Environmental Research Letters

LETTER • OPEN ACCESS

Reports of coal's terminal decline may be exaggerated

To cite this article: Ottmar Edenhofer *et al* 2018 *Environ. Res. Lett.* **13** 024019

IOP Publishing Environ. Res. Lett. 13 (2018) 024019 https://doi.org/10.1088/1748-9326/aaa3a2

Environmental Research Letters

OPEN ACCESS

RECEIVED
26 May 2017

REVISED
22 September 2017

ACCEPTED FOR PUBLICATION
22 December 2017

PUBLISHED
7 February 2018

LETTER

Reports of coal's terminal decline may be exaggerated

Ottmar Edenhofer[1,2,3], **Jan Christoph Steckel**[1,2,3,4], **Michael Jakob**[1] and **Christoph Bertram**[2]

[1] Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany
[2] Potsdam Institute for Climate Impact Research, Potsdam, Germany
[3] Technische Universität Berlin, Department Economics of Climate Change, Berlin, Germany
[4] Author to whom any correspondence should be addressed.

E-mail: steckel@mcc-berlin.net

Keywords: Paris Agreement, coal, (I)NDCs, carbon lock-in

Supplementary material for this article is available online

Abstract

We estimate the cumulative future emissions expected to be released by coal power plants that are currently under construction, announced, or planned. Even though coal consumption has recently declined and plans to build new coal-fired capacities have been shelved, constructing all these planned coal-fired power plants would endanger national and international climate targets. Plans to build new coal-fired power capacity would likely undermine the credibility of some countries' (Intended) Nationally Determined Contributions submitted to the UNFCCC. If all the coal-fired power plants that are currently planned were built, the carbon budget for reaching the 2 °C temperature target would nearly be depleted. Propositions about 'coal's terminal decline' may thereby be premature. The phase-out of coal requires dedicated and well-designed policies. We discuss the political economy of policy options that could avoid a continued build-up of coal-fired power plants.

1. Introduction

The Paris Agreement, to which the 196 parties of the United Framework Convention on Climate Change (UNFCCC) agreed at the 21st Conference of the Parties (COP21), is generally perceived as a diplomatic success. Although the goals outlined in the voluntary (Intended) Nationally Determined Contributions—(I)NDCs—to reduce emissions are not in line with emission trajectories that would stabilize global mean temperatures at 'well below 2 °C' [1], they would still constitute a departure from current trends [2] and could provide an entry point for more ambitious climate policies [1]. The Paris Agreement entered into force on 4 November 2016.

In parallel with this political success, global greenhouse gas (GHG) emissions may already have peaked as a result of slowed economic growth and a surge in renewable energy use [3]. For instance, solar power deployment since the year 2000 has exceeded even the most optimistic projections [4]. As a consequence, some energy analysts argue that solar power will push the most emission-intensive primary energy carrier, namely coal, out of the market [5]. Recent developments could be interpreted as first signs that this is already happening. After several decades of robust growth in coal consumption and a build-up of capital stock of coal-fired capacity, the most recent data suggest that in 2016 global coal consumption declined by roughly 1.7%, and coal production by as much as 6.2% [6]. Some important coal-consuming countries (especially China and India) have shelved the construction of several coal-fired plants that had been announced or were in the planning stage (see figure S1 in the supplementary information available at stacks.iop.org/ERL/13/024019/mmedia). Economically recoverable coal reserves may also be substantially lower than commonly assumed [7]. Are these signs of 'coal's terminal decline', as suggested by the thus titled Greenpeace report [8]?

As will be demonstrated in this paper, the continued reliance on coal-fired power plants in a number of major emerging economies could still turn out to be a massive stumbling block for climate change mitigation. Coal-fired power plants currently announced, planned, or under construction will, over the course of their expected life-time, generate a substantial amount of emissions in addition to those that are already 'locked in' (i.e. which will likely be generated in the future by already existing infrastructure). Unless these power plants are retired well before their expected life-time, which would increase mitigation costs and constitute a formidable political challenge, their associated emissions jeopardize the achievement of the (I)NDC targets as well as effective long-term climate change mitigation. Hence, we argue that dedicated policies to phase out coal are needed to hedge against political uncertainty and allow for credible commitment to ambitious long-term mitigation targets.

The motivation for this study is outlined in section 2, followed by a description of materials and methods in section 3. An analysis of how increasing coal use undermines the credibility of (I)NDCs is presented in section 4, and section 5 discusses the implications for long-term climate targets. Section 6 assesses the political economy of policy options to avoid that announced and planned coal-fired capacities come to fruition. Section 7 concludes.

2. Motivation

Previous analyses have shown that increasing coal use could result in 2030 emission levels surmounting the range that would limit global warming to below 2 °C [9]. Yet these studies do not account for the important role of committed emissions from coal-fired power plants for emission reductions at later stages, i.e. beyond 2030. To achieve a given temperature target, such as 2 °C, it is insufficient to limit emissions to a certain level until a certain date, such as 2030.

The long-term implications of infrastructure investments, especially in the power sector, are assessed in a growing literature on carbon lock-in [10–13]. These studies emphasize that due to long life-times, existing infrastructure is likely to generate substantial 'committed' emissions in the next decades, thus posing a considerable challenge for decarbonization efforts. For instance, Davis and Socolow [10] demonstrate that taking into account only those fossil-fired power plants operating in 2012, emissions of approximately 192–439 $GtCO_2$ are to be expected during their assumed lifetimes.

The effect of committed emissions has also been examined in integrated assessment model scenarios. Bertram *et al* [14] demonstrate that less stringent near-term climate policies can be expected to lead to additional coal-based electricity generation. The introduction of ambitious long-run climate targets leads to the premature retirement of significant coal capacity. Pfeiffer *et al* [15] show that the existing power sector infrastructure responsible for generating emissions may already have exceeded the '2 °C capital stock'. That is, in order to keep global mean temperature increase below 2 °C, the building of new emission generating electricity infrastructure would not be permitted unless existing power plants are either retired or retrofitted with carbon capture and sequestration technologies.

