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Coal-exit health and environmental damage reductions outweigh economic impacts

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Cheap and abundant coal fuelled the industrialization of Europe, North America and Asia[1]. However, the price tag on coal has never reflected the external cost to society; coal combustion produces more than a third of today's global CO_2 emissions and is a major contributor to local adverse effects on the environment and public health, such as biodiversity loss and respiratory diseases. Here, we show that phasing out coal yields substantial local environmental and health benefits that outweigh the direct policy costs due to shortening of the energy supply. Phasing out coal is thus a no-regret strategy for most world regions, even when only accounting for domestic effects and neglecting the global benefits from slowing climate change. Our results suggest that these domestic effects potentially eliminate much of the free-rider problem caused by the discrepancy between the national burden of decarbonization costs and the internationally shared benefits of climate change impact mitigation. This, combined with the profound effect of closing around half of the global CO_2 emissions gap towards the 2 °C target, makes coal phase-out policies attractive candidates for the iterative strengthening of the nationally determined contributions pledged by the countries under the Paris Agreement.

Only a tight cumulative CO_2 emissions budget remains for humanity if warming is to be limited to well below 2 °C, or even 1.5 °C (ref. [2]), as stated in the Paris Agreement. However, global GHG emissions are still rising[3], and the currently pledged nationally determined contributions (NDCs) until 2030 are known to be insufficient to bridge the emission gap to a 'Paris compliant' emission pathway[4].

Fossil fuels in general, and coal use in particular, are not only responsible for the bulk of GHG emissions but are also major contributors to the non-climate environmental footprint of human activity along their whole life cycle, upstream when mining as well as by the combustion itself.

In contrast to climate change damages, these impacts are mainly local and near term (intragenerational) and may, therefore, figure prominently in policymakers' energy strategy considerations[5]. Considering the full spectrum of positive local health and environmental effects of phasing out coal could outweigh negative economic effects and therefore help to address the free-riding problem of the 'tragedy of the global commons' in the context of international climate policy[6,7]. Moreover, climate policies come with the additional challenge of intergenerational free-riding since consumption benefits of weak climate policy are enjoyed today at the expense of reduced welfare of future generations. Here, the near-term characteristics of health and environmental benefits can provide incentives for immediate climate action.

The existing literature has investigated the importance of coal phase-out policies as an early entry point to achieve global mitigation targets in line with the Paris Agreement[8–10]. However, less research has been devoted to the regional effects of phasing out coal on the economy, the environment and human health and the implications for global GHG emissions.

In this study, we provide an estimate of the relative magnitudes of direct policy cost (macroeconomic consumption losses) compared with indirect social cost savings from the reduced impact on human health and the environment, addressing calls for an integrated approach to energy sustainability[11,12]. Subtracting the direct policy cost from indirect social cost savings, referred to as local co-benefits, results in the net societal effect of the policy intervention. This indicates to what extent the consideration of local co-benefits of climate and energy policies can provide incentives on the country level to pursue ambitious climate policies. Finally, to put these local co-benefits in perspective, we add indicative values of the global social cost of carbon (SCC) of US\$100 tCO_2^{-1} as a metric of the global economic damages of climate change and thus global co-benefits of reducing CO_2 emissions.

We develop an interdisciplinary modelling framework incorporating an integrated assessment model (IAM), prospective life-cycle assessment (LCA) modelling and an explicit air pollution model (see Methods for a detailed description of the framework and Supplementary Fig. 1 for an illustration of the modelling chain). The consistent modelling framework allows a scenario analysis of both the direct policy cost and the indirect social cost from the most crucial environmental stressors of alternative climate and energy policy regimes while accounting for interactions and leakage effects between sectors, between regions and over time.

We compare three policy scenarios with a reference scenario that does not comprise any additional energy or climate policies. The socioeconomic drivers and assumptions for the energy–economy system (energy demand, economic development) as well as the impact side (population development and demographics, urbanization) are chosen in accordance with the Shared Socioeconomic Pathways 2 'middle-of-the-road' scenario[13]. The NDC scenario implements NDCs as currently pledged until 2030 under the Paris Agreement. After 2030, national mitigation efforts are extrapolated by assuming gradually tightened technology targets and convergence towards an end-of-the-century CO_2 price of US\$70 t^{-1}. The 2 °C scenario limits the global mean temperature rise by the end of the century to 2 °C through cost-effective global uniform carbon

