Socio-political feasibility of coal power phaseout and its role in mitigation pathways

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Abstract: In IPCC pathways limiting warming to 1.5˚C, global coal power generation declines rapidly, due to its emissions intensity and substitutability. However, we find that in highly coal-dependent countries - China, India and South Africa - this translates to a national decline twice as fast as achieved historically for any power technology in any country, relative to system size. This raises questions about socio-political feasibility. Here we constrain an integrated assessment model to the Powering Past Coal Alliance's differentiated phaseout timelines of 2030 in OECD/EU and 2050 elsewhere, which for large coal consumers lies within the range of historical transitions. We find that limiting warming to 1.5˚C then requires CO2 emissions reductions in the Global North to be 50% faster than if this socio-political reality is neglected. This additional mitigation is focused in Europe and the USA, in transport and industry, and implies faster decline in global oil and gas production.

The rapid phaseout of coal-fired power generation is key to achieving the goals of the Paris climate agreement, and urgent for reducing air pollution impacts on health[1]. However, the pace of global phaseout proposed in techno-economic optimising models may be "at the limits of societal feasibility"[2] in countries that depend heavily on coal. IPCC-assessed 1.5˚C pathways see a median 88% worldwide reduction in unabated coal generation from 2020 to 2030 (Fig. 1), and considerably faster declines in coal consumption as a whole (73%) than oil (10%) or fossil methane gas (hereafter referred to as gas) (14%).

Power generation is the primary use of coal today, accounting for over 60% of total global consumption[3]. However, since coal provides 26% of power generation in high-income countries, compared to 49% in low- and middle-income countries[4], an excessive focus on coal phaseout as the primary mitigation tool can create a perverse narrative that developing countries must contribute more to mitigation than developed countries.

This study explores socio-political feasibility - a key dimension of feasibility that is not well characterised in integrated assessment models (IAMs) - in relation to coal power phaseout. Unlike physical feasibility, societal feasibility does not indicate hard limits[5], but is conceived as a comparative concept, wherein path A is judged more or less feasible than path B[6].

There are many societal factors determining a feasible pace of transition, including the political influence of affected actors (workers, companies, communities), the economic costs, the values of decision-makers and social acceptance of change. In particular, the dominance of an incumbent causes socio-political inertia in the energy system due to the threat of lost jobs and stranded assets[7],[8],[9], often referred to as "carbon lock-in"[10],[11],[12]. As a quantitative indicator of these multiple and complex dimensions, here we benchmark proposed coal phaseouts at the national level against the fastest historical energy transitions (which in turn were constrained by these same types of factors).

The feasible pace of energy transition in IAMs, compared to the historical record, has been studied in relation to diffusion rates of new technologies[13,14], but less in decline of incumbent technologies and often only at global level[15]. Yet Vinichenko et al.[16] find that half of IPCC 1.5˚C scenarios see a faster decline of coal power in Asia than any historical power transition. This important finding may even understate the problem, as regional aggregation masks both the concentration of coal consumption in a few countries, and the socio-political constraints that manifest at a national level[17].

Our analysis proceeds through three stages. First, we draw lessons from historical transitions in the power sector across 144 countries, using data from the IEA dating back to 1960 for OECD countries and 1971 for non-OECD countries. We map the fastest transitions for each country on two important general dimensions of system inertia that make transition more difficult: the size of the system and the degree of the incumbent technology's dominance within it. In contrast to techno-economic dimensions of feasibility - reflected for example in age of generation fleet[18], growth rate of generation[19,] flexibility of the electricity system[20], and wider institutional capacity[21] - socio-political feasibility reflects resistance to change by actors such as companies, workers, subnational governments and state institutions. The size of a country's generation system is important because larger systems carry more inertia[22,23], as in the analogy of turning a supertanker. A larger system has more power plants, more employees and more or larger companies, each slowing the process of transition. Meanwhile, dominance by an incumbent creates institutional and societal feedbacks that slow system change[24]. To partly capture dominance effects, we measure transition pace through the percentage-point decline in a technology's or fuel's share of generation (rather than using a negative compound growth rate, which would have omitted this dimension): a percentage-point decline can only be high where a technology's share is initially high.