This paper extends previous work on committed emissions of existing energy infrastructure by shifting the focus from historical developments to coal capacity either currently under construction, announced, or in the planning stage. This is especially important as the coal-use landscape is changing. Declining use in industrialized countries and China, and increasing use elsewhere possibly means that despite flat coal use, the amount of committed emissions will increase in actual fact as old plants are being replaced by new ones. In other words, coal is far from being in a 'terminal decline', at least not in all markets and therefore not fast enough to reach set climate targets at low cost.

In contrast to model-based studies analyzing the options for climate change mitigation under a range of assumed future developments, we explore the implications of energy policies that are currently in place, in particular with regard to the construction of new coal power plants. The central question we address is what amount of future cumulative emissions will be additionally locked-in if these plants come online. This analysis allows the identification of countries expected to show the largest increase in coal-fired capacity, which might therefore merit special attention by the international climate policy community.

3. Materials and methods

Emissions for existing power plants were calculated based on data by Shearer *et al* [16] and the Global Plant Tracker [28]. A power plant life-time of 40 years was assumed where an explicit retirement date was not available. For planned plants (announced, pre-permitted, permitted) and plants under construction data were taken from Shearer *et al* [16]. All plants under construction and in the planning phase were assumed to be operational by 2030. The latter are marked separately to reflect different (i.e. higher) probabilities with regard to planned capacity still being cancelled (for a detailed regional analysis of historical values see [16]). The calculation of power plant emissions is based on (announced) capacities. Whereas emissions might be lowered by retrofitting power plants with carbon capture and sequestration (CCS), to our knowledge none of the plants currently planned is designed to be capture-ready. For this reason, we assume that these plants will emit at a constant rate over their entire life-time. To calculate emissions, the average heat rates for different coal types and average emission factors for different combustion technologies were used on a plant level [28], resulting in a median load factor of 0.593. To calculate lower and higher bound emission estimates, this capacity factor is varied between 0.368–0.797 [17][5].

[5] Note that 0.368 refers to the minimum value (for Russia) given by the IEA WEO 2016 in a comparison of various major coal using countries, while 0.797 refers to the maximum value (for Japan).

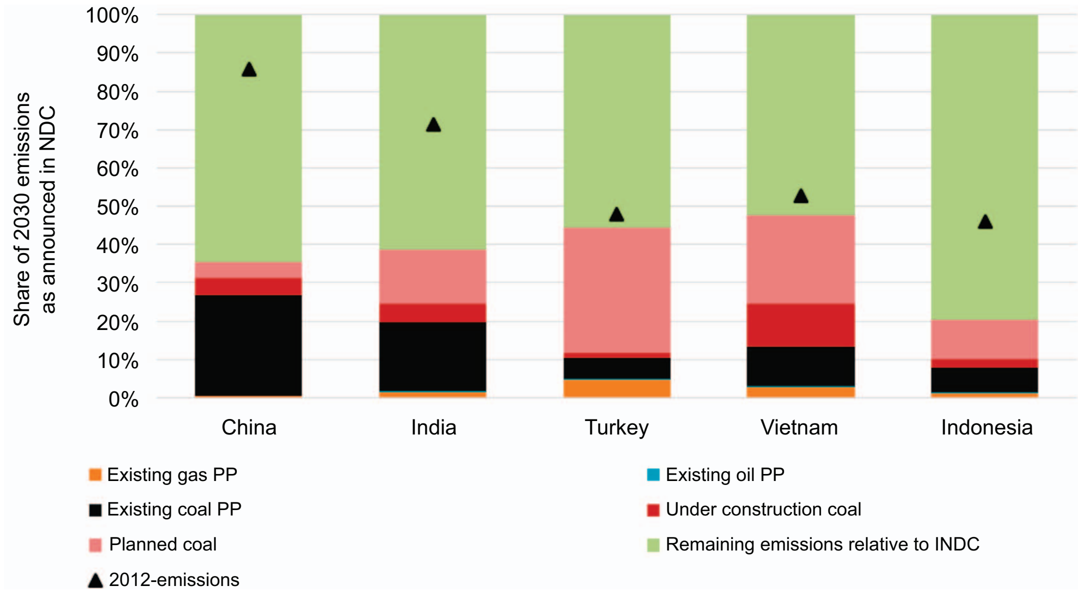

Figure 1. Percent of 2030 (I)NDC pledges (upper bound estimates) decomposed into different (potential) emission sources, including infrastructure in the power sector planned, existing, or under construction. Countries selected are those with the highest investment in forthcoming coal power capacity (either under construction or planned), accounting for at least 5% of resulting emissions on the global scale. The emissions shown here would accrue if all coal capacity either under construction or planned would be online in 2030. All power plants built before 1990 are assumed to be offline by 2030. Data sources: [2, 10, 16, 18], see also SI for details on calculation.

In figure 1 we show emissions data for the year 2012 to illustrate how (I)NDC targets relate to current emissions, taken from the Emission Database for Global Atmospheric Research EDGAR [18]. Note that data were used referring to CO_2-eq. (i.e. including all greenhouse gases) in order to be consistent with emissions data on (I)NDCs. Countries' (I)NDCs emission data were retrieved from the UNFCCC [19] when countries formulated their targets in CO_2-eq. (Indonesia, Turkey and Vietnam). For China and India, where only CO_2 targets are communicated to the UNFCCC, we rely on the UNEP Emissions Gap Report [2], which includes projections for non-CO_2 GHGs (see SI for details)[6].

