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Coal exit health and environmental damage reductions outweigh economic impacts, Nature Climate Change (2020) (accepted version)

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Cheap and abundant coal fueled the industrialization of Europe, North America, and Asia¹. However, the price tag on coal has never reflected the external cost to society; coal combustion emits more than a third of today’s global CO_2 emissions and it 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°C², as stated in the Paris Agreement. However, global greenhouse gas emissions are still rising³ and the currently pledged Nationally Determined Contributions (NDC) up until 2030 are known to be insufficient to bridge the emission gap to a “Paris compliant”

emission pathway⁴.

Fossil fuels in general, and coal use in particular, are not only responsible for the bulk of greenhouse gas 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 (intra-generational), and may, therefore, figure prominently in policymakers' energy strategy considerations⁵. 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 inter-generational 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, environment, and human health and the implications for global greenhouse gas emissions.

In this study, we provide an estimate of the relative magnitudes of direct policy cost (macroeconomic consumption losses) compared to 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 100 \$/t CO_2 , 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 modeling framework integrating an integrated assessment model (IAM), prospective Life Cycle Assessment Modeling (LCA) and an explicit air pollution model (see the methods section for a detailed description of the framework and SI-1.1 Fig. SI-1 for an illustration of the modeling chain). The consistent modeling 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 demograph-

ics, urbanization) are chosen in accordance with the SSP2 ‘middle-of-the-road’ scenario¹³. The *NDC* scenario implements nationally determined contributions 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 70\$/t. The $2^\circ C$ scenario limits the global mean temperature rise by the end of the century to $2^\circ C$ through cost-effective global uniform carbon pricing across regions and sectors. Finally, we construct the *coal exit* scenario by imposing a $2^\circ C$ 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 $2^\circ C$ scenario across regions, sectors, and time.

Figure 1: |**Energy system transformation pathways and emissions across scenarios.**
a Global Primary Energy and Electricity production. **b** Carbon dioxide 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 SI-1.1 Fig. SI-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 panel **c** for the Coal exit scenario relative to the Reference scenario in 2050.

We find that currently pledged NDCs only have a small transformation effect on primary energy supply and electricity generation, and only lead to marginal reductions in global CO_2 emissions, see Fig. 1a, a result well aligned with previous studies^{14,15}. (see SI-1.2 Fig. SI-3-5 for the regional results) In particular, emission reductions are small for China (Fig. 1b middle column) and negligible for India (left column), whose greenhouse gas intensity reduction target under the NDC is non-binding. Coal utilization stagnates at today's levels and is only slightly reduced compared to 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, on the other hand, 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 coal in the power sector and oil, gas, and biomass 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°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 SI-1.3 Fig. SI-8-11 for global absolute, regional and sectoral results).

Figure 2: |Globally aggregated direct policy cost and environmental and health cost/benefits relative to annual 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, i.e., 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 100US\$/t 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.

Figure 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 between cost and benefits.

Fig. 2 shows that the NDCs only yield small air pollution-related societal cost co-benefits. Nevertheless, other local human health and environmental co-benefits in combination with low direct policy cost lead to a net positive societal effect (black line, see SI-1.4 Fig. SI-12-25 for stressor category and sectoral results and Fig. SI-26-28 for regional results).

In the 2°C scenario, on the other hand, direct policy cost increase 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 e.g. 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 3.4 trillion US\$ (1.5% of GDP PPP) in 2050, equal to 370 US\$ 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 to the 2 °C goal (see SI-1.1 Fig. SI-6). To illustrate the effect of climate change damages, we add a global uniform SCC of 100 US\$/t CO_2 (see 1.4.4 for a discussion on 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 SI-1.4 Fig. SI-29). Additionally, 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 50 US\$/t CO_2 or lower are assumed due to lower long term mitigation cost mentioned above. The ranges reflect the uncertainty introduced by the monetary valuation of impacts (see SI-1.5 for a detailed discussion of the uncertainty of the modeling 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.

Fig. 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 (break-even is represented by the dashed line, see SI-1.4 Fig. SI-30 for the uncertainty analysis and SI-1.1 Fig. SI-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 SI-1.4 Fig. SI-32 for all time steps and scenarios). The 2°C scenario, on the other hand, shows a more scattered picture; China and India (high air quality benefits), as well as Europe, Japan, and the USA (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 taken into account based on a global uniform SCC, all regions break even (see SI-1.4 Fig. SI-31).

