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Ambitious climate targets can make the phaseout of India's coal-fired power plants cost-beneficial

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Abstract

Given the urgency of climate change and the need for an energy transition, global coal power generation is rapidly declining. However, coal transition strategies optimized for cost-benefit and aligned with climate targets remain underexplored. Here, we develop a Plant-level Mixed-Integer Nonlinear Dynamic Optimization Model to conduct a cost-benefit optimization analysis for India's coal-fired power plants, through which the study proposes differentiated phaseout roadmaps aligned with the 1.5°C and 2°C climate targets. Our findings suggest that ambitious climate targets can yield more significant economic benefits, and more aggressive coal power retirement strategies are economically feasible. For example, Chhattisgarh and Uttar Pradesh could achieve the total net benefits of 171 and 110 billion US dollars in the 1.5°C and 2°C scenarios. Furthermore, incorporating social benefits into the evaluation will enhance the feasibility of the coal phaseout and reinforce India's decarbonization commitments.

41 **Introduction**

42   Economies worldwide are threatened by the losses and damages caused by climate

43 change, making climate mitigation a global concern. India, the third-largest carbon-

44 emitting country globally, derives more than half of its carbon dioxide (CO_2) emissions

45 from coal power[1–3]. Therefore, coal power plays a pivotal role in achieving emission

46 mitigation goals. For the world to have a chance of meeting the Paris Agreement's

47 temperature target, India needs to transition away from fossil fuels quickly[4–6].

48   The phaseout of coal power will result in both positive and negative effects. From

49 one perspective, this transition may cause carbon-intensive assets to depreciate or retire

50 before their expected lifetimes, resulting in stranded assets[7,8]. Studies have also found

51 that India faces a high risk of stranded assets[9,10]. Additionally, the phaseout of power

52 plants will interrupt their profitability, leading to cumulative profit losses over their

53 expected lifespan. This interruption affects the financial stability of the power plant, as

54 the revenue streams expected during the remaining operational years are lost.

55 Furthermore, with the acceleration of the energy transition, the coal mining industry

56 and related sectors supporting coal-based power generation will lose market share and

57 employment opportunities, resulting in decreased tax revenues in coal-dependent

58 regions[11]. From another perspective, this transition will generate social benefits by

59 avoiding carbon emissions and thereby mitigating current and future climate damages.

60 These avoided damages include impacts on agricultural production, reduced labor

61 productivity, property losses, increased frequency of disasters, and induced

62 migration[12,13]. In addition, actions to reduce carbon emissions often decrease associated

63 air pollutants, yielding co-benefits for air quality and public health[14,15]. Recent findings

64 suggest that the negative impacts of climate change are concentrated in developing

65 economies, commonly referred to as low- and middle-income economies according to

66 the World Bank's classification[16]. Among them, India bears the highest social cost of

67 carbon[17,18]. Hence, these developing economies will implement higher carbon taxes for

68 the nation's benefit[18]. Overall, these positive and negative effects, crucial for India's

69 coal power transition, remain unclear. In future coal power planning, it is essential to

70 fully consider both benefits and losses to conduct a comprehensive assessment of

71 decisions.

72 The Indian government is actively accelerating the deployment of renewable

73 energy to achieve the target outlined in its updated Nationally Determined

74 Contributions (NDCs), aiming for 500 gigawatt (GW) of non-fossil fuel installed

75 capacity by 2030[19]. As a result, India ranked fourth globally in renewable energy

76 capacity in 2023[20]. However, despite these efforts, the country remains heavily reliant

77 on coal. As of 2020, the total installed capacity of operational coal-fired power plants

78 was 233 GW, with an additional 53 GW of planned and under-construction units

79 expected to come online by 2030. Moreover, with approximately 20% of its coal

80 consumption reliant on imports, rising global coal prices are likely to intensify future

81 coal supply pressures, substantially driving up the cost of coal-fired power generation

82 and highlighting the urgent need to reduce India's overreliance on coal[21,22].