In section 4, we contrast committed emissions from existing and planned coal plants with emissions implied by the respective (I)NDCs. Several (I)NDCs specify peak years or intensity targets instead of emission levels, thereby leaving room for interpretation, for instance with regard to economic growth rates or rates of emission growth prior to the peak. Some (I)NDCs specify targets conditional on e.g. financial assistance from abroad. We show results for the upper bound range (i.e. more ambitious) of emission reductions achieved by the (I)NDCs, as these can be regarded to be the more relevant (albeit still insufficient) starting points for mitigation action that is in line with the targets of the Paris Agreement.

[6] Note that calculations in figure 1 are based on estimates given in the 2015 version of the UNEP Emissions Gap Report. A range of additional estimates is reported in the subsequent reports 2016 and 2017, which do not qualitatively change the results given in figure 1.

Section 5 compares the emission commitment of existing, planned, and announced power generation capacity under construction with long-term scenarios. Data on committed emission was taken from Shearer *et al* [16], see above for a more detailed description. Existing power plants that had exceeded their 40 year lifetime but were still running in 2016 are assumed to be shut down before 2025. If no specific date is given in the original data, we assume that plants under construction at the end of 2016 will be operational by 2020. With respect to 'planned coal', 'permitted' and 'pre-permitted' plants are assumed to be online in 2025, announced plants are assumed to be online in 2030. The emission scenario for a 2 °C target has been calculated with the integrated assessment model REMIND [20]. It assumes regional implementation of (I)NDCs, including emissions targets as well as land-use and energy sector policies, and considers all contributions submitted by 2 October 2015. This scenario anticipates a continuation of policy ambition levels implied by (I)NDCs after 2030 (as in the (I)NDC-extended scenario of the same report) and eventually shifts to an optimal policy to achieve a 2100 forcing target of 2.6 W m^{-2} (see chapter 4 of the MILES [1] study).

4. Coal and the (I)NDCs

Continued investments into coal lead to an ongoing carbonization of energy systems (sometimes referred to as a renaissance of coal) in many countries [21]. This will make it difficult for those countries to reach their intended mid-term mitigation targets outlined in the (I)NDCs. Nearly three quarters (73%) of the global coal-fired capacity currently under construction or planned—and hence related future emissions—are located in the top five countries with respect to power plants in the pipeline, i.e. China, India, Turkey, Vietnam, and Indonesia, which are all newly industrializing countries [16]. While China and India have reduced their plans to build new coal-fired power plants between 2015 and 2016, other countries, such as Bangladesh, Pakistan or Egypt have significantly increased them (see also figure S1). Egypt, which to date has been a comparatively minor coal consumer country, has planned additions of slightly less than 25 GW of coal-fired capacity. This would increase total capacity in the country almost eight-fold.

In the past, investments in new coal capacity were dominated by China, the world's largest coal consumer accounting for about half of the world's total. Chinese coal use has recently slowed, and might even have passed its peak [22]. However, data suggest that China will invest in coal-fired plants abroad, while their domestic market increasingly saturates [23]. Even if China's coal use has peaked, lower domestic rates of coal consumption would still consume a considerable share of the remaining carbon budget. Increasing coal use in other countries may also act to offset at least some of the reductions achieved in China.

(I)NDCs allow for annual emissions to increase by a certain extent until 2030. Relative to 2012 emissions, these increases range from 17% for China to more than 100% for Turkey and Indonesia (as indicated by the black triangles in figure 1, displaying 2012 emissions as a fraction of the (I)NDC target). In view of the sharp emission reductions required in the mid- to long-term to achieve the Paris Agreement, these five countries' (I)NDCs appear to be of limited ambition. This evaluation in line with the assessment of the Climate Action Tracker. The Tracker rates the (I)NDCs of China, India, and Indonesia as 'medium', meaning that they are '[n]ot consistent with limiting warming below 2 °C as it would require many other countries to make a comparably greater effort and much deeper reductions', and that of Turkey even as 'inadequate' ([24], Vietnam is not included in their rating).

Nevertheless, the emissions that would be released by existing and planned coal plants in the aforementioned countries account for a significant share of the maximum amount of 2030 emissions to which their (I)NDCs commit. For example, in China, India, Turkey, and Vietnam, these emissions would represent between 36% and 48% of the 2030 emissions targeted in their (I)NDCs. In Turkey and Vietnam, emissions from coal capacity currently planned and/or under construction would—if added to the committed emissions from existing plants—be comparable to overall 2012 greenhouse gas emissions levels.

The challenge of meeting (I)NDCs in the face of growing coal use is also apparent from table 1, which compares the changes of emissions from coal-fired power plants and from all other sources projected until 2030. For all five countries, emissions from coal-fired power plants increase significantly more than emissions from all other sources. For instance, in China and Vietnam emissions from all sources except coal-fired power plants would be permitted to increase by no more than 12% and 14%, respectively. This is especially striking for Vietnam, for which construction of all coal-fired power plants planned would mean a more than nine-fold increase in emissions stemming from such plants. Taking into account that the power sector in general, and particular fuel switch away from coal, offers the most cost-effective mitigation option [25], such developments in these countries' energy sectors would at least represent unbalanced approaches to climate policy. Lacking cost-efficiency could, even if it is perhaps not the most decisive element of climate policy making, nevertheless greatly affect the credibility of these countries' (I)NDCs.

Table 1. Percentage change in CO_2 emissions from coal-fired power plants (first column) and all other emission sources (second column) between 2012 and 2030 for China, India, Turkey, Vietnam and Indonesia. Source: [17, 18].

	Change in emissions from coal-fired power plants (2012–2030)	Change in all other emissions (2012–2030)
China	26%	12%
India	84%	23%
Turkey	412%	50%
Vietnam	948%	14%
Indonesia	196%	105%

In sum, planned investments in coal-fired power plants could even undermine the (I)NDCs' relatively low ambitions for those countries in which the largest additions in coal-fired capacities are forthcoming. In light of such heavy investments in coal-fired power, it seems questionable that these countries will embark on ambitious reduction efforts in other sectors, such as transport or industry. This will thus affect their (I)NDCs' credibility.