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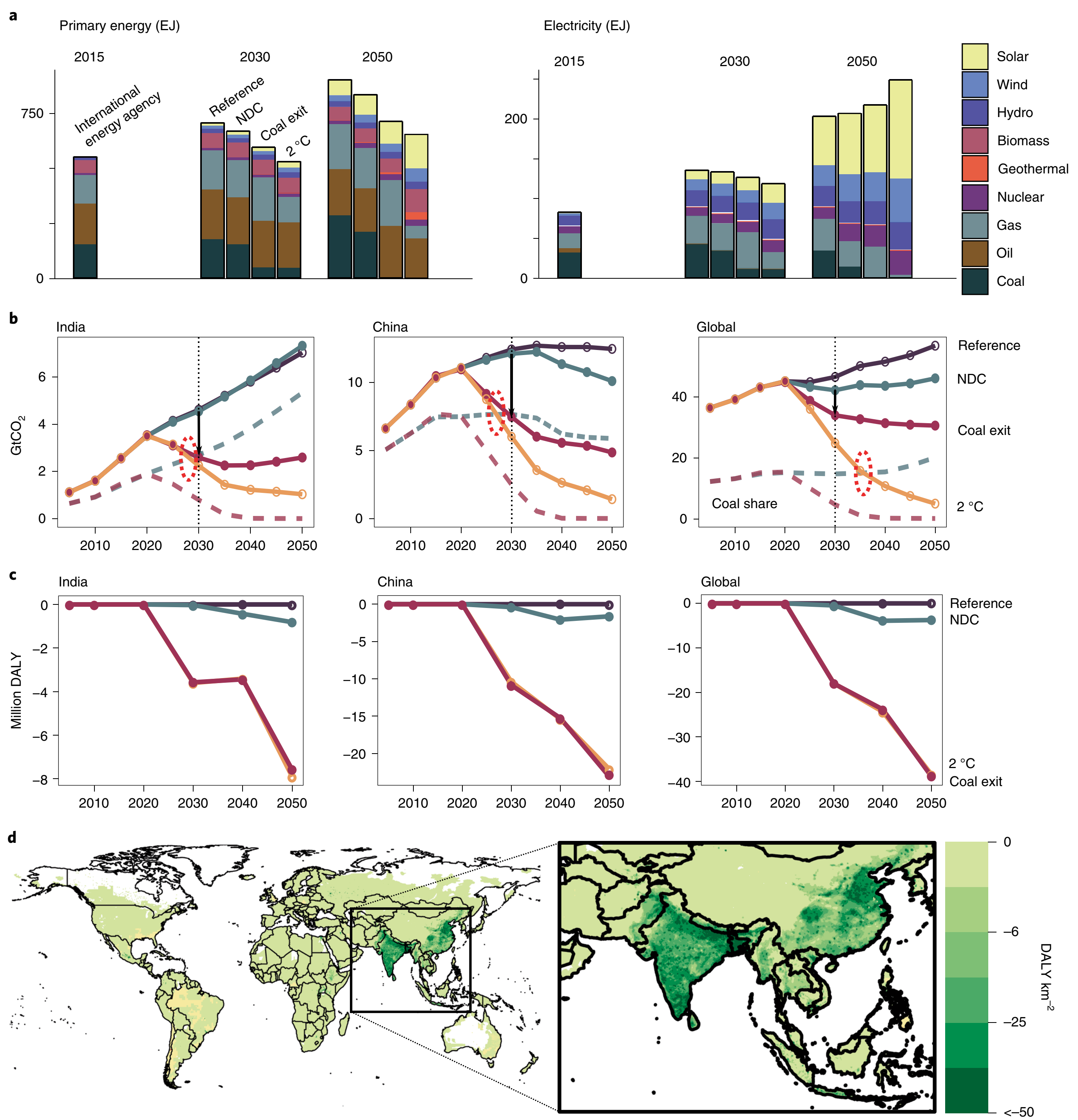

Fig. 1 | Energy system transformation pathways and emissions across scenarios. a, Global primary energy and electricity production. **b**, The CO_2 emissions of India, China and globally. Emissions from coal for the NDC and coal-exit scenarios are displayed by the dashed lines. In the NDC scenario, coal emissions alone exceed the 2 °C carbon budget before 2050, as highlighted by the red ellipses. The arrows illustrate the narrowing effect of the coal exit on the emission gap between the NDC and 2 °C for the year 2030. The regional CO_2 budgets of the 2 °C scenario reflect a cost-optimal allocation calculated endogenously through interactively adjusting a globally uniform carbon price, assuming equal marginal abatement cost curves (see Supplementary Fig. 6 for the corresponding regional CO_2 price pathways). **c**, Air pollution-related health impacts as the difference of million disability-adjusted life years (DALY) between policy scenarios and the reference scenario for India, China and the world. **d**, Spatial distribution of health impact shown in **c** for the coal-exit scenario relative to the reference scenario in 2050.

pricing across regions and sectors. Finally, we construct the coal-exit scenario by imposing a 2 °C compliant cap on the coal use, while otherwise assuming the implementation of the current policies as in the NDC scenario. This cap models coal phase-out policies that limit coal utilization to a carbon pricing pathway in line with the 2 °C scenario across regions, sectors and time.