Second, we use the TIAM-UCL model - which has a typical IAM pace of coal phaseout (Fig. 1) - to disaggregate the global coal power phaseout by country and compare this with historical experience on the two dimensions above. The Powering Past Coal Alliance (PPCA)[25] – an international coalition established in 2017 to encourage countries to phase out coal power –

proposes a differentiated phaseout timeline: by 2030 in OECD and EU members, and by 2050 in other countries. We also compare this pace with the historical record.

Third, we constrain TIAM-UCL to reduce coal generation no faster than that timeline in any country, to explore how this affects the balance of mitigation across countries, sectors and fuels. This can be considered a good measure of feasible pace of coal phaseout both because we find that it falls within the range of historical transitions (Results), and because it is a "real-world" determination (rather than a modeller's own estimation) of what is judged societally feasible for different countries and politically feasible in terms of differentiating efforts between them.

RESULTS

Historical transitions in national power generation

We first consider the historical transitions, comparing countries' fastest 10-year reduction in a fuel or technology's share of generation, against the size of the generation system (Fig. 2). Several observations may be made. First, the graph confirms the prior finding[26] that faster transitions are possible in smaller power systems. To see this intuitively, the "transition" can be almost instantaneous in small countries, such as Malta's 2012-17 conversion of Delimara, its sole power station, from heavy oil to gas. As systems get larger, less rapid transitions have been achieved.

Second, there is a large spread. Some countries' power systems have been highly stable over the period, especially where they are dominated by a single source. For example, in Norway, where hydro has consistently provided above 94% of power, the fastest transition was a mere 5 percentage point decline in 2000-2010. Other countries have gone through two or more major transitions, such as Togo, Malaysia, Denmark and Japan.

Third, the countries closest to the "world record" pace of transition are all relatively wealthy, reinforcing the causal link between socioeconomic capacity and phaseout feasibility[27,28]. Among poorer countries, the fastest transitions were generally driven primarily by external events, and often to the countries' cost. For example, modestly-growing gas and renewables gained a 22% share of Jamaica's generation only after oil generation collapsed due to oil price rises[29].

Modelled coal decline pathways under Paris-aligned scenarios

Using the global energy system model TIAM-UCL to disaggregate global change to the national level, we compare the modelled 2020-30 change in coal power on the "average" and "world record" of historical transitions (defined in Fig. 2), for the ten largest (in 2019) coal-power-consuming countries[30 (Fig. 3a)]. For China, India and South Africa, coal declines around twice as fast as any decline seen for any country, relative to its size. Comparable pace has occurred only in much smaller countries: for example, China would need to reduce its coal power in the 2020s as quickly as Belgium in the 1960s (Fig. 2) – a system just 0.4% of the size of China's. In addition, China, India and South Africa must not only reduce coal's share of generation respectively by 20, 25 and 30 percentage points in a decade, but must do so for three decades in a row.

We now consider these same 10 countries, but with coal power phased out by the 2030/2050 deadlines adopted by the PPCA, assuming a linear decline in coal's share of generation to zero on those dates (Fig. 3b). This is instructive, because it reflects a phaseout pace at the high end of political ambition in the real world. In this case, most of the top 10 countries are just inside or just outside the "world record"; only Indonesia and Russia decline more slowly than the average line. This suggests that for most of the largest coal consumers, the PPCA timelines are close to the limits of feasibility based on historical precedent, such that it is hard to imagine a faster phaseout; in other words, they could be characterised as "difficult but possible". Note that worldwide adoption of PPCA would be a significant increase of ambition from current levels for many countries, including the largest coal consumers; note also that adoption in itself does not guarantee implementation of the commitments. This has implications for where, how and how much mitigation efforts must be made, which we turn to in the next section. However, Indonesia, Russia and some smaller or less coal-dependent power systems may be able to move faster than this timeline.

Consequences of slower coal phaseout for 1.5°C pathways

We now assess the implications for the wider energy system transition if the pace of coal decline in key coal consuming regions is constrained. We constrain the model to phase out coal power no faster than the PPCA timeline in each country/region, and compare 1.5°C scenarios with (labelled 'PPCA') and without (labelled 'Default') this constraint (see Methods).