5. Coal undermines long-term climate targets

Building up new coal-fired power plants would not only endanger the (I)NDCs of the major coal consumers examined in the previous section, but also have important implications for global climate change mitigation. Emissions that would result from the construction of all currently envisaged coal-fired power plants will, even if the targets laid out in the (I)NDCs are actually reached, undermine long-term climate targets. With future temperature increase being a function of the cumulative amount of emissions released into the atmosphere [26], the feasibility of specific climate targets crucially depends on the speed at which emissions can be reduced. To have a good chance (66%) of keeping global temperature increase below 2 °C, around 700 Gt CO_2 (with an uncertainty range of ±275 Gt CO_2) can still be emitted from 2016 on [18]. If

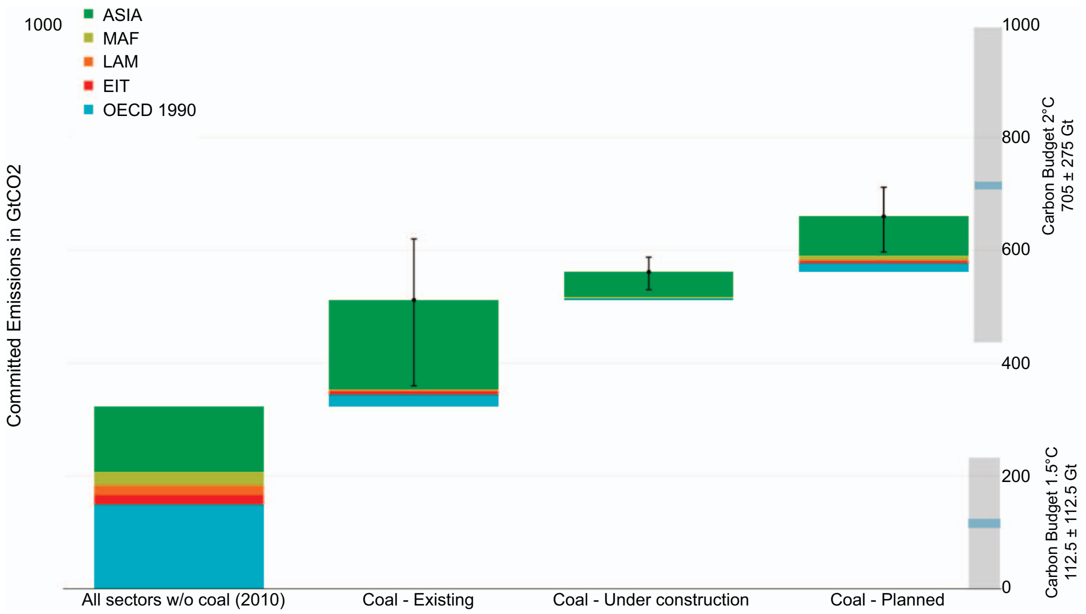

Figure 2. Committed emissions to the atmosphere decomposed into contributions of coal (existing, under construction and planned) and other economic sectors for different regions (region categorization RC5 as defined in the IPCC AR5 [25]); uncertainty ranges indicate differing lifetimes (30 yrs–50 yrs) and coal fired power plants' capacity factors (37%–80%); emission factors are specific to the power plants [16, 28]. 'All sectors w/o coal' only includes committed emissions for infrastructures that has been constructed before 2010 as calculated by Davis *et al* [29]. For the calculation of 'all sectors' medium lifetimes of infrastructure as reported by Davis *et al* were assumed. Data Source: [16, 25, 29].

used to the end of its lifetime, the existing infrastructure (including coal-fired power plants, but also buildings, transportation infrastructure etc.) is estimated to produce emissions that are in the range of roughly 500 Gt CO_2 [13], as shown in figure 2. Coal-fired power plants that are under construction or planned would account for committed emissions of approximately 150 Gt CO_2 if fully realized and thus almost exhaust the still remaining 2 °C budget. That is, these new additions alone would consume more than one fifth of the available carbon budget for a 2 °C target. Those emissions would add to the roughly 190 Gt of CO_2 committed by existing coal-fired power plants that were built until the end of 2016. Even though the carbon budget for a 1.5 °C target is to date not fully explored and hence subject to substantial uncertainty, available estimates based on the IPCC AR5 arrive at a median of roughly 113 Gt CO_2 (with an uncertainty range of ±112.5 Gt CO_2)[7]. This budget would already be exceeded by the emissions locked in by those coal power plants projected to be built during the next years.

Another perspective to look at the amount of locked in emissions is a comparison to scenario analyses. Ambitious mitigation scenarios assessed in the IPCC (RCP 2.6) see cumulative emissions from (unabated) coal to be in the range of 95 Gt, starting from 2017[8], indicating that some existing plants would actually need to emit less than currently expected, not to speak of newly built power plants already in the pipeline.

Constructing new coal plants in the next years would create path dependencies and thus severely restrict the policy options for climate change mitigation measures for the next decades. Carbon lock-in would slow down the transformation of the global energy system until well after 2030. Even if annual emissions decline in the future, new coal-fired power plants are likely to substantially decelerate this decline, depleting the carbon budget still available prematurely. In addition, even a declining capacity of coal-fired plants can mean an increasing amount of committed emissions, as old plants with only a short remaining life-time are replaced by new ones that have several decades of operation ahead of them.

