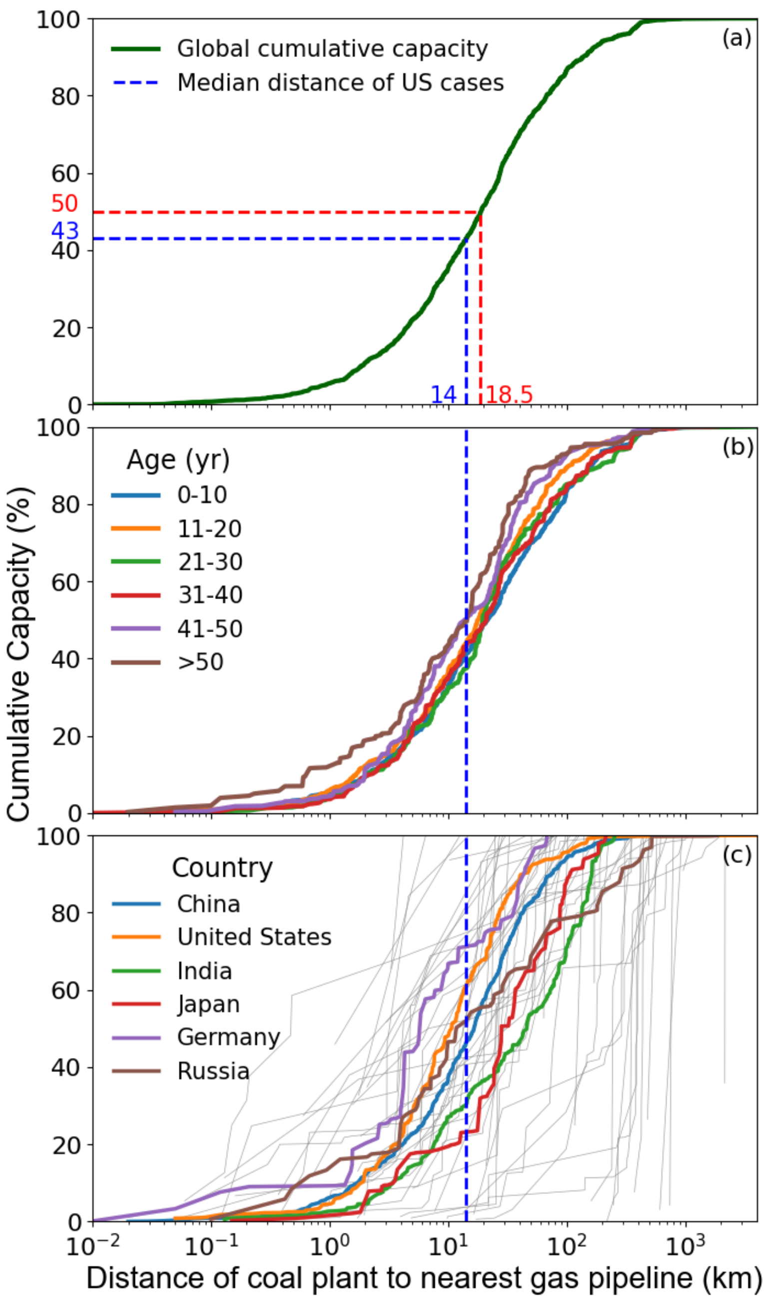

Figure 2. (a) Cumulative capacity of global coal power plants as a function of distance of coal plant to nearest gas transmission pipeline. The median distance of 43 previous U.S. coal-to-gas conversion projects is 14 km (blue dashed line). (b) Cumulative capacity of global coal power plants as a function of distance of coal plant to gas pipeline, disaggregated by coal plant age cohort. (c) Cumulative capacity of global coal power plants as a function of distance of coal plant to gas pipeline across individual countries. The distributions of several major coal power countries are highlighted – China (blue), the U.S. (orange), India (green), Japan (red), Germany (purple), and Russia (brown). All other countries are shown in grey lines.

Globally, the top 5 countries with the largest coal power capacity are China, the United States, India, Japan, and Germany. Figure 3 shows the distribution of the distance of coal plant to gas pipeline by country. Germany and U.S have coal power capacities that are close to gas pipelines with a median nearest pipeline distance of 7 km and 12 km, respectively. However, most of India's and Japan's coal power plants lack nearby gas pipeline infrastructure with a median nearest pipeline distance of 35 km and 37 km, respectively. The distribution of coal plant to pipeline distance in China is spread evenly, with 46% of coal capacity within 14 km of a nearby pipeline. These distributions provide an indication of the infrastructural feasibility of coal-to-gas switching in different countries. Globally, China and the U.S. have the top two largest coal power capacities and pipeline availability is unlikely an obstacle to coal-to-gas transition for approximately 50% of their total coal capacity. Even though India is the third-largest coal power country, only 30% of its coal power capacity is a likely candidate for coal-to-gas substitution based on pipeline availability constraints.