The slower decline in coal generation leads to a change in fossil fuel primary energy (Fig. 4a and 4b). Under the PPCA scenario, slower coal decline is compensated by more rapid reduction in gas and oil, with gas peaking earlier in 2025, compared to 2030 in the unconstrained case. As for where this is produced, the acceleration of decline in oil and gas is unevenly distributed between regions. The United States, Australia and Mexico see the largest proportional reductions in cumulative gas production over the period 2020-2050 with respectively 20%, 12% and 11% (Fig. 4c). Western Europe (Norway) and the United States have the largest proportional reductions in cumulative oil production with 19% and 12% respectively (Fig. 4d).

A key impact of the constraint is a shift in mitigation effort at the regional level. A slower decline in coal-dominated non-OECD countries such as China and India (with a 2050 PPCA coal phaseout deadline) means that other regions will need to mitigate faster (Fig. 5a). We find the annual rate of change of CO2 emissions accelerates from -10.4% to -16.6% in the United States, from -8.1% to -12.5% in Europe, and from -7.7% to -10.7% in Other Global North. In China, India and Other Global South, the average rate of emissions reduction is unchanged over 2020-2045, but the timing is delayed, with slower reductions in 2020-2030 and faster over 2035-2045.

From a sectoral perspective, with the increase in power sector emissions, it is the transport sector that provides the majority of additional mitigation required, with a contribution also from the industry sector (Fig. 5b, 5c). Overall, the effect is that cumulative emissions are higher to 2045 under the PPCA case but are then balanced by additional mitigation in 2050 and beyond, as shown by the 'net change' trend line.

More specifically, the transport reductions come primarily from faster reduction in oil use in cars (mostly before 2035), road freight (2035-2045) and shipping (2040 to 2050) (Fig. 5d).

In many IAMs, including TIAM-UCL, the carbon price is a key mechanism for driving mitigation efforts, often as a proxy for more qualitative real-world policies (in contrast, for example, to the International Energy Agency's World Energy Model, which uses multiple layers of specific policy assumptions and correspondingly lower carbon prices). In the 1.5°C PPCA scenario, the effective carbon price rises to $700/ton in 2050, compared to $420/ton in the Default scenario (Supplementary Figure 2).

DISCUSSION

This study reinforces the importance of rapidly phasing out coal power generation, but observes that the challenge of coal phaseout is unevenly distributed. We make this judgement on the basis of the size and diversity of countries' power systems, even before considering typical measures of international climate equity such as differentiated responsibilities and respective capabilities. While efforts to reflect social or political values in models are in their infancy[31,32,33], the very purpose of global energy system modelling in informing policy may be under challenge if some solutions (including economically optimal ones) are not socio-politically feasible.

Models deploy multiple mitigation options, and less mitigation in one area can be balanced by more mitigation in another, while achieving the same overall emissions or temperature goal. Our comparative analysis enables us to change the question from "Is 1.5°C feasible?" to "What would be a more feasible path to 1.5°C?" This is important because modelled pathways aligned with the Paris goals influence the ambition towards which governments aspire, especially given the pathways' prominence in IPCC reports[34,35]. If such pathways rely on an infeasible pace of coal power phaseout, they risk guiding policies towards insufficient mitigation in other countries, sectors and fuels.

The PPCA aims "to lead the rest of the world in committing to an end to unabated coal power, ... recognis[ing] that not all countries can completely phase out the use of unabated coal at the same rate"[36]. Its differentiated timelines were based on an IAM study, but adding equity considerations to complement the least-cost analysis[37]. Although they were not designed using a feasibility analysis, we find the PPCA's timelines fall within - though often at the limits of - historical experience.

We are not claiming that our PPCA-based scenario reflects a politically optimal or most-feasible solution, rather that it addresses one large feasibility issue in the coal sector that is common to many energy system models. Like other models, TIAM-UCL contains numerous other constraints to reflect feasibility, each informed by the literature and/or statistical or econometric data. These constraints include the pace at which infrastructure or systems can be built out, the availability of land or resources, and the pace at which consumer choices change. There is a large literature on feasibility of levels of carbon dioxide removal in IAMs[38],[39], again reflected in TIAM-UCL and other models, and on more techno-economic feasibility indicators such as carbon price, mitigation cost or flexibility of mitigation options[40],[41].