We find that currently pledged NDCs have only a small transformation effect on primary energy supply and electricity

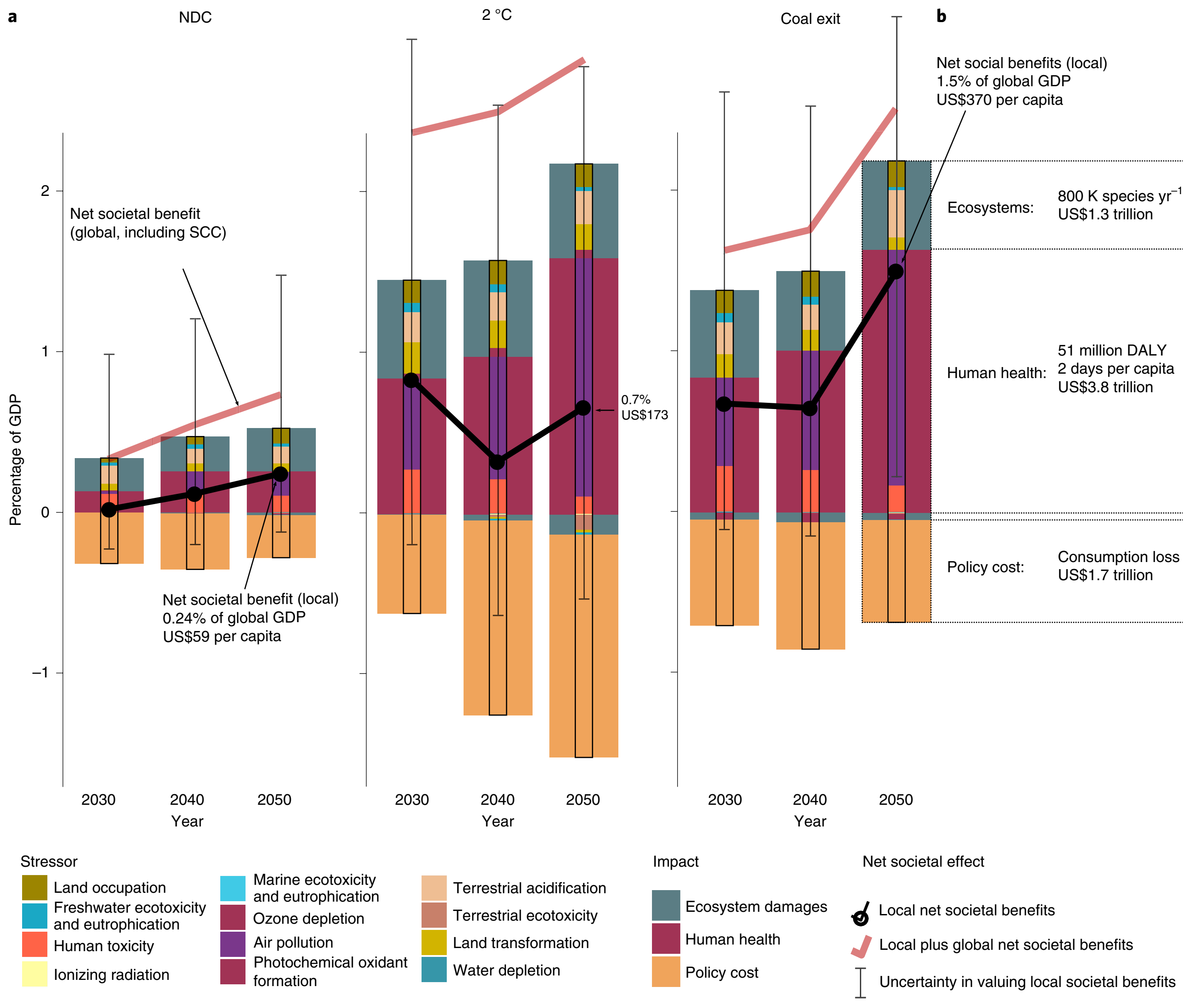

Fig. 2 | Globally aggregated direct policy cost and environmental and health cost/benefits relative to annual gross domestic product (GDP) purchasing power parity (PPP). a, Direct annual policy cost and globally aggregated monetized values of local health and environmental effects across policy scenarios relative to the reference scenario. Direct annual policy cost is derived from macroeconomic consumption loss, human health impacts are valued through willingness-to-pay metric and environmental damages are valued through restoration cost. The inner bars show the cost/benefits for the different categories (stressors). For the outer (thick) bars, stressors are grouped by the impact channels: that is, ecosystem damages, human health and direct policy cost. Solid black lines indicate the resulting net societal effect: the aggregated local co-benefits minus direct policy cost. For the red lines, we add the global benefits in the form of the SCC of US\$100 t^{-1} to the net societal benefits. The whiskers indicate the uncertainty ranges of the net societal benefit from the translation of human health and environmental impacts into the social cost. **b**, Benefits of the coal-exit scenario for the year 2050 in absolute terms.

generation, and lead only to marginal reductions in global CO_2 emissions (Fig. 1a), a result well aligned with previous studies[14,15] (see Supplementary Figs. 3–5 for the regional results). In particular, emission reductions are small for China (Fig. 1b) and negligible for India (Fig. 1b), whose GHG intensity reduction target under the NDCs is non-binding. Coal utilization stagnates at today's levels and is only slightly reduced compared with the reference scenario. Consequently, coal-related CO_2 emissions alone already exceed the total CO_2 emissions under cost-optimal 2 °C compliant policies by 2035 on a global level and even before 2030 for China and India, as indicated by the red circle in Fig. 1b.