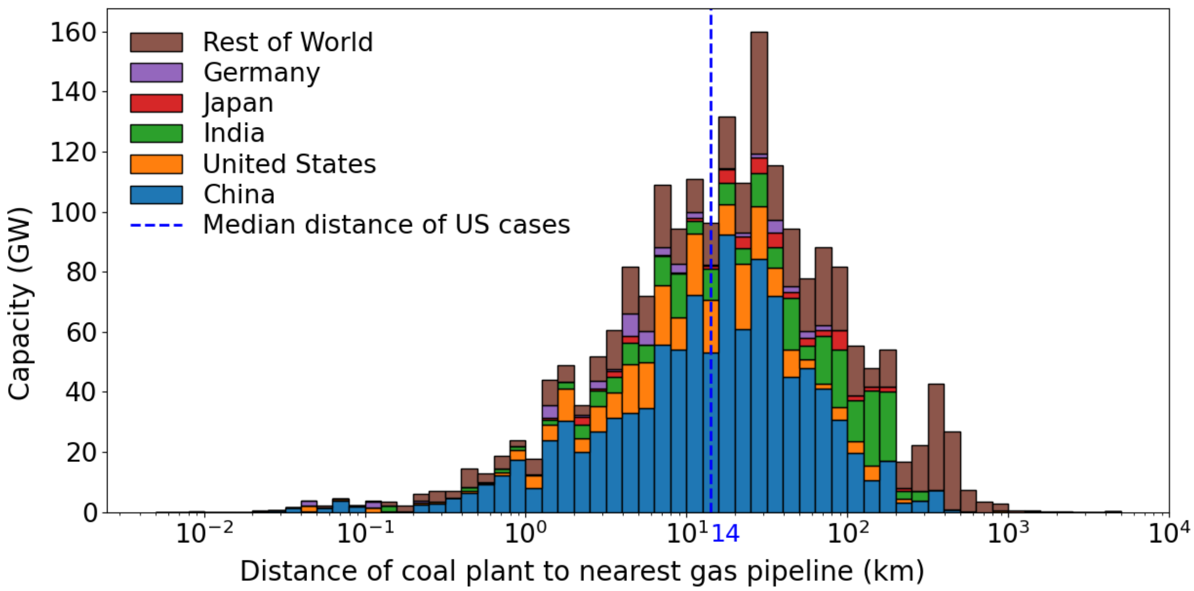

Figure 3. Distribution of the distance of individual coal power plants to nearest gas transmission pipeline in China (blue), the U.S. (orange), India (green), Japan (red), Germany (purple), and other countries (brown).

Pipeline availability vs. other attributes

All things being equal, coal plants that have nearby access to gas pipelines tend to have a higher potential for coal-to-gas switching. However, other attributes such as coal plant age, availability of cheap NG, domestic production, and energy security via increased exports also factor in decision making. Figure 4 compares the median nearest-pipeline distance for coal plants in each country with two critical attributes that factor into decision-making about coal-to-gas switching – the average age of coal plants (Figure 4a) and excess domestic NG production (Figure 4b).

The impact of coal plant age is multidimensional. On one hand, older coal power plants are approaching the end of their operational lifetimes and have largely recovered capital investment, thus making it economically feasible to be retrofitted and repowered as a gas plant to continue operations. Moreover, older plants also have limited or no air quality control systems (AQCS) in place, and the cost of adding an AQCS to comply with environmental regulations such as the US Mercury and Air Toxics Standards is high [38]. Thus, compared to retrofitting older coal plants to comply with environmental regulations, it is likely more cost-effective to convert a coal boiler to fire NG, reducing both air pollutants and GHG emissions. However, this also requires investments in upgrading older and less efficient combustion technologies. On the other hand, newer coal plants are more urgent to switch to gas-based power generation to avoid long lifetimes of coal generation and resultant GHG emissions. Although newer coal plants are likely to have pollution control devices installed, operating them through their designed lifetimes will jeopardize the ability to achieve the goals of the Paris Agreement [39]. Thus, coal-to-gas switching of newer coal plants is likely to have a higher impact on reducing long-term GHG emissions compared to that of older coal plants. Highly polluting older coal plants are better retired and replaced either with efficient combined cycle gas plants or with zero-carbon sources like wind and solar.