Hence, the prevalence of coal in the power sector would constitute a stark deviation from a 2 °C mitigation pathway that is cost-optimal in the long-term (see figure 3). This 2 °C scenario calculated for the MILES [1] report using the REMIND model takes into account the constraint that the (I)NDCs foresee a further increase in emissions until the year 2030. Hence, it deviates from unconstrained mitigation scenarios, which typically project emissions to peak by or even before 2020 [25]. This scenario shifts a larger share of emission reductions to the second half of the century than conventional 2 °C scenarios, so that it can be considered to be of lower ambition in the

[7] One newer study implies that the available budget for achieving 1.5 °C might be larger and in the magnitude of what was assumed previously to be available for achieving 2 °C with a high probability [27]. We consider those results as an optimistic estimate. For this reason, we rely on the estimates reported in the IPCC AR5 [26].

[8] This number constitutes a median value. The minimum value is 19 Gt, the maximum 311 Gt and the 25th/75th interquartile range is 42 Gt/198 Gt. Note that values calculated by the IPCC (starting from 2010) are corrected here to make numbers comparable to values given above (starting in 2016).

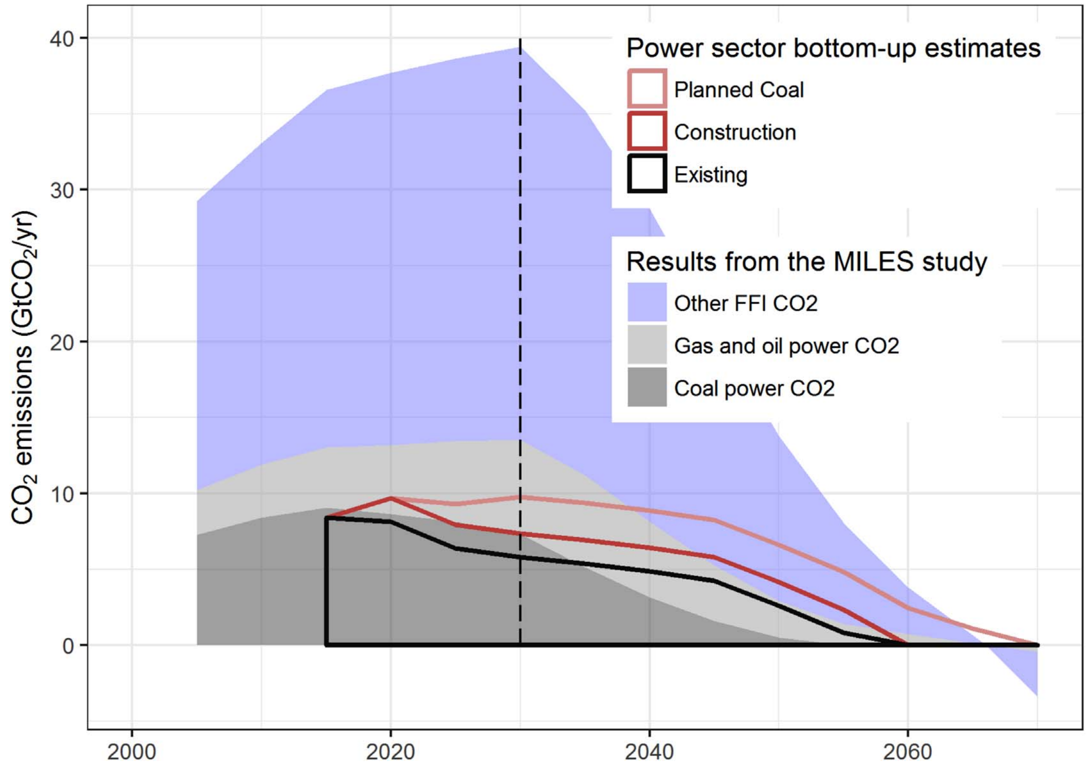

Figure 3. Bottom-up estimates of global CO_2 emissions committed from power plants that are existing, under construction or planned (bordered areas, [10, 16, 28]). Estimates are compared with optimal emission trajectories in a scenario that limits the increase of global mean temperature to 2 °C, taking (I)NDC targets into account [1]. Colored areas for comparison show modeled CO_2 emissions from fossil fuel combustion and industry (FFI) decomposed into three categories. Note that coal used with CCS is not shown for the bottom-up estimates.

near- and mid-term. Nevertheless, it projects an immediate decline in coal-fired capacities—even as current plans correspond to further increases.

If all coal-fired power plants currently announced, planned or under construction are realized, coal emissions will exceed the total emissions allowed by the entire power sector by 2040 (i.e. including emissions from gas- and oil-fired plants; see light and dark grey areas in figure 3) and by 2050 account for about half of the total fossil fuels emissions (including those from transport, industry and residential) projected in this scenario. This makes it impossible to achieve the required zero net emissions by 2065 without early retirement of power plants.

Increasing coal emissions could be counterbalanced by more ambitious reductions in other sectors, or sizable amounts of negative emissions in the future (e.g. by capturing CO_2 from the atmosphere and storing it in e.g. underground reservoirs) [30]. As such, ongoing investments in coal do not automatically render the 2 °C target impossible. However, as the most cost-efficient opportunities to reduce emissions are typically within the power sector [19], pursuing such paths would cause the costs of emission reduction after 2030 to increase significantly. Such an increase in mitigation costs could put governments under increased pressure by domestic interest groups to soften targets, thereby making ambitious domestic climate policies and future international cooperation less likely.

If UNFCCC member states are to achieve the goals set out in the Paris Agreement, they will need to reconsider their national energy and climate policies and derail current plans for additional coal fired power capacity. Despite recent cost reductions, renewable energy can still not compete with cheap coal and natural gas [31], in particular when intermittent renewable energy sources like wind and solar are deployed on a large scale [32]. Existing capital market constraints in developing and newly industrializing countries favor coal despite physical good conditions for capital-intensive renewable energy [33]. While shale gas has driven down natural gas prices in the US to levels nearly equal to those of coal (per GJ), in most other regions (particularly in Asia) coal has been the least-cost power generation option for the last decade [34]. For this reason, we caution against the view that the issue of coal will be solved more or less automatically by cheaper renewables. Instead, phasing out coal requires dedicated policies.