The coal-exit scenario, however, leads to a substantial transformation of the energy system. Coal is reduced to about one-quarter of today's levels in 2030 and almost completely phased out until 2050. Consequently, primary energy demand is reduced and solar, wind and especially gas substitute for coal in the power sector and oil, gas and biomass substitute for coal in the industry and buildings sector. As a result, the global CO_2 emission gap between the NDCs and the 2 °C scenario is narrowed in the short term and almost closed for China and India. Even more drastic are the effects on air pollution, as can be seen in the number of mitigated DALY in Fig. 1c: impacts are decreased to similar levels as the 2 °C scenario, improving global public health by 40 million DALY in 2050, most of which are located in Asia (see Fig. 1d). This is the result of the high baseline coal utilization and demographic characteristics (population growth in India, demographic susceptibility in China, overall high population density and urbanization, see Supplementary Figs. 8–11 for global absolute, regional and sectoral results).

Figure 2 shows that the NDCs yield only small air pollution-related societal cost co-benefits. Nevertheless, other local human

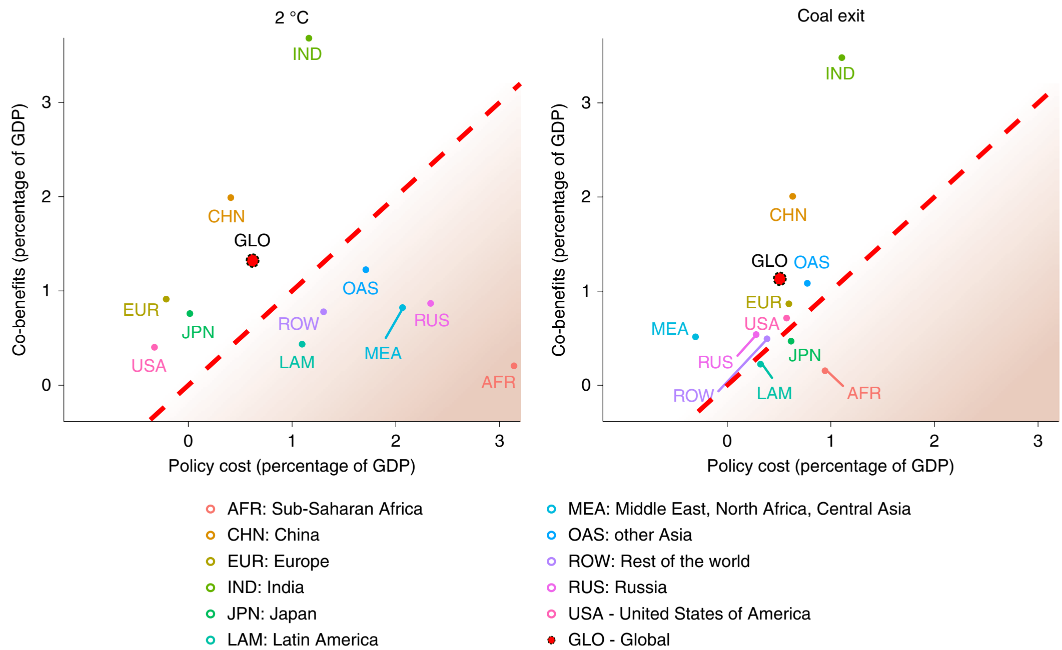

Fig. 3 | Regional analysis of local co-benefits and direct policy cost relative to annual GDP PPP. Discounted co-benefits and direct policy cost for all world regions in the 2 °C and coal-exit scenarios until 2050 with a discount rate of 5%. The dashed line indicates the break-even line between cost and benefits.

health and environmental co-benefits in combination with low direct policy cost lead to a net positive societal effect (black line, see Supplementary Figs. 12–25 for stressor category and sectoral results and Supplementary Figs. 26–28 for regional results).

In the 2 °C scenario, by contrast, direct policy cost increases to 1.5% of GDP PPP in 2050. However, the associated higher local co-benefits of mainly air pollution, as well as human toxicity, terrestrial acidification, and land-related biodiversity benefits result in positive global aggregate net societal benefits, reaching 0.5% of GDP PPP in 2050.