83 Global and regional studies have utilized unit-level data, considering the

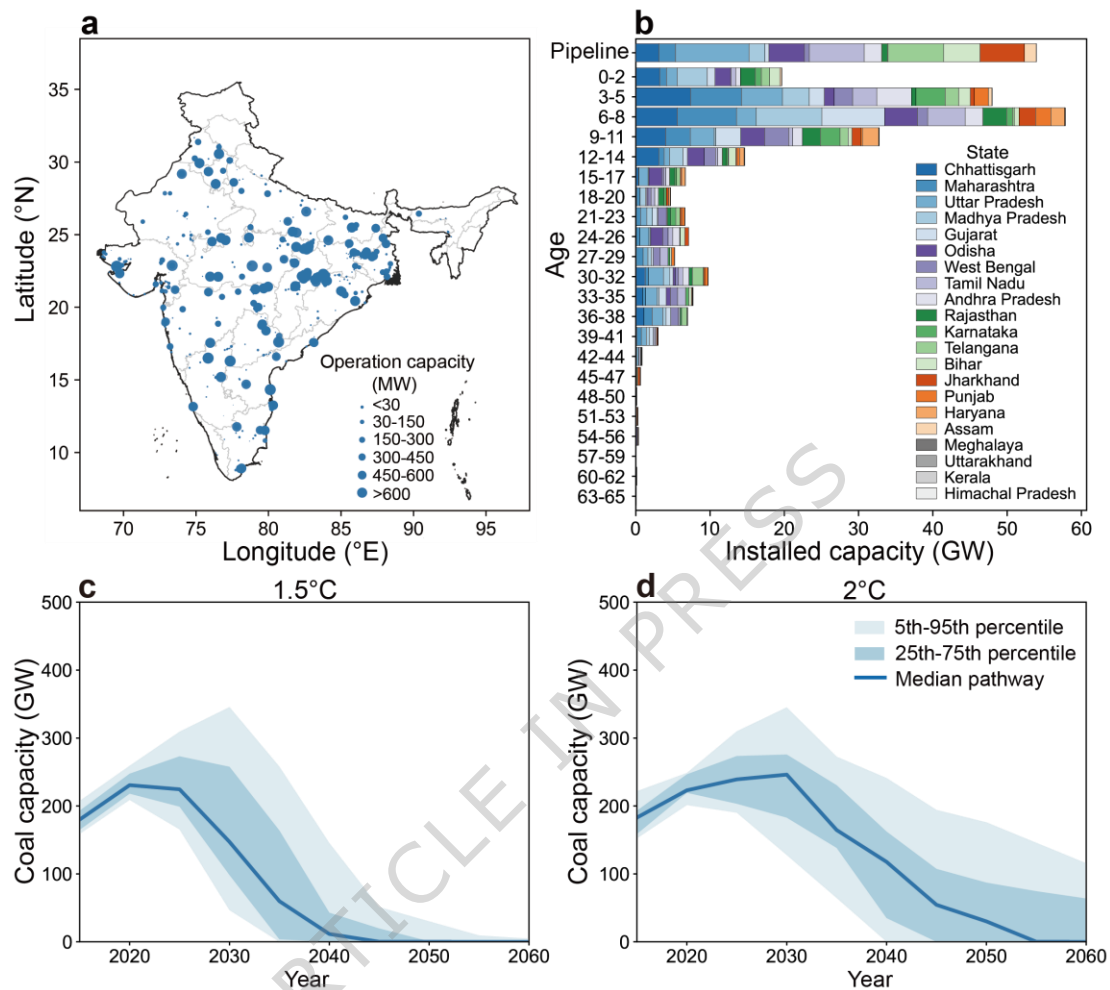84 heterogeneity of various factors and revealing the pathways for fossil fuel phaseout[23–

4

85   [27]. However, most evaluations are based on the multi-criteria decision analysis method