6. The political economy of phasing out coal

Our estimates suggest that—if completed—the current plans for new coal-fired capacity would likely close the door on ambitious climate change mitigation targets. Even though some planned coal-fired projects have been shelved in China and India in 2016, it is far from

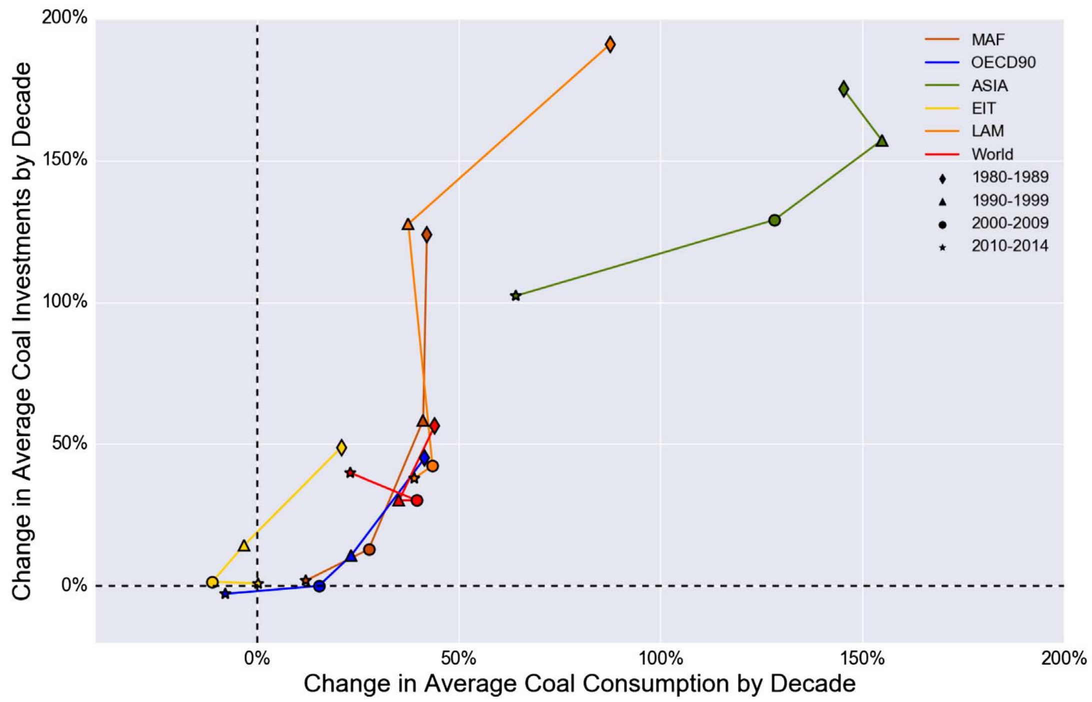

Figure 4. Decadal changes of average coal consumption in the electricity sector (*x*-axis) and average investment in coal-fired generation capacity (*y*-axis) for different regions (region categorization RC5 as defined in the IPCC AR5 [25]). Data source: [28, 35]. Note: please see figures S2 and S3 for annual changes.

clear that coal is indeed in decline, as other countries are ramping up their investments in coal-fired power plants. For instance, planned future investments in coal increased almost eightfold in Egypt, about doubled in Pakistan, and increased by more than half in Japan and the Philippines between 2015 and 2017 (see figure S1 in the supplementary information). This suggests that coal is, despite its severe implications for the climate as well as local air pollution, still regarded to be a reliable and affordable source of energy. This can be confirmed by looking at decadal data (figure 4). Although the rate of growth has slowed in recent years, investment as well as consumption of coal have, with very few exceptions, shown continuous growth over the last 40 years in all world regions.

As we have argued in section 5, even though coal use has grown less rapidly in recent years, coal-fired plants currently in the pipeline would almost completely exhaust the remaining carbon budget consistent with the Paris Agreement. In order to achieve international climate targets, coal consumption and coal investment need to decline substantially, i.e. show negative growth rates (lower left quadrant in figure 4). It is frequently argued that current investments in coal-fired capacity will lead to 'stranded assets' [36, 37]. Indeed, it is tempting to assume that—given its incongruity with international climate targets—today's investments in coal will need to be written off early. Some have warned that this might lead to a 'carbon bubble' with potential negative consequences for financial markets [36, 38]. However, this argumentation tends to ignore political economy obstacles. Instead of being stranded, current investments can also be seen as an indication that investors do not believe in future climate policy or that they are confident in their own lobbying power. Rather than assuming that coal power plants announced, planned, or already under construction will increasingly be shelved, policy environments allowing for credible commitment to the targets laid out in the Paris Agreement—i.e. that reduce coal use—need to be put into place.

Several possibilities to prevent the construction of new unabated coal-fired power plants (i.e. without CCS) have been proposed. A properly sequenced closure of coal mines in key supplier nations would squeeze coal out of the global energy system at relatively low economic costs [39]. On the level of power plants, performance standards that increase in stringency over time could provide incentives to forgo planned investments. Such foregone investments would occur if it was expected that the planned plants will not be in accordance with these standards in the future. Emphasizing the associated health co-benefits of a dedicated coal phase-out could substantially increase public support for policies to reduce coal consumption. Some countries, in particular China, have already closed existing coal power plants and shelved a number of plans for new construction, presumably due to local air pollution concerns [40]. For instance, an influential report estimates that the full social costs of GHG emissions are close to US$ 150 per tCO_2, of which air pollution caused by coal accounts for a substantial share [41]. Figuring these costs in the evaluation of energy investments would make coal economically unattractive even for countries for which climate change mitigation does not rank highly on the political agenda. Carbon pricing would make carbon-intensive coal economically unattractive and thus promote alternative, low-carbon, energy sources. Substantial additional benefits would also accumulate, such as raising revenues for the public budget [42].