A key factor in decisions about coal-to-gas switching of coal plants is the availability of NG. Figure 4(b) compares country-level excess NG production – defined as a ratio of domestic production to consumption ('excess NG production ratio') - with nearest pipeline distance. When domestic NG production is more than consumption (excess NG production ratio >1), access to NG is readily available at a low cost, making a country more suited to a coal-to-gas transition. The U.S., with an excess production ratio of 1.1, significantly reduced emissions from the power sector in part because of a large-scale coal-to-gas transition [40]. If NG production is less than consumption (excess NG production ratio <1), a country would need to rely on LNG or pipeline imports to achieve a coal-to-gas transition, thereby increasing exposure to volatile markets and supply variability. Japan's closure of nuclear power plants in the aftermath of Fukushima resulted in significant increases in LNG imports to meet electricity demand. The average price of imported NG in Japan was $7.9 per mmBtu in 2020, compared to a domestic price of $2 per mmBtu in the US [41].

Thus, the intersecting influences of coal fleet age, pipeline availability, and excess NG production ratio divide the global coal fleet into four regimes based on the availability of nearby pipeline, availability of low-cost NG supplies, and its significance in reducing global GHG emissions. For discussions of the age of the coal fleet, these four regimes can be categorized as – feasible/significant, feasible/insignificant, infeasible/significant, and infeasible/insignificant. For discussions of the availability of domestic NG, the four regimes can be categorized as – feasible/available, infeasible/available, feasible/unavailable, and infeasible/unavailable. By analyzing the position of countries in the context of this matrix, we can determine the most likely candidate countries for a coal-to-gas transition on the basis of the availability of a nearby pipeline, the access to low-cost NG, and the potential for coal-to-gas switching to have a significant impact on reducing GHG emissions. Although other metrics such as costs, national climate policy, or political economy, will be part of the decision to gasify coal plants, physical constraints from the pipeline and NG availability assume primacy. We make a few critical observations.

First, are the most promising countries for coal-to-gas switching, those that have access to nearby gas pipelines, operate younger coal fleets with significant potential for "avoided" emissions through coal-to-gas switching (feasible/significant quadrant), and produce abundant domestic, low-cost NG (feasible/available quadrant). These countries face the lowest risk in embarking on large-scale coal-to-gas transition projects as an interim step towards sector-wide decarbonization. The shale revolution of the past decade that resulted in the long-term availability of low-cost domestic NG in the U.S. led to widespread coal-to-gas transition projects. Recent studies have demonstrated that this switching was responsible for over a third of emissions reductions observed in this power sector since 2005 [40]. Importantly, the remaining coal plants in the US are significantly older with an average fleet age of 44 years, thus reducing the potential for "avoided" emissions through the coal-to-gas transition. This demonstrates an important dynamic about the nature of this transition – countries that are likely to benefit from such a transition would eventually move to a regime where additional transition is unlikely to provide significant "avoided" emissions benefits. This is because, as younger coal plants switch to using gas as an emissions reduction measure, older coal plants at the end of their lifetimes are more likely to be replaced by low or zero-carbon sources due to limited benefit from "avoided" emissions. Countries in the feasible/insignificant quadrant represent those whose coal fleets are near an existing pipeline, thereby making it easier for a coal-to-gas transition project at a relatively low cost. However, these countries also have old coal fleets (e.g., Russia and the U.S., with an average fleet age of 45 and 44 years, respectively), and GHG reduction benefits are limited from coal-to-gas switching without significant extension in the life of the plant. In these countries, a direct switch to zero or low-carbon sources of electricity would be the most effective option for decarbonization.

Second, there are countries where a coal-to-gas transition is unlikely to be a near-term decarbonization solution. These are countries that do not have access to nearby gas pipelines, operate near end-of-life coal fleets such that "avoided" emissions are low (infeasible/insignificant quadrant), and must rely on imported NG to supply gas power plants (infeasible/unavailable quadrant). South Africa is a prominent example – the aging coal-fleet coupled with a lack of domestic NG is better suited for a transition to zero or low-carbon sources of electricity rather than through an intermediate coal-to-gas switching process. Building significant new NG infrastructure in the countries or new LNG import facilities risks lock-in consumption of NG beyond the period it is compatible with Paris targets [39, 42-44].

Third, a majority of global coal fleets are in the intermediate space of balancing two contrasting conditions: on the one hand, the availability of a young coal fleet implies high "avoided" emissions potential through coal-to-gas switching; on the other hand, lack of sufficient domestic NG resources exposes such countries to volatile NG imports. In addition, coal plants in these countries generally lack access to nearby gas pipelines, and new construction of NG gas infrastructure can be expensive and risks creating carbon lock-in. This space is occupied by countries in the infeasible/significant quadrant based on the average age of the coal fleet and the infeasible/unavailable quadrant based on a lack of access to low-cost, domestic NG. Several countries in Asia fall under this category. India, for example, has the second-largest coal fleet in the world with an average age of 17 years – a coal-to-gas transition can contribute to significant power section emissions reductions. However, the combination of a limited gas pipeline network and high dependence on imported LNG makes a large-scale coal-to-gas transition unlikely. LNG imports are prioritized for other sectors of the economy such as agriculture and industrial use. This is evident in India's National Electricity Plan which focuses on expanding zero-carbon electricity sources (solar, wind, nuclear, hydro) rather than an expansion of gas-based power generation [45]. By contrast, Japan has relied heavily on LNG imports to operate gas-fired power generation due to recent nuclear plant closures following the Fukushima disaster. Given the small distance between LNG regasification terminals to power plants, the lack of NG pipelines is not a significant factor in the development of gas-fired power generation. However, recent volatility in international gas markets and resulting high prices are likely to make Japan and other countries reliant on LNG imports to re-think national energy security strategy, with a potentially rapid move away from NG [46].