As previously noted, socio-political feasibility reflects the relative political efforts needed to overcome multiple and complex societal inertias, rather than hard limits. It is thus possible that future transitions could proceed faster than past ones. However, the historical record provides an instructive benchmark against which to measure the challenges, since past transitions were constrained by similar inertias, sometimes outweighed by strong incentives for change. The historical transitions considered in this study include several driven by major policy efforts, such as many countries' reduction in oil power generation following the price crises of the 1970s, Japan's phaseout of nuclear power following the 2012 Fukushima accident, and the UK's world-leading phaseout of coal power over the last decade. They also include rapid changes driven by events that have either opened access to fuels (e.g. South Africa after apartheid; the Netherlands' and Azerbaijan's discovery of gas) or closed it (e.g. Iraq's loss of Iranian gas during the 1980-88 war).

One reason feasibility questions arise in optimisation modelling is because a "pure", unconstrained optimisation model would tend to near-instantaneously switch the system to whichever options are cheapest. In order to make an optimisation model useful for policy, constraints must be included to achieve greater realism. This goes to the heart of what model results mean and represent. Li and McDowall[42] observe that "the result is not a strict techno-economic optimisation, but something slightly different: a *socio-technically plausible optimisation*. This has different epistemic claims, i.e. it is claiming not only that it is the optimum of a given set of possibilities, but also that the possibility space being assessed represents the *realistic* space in socio-technical terms."

However, applying too many constraints can lead to the modeller effectively steering the model towards their pre-judged ("realistic") pathway[43]. The same concern arises in simulation models, where programmed rules are explicitly used to represent how the real world works. Furthermore, judgments of what is realistic and/or socio-politically feasible are inherently values-based[44]. For these reasons, modellers are understandably reticent about adding more constraints or rules; yet at the same time policymakers need models to be realistic and relevant[45]. A central lesson of this study is that a decision *not* to apply a constraint may be as impactful as a decision to apply one, and may rely as much on a value judgement or on the modeller's subjective perceptions of where challenges lie[46]. Indeed, models tend to be conservative about feasible growth of new technologies, even while rapid decline of incumbents in unconstrained[47]. To reflect feasibility in IAMs, then, a key may be to make the judgments more transparent and systematic[48].

Expanding comparative feasibility analysis beyond coal power phaseout suggests a fruitful area of future research, to reveal the implicit rates of growth and decline that arise from models alongside explicit user constraints. This would allow model users to see which judgments have been made, and accept or challenge them. It could also enhance policymakers' ability to interpret and understand models.

In the example raised in this study, energy system models have rightly highlighted the relative advantages of coal phaseout in mitigation, but relied on it to an extent that raises socio-political feasibility concerns in the countries where coal use is concentrated. Rebalancing mitigation measures could show more feasible paths to achieving the Paris Agreement goals.

METHODS

Historical transitions

The first part of this paper compares the pace of proposed coal phaseouts with the fastest historical transitions in the power generation sector.

Data on countries' historical shares of power generation are sourced from IEA (2019), going back to 1960 for OECD countries and 1971 for non-OECD countries. For each of the 144 countries in the IEA dataset, the fastest percentage-point reduction in a fuel's share of power generation over any ten-year period is identified, and plotted against the country's total generation at the start of the 10-year period. The rationale for this approach is as follows.

While intuitive and simple, the weaknesses of the percentage-point-decline metric are that it reflects only partial transitions and that it may be distorted in smaller countries where there are temporary effects or a highly fluctuating power mix. However, in both respects this suggests that present transitions may be slower than comparison with the historical transitions suggests; accounting for these effects would thus lead to stronger results than we find. Furthermore, since it measures change in a technology's share of total generation, it does not account for growth of the system as a whole: declines may be exaggerated in fast-growing systems.