To conclude, we find an accelerated global coal phase-out to be a policy with immediate and strong CO_2 emission reduction effects, significantly 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 significant bearing on international climate policy. For most countries, and in particular, the world's largest CO_2 emitters (China, India, Europe, USA), 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 inter-regional and inter-generational 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. Additionally, in contrast to climate impacts, these local co-benefits are not particularly sensitive to different discount rates, stimulating immediate action (see SI-1.2 Figure SI-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 Nationally Determined Contributions. Here, front-runner countries could agree on ambitious individual time-lines and/or a majority is formed, committed to phasing out coal at a similar pace to avoid market distortions (see the Powering Past Coal Alliance¹⁰). 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 governments¹⁰, vested interests of (often state-owned) power companies, distributional (equity) effects and the difficulties to enforce 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 increase 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. Additionally, 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.

1. Methods

The modeling framework is designed as an interdisciplinary model chain, building on research of many disciplines. This study contributes to the development of the individual modeling steps, as described in the subsections below, and combines them in a consistent framework, thus facilitating a comprehensive assessment of economic, environmental and human health effects of policies (see SI-1.1 Fig. SI-1 for a schematic of the modeling framework).

The effects of policies on the climate, energy system and economy are derived with the REMIND IAM system. REMIND is a hybrid modelling system that represents macro-economic drivers of growth, investment and energy demand in 11 world regions in combination with a technology-rich bottom-up representation of

energy systems¹⁸. 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 SI results files. The levelized cost of electricity for selected technologies are available in the SI-1.2 Table SI-2.

The effects on non-climate environmental and human health impacts are analyzed 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 REMIND¹⁹. Resulting human health impacts are estimated via an atmospheric chemistry model and non-linear, disease specific epidemiological response functions²⁰. (2) Other human health and ecosystems damage impact channels are based on LCA of all regional energy systems²¹ using the ReCiPe methodology[Goedkoop2013]. Including the whole life cycle is crucial since the trend towards renewable energy generation technologies shifts impacts from direct emissions (e.g., burning fossils) to indirect emissions (e.g., construction of energy infrastructure, or land-use for bioenergy).

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

1.1. Energy-Economy-Climate Modeling

The starting point of the model chain is the global energy-economy general equilibrium model REMIND²² linking a macro-economic growth model with a bottom-up energy system model^{18,23}. It is an integrated assessment model, built around a Ramsey-type growth macroeconomic core which maximizes inter-temporal 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 modeled by representing full capacity vintage structure, technological learning, and technology ramping cost, see the SI for result files.

1.2. Life Cycle Assessment

Life Cycle Assessment 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 (i.e., emissions, natural resources and waste) to and from the biosphere are compiled for specific (industrial) products²⁴. 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 storage²⁵. 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 SI, 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 a) to change the technology shares in electricity grid mixes; b) to change the effectiveness of pollution control devices in electricity generation technologies, and c) 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 method²⁶. All results, including technology and region specific mind-, end-point, and monetized results can be found in the SI files.

1.3. 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 model²⁷. 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 modeled employing the global linearized atmospheric chemistry transport model TM5-FASST²⁸ covering SO_2 , NO_x , black carbon(BC), organic matter(OM), NH_3 , volatile organic carbon (VOC), CH_4 and primary $PM_{2.5}$.

The air pollution related health impact assessment is based on the Global Exposure Mortality Model developed by Burnett et al.²⁰. Disease end-points considered are ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD) and lung cancer (LC), and for children under 5, acute respiratory lung infection (ALRI). 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-hr maximum concentrations²⁹. We calculate 192 million DALY for the year 2015 which is in line with the research from Burnett et al.²⁰ (see SI-1.1 Fig. SI-2).

The relative risk R is a function of the concentration c calculated through the Global Exposure Mortality Model which shapes are determined by θ_d , α_d , μ_d and ν_d , the disease endpoints d specific results are shown in Fig. 5:

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

The Global Exposure Mortality Model has a supra-linear shape and drop to one at a theoretical minimal risk concentration c_{cf} of $2.4 \mu\text{g}/\text{m}^3$. Multiplying the attributable fraction a with the baseline mortality rate³⁰ y_0 and exposed population p 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 disability adjusted life year (DALY) concept. This is an aggregate measure combining the years lost through premature death compared to the life expectancy and the years living less than optimal health. We calculate the disease z and demography d specific DALY for every time step and region by relating them to the base year premature deaths DALY ratio reported in the Global Burden of disease study of 2017³².

$$DALY_{r,t} = \sum_{i=1}^z \sum_{i=1}^d DALY_{z,d,r,2015} / m_{z,d,r,2015} * m_{z,d,r,t}$$

1.4. Monetary valuation of impacts

1.4.1. 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 estimate the value of a statistical life (VSL)³³. In contrast to revealed preference methods, these number 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 3.6 million US\$ for the EU in 2005 with a low and high estimate range from 1.8 to 5.4 million US\$, which we use for the uncertainty. We relate the VSL to the baseline DALY/mortality ratio and thus calculate the value of one DALY, about 120 k US\$ 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 section below.