Fourth, coal fleets in Europe represent the final category in the coal-to-gas transition. Europe has an extensive gas pipeline network that makes a coal-to-gas transition physically feasible. However, the average age of the coal fleet is 38 years, near the end of their typical lifetime, and has limited potential for "avoided" GHG emissions. Furthermore, European countries also significantly rely on NG imports through pipelines (Russia) and LNG to meet demand. Thus, they occupy the space in the feasible/insignificant quadrant because of the aging coal fleet and the feasible/unavailable quadrant because of a lack of domestic NG supplies. Germany, for example, relies on NG for about a third of its total electricity production. With the recent shutdown of their nuclear fleet, their reliance on imports from Russia has increased over the past decade. European political economy also plays a critical role in this transition. In 2020, renewable energy sources represented the largest source of power generation (23.8%) [3], and the fraction is targeted to reach more than 80% by 2050 [36]. The war between Russia and Ukraine has also forced the EU to consider a significant reduction in imports of NG from Russia in the near term, thereby potentially accelerating the transition to renewable and other domestic sources of power.

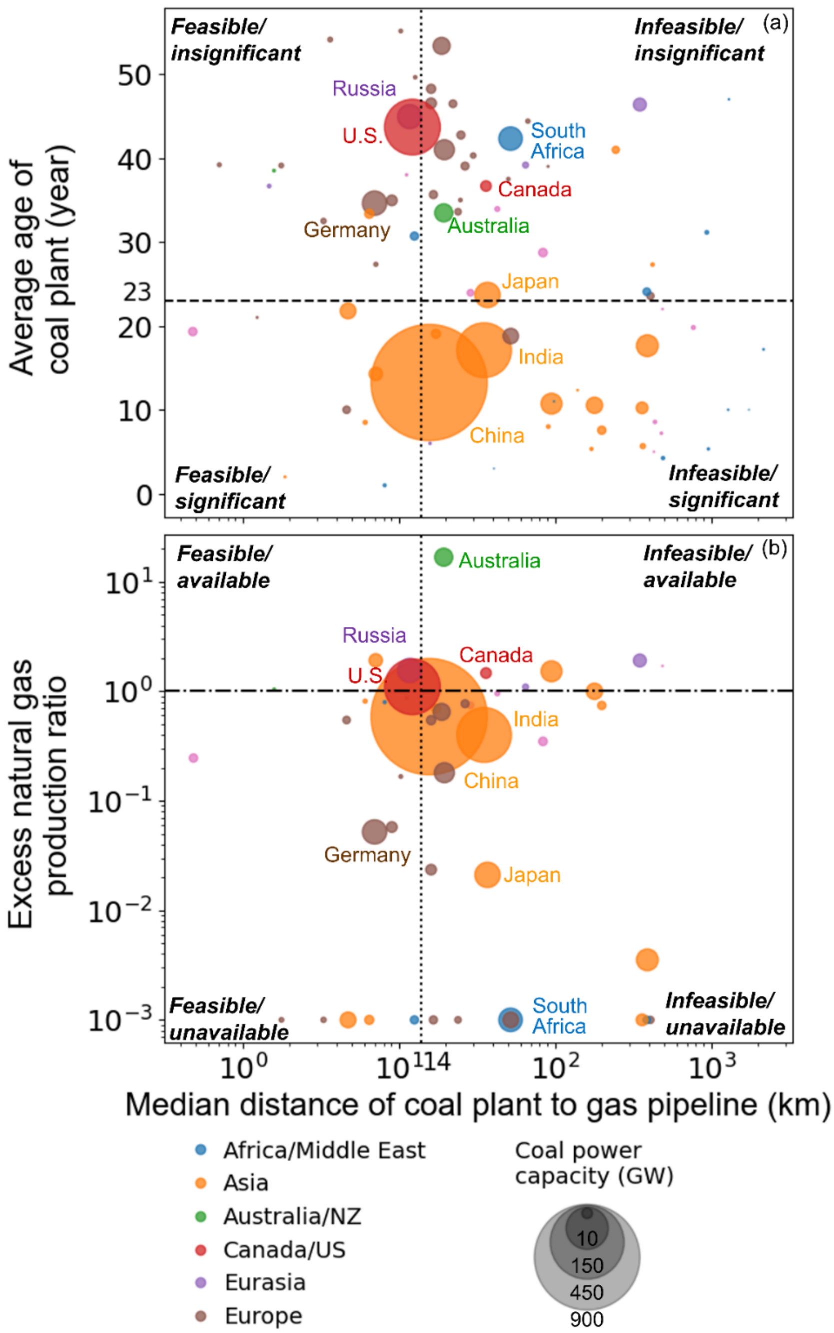

Figure 4. National median distance of coal plant to gas pipeline vs (a) national average coal power plant age and (b) excess natural gas production ratio expressed as a fraction of natural gas production to consumption in 2020. Different colors represent countries in 7 regions of the world – Africa/Middle East (Blue), Asia (orange), Australia/NZ (green), Canada/US (red), Eurasia (purple), and Europe (Brown). Black dotted line is the median distance of coal plant to gas pipeline (14 km) derived from the U.S. coal-to-gas transition projects. Black dashed line represents the average age of global coal power plants (23 years). Black dashed-dotted line represents a breakeven scenario where domestic natural gas production equals consumption. The area of the circle for different countries corresponds to the total coal power capacity in that country. Some major countries are labeled.

Discussion

This study investigates the role of pipeline availability constraints on the feasibility of the global coal-to-gas transition in the power sector. This constraint is a critical factor because of the costs, local opposition, and regulatory hurdles associated with building new gas pipeline infrastructure. Although coal-to-gas transition can significantly reduce global carbon emissions such as in the U.S., their feasibility varies significantly by geography, coal fleet age, and access to low-cost NG. Our results provide insights into regions where such transitions are feasible, contribute to significant "avoided" carbon emissions, and would require minimal infrastructure investments. Our study presents a best-case scenario, given that existing pipelines might already be operating near full capacity to supply gas to other sectors, thus requiring an expansion for supplying power plants.