In the short term, the coal-exit scenario has a similar effect in terms of local benefits and direct policy cost as a cost-effective 2 °C scenario. However, in contrast to the 2 °C scenario, no further long-term transformation, for example, phase-out of gas or transport decarbonization, is induced, highlighting the role of coal phase-out policies as an early entry point, which needs to be complemented by stringent climate policies to avoid carbon lock-in of other fossil fuels[16,17]. This results in global net societal benefits of US\$3.4 trillion (1.5% of GDP PPP) in 2050, equal to US\$370 per capita on average. The main reason for these high benefits is lower mitigation cost through low corresponding prices of CO_2 in the long term compared with the 2 °C goal (see Supplementary Fig. 6). To illustrate the effect of climate change damages, we add a global uniform SCC of US\$100 tCO_2^{-1} (see section titled 'Global impacts' for a discussion of SCC). The red line illustrates adding these reductions to the local benefits. Under this assumption, the gross local benefits are in the same order of magnitude as the SCC for all scenarios (see Supplementary Fig. 29). In addition, the 2 °C scenario outperforms the coal-exit scenario, reaching a net benefit of 2.8% of GDP PPP in 2050. However, this would flip in 2050 if SCC of around US\$50 tCO_2^{-1} or lower is assumed due to lower long-term mitigation cost mentioned in the preceding. The ranges reflect the uncertainty introduced by the monetary valuation of impacts (see Supplementary Information for a detailed discussion of the uncertainty of the modelling framework). Although the uncertainty is substantial, the positive net social benefit of exiting coal is robust. Only very optimistic assumptions about the cost of environmental damages and human health push them close to zero in 2050 and below in the previous years, while pessimistic assumptions raise these costs by a factor of two to three.

Figure 3 shows that almost all world regions exceed their direct policy cost of exiting coal (mostly GDP loss and higher energy-system investment cost) by human health and environmental benefits until 2050 (the break-even line is represented by the dashed line; see Supplementary Fig. 30 for the uncertainty analysis and Supplementary Fig. 7 for the decomposition of regional and global policy costs).

Only sub-Saharan Africa, Latin America and Japan, regions with low air quality-related health benefits, face higher costs than benefits (see Supplementary Fig. 32 for all time steps and scenarios). The 2 °C scenario, however, shows a more scattered picture; China and India (high air-quality benefits), as well as Europe, Japan and the United States (low direct policy cost) yield net positive societal effects while the rest of the regions face higher direct policy cost than local co-benefits. That being said, when the global benefits of reduced climate change damages are considered on the basis of a global uniform SCC, all regions break even (see Supplementary Fig. 31).

To conclude, we find an accelerated global coal phase-out to be a policy with immediate and strong CO_2 emission reduction effects, substantially narrowing the gap between the NDCs and a 2 °C compliant pathway. Impressively, the cost of such a policy is overcompensated through environmental and public health co-benefits, resulting in a global net positive societal effect even if climate benefits were to be ignored.

These results have important bearing on international climate policy. For most countries, and in particular, the world's largest CO_2 emitters (China, India, Europe, the United States), we find local co-benefits of all examined climate policy scenarios (2 °C, coal exit) of such large magnitude that they can play an important role to overcome the interregional and intergenerational free-rider problem of climate policy: their domestic monetized environmental and health benefits exceed direct policy cost, thus creating an incentive to act even if others do not. Exiting coal emerges here as a particularly valuable climate policy entry point as it reduces CO_2 emissions at relatively low cost while reaping most of the local environmental co-benefits. In contrast to climate impacts, these local co-benefits are not particularly sensitive to different discount rates, stimulating immediate action (see Supplementary Fig. 32).

In addition, the tangibility and possible unifying nature of coal phase-out policies could make them particularly interesting for the next round of the NDCs. Here, front-runner countries could agree on ambitious individual time lines and/or a majority could be formed, committed to phasing out coal at a similar pace to avoid market distortions (for example, the Powering Past Coal Alliance[10]). At the same time, the local nature of the co-benefits and the identification as a robust 'no regret' strategy can support the call of national, regional and local groups for the introduction or strengthening of coal phase-out policies, an important part of the puzzle to overcome known issues of political economy of coal, such as dysfunctional governments[10], vested interests of (often state-owned) power companies, distributional (equity) effects and the difficulties of enforcing the polluter-pays principle caused by complex emission–impact relationships. This complexity causes various uncertainties in the proposed framework, particularly regarding the valuation of environmental damages, and future research should be devoted to further increasing the robustness of results.

While the coal exit is a crucial early entry point, it is imperative that it be complemented by further climate policies to reach a goal in line with the Paris Agreement and to avoid the lock-in of other fossil fuels. In addition, the societal benefits of mitigation action further increase if avoided climate damages are taken into account. Therefore, a holistic response to the climate and environmental crisis will eventually have to achieve almost full-scale decarbonization of power supply and thus also entail a deep reduction of not only coal but also oil and gas and address non-electric energy demands in transportation, buildings and industry sectors as well as resource efficiency.