86   for energy planning and scenario comparisons[28]. These studies usually consider each

87   criterion and assign relative weights for decision aggregation, where the weights are

88   often subjective and preference-based. Moreover, investigations on stranded assets due

89   to coal power transition[9,29–31] also generally believe that ambitious climate policies will

90   lead to more stranded assets, but largely ignore the economic benefits of carbon

91   emission reduction. A few studies have considered the carbon benefits of eliminating

92   coal power and conducting cost-effectiveness analysis[32], but the optimal solution has

93   yet to be provided. Although the cost-benefit analysis can provide a comprehensive

94   evaluation by converting all impacts into monetary terms[33], coal power transitions will

95   always be challenging regarding cost and benefit in the future. If the costs and benefits

96   are incorporated into comprehensive assessments of coal facilities' retirement and new

97   construction, it will help promote coal power transition policies in developing countries

98   consistent with the Paris Agreement.

99   Despite substantial progress in renewable energy capacity expansion and a clearly

100   defined strategic intent to develop renewable energy over the next decade, the timeline

101   and pathway for India's transition away from coal remain uncertain, particularly

102   regarding the specific retirement schedule of individual coal-fired power plants. To fill

103   this research gap, this study formulates a dynamic optimization problem to determine

104   the optimal retirement schedule for India's coal-fired power plants under the national

105   carbon emission reduction pathway (CERP) established by the Intergovernmental Panel

106   on Climate Change (IPCC). In this context, this study develops the Plant-level Mixed-

107   Integer Nonlinear Dynamic Optimization Model (MIND-Plant). The model

108   incorporates the evolution of the power system under 1.5°C and 2°C climate target

109   scenarios, balancing environmental benefits (carbon emission reductions and avoided

110   health risks), economic costs (profitability losses and stranded asset risks), and social

111   risks (employment impacts). The optimization is performed iteratively using the Gurobi

112   Optimizer version 10.0.3 to generate a progressive power plant retirement schedule,

113   designing a gradual coal phaseout pathway aligned with India's energy transition goals.

114   Specifically, the model assigns a binary decision variable to each power unit, indicating

115   whether it should retire in a given year. It then calculates the cumulative impacts across

116   four dimensions from the retirement year until the end of its expected lifespan. The

117   optimization process maximizes overall benefits and minimizes total costs, balancing

118   these impacts to determine the optimal retirement year for each unit, ultimately solving

119   the global optimum of this nonlinear problem. This study applies the optimization

120   framework to analyze India's coal power transition, and the results revealed optimal

121   coal phaseout pathways from 2020 to 2060 under different climate targets. The findings

122   indicated that to achieve the 1.5°C and 2°C climate goals, the average operational

123   lifespan of India's coal-fired power plants will be reduced by 12 years and 5 years,

124   respectively. The plant-level coal phaseout roadmap developed in this study could guide

125   the orderly retirement of India's coal power plants and contribute to achieving India's

126   carbon reduction commitment under the 2030 NDC, providing a scientific basis for

127   power transition pathways and policy formulation.

128

129 **Results**

130 **Characteristics and retirement pathways of India's coal power units**

131

132 **Fig. 1 | Characteristics of India's coal power units and climate target pathways. a**

133 Geographic locations and the installed capacities of individual operating units in India.

134 The map is based on factual evidence and displays the non-disputed areas under actual

135 control. **b** Total installed capacity and age structure of operating units in each state (the

136 baseline year is 2020), as well as the capacity of units under construction or planned

137 (Pipeline). Capacity is expressed in megawatts (MW) at the unit level and in gigawatts

138 (GW) at the state level. **c, d** India's coal power capacity pathways consistent with