Generally, younger coal plants make up the majority of global coal power capacity, whereas newer plants are farther away from available gas pipelines compared to older plants. Given the operational lifetimes of coal plants and the pipeline availability constraint on the coal-to-gas transition, mid-age coal plants (10- to 30-year) represent the largest capacity of potential candidates for coal-to-gas switching. In total, we find that only 43% of global coal capacity has a gas pipeline within the distance empirically observed in recent coal-to-gas transitions. Pipeline availability is likely not a constraint for this transition in the United States, Canada, Russia, and Europe. More than half of the coal power capacities of Germany, the United States, and Russia are located close to existing gas pipelines to enable switching from coal to gas without significant infrastructure investments. On the other hand, the majority of the coal fleet in India and South Africa do not have nearby gas pipelines and are unlikely to be good candidates for this transition.

Besides pipeline availability, the potential for coal-to-gas transition will be impacted by other factors including coal fleet age and the politics of energy security such as import dependence. This study puts emphasis on infrastructure limits to the coal-to-gas transition, given the risk of locking in higher carbon infrastructure. For example, the existence of excess NG production can contribute to coal-to-gas switching to deliver rapid carbon savings. Integrating gas pipeline infrastructure constraints, the age and capacity of coal power plants, and the availability of NG, a high potential for coal-to-gas transition in the power sector exist in countries that have access to nearby gas pipelines, operate younger coal plants with significant potential for the "avoided" GHG emissions, and has access abundant domestic, low-cost NG. However, most global coal fleets are in the intermediate space of balancing two contrasting conditions – having a younger coal fleet with high "avoided" emissions potential through coal-to-gas switching, but not having access to abundant, low-cost, domestic NG resources. Whether a large-scale, coal-to-gas transition can take place (or is even desirable) in such countries is an open question for national governments seeking to balance energy security, climate action, and energy access.

That coal to gas transition has reduced carbon emissions from the power sector is not in doubt – the US and the UK are proof of its success. However, it is unclear if the success of that transition can be replicated around the world. The industry consensus is generally in the affirmative. Yet, this work shows that such a transition is likely to be location-specific and depends on several constraints. Of these, the primary constraint remains the availability of a nearby gas transmission pipeline to supply coal power plants. National-level conversations in countries with significant coal-based generation are essential to moving from possibilities to practicalities of a coal-to-gas transition. Indeed, there is significant near-term potential – even converting 40% of global coal plants that have nearby pipeline access to using gas will contribute to emissions reductions. But such transitions are unlikely to be universal without significant investments into expanding NG infrastructure primarily in developing countries.