We use the timelines of the Powering Past Coal Alliance (PPCA) as a measure of maximal political ambition, since those timelines have been selected by governments seeking to form a large coalition. At the COP26 climate summit, 46 national governments signed a statement committing to coal phaseout "in the 2030s (or as soon as possible thereafter) for major economies and in the 2040s (or as soon as possible thereafter) globally"; however, we have not used this new timeline because the definitions and dates are unspecific and imprecise[49].

In this comparison (unlike the subsequent modelling), we interpret the PPCA timeline as a linear decline over the three decades 2020-2050 for non-EU, non-OECD countries. In reality, an s-curve is a more likely shape, and so a PPCA phaseout may see faster decline in the 2030s and slower in 2020s and 2040s; however, we use the linear assumption since we focus the comparison on the 2020s (which is the period of fastest decline in default modelled scenarios) and the decline may be seen as an average over the full three-decade period.

The TIAM-UCL model

To explore the implementation of the PPCA and its implications for the phase out of coal generation, we used the TIMES Integrated Assessment Model at University College London (TIAM-UCL)[50]. This model provides a representation of the global energy system, capturing primary energy sources (oil, fossil methane gas, coal, nuclear, biomass, and renewables) from production through to their conversion (electricity production, hydrogen and biofuel production, oil refining), their transport and distribution, and their eventual use to meet energy service demands across a range of economic sectors. Using a scenario-based approach, the evolution of the system over time to meet future energy service demands can be simulated, driven by a least-cost objective. The model uses the TIMES model framework (described in SI section 6).

The model represents the countries of the world as 16 regions (SI section 4), allowing for more detailed characterisation of regional energy sectors, and the trade flows between regions. Upstream sectors within regions that contain members of OPEC are modelled separately, so as an example, the upstream sector in the Central and South America (CSA) region will be split between OPEC (Venezuela) and non-OPEC countries. Regional coal, oil and fossil methane gas prices are generated within the model. These incorporate the marginal cost of production, scarcity rents (e.g. the benefit foregone by using a resource now as opposed to in the future, assuming discount rates), rents arising from other imposed constraints (e.g. depletion rates), and transportation costs but not fiscal regimes. This means full price formation, which includes taxes and subsidies, is not captured in TIAM-UCL, and remains a contested limitation of this type of model[51]. Further information on the model characterization of fossil resources can be found in SI section 5.

The model has a limited number of technological options to remove emissions from the atmosphere via carbon dioxide removal, including a set of bioenergy with carbon capture and storage (BECCS) technologies, in power generation, industry, and in H_2 and biofuel production. The primary limiting factor on these technologies is the global bioenergy resource potential, set at a maximum 112 EJ per year, in line with estimates from the UK Committee on Climate Change (CCC) biomass report[52]. This is a lower level than the biomass resource available in many other integrated assessment scenarios for 1.5°C (which can be up to 400 EJ/yr)[53,54], and is more representative of an upper estimate of the global resource of truly low-carbon sustainable biomass based on many ecological studies[55] (Supplementary Table 3). TIAM-UCL also includes CO_2 emissions from land use, land use change and forestry (LULUCF) at the regional level, based on exogenously defined data from the IMAGE model[56]. Here we use a trajectory based on that model's SSP2 RCP2.6 scenario which leads to global net negative CO_2 emissions from LULUCF from 2060 onwards.

Future demands for energy services (including mobility, lighting, residential, commercial and industrial heat and cooling) are exogenously defined and drive the evolution of the system so that energy supply meets demands across the time horizon (i.e. 2005-2100). Here we use energy service demands derived from Shared Socio-economic Pathway 2 (SSP2)[57]. The model was also run with an elastic demand function, with energy service demands reducing as the marginal price of satisfying the energy service increases. Decisions around what energy sector investments to make across regions are determined based on the cost-effectiveness of investments, taking into account the existing system today, energy resource potential, technology availability, and crucially policy constraints such as emissions reduction targets. The model time horizon runs to 2100, in line with the timescale typically used for climate stabilisation.