Despite its comparatively low economic costs, any approach to phase out coal could be difficult to achieve politically. Dedicated compensation schemes, such as retraining and early retirement of employees, will need to be developed to ease the burden of adjustment [43]. Experiences from similar undertakings, such as Germany's nuclear phase out, or Iran's reform of subsidies for petrol and natural gas, could provide important insights on how to increase public acceptance of coal phase-outs. The feasibility of a transition away from unabated coal will also depend on available technological alternatives and accompanying policy instruments. For example, policies that de-risk investments into low-carbon technology can significantly lower the carbon price level necessary to induce a coal phase-out [44]. In addition, increased deployment of low-carbon energy sources will require improved grid integration to be able to deal with the variable availability of solar and wind power appropriately [32].

Efforts to phase out coal will also require support from the international community. Countries refraining from coal use or extraction should be compensated accordingly. Otherwise, poor countries are unlikely to bear the additional costs of clean energy sources [45], especially with regard to the required high initial investment costs in the face of capital constraints [44]. Such support could take the form of e.g. prioritized access to climate finance or other forms of multilateral development assistance [46], as well as preferential loans, de-risking instruments, or developing roadmaps and sharing of experiences regarding policy design. Multilateral development banks (MDBs) could apply shadow carbon prices for the evaluation of their investment portfolios in the range suggested by a recent report on carbon pricing [47]. Future rounds of negotiations under the UNFCCC or other international forums, such as the G-20, need to work in this direction.

7. Conclusions

This paper has shown that construction of all coal-fired power plants currently announced, planned or under construction would seriously endanger national and international climate targets. Although a number of countries, most prominently China, have shelved the construction of some coal-fired plants that had previously been under consideration, a sizable amount of coal-fired capacity is still announced, planned, or already under construction. Some countries have increased their planned future capacities substantially. If this coal-fired capacity comes to fruition, ambitious climate change mitigation targets would become much more difficult, or even infeasible, to achieve.

Recent cost reductions for renewable energy technologies give rise to the hope that governments will find it in their self-interest to implement cleaner energy sources. Yet, trusting that a large share of forthcoming coal-fired power plants will not be realized could turn out to be a gamble for the global climate. Even if costs for renewables continue to decline as they did in recent years, the way to a power system based on renewables could still be a tough one to master. Potential obstacles include technical problems (and additional costs) related to grid integration as well as the political influence of coal owners, utilities and unions representing workers that would be adversely affected by coal's demise. The vow of US President Donald Trump to support a declining coal industry clearly illustrates how political incentives can be more powerful than economic considerations in the formulation of energy policy. Once investments for new coal-fired power plants are sunk, these plants are unlikely to be shut down after only a few years of operation. In this case, technological improvements for renewable energies would most likely turn out to be 'too little, too late' to achieve the targets of the Paris Agreement. By contrast, policies to take most coal-fired power plants that are announced, planned or under construction out of the coal pipeline would constitute a smart hedging strategy decreasing political uncertainty and allowing for credible commitment to ambitious long-term mitigation targets [48].

Acknowledgments

We thank Ted Nace and Christine Shearer from CoalSwarm for information on ownership structures of coal plants and assistance with the Global Coal Plant Tracker database, Jan Christoph Minx for the 2016 updated data on carbon budgets and Lorenzo Montrone, Tom Schulze and Fee Stehle for excellent research assistance. We also thank Kristin Seyboth and participants of the International Conference on Fossil Fuel Supply and Climate Policy in Oxford for valuable comments. We gratefully acknowledge funding from the German Federal Ministry of Education and Research (BMBF), funding code 01LS1610B (pep 1.5).

ORCID iDs

Michael Jakob https://orcid.org/0000-0001-5005-3563

References

[1] MILES Project Consortium 2015 Beyond the Numbers: Understanding the Transformation Induced by INDCs (www.iddri.org/Publications/Beyond-the-numbers-Understanding-the-transformation-induced-by-INDCs)

[2] UNEP Emissions Gap Report 2015 A UNEP Synthesis Report 2015 (https://uneplive.unep.org/media/docs/theme/13/EGR_2015_301115_lores.pdf)

[3] Peters G P *et al* 2017 Key indicators to track current progress and future ambition of the Paris agreement *Nat. Clim. Change* **7** 118–22

[4] Creutzig F, Agoston P, Goldschmidt J C, Luderer G, Nemet G and Pietzcker R C 2017 The underestimated potential of solar energy to mitigate climate change *Nat. Energy* **2** 17140

[5] Bloomberg New Energy Finance 2017 New Energy Outlook (https://about.bnef.com/new-energy-outlook/)

[6] BP Statistical Review of World Energy 2017 (www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bpstatistical-review-of-world-energy-2017-full-report.pdf)

[7] Ritchie J and Dowlatabadi H 2017 The 1000 GtC coal question: are cases of vastly expanded future coal combustion still plausible? *Energy Econ.* **65** 16–31

[8] Greenpeace 2015 Coal's terminal decline (www.greenpeace.org/international/Global/international/briefings/climate/COP21/Coals-decline-report-PRESS-new.pdf)

[9] van Breevoort P *et al* 2015 The Coal Gap: planned coal-fired power plants inconsistent with 2 °C and threaten achievement of INDCs (http://climateactiontracker.org/assets/publications/briefing_papers/CAT_Coal_Gap_Briefing_COP21.pdf)

[10] Davis S J and Socolow R H 2014 Commitment accounting of CO_2 emissions *Environ. Res. Lett.* **9** 84018

[11] Erickson P, Kartha S, Lazarus M and Tempest K 2015 Assessing carbon lock-in *Environ. Res. Lett.* **10** 84023