Methods

Pipeline availability near global coal power plants

We gathered unit-level data on coal power plants that are in operation as of August 2021 from comprehensive global datasets [47, 48]. The compiled dataset covered 2425 operating coal plants, and nearly 6600 individual generators, with a total capacity of 2076 GW. In addition, we also assembled geospatial data associated with each coal plant including operating city and country, capacity, and start year of operation. Gas pipeline data are derived from the global fossil infrastructure tracker database, developed and maintained by the Global Energy Monitor [49]. Pipeline routes were gathered from publicly available information and maps from industry, news, and government sources or publications. Pipeline coordinates were determined by geo-referencing route images using QGIS 3.4.12 [50]. More than 1,900,000 km of approximately 1700 gas pipelines that are operating, under construction, and idle are included in the analysis. Global NG production and consumption data at the country level are obtained from the U.S. Energy Information Administration (EIA) and BP Statistical Review of Energy 2021 [41, 51].

The feasibility of coal-to-gas switching is dependent on the availability of a nearby gas pipeline to supply gas to the coal plant. The nearest distance between a coal plant and a pipeline is calculated using the proximity tool in ArcGIS. Only major NG transmission pipelines that can deliver volume flows necessary to operate an NG-fired power plant are considered. Smaller gathering and distribution pipelines that are typically used for residential and commercial use are not included in this analysis. This is justified because over 90% of power plants are located outside city limits, where major trans-national and interstate pipelines terminate.

Empirical coal plant to gas pipeline distance distribution

In the absence of established industry-wide standard on the economics of adding new pipeline segments to connect coal plants with nearby existing pipelines, we evaluated all prior coal-to-gas conversions in the U.S. between 2010 and 2019. Overall, there were 43 coal-to-gas transitions in the US – analyzing new pipeline capacity built to supply these plants with gas provides us with an empirical estimate of the median coal-to-gas pipeline distance.

A two-step approach was used to identify coal plant repowering cases using U.S. EIA form 860 which required firms to identify planned changes from the primary energy source used to produce electricity since 2007. In step one, we determine those units that reported "*planned energy source 1*" changes indicating the plan to repower from coal to gas. In step two, we cross-referenced these "*planned energy source 1*" changes with the actual listed planned energy source 1 in subsequent years of operation to confirm the coal to gas switching. This two-step verification process was critical as several units are listed with planned energy source changes over multiple years that did not occur. We identified 43 coal-fired units that applied and switched from coal to gas fuel between 2010 and 2019. The distance of coal plant to gas pipeline varied between 0.06 and 161.6 km with a median of 14 km and an average of 28 km (see SI section S1).

Data availability statement

All data that support the findings of this study are publicly available.

Acknowledgments
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Author contributions

A.P.R. and S.H.S. conceived the study. S.Y. compiled and verified the data underlying this study and developed the technical analyzes. S.Y., A.P.R., and S.H.S. discussed and interpreted the results. All authors contributed to writing the paper.

Competing interests

The authors declare no competing interests

Supporting Information

S1. Data sources

Table S1 summarizes the data sources used in this study.

Table S1 *Summary of data sources*

Dataset	Source	Feature
Global coal power plant	World Resources Institute [47]	Plant-level, operating plants
	Global Coal Plant Tracker [48]	Unit-level, include all status
US previous conversion cases	EIA-860 form [52]	Plant-level, energy sources
Global gas pipelines	Global Fossil Project Tracker [49]	Operating, under-construction, and idle
NG production and consumption	EIA and BP Statistical Review	Data of 2021

Figure S1 shows the locations of all prior coal-to-gas conversions in the US power sector between 2010 and 2019. 43 coal-fired units that applied to switch from coal to gas fuel are identified. Most of the plants had nearby gas pipelines to facilitate the coal to gas switching.

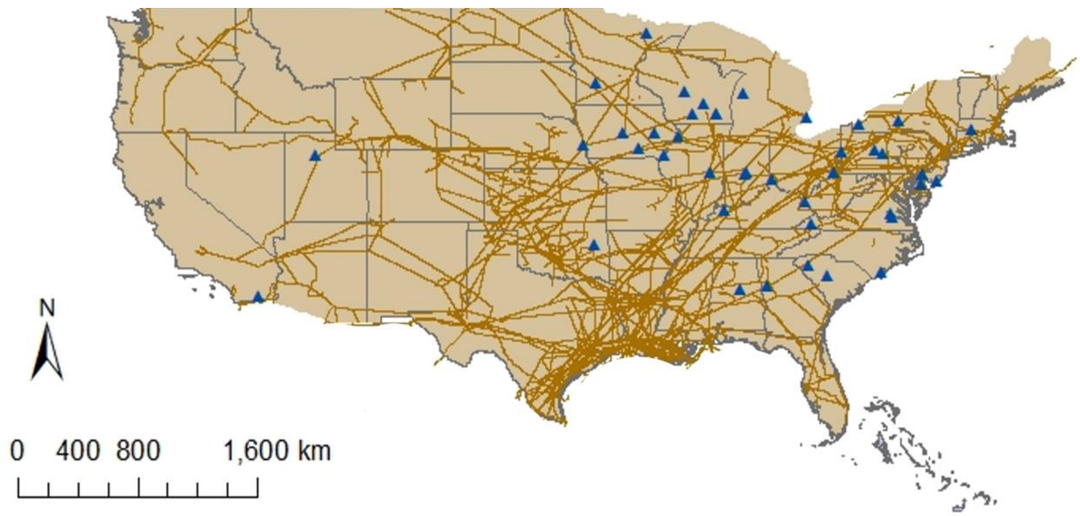

Figure S1. *The locations of all U.S coal power plants with coal-to-gas conversions between 2010 and 2019 (blue triangles) and the network of the national gas transmission pipelines (orange lines).*