In conjunction with a cumulative CO_2 budget, an upper limit is placed on annual CH_4 and N_2O emissions based on pathways from the IPCC's Special Report on 1.5°C scenario database[58]. We select all pathways that have a warming at or below 1.5°C in 2100 and take an average across these scenarios to derive a CH_4 and N_2O emissions trajectory that is in line with a 1.5°C world. Further information on key assumptions used in the model is provided in SI section 4. The TIAM-UCL model version used for this analysis was 4.1.1, and was run using TIMES code 4.2.2 with GAMS 27.2. The model solver used was CPLEX 12.9.0.0. Further detail on the model version used can also be found in Welsby et al. 2021[59].

Scenario design / implementation

The scenarios modelled using TIAM-UCL in this work aim to address two key sensitivities which act to shape our findings.

Firstly, while the deadline for the cessation of coal electricity generation in each country is clear under PPCA, the pathway from today to that time is not. With this in mind we explore four options for the shape of the decline constraint on coal generation within each TIAM-UCL region. This constraint acts to ensure that over time a minimum amount of coal generation is still in each power system up to the phase out year. We note that this is a lower constraint in the sense that the model can choose to increase coal generation above the minimum specified along the trajectory, although, given the global carbon budgets described below, it is generally unlikely to do so. The aim here is to span a wide range of potential options so that we can understand how sensitive our results are to this particular modelling assumption. To that end we include (SI section 2):

i) A linear decline from today to the phase out year on share of coal generation within the power system (PPCA-Linear)

ii) An s-curve or logistic function on share of coal generation from today to phase out with a mid-point of 2035. This is our central case and it is the results from this scenario that we display throughout the main manuscript (PPCA-LogisticShare)

iii) An s-curve on absolute coal generation from today to phase out with a mid-point of 2035 (PPCA-LogisticAbs)

iv) An s-curve on absolute coal generation from today to phase out with a mid-point of 2040 (PPCA-LogisticAbs40)

The functional form of the logistic function used here is:

$$f(t) = F - \frac{F}{(1 + e^{-k(t-t_0)})}$$

where F is the asymptote, k determines the steepness (here we use k = -0.46, so that in 2050 0.1% of the asymptote value is reached) and t_0 is the mid-point of the s-curve. Applying this function to absolute coal generation and the share of coal in the power mix (in separate cases as outlined above), creates four distinct and plausible decline pathways (Supplementary Figure 4) for various countries and Europe. We observe that the result in some of these pathways, e.g. PPCA-Linear, in some countries, e.g. India, is that absolute coal generation first declines and then increases between 2030 and 2040. This occurs because of the interaction between a rapidly growing power sector, in terms of generation, and the decline pathway which forces a minimum amount of power to come from coal generation.

The choice of the s-curve is informed by standard modelling approaches for technology diffusion[60], while Marchetti and Nakicenovic[61] theorise a logistic s-curve also for decline of incumbents. It also follows the intuition that initial efforts to reduce coal generation will slowly bend the curve, before moving into a phase of rapid decline, then slowing down as the last plants become more difficult to remove as they play a specific role in supporting parts of the system. We select our central case, i.e. PPCA-LogisticShare, because it offers a balanced position between our four coal decline constraints in terms of its global carbon price trajectory (see Supplementary Figure 2), i.e. it sits between the extremes of the options explored here.

For TIAM-UCL regions which contain both OECD/EU and non-OECD/EU countries, we assume today's fraction of OECD/EU coal generation in absolute amount or share terms declines linearly to phase out (2030) while the non-OECD/EU fraction is exposed to the pathway constraints defined above.

Secondly, the decarbonisation ambition level, expressed here in terms of a carbon budget and associated probability of limiting warming to a certain level above pre-industrial temperatures, substantially impacts the energy system transition modelled by TIAM-UCL. Here we opt to model two cumulative budgets (from 2018): i) a 580 GtCO2 case with a 50% probability of limiting warming to 1.5°C and ii) a 1170 GtCO2 case with a 66% probability of limiting warming to 2°C, both taken from the IPCC's Special Report on 1.5 Degrees[62]. The former, our principle case, broadly captures a Paris Agreement aligned world while the latter contrasts this with a sizable drop in ambition.

Data availability

The results data and key source data in the figures (including in the Supplementary Information) are available via Zenodo at https://zenodo.org/record/7313951#.Y25lpuTP2Uk. Source data are provided with this paper.