Our results second the call for an integrated assessment of climate protection and multiple, complementing benefits of sustainable development and echo the call for policymakers to inject this concept into climate negotiations and policy design.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-020-0728-x.

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Methods

The modelling framework is designed as an interdisciplinary model chain, building on research of many disciplines. This study contributes to the development of the individual modelling steps, as described in the following subsections, and combines them in a consistent framework, thus facilitating a comprehensive assessment of economic, environmental and human health effects of policies (see Supplementary Fig. 1 for a schematic of the modelling framework).

The effects of policies on the climate, energy system and economy are derived with the Regional Model of Investments and Development (REMIND) IAM system. REMIND is a hybrid modelling system that represents macroeconomic drivers of growth, investment and energy demand in 11 world regions in combination with a technology-rich bottom-up representation of energy systems[18]. The land-use related effects are captured by running REMIND in conjunction with an emulator of the global land and water-use model MAgPIE, ensuring consistency between the energy–economy–climate and land water-use systems. All results, including technology-specific cost assumptions, can be found in the Supplementary Information. The levelized costs of electricity for selected technologies are available in Supplementary Table 2.

The effects on non-climate environmental and human health impacts are analysed by a dual approach, focusing on a holistic representation of life-cycle impacts. (1) Air pollutant emissions, the most significant contributor to local health impacts, are represented by source in REMIND[19]. Resulting human health impacts are estimated via an atmospheric chemistry model and nonlinear, disease-specific epidemiological response functions[20]. (2) Other human health and ecosystems damage impact channels are based on LCA of all regional energy systems[21] using the ReCiPe methodology[22]. Including the whole life cycle is crucial since the trend towards renewable energy generation technologies shifts impacts from direct emissions (for example, burning fossil fuels) to indirect emissions (for example, construction of energy infrastructure or land use for bioenergy).

We evaluate all impacts in terms of their effect on human health, measured by DALY, and environmental damage, measured in potential species loss over time. We then monetize health effects by willingness-to-pay valuation, environmental damages though potential land restoration cost and direct policy cost through macroeconomic consumption loss, constructing a unified metric of social cost. Feedback from the effect of damage to the environment and human health (for example, workforce loss, health expenditures) on GDP is not considered.

Energy–economy–climate modelling. The starting point of the model chain is the global energy–economy general equilibrium model REMIND[23] linking a macroeconomic growth model with a bottom-up energy system model[18,24]. It is an integrated assessment model built around a Ramsey-type growth macroeconomic core that maximizes intertemporal welfare. The associated energy demands are fulfilled by the energy system model covering primary, secondary and final energy markets as well as renewable energy potentials. Here, more than 50 conversion technologies are considered, including the development of system characteristics and cost. Major drivers of inertia and path dependencies are modelled by representing full-capacity vintage structure, technological learning and technology ramping cost (see Supplementary Information for results).

LCA. LCA is an established method to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. To this end, inventories of environmentally relevant flows (that is, emissions, natural resources and waste) to and from the biosphere are compiled for specific (industrial) products[25]. In a second step, the flows are characterized by their effect on human health and ecosystem quality according to impact assessment methods.

To calculate the life-cycle impacts of activities represented in REMIND, we start with the ecoinvent database (version 3.5, cut-off system model)[21] supplemented with additional datasets for expected future technological development, such as in carbon capture and storage[26]. This database allows us to calculate both the direct emissions of energy generation and use and indirect emissions due to plant construction and maintenance, fuel extraction, refinement and transport, as well as all other material and energetic inputs needed for the policy scenarios. Using an open-source tool chain, described in the Supplementary Information, we used the policy scenario outputs to systematically modify the industrial supply chains given in ecoinvent to account for future energy system changes. Specifically, we used REMIND policy scenario outputs at each time step (1) to change the technology shares in electricity grid mixes; (2) to change the effectiveness of pollution control devices in electricity generation technologies and (3) to change the fuel or conversion efficiencies of electricity generation technologies. In cases where REMIND did not provide direct estimates of emissions, we used changes in fuel efficiency as proxies to linearly adjust emission levels. As LCA databases form an interconnected global supply chain, our changed electricity generation is used throughout the database, making all consuming technologies cleaner. However, we note that we did not alter non-electricity technologies to account for future changes in efficiency or pollution control, and as such the LCA results are conservative in that most industrial processes are expected to be cleaner than we estimate in the future. We use our modified database to calculate the impact of one kilowatt-hour of high-voltage electricity at each time step for each policy scenario, using human health and ecosystem quality endpoint values from the ReCiPe life-cycle impact assessment method[22]. All results, including technology and region-specific mid-, endpoint, and monetized results, can be found in the Supplementary Information.