Figure S2 shows the distribution of the distance of coal power plant to gas pipeline in all prior coal-to-gas conversions in the U.S. between 2010 and 2019. A large proportion of coal power capacity (~80%) that switched to using gas as primary fuel had access to a gas pipeline that was less than 40 km away. The distance of coal plant to nearby gas pipeline varied between 0.056 km and 161.64 km with a median of 14 km and an average of 28 km. This statistical analysis provides us with an empirical estimate of median coal-to-gas pipeline distance that is feasible in the absence of an industry-wide standard. While it is possible that longer pipelines could be built with additional investment, the example of the US coal-to-gas conversions represents a best-case scenario where low-cost natural gas became abundantly available.

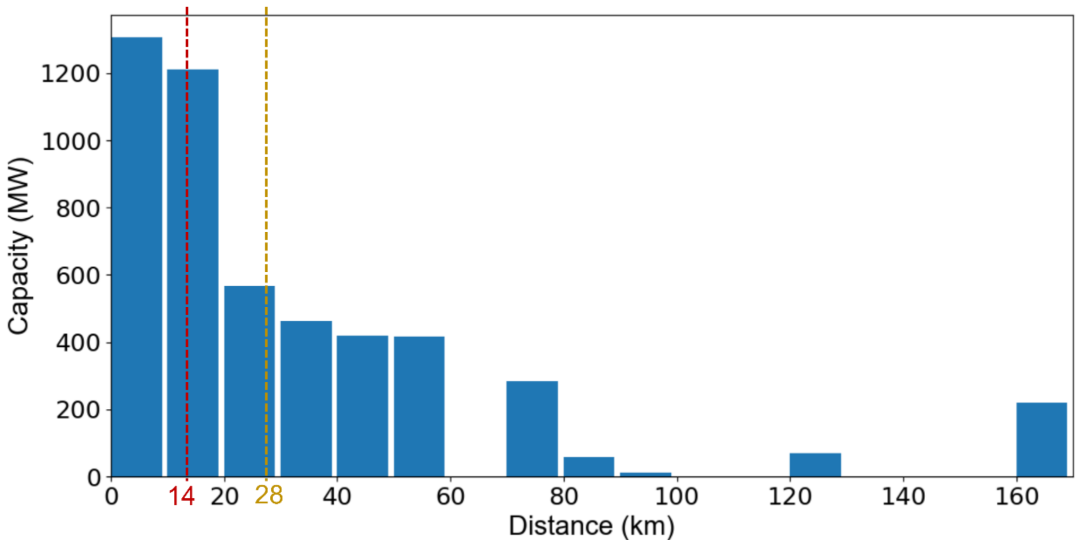

Figure S2. *Distribution of the distance of coal power plant to gas pipeline of the U.S. previous conversion cases. Red and yellow dashed lines represent the median of 14 km and the average of 28 km, respectively.*

S2. Gas pipeline availability in different regions

The infrastructure availability of gas pipelines varies significantly across different regions. Figure S3 depicts the distribution of the distance of coal plant to gas pipeline for regions using density curves of coal power capacity (violin plots). The width of each curve corresponds with the frequency (the magnitude of coal power capacity) at a given distance to a nearby pipeline in each region. We note two critical insights.

First, there are three types of curve shapes: wider bottoms, wider tops, and equal tops and bottoms, all with a small number of outliers. Curves with wider bottoms and narrower tops indicate that there is less coal power capacity that is subject to pipeline availability constraints; shapes with narrower bottoms and wider tops reflect the lack of available gas pipelines near a majority of coal power plants in that region; the shapes with a similar width from top to bottom indicate an even distribution of the distance of coal plant to gas pipeline. Notably, the curves of Canada/US and Europe belong to type one where the geographical constraint is not a key factor in the feasibility of coal-to-gas transition in the power sector. Asia, Africa and the Middle East, and Australia/NZ are characterized by the second type– where pipeline availability places limits on a widespread coal-to-gas transition. However, there are also significant differences within regions (see Figure 2 in the main text) – for example, China has an extensive gas pipeline network and therefore potential for coal-to-gas switching while only 30% of India's coal capacity is within 14 km of a nearby pipeline.