Code availability

The underlying code (mathematical equations) for the model is available via GitHub (https://github.com/etsap-TIMES/TIMES_model). The full model database is also available via Zenodo (https://zenodo.org/record/7313951#.Y25lpuTP2Uk). Given the complexity of the model, further guidance will be provided on model assumptions upon reasonable request from the corresponding author.

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Contributions

G.M. designed the study, with contributions from S.P. G.M. compiled historical data and conducted the comparison of phaseout pace. J.P., S.P and D.W. conducted the TIAM-UCL modelling with contributions from G.M. S.P. led on presentation of modelling results. D.W. led on supplementary information. G.M. led on drafting of manuscript, with contributions from all.

Competing interests

The authors declare no competing interests.

Figure legends

Fig. 1: Decline in fossil fuel usage from 2020 to 2030 in IPCC 1.5°C low-overshoot pathways and in TIAM-UCL. Change in fossil fuel (a) primary energy and (b) unabated power generation. Red lines show the core 1.5C- scenario in TIAM-UCL (referred to later in this paper as "default"). Boxes show first quartile, median and third quartile. Whiskers show maxima and minima, excluding outliers, which are shown as dots. n=95. IPCC pathway data taken from AR6 Scenario Explorer and Database hosted by IIASA, https://data.ene.iiasa.ac.at/ar6/

Fig. 2: Countries' fastest 10-year declines in a technology's generation share, 1960-2018 for OECD countries and 1971-2017/18 for non-OECD countries. For each country, the fastest percentage-point reduction in a fuel's share of power generation over any ten-year period is plotted against the country's total generation at the start of that period. The full data are tabulated in Supplementary Data 1. The dashed line shows the least-squares best fit, and may be interpreted as an "average" pace of all countries' fastest transitions, relative to the size of their generation systems.

The solid line is the closest line to the x-axis that contains all the points, and represents the "world record" of the fastest transitions by the fastest countries. Note that these lines are included to illustrate the range of the data set rather than hypothesise a particular relationship. While most historic transitions have been driven by technical and economic factors more than deliberate policy, two well-known policy-driven transitions are also plotted for illustration, marked with crosses: the UK's climate-motivated coal phaseout in recent years and Japan's post-Fukushima nuclear phaseout, neither was that country's fastest transition.

Fig. 3: Coal power decline, 2020-30 under climate constraints, compared to historical power transitions. For ten largest coal-consuming countries, implied 2020-30 reduction in coal share of generation**,** a) in 1.5C_default scenario in TIAM-UCL; b) on PPCA timeline assuming linear decline from 2020 to 2030 (OECD/EU) or from 2030 to 2050 (other countries)s. Red lines indicate fastest historical transitions from Fig. 2

Fig. 4. Energy system implications of PPCA constraint in 1.5°C scenario. a) Global fossil fuel production trajectories, 2020-50, with (labelled 'PPCA') and without (labelled 'Default') constraint on coal power phaseout to PPCA timeline; b) change in cumulative production under PPCA compared to default scenario and differences as a percentage of default scenario cumulative production, and c) change in regional gas production and d) regional oil trajectories under the PPCA 1.5°C scenario, relative to non-PPCA case, 2020-50. The red dashed line shows the overall % change for global production.

Fig. 5. CO2 emissions with and without PPCA constraint in the 1.5°C scenario. a) Annual rate of change of CO2 emissions under 1.5°C PPCA and Default scenarios, 2020-2045. The time horizon in the plots only extends to 2045, as for many countries, CO2 emissions are negative in 2050 and therefore an annual rate of change cannot be calculated. OGS = Other Global South (to include Africa, Latin America, Other Developing Asia, Mexico, and Middle East); OGN = Other Global North (to include Canada, Australia, Japan, South Korea, and Russia and former Soviet states). b) Total CO2 emissions for selected sectors under PPCA and default cases. The buildings sector is not shown, because there is no significant difference in buildings emissions between the PPCA and Default scenarios. c) difference in sectoral CO2 emissions between PPCA and default cases d) difference in transport sector CO2 emissions between PPCA and default cases.

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