1.4.2. *Environment*

The environmental impact is measured in potential biodiversity loss [species.year] which can be interpreted as the number of species that has 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 108.4 million km² area. A main simplification is the assumption of an 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 cost for different land-use types for the EU, building on the work of Köllner³⁵. 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.year per m² from “built up land” for an average land-use mix for a ten year period. The associated cost of 0.165 US\$2005/(PDF m² year) can now be divided by the global species density which results in 11.15 million US\$2005/species.year. We use the lowest and highest restoration cost land-use types from ‘built up land’ as uncertainty ranges, these are 0.018 for “integrated arable” and 0.9 US\$2005/(PDF m² year) for ‘forest edge’.

1.4.3. *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 purchasing power parity per capita Y and an elasticity ε of 1.2 and 0.8 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 the SI-1.1 Table SI-1.

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

1.4.4. *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 in the range of around 40 US\$/t³⁶, recent research points towards higher estimates and argues

for a lower bound of 125 US\$/t³⁷. In this study, the global climate change damages are used as a hallmark to which local co-benefits are compared to. We therefore opt for a global uniform value of 100 US\$/t and keep it constant over time.

1.5. Uncertainty

The modeling framework is subject to various uncertainties embodied in every step of the modeling chain, from economy-energy-climate modeling 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 rates³⁸, since they affect what technologies substitute coal, the inertia of the energy system, and associated mitigation cost. However, multi-model studies showed that the general decarbonization strategies are robust across many different models³⁹.

On the impact side of the modeling framework, the air pollution related human health impacts have received a lot of attention in the research community due to its 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 latest research in this field.

The life cycle assessment modeling of other human health and environmental damages is based on an extensive data set 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 especially 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 socio-economic 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 consistent data set 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 model 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.

2. Data availability statement

The data supporting the findings of this study are available within the paper, its supplementary information files and in the following repositories. Energy-economy-climate modeling: REMIND (github.com/remindmodel/remind); Life Cycle Assessment: Notebooks and data for LCA calculations (github.com/rauner/holistic-coal-exit); Air pollution: Air pollution emissions, concentrations, human health impact (github.com/rauner/air-pollution).

3. Code availability

The code supporting of this study is available within the paper, its supplementary information files and in the following repositories. Energy-economy-climate modeling: REMIND (github.com/remindmodel/remind); Life Cycle Assessment: Notebooks and data for LCA calculations (github.com/rauner/holistic-coal-exit), Brightway2 (bitbucket.org/cmutel/brightway2), Wurst (github.com/IndEcol/wurst), rmnd-lca (github.com/Loisel/rmnd-lca); Air pollution: Air pollution emissions, concentrations, human health impact (github.com/rauner/air-pollution); Spatial unit value transfer: Value transfer (github.com/rauner/air-pollution/blob/master/calcMonetization.R).

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6. Author Contributions

S.R., N.B., and G.L. designed the research. S.R. designed the modeling 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 life cycles assessment analysis. S.R. created the figures and wrote the paper with inputs and feedback from all authors.

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Coal exit health and environmental damage reductions outweigh economic impacts

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SI-1 Supporting Information

SI-1.1. Methods

Figure SI-1: **Modelling framework.** Modelling framework of the cause effect chain of energy-economy-climate to monetized health and environmental impacts. The Integrated Assessment Energy-Economy Climate model REMIND is the starting point of the modelling chain. The policy cost are directly calculated from REMIND through climate policy induced consumption losses relative to the no policy Reference scenario. The right path represents the specific air pollution human health model chain, including the simplified Chemical Transport model and spatial population, urbanization and demography data. The middle path illustrates the Life Cycle Assessment model which covers non-air pollution human health impacts and ecosystem damages.