Second, the average distances of coal plant to gas pipeline in all the regions are larger than the empirical distance of 14 km. Whereas the median of the distance of Canada/US (12.5 km) is slightly smaller than the threshold, and Asia, Europe, and Australia/NZ are just slightly over the threshold, which are 19.4 km, 19.2 km, and 18 km, respectively. Combined with the shape of the curves, these results suggest that a coal-to-gas transition is more likely to happen in Canada/US and Europe than in Africa or Asia.

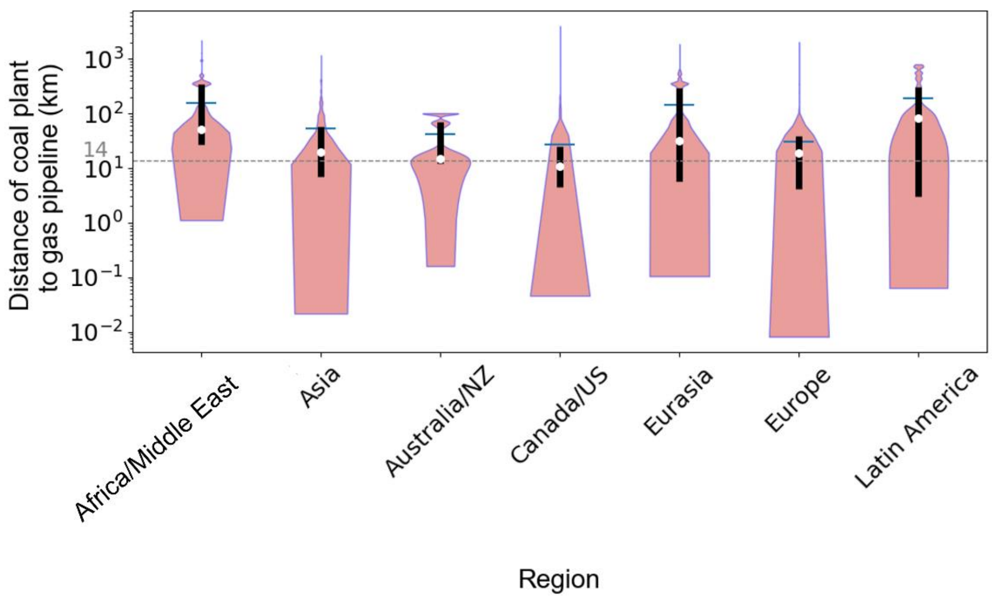

Figure S3. *Violin plot of nearest distance between coal plants and gas pipelines for regions in the world. The shape shows the distribution (probability density of generation capacity) of distance, white dot indicates the regional median distance, blue segment depicts the average distance, the edge of black vertical segment indicates 25th and 75th percentile, grey dotted line is the median pipeline distance derived from US previous coal-to-gas conversion projects.*

S3. Distribution of the age of global coal power capacity

The distribution of the age of global coal power capacity is shown in Figure S4. Globally, half of the global coal power plant capacities are younger than 13.2 years. 75% of global coal power capacity is younger than the typical designed lifetime of coal power plants of 30 years. Younger coal plants make up the majority of global coal power capacity.

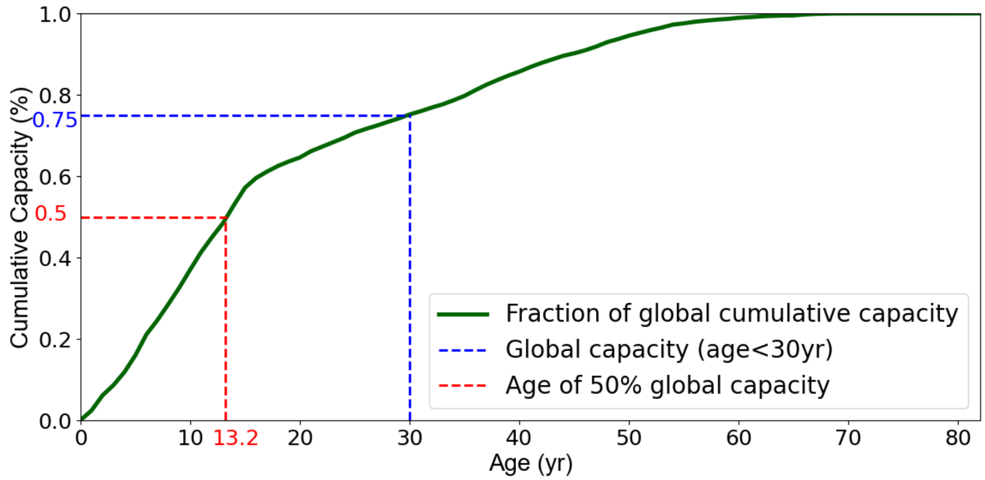

Figure S4. *Cumulative capacity as a function of the age of global coal power plants*

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