Air pollution. We model the air pollution emissions and the development of air pollution control policies as well as technology research, development, deployment and diffusion through the change of technology-specific aggregated emission factors over time derived from the GAINS model[27]. See Rauner et al.[19] for an extended description of the air pollution model chain.

The resulting air chemistry, influenced by these air pollution emissions, is modelled employing the global linearized atmospheric chemistry transport model TM5-FASST[28] covering SO_2, NO_x, black carbon, organic matter, NH_3, volatile organic carbon, CH_4 and primary fine particulate matter ($PM_{2.5}$).

The air pollution-related health impact assessment is based on the Global Exposure Mortality Model developed by Burnett et al.[20]. Disease endpoints considered are ischaemic heart disease, cerebrovascular disease (stroke), chronic obstructive pulmonary disease and lung cancer and, for children under five, acute respiratory lung infection. The toxicity of $PM_{2.5}$ is assumed to be uniform with regards to inhaled mass (exposure). The O_3 health impact assessment is based on the seasonal (April–September) average daily 1 h maximum concentrations[29]. We calculate 192 million DALY for the year 2015, which is in line with the research from Burnett et al.[20].

The relative risk R is a function of the concentration c calculated through the Global Exposure Mortality Model, whose shapes are determined by the paramter estimates θ_d, α_d, μ_d and ν_d; the disease endpoints d specific results are shown in Supplementary Fig. 2:

$$R(c)_d = \begin{cases} 1 & \text{if } c <= c_{cf} \\ e^{\theta_d log(c/\alpha_d+1)/(1+e^{-(c-\mu_d)/\nu_d})} & \text{if } c > c_{cf} \end{cases}$$

The Global Exposure Mortality Model has a supra-linear shape and drop to one at a theoretical minimal risk concentration c_{cf} of 2.4 μg m^{-3}. Multiplying the attributable fraction a with the baseline mortality rate[30] y_0 and exposed population p (ref. [31]) to calculate mortalities:

$$a_d = \frac{R_d - 1}{R_d}$$

$$\Delta m = \sum_{i=1}^{z} y_{0,d}\ a_d\ p$$

We assess not only mortality but also morbidity in a consistent integrated framework through the DALY concept. This is an aggregate measure combining the years lost through premature death compared with the life expectancy and the years living less than optimal health. We calculate the disease (z) and demography (g) specific DALY for every time step (t) and region (r) by relating the base year premature deaths (m) to the DALY ratio reported in the Global Burden of Disease Study of 2017 (ref. [32]):

$$\mathrm{DALY}_{r,t} = \sum_{i=1}^{z} \sum_{i=1}^{g} \mathrm{DALY}_{z,g,r,2015} / m_{z,g,r,2015}\, m_{z,g,r,t}$$

Monetary valuation of impacts. *Human Health.* We employ a willingness-to-pay approach to translate human health impacts into social cost. Our calculations are based on a meta-analysis of stated-preference studies by the Organisation for Economic Co-operation and Development, which estimates the value of a statistical life[33]. In contrast to revealed preference methods, these numbers are not based on empirical data; however, they can be applied to a large set of the population and regions. The recommended base value derived by the meta regression of available literature is US$3.6 million for the Europen Union in 2005 with a low and high estimate range from US$1.8 million to US$5.4 million, which we use for the uncertainty. We relate the value of a statistical life to the baseline DALY/mortality ratio and thus calculate the value of one DALY, about US$120K for the EU-28 in 2005. VODALY reflect the amount a person is willing to pay to mitigate the mortality risk of one life year and the risk of one life year of non-optimal health. These values are adjusted over country and time using the spatial unit value transfer method described in the following section.

Environment. The environmental impact is measured in potential biodiversity loss (in species.year), which can be interpreted as the number of species that have a high probability of disappearing due to unfavourable conditions. The concept is applied to the global terrestrial species density of 1.6 million species on an area of 108.4 million km^2. A main simplification is the assumption of a uniform distribution of terrestrial species on the global land surface. More research should be devoted to increasing the spatial detail through region-specific analysis of ecosystem damage, effects on aquatic animals and methods to couple them to energy–economy–climate models.

We value the potential biodiversity loss by the associated marginal habitat restoration cost. Essentially, the value we use reflects how much it costs to restore the habitat where a certain biodiversity is likely to reemerge once it was diminished by human influence. Ott et al.[34] calculated the cost for different land-use types for the European Union, building on the work of Köllner[35]. These values are adjusted using the spatial unit value transfer method described in the next section. We extract the marginal cost to improve the habitat for one species per year per m^2 from 'built up land' for an average land-use mix for a 10 yr period. The associated cost of US$_{2005}$0.165 potentially disappeared fraction (PDF)$^{-1}$ m^{-2} yr^{-1} can now be divided by the global species density, which results in US$_{2005}$11.15 million per species per year. We use the lowest and highest restoration cost land-use types from 'built up land' as uncertainty ranges; these are US$_{2005}$0.018 PDF^{-1} m^{-2} yr^{-1} for 'integrated arable' and US$_{2005}$0.9 PDF^{-1} m^{-2} yr^{-1} for 'forest edge'.