Table SI-1: |**Value transfer coefficients.** Value transfer coefficients of the Reference case for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) in 2015, 2020, 2030, 2040 and 2050. They are applied to the base value of human health 118421.1 US\$ per VDaly and the ecosystem damages of 111,486,487.2 US\$ per species.yr.

region	2015	2020	2030	2040	2050
LAM	0.500152	0.386202	0.513897	0.666233	0.858463
OAS	0.289746	0.343485	0.452139	0.580002	0.73834
AFR	0.104607	0.108863	0.155965	0.221625	0.320949
EUR	0.954087	1.025294	1.212767	1.429472	1.654259
ROW	1.084928	0.814886	0.962879	1.137768	1.333285
MEA	0.519368	0.575502	0.746901	0.925411	1.109441
CHN	1.275278	1.422803	1.669215	1.891424	2.090629
IND	0.106028	0.132382	0.230956	0.360532	0.527048
JPN	1.169837	1.216918	1.354231	1.474302	1.606203
USA	1.545993	1.652051	1.840732	1.976144	2.083858
RUS	0.55785	0.688134	1.015309	1.352588	1.6276

Figure SI-2: |**Global Exposure Mortality Model@Burnett2018.** Integrated exposure response functions describing the relationship between annual mean ambient $PM_{2.5}$ and relative risk of the five disease endpoints considered. Shading indicate the uncertainty ranges around the employed medium estimate.

SI-1.2. Energy-Economy-Climate Modeling

Table SI-2: **Levelized cost of electricity (LCOE)**. Global average generation LCOE in \$/MWh for selected technologies of a new power plant build in the time step. LCOEs do not include a CO_2 price and other taxes but storage cost associated with renewable energy penetration.

Scenario	Power generation technology	2015	2030	2050
Reference	Coal Pulverized Coal w/o CCS	63.81	69.15	77.85
NDC	Coal Pulverized Coal w/o CCS	63.81	68.72	74.88
Coal exit	Coal Pulverized Coal w/o CCS	61.85	60.91	60.49
2°C	Coal Pulverized Coal w/o CCS	63.81	66.24	88.08
Reference	Gas Natural Gas Combined Cycle w/o CCS	53.99	61.80	70.72
NDC	Gas Natural Gas Combined Cycle w/o CCS	53.99	63.18	72.12
Coal exit	Gas Natural Gas Combined Cycle w/o CCS	53.99	66.20	74.52
2°C	Gas Natural Gas Combined Cycle w/o CCS	53.99	64.88	73.63
Reference	Solar PV	76.89	43.36	35.83
NDC	Solar PV	76.89	41.74	35.69
Coal exit	Solar PV	77.02	41.47	35.87
2°C	Solar PV	76.89	41.77	36.36
Reference	Wind	64.58	56.93	54.82
NDC	Wind	64.58	56.25	54.66
Coal exit	Wind	64.58	56.05	54.58
2°C	Wind	64.58	54.52	54.13

Figure SI-3: **Primary energy.** Primary energy mix for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.

Figure SI-4: **Secondary energy - electricity.** Secondary energy - electricity mix for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.

Figure SI-5: **Carbon dioxide (CO_2) emissions.** CO_2 emissions for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World until 2050. The share of coal related emissions is indicated by the dashed line.

Figure SI-6: |Carbon dioxide (CO_2) prices. CO_2 prices for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World until 2050.

Figure SI-7: **Decomposition of mitigation cost.** Decomposition of regional mitigation cost until 2050 for the NDC, 2°C and coal exit scenario compared to the Reference case relative to GDP PPP discounted with a rate of 5%.

GDP loss and energy system related investment cost dominate the mitigation cost in the coal exit and 2 °C scenario for India, China and globally. Global cost savings are mostly comprised of lower non-energy investment cost and additionally less variable cost of the energy system in the 2 °C scenario. The impact of exiting coal on consumption is most prominent in coal exporting regions such as the USA and ROW (including Australia) through lower revenues and higher cost for alternative fuel for coal importing regions such as Japan and China.

SI-1.3. Air pollution

We find that exiting coal leads to similar air pollution health impact reductions as the 2°C scenario. The substitution of coal with gas and oil leads to slightly higher emission; however, emission factors for gas decrease substantially in the long term and biomass related air pollution emissions are higher in the 2°C scenario.

Phasing out coal leads to substitution effects, especially gas substitute coal in the power sector and oil, gas and biomass in the industry and buildings sector. However, there are effects that further lower air pollution emissions: India, for example is a fast growing economy that is expected to double its GDP in the next 15 years while continuing the trend of a growing population. This results in a tripling of transport demand from until 2040, which is the major emitter of NOx. In this context, the coal exit significantly increases the oil price compared to the 2°C scenario (22% in 2030), which has a twofold effect leading to lower air pollution emission: 1) The higher price for liquids based final energy reduces the transport demand (37% in 2030) and 2) leads to a substitution of oil with electricity based mobility (65% higher rate of electrification).