[12] Unruh G C U 2000 Understanding carbon lock-in *Energy Policy* **28** 817–30

[13] Davis S J, Caldeira K and Matthews H D 2010 Future CO_2 emissions and climate change from existing energy infrastructure *Science* **329** 1330–3

[14] Bertram C, Johnson N, Luderer G, Riahi K, Isaac M and Eom J 2015 Carbon lock-in through capital stock inertia associated with weak near-term climate policies *Technol. Forecast. Soc.* **90** 62–72

[15] Pfeiffer A, Millar R, Hepburn C and Beinhocker E 2016 The 2 °C capital stock for electricity generation: committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy *Appl. Energy* **179** 1395–408

[16] Shearer C, Ghio N, Myllyvirta L, Yu A and Nace T Boom and Bust Tracking the global coal plant pipeline Coal Swarm, Sierra Club and Greenpeace [Internet] 2017 (https://endcoal.org/global-coal-plant-tracker/reports/boom-bust-2017/)

[17] IEA 2016 *World Energy Outlook* (Paris: International Energy Agency)

[18] EDGAR 2015 *EDGAR—Emission Database for Global Atmospheric Research* (http://edgar.jrc.ec.europa.eu/overview.php?v=GHGts1990-2012)

[19] UNFCCC 2015 (I)NDCs as communicated by Parties (www4.unfccc.int/submissions/(I)NDC/Submission%20Pages/submissions.aspx)

[20] Luderer G *et al* 2016 Description of the REMIND model (Version 1.6)

[21] Steckel J C, Edenhofer O and Jakob M 2015 Drivers for the renaissance of coal *Proc. Natl Acad. Sci.* **112** E3775–81

[22] Qi Y, Stern N, Wu T, Lu J and Green F 2016 China's post-coal growth *Nat. Geosci.* **9** 564–6

[23] Urgewald 2017 Companies on Coal Expansion Course Exposed (coalexit.org)

[24] Climate Action Tracker 2017 Tracking (I)NDCs (http://climateactiontracker.org/indcs.html)

[25] IPCC 2014 Climate change 2014: mitigation of climate change *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press)

[26] IPCC 2015 Climate change 2014: synthesis report *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed R K Pachauri and L A Meyer (Switzerland: IPCC) p 151

[27] Millar R J *et al* 2017 Emission budgets and pathways consistent with limiting warming to 1.5 °C *Nat. Geosci.* **10** 741–8

[28] CoalSwarm 2017 Global Coal Plant Tracker

[29] Davis S J, Caldeira K and Matthews H D 2010 Future CO_2 emissions and climate change from existing energy infrastructure *Science* **329** 1330–3

[30] Fuss S *et al* 2014 Betting on negative emissions *Nat. Clim. Change* **4** 850–3

[31] Kuang M 2014 APAC LCOE UPDATE. A race between renewable penetration and fuel prices Bloomberg New Energy Finance (http://first.bloomberglp.com/documents/93517_LevelisedCostofElectricityUpdate.pdf)

[32] Hirth L, Ueckerdt F and Edenhofer O 2015 Integration costs revisited—an economic framework for wind and solar variability *Renew. Energy* **74** 925–39

[33] Schmidt T S 2014 Low-carbon investment risks and de-risking *Nature Clim. Change* **4** 237–9

[34] World Energy Council 2013 World Energy Perspective Cost of Energy Technologies (www.worldenergy.org/wp-content/uploads/2013/09/WEC_J1143_CostofTECHNOLOGIES_021013_WEB_Final.pdf)

[35] IEA 2016 World Energy Statistics

[36] Initiative CT 2013 *Unburnable Carbon: 2013 Wasted Capital and Stranded Assets* (Carbon Tracker and Grantham Research Institute) (http://carbontracker.live.kiln.digital/Unburnable-Carbon-2-Web-Version.pdf)

[37] McGlade C and Ekins P 2015 The geographical distribution of fossil fuels unused when limiting global warming to 2 °C *Nature* **517** 187–90

[38] Prudential Regulation Authority 2015 The impact of climate change on the UK insurance sector (https://www.bankofengland.co.uk/prudential-regulation/publication/2015/The%20impact%20of%20climate%20change%20on%20the%20UK%20insurance%20sector)

[39] Collier P and Venables A J 2014 Closing coal: economic and moral incentives *Oxford Rev. Econ. Pol.* **30** 492–512

[40] Reuters 2015 Chinese capital shuts third coal-fired plant in war on smog (www.reuters.com/article/us-china-pollution-beijing-idUSKBN0MG1D120150320)

[41] Coady D, Parry I W H, Sears L and Baoping S 2015 How large are global energy subsidies? (www.imf.org/external/pubs/cat/longres.aspx?sk=42940.0)

[42] Edenhofer O *et al* 2015 Closing the emission price gap *Glob. Environ. Change* **31** 132–43

[43] Trebilcock M J 2014 *Dealing with Losers: The Political Economy of Policy Transitions* (Oxford: Oxford University Press)

[44] Hirth L and Steckel J C 2016 The role of capital costs in decarbonizing the electricity sector *Environ. Res. Lett.* **11** 114010

[45] Jakob M and Steckel J C 2014 How climate change mitigation could harm development in poor countries WIREs *Clim. Change* **5** 161–8

[46] Steckel J C, Jakob M, Flachsland C, Kornek U, Lessmann K and Edenhofer O 2017 From climate finance toward sustainable development finance: from climate finance toward sustainable development finance *Wiley Interdiscip. Rev. Clim. Change* **8** e437

[47] Carbon Pricing Leadership Coalition 2017 Report of the High-Level Commission on Carbon Prices (www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices/)

[48] Nemet G F, Jakob M, Steckel J C and Edenhofer O 2017 Addressing policy credibility problems for low-carbon investment *Glob. Environ. Change* **42** 47–57