Spatial unit value transfer. The lack of consistent studies estimating both the human health and environmental monetization, V, for all regions of the world necessitates a method to spatially and temporally transfer the employed valuation. We use the unit value transfer method, adjusting with country-specific GDP PPP per capita, Y, and an elasticity, ε, of 1.2 and 0.8, respectively, for countries with a lower and higher income than the reference region EU-28 in the base year 2005. The resulting valuation coefficients aggregated over world regions can be found in Supplementary Table 1.

$$V_{c,t} = V_{\mathrm{EU},2005} \frac{Y_{c,t}^{\varepsilon}}{Y_{\mathrm{EU},2005}}$$

Global impacts. We add a global uniform SCC to illustrate the effect of the scenarios on global climate change damages. The estimates vary widely in literature without conclusive estimates. Although meta studies estimate the SCC to be around US$40 t^{-1} (ref. [36]), recent research points towards higher estimates and argues for a lower bound of US$125 t^{-1} (ref. [37]). In this study, the global climate change damages are used as a hallmark with which local co-benefits are compared. We therefore opt for a global uniform value of US$100 t^{-1} and keep it constant over time.

Uncertainty. The modelling framework is subject to various uncertainties embodied in every step of the modelling chain, from economy–energy–climate modelling to impact quantification and monetary valuation.

The most-relevant uncertainties of the economy–energy–climate model for this study are technology cost, renewable energy potentials, technological learning and scale-up rates[38] since they affect what technologies substitute coal, the inertia of the energy system and associated mitigation cost. However, multimodel studies showed that the general decarbonization strategies are robust across many different models[39].

On the impact side of the modelling framework, the air pollution-related human health impacts have received a lot of attention in the research community due to their identification as one of the major causes of global premature mortality. We are therefore able to model the cause–effect chain of emissions, concentrations and human health impacts spatially explicit and validate the results with the latest research in this field.

The LCA modelling of other human health and environmental damages is based on an extensive dataset supplied by sector experts and constantly reviewed and validated. Uncertainty of the emissions part mainly lies in difficult attribution of emissions, lack of spatial data and the consistent coupling with the IAM system. Translating the emissions into impacts is based on established methods; however, they rely on static simplified models, and aggregating these impacts into the two categories, human health and environmental damages, is subject to higher uncertainty. Future research should be devoted to the consistent prospective coupling of LCA and IAM models as well as the development of time-, region- and socioeconomic development-specific characterization factors.

The highest uncertainty of this framework is introduced by the monetary valuation of impacts. The valuation of human health is based on a synthesis of results of stated-preference approaches and not empirical data. The lack of a consistent dataset further requires a value transfer over space and time, which lacks other factors than GDP. The environmental damage valuation is subject to the same transfer uncertainty as well as uncertainty in the restoration cost data. Further research should be devoted to modelling environmental quality and its monetary value. Another source of uncertainty is how much human health and environmental damages would affect the economy. We only value these impacts but do not implement a feedback.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
The data supporting the findings of this study are available within the paper, its supplementary information files and in the following repositories. The energy–economy–climate model REMIND is available at github.com/remindmodel/remind. The Life Cycle Assessment notebooks and data are available at github.com/rauner/holistic-coal-exit. The air pollution data is available at github.com/rauner/air-pollution.

Code availability
The code used to generate the energy–economy–climate model REMIND can be accessed at github.com/remindmodel/remind. The code used to generate the Life Cycle Assessment results can be accessed at github.com/rauner/holistic-coal-exit, at bitbucket.org/cmutel/brightway2 (Brightway2), at github.com/IndEcol/wurst (Wurst), and at github.com/Loisel/rmnd-lca (rmnd-lca). The code used to generate the air pollution results can be accessed at github.com/rauner/air-pollution.

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Author contributions
S.R., N.B. and G.L. designed the research. S.R. designed the modelling framework and performed the integrated assessment analysis. S.R. and R.V.D. performed the air pollution analysis. S.R., A.D. and C.M. performed the LCA analysis. S.R. created the figures and wrote the paper with inputs and feedback from all authors.

Competing interests
The authors declare no competing interests.

Additional information
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Software and code

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Data collection	No software was used to collect data.
Data analysis	The REMIND model is written in GAMS 25.0.2 and solved with the solver CONOPT 3 version 3.17G. The air pollution model is written in R version 3.3.3, see [https://github.com/rauner/air-pollution] for the source code. The life cycle assessment model is written in Python version 3.7.4, see [https://github.com/rauner/holistic-coal-exit] for the source code.

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