Figure SI-8: |Air pollution concentration. Global mean annual $PM_{2.5}$ concentration [$\mu g/m^3$] for the year 2015 and 2050 of the NDC, 2°C and coal exit scenario. Bars represent the population living under concentrations of $>50 \mu g/m^3$ (red), $50 > x > 35 \mu g/m^3$ (orange), $35 > x > 20 \mu g/m^3$ (light orange), $20 > x > 10 \mu g/m^3$ (yellow) and $<10 \mu g/m^3$ (green)

Figure SI-9: **Air pollution health impact.** Global health impact of $PM_{2.5}$ and O_3 in terms of annual premature deaths [$cases/km^2$] for the year 2015 and relative to 2015 for the year 2050 of the NDC, 2°C and coal exit scenario. Markers represent values for stringent (⊗) and fixed emission factor (+) sensitivity cases, see Rauner, S. et al. Air Quality Co-benefits of Ratcheting-up the NDCs. Climatic Change (in review) for a description of sensitivity cases.

Figure SI-10: **Air pollution impact on Secondary Energy level [DALY]**. Air pollution impact on Secondary Energy level for the NDC, Coal exit and 2°C scenario relative to the Reference until 2050.

Figure SI-11: **Regional Air pollution impact [DALY/capita]**. Regional Air pollution impact for the Reference, NDC, Coal exit and 2°C scenario until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

SI-1.4. Life Cycle Assessment

Figure SI-12: **Total global absolute impacts.** Total global absolute impacts for the NDC, Coal exit and 2°C scenario relative to the Reference until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

Figure SI-13: |**Global absolute impacts of Secondary Energy - Electricity.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m²] and Ozone depletion [kg CFC-11 eq].

Figure SI-14: |Global absolute impacts of Secondary Energy - Heat|Geothermal. Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

Figure SI-15: |Global absolute impacts of Secondary Energy - Heat|Coal. Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

Figure SI-16: **|Global absolute impacts of Secondary Energy - Solids|Coal.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m²] and Ozone depletion [kg CFC-11 eq].

Figure SI-17: **|Global absolute impacts of Secondary Energy - Solids|Gases.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

Figure SI-18: |Global absolute impacts of Secondary Energy - Heat|Gas. Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

Figure SI-19: |**Global absolute impacts of Secondary Energy - Liquids**. Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

SE|Liquids

Figure SI-20: **Global absolute impacts of Secondary Energy - Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m²] and Ozone depletion [kg CFC-11 eq].

Figure SI-21: |Global absolute impacts of Secondary Energy - Heat|Biomass. Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

Figure SI-22: **|Global absolute impacts of Secondary Energy - Solids|Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m²] and Ozone depletion [kg CFC-11 eq].

Figure SI-23: **Global absolute impacts of Secondary Energy - Hydrogen.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

SE|Hydrogen

Figure SI-24: |Global absolute impacts of Secondary Energy - Solids|Traditional Biomass. Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

SE|Solids|Traditional Biomass

Figure SI-25: |Global absolute cost of Secondary Energy - Electricity [US\$]. Global absolute cost of Secondary Energy - Electricity for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050.

Figure SI-26: **Regional local monetized impacts as a share of GDP PPP.** Regional local monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

Figure SI-27: **Regional local monetized impacts.** Regional local monetized impacts for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

Figure SI-28: **Regional local and global monetized impacts as a share of GDP PPP.**

Regional local and global monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

Figure SI-29: |Global local and global monetized impacts as a share of GDP PPP. Global local and global monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

Figure SI-30: **Regional analysis of local co-benefits and direct policy cost relative to GDP PPP.** Discounted co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rate of 5%. The dashed line indicates the break-even between cost and benefits. The whiskers indicate the uncertainty ranges of human health and environmental impact translation into social cost.

Figure SI-31: **Regional analysis of local and global co-benefits and direct policy cost relative to GDP PPP.** Discounted local, global co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rate of 5%. The dashed line indicates the break-even between cost and benefits.

Figure SI-32: **Regional analysis of local co-benefits and direct policy cost relative to GDP PPP.** Undiscounted co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP. The dashed line indicates the break-even between cost and benefits.

Figure SI-33: **Regional analysis of local and global co-benefits and direct policy cost relative to GDP PPP.** Discounted local, global co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rates of 2.5, 5 and 7.5%. The dashed line indicates the break-even between cost and benefits. The whiskers indicate the uncertainty ranges of human health and environmental impact translation into social cost.