139 limiting warming to 1.5°C and 2°C. The dark lines indicate median pathways, with
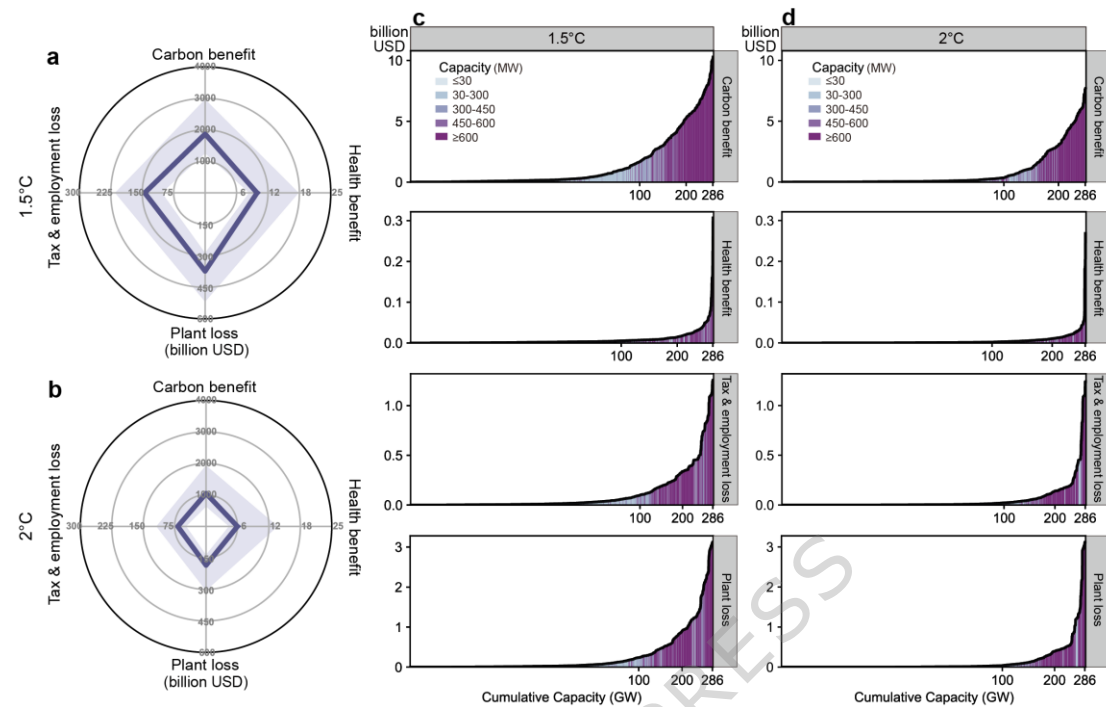
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shaded areas representing the 5th–95th percentile range (light shading) and the 25th–75th percentile range (dark shading). The raw scenario data is sourced from the Sixth Assessment Report (AR6) Scenario Database[34]. The base map was obtained from Esri ArcGIS 10.8. Map images © Esri and its licensors. Used under license.

The spatial distribution of coal-fired power plants in India is illustrated in Fig. 1a. Coal power units are located across 21 states, with a total installed capacity of 233 GW as of 2020, primarily concentrated in the western and eastern regions. The top three states in terms of capacity are Chhattisgarh, Maharashtra, and Uttar Pradesh, with installed capacities of 27 GW, 25 GW, and 24 GW, respectively, accounting for 33% of the national total. Figure 1b illustrates the age structure of operating units, with 57% commissioned between 2000 and 2020, indicating a relatively young fleet. Additionally, approximately 53 GW of capacity is under construction or planned, and it is expected to come online within the next decade, with Uttar Pradesh leading with about 10 GW.

The climate target pathways used in this study (Fig. 1c, d) show the projected trend in India's coal power capacity, which is expected to peak between 2020 and 2030. The median pathway suggests that to limit warming to 1.5°C, coal capacity will gradually phase out by around 2045, while for a 2°C target, it will phase out by around 2055. Under stricter climate goals, coal retirement will accelerate to achieve higher emissions reduction targets.

160 **Multidimensional effects of coal power phaseout based on cost-benefit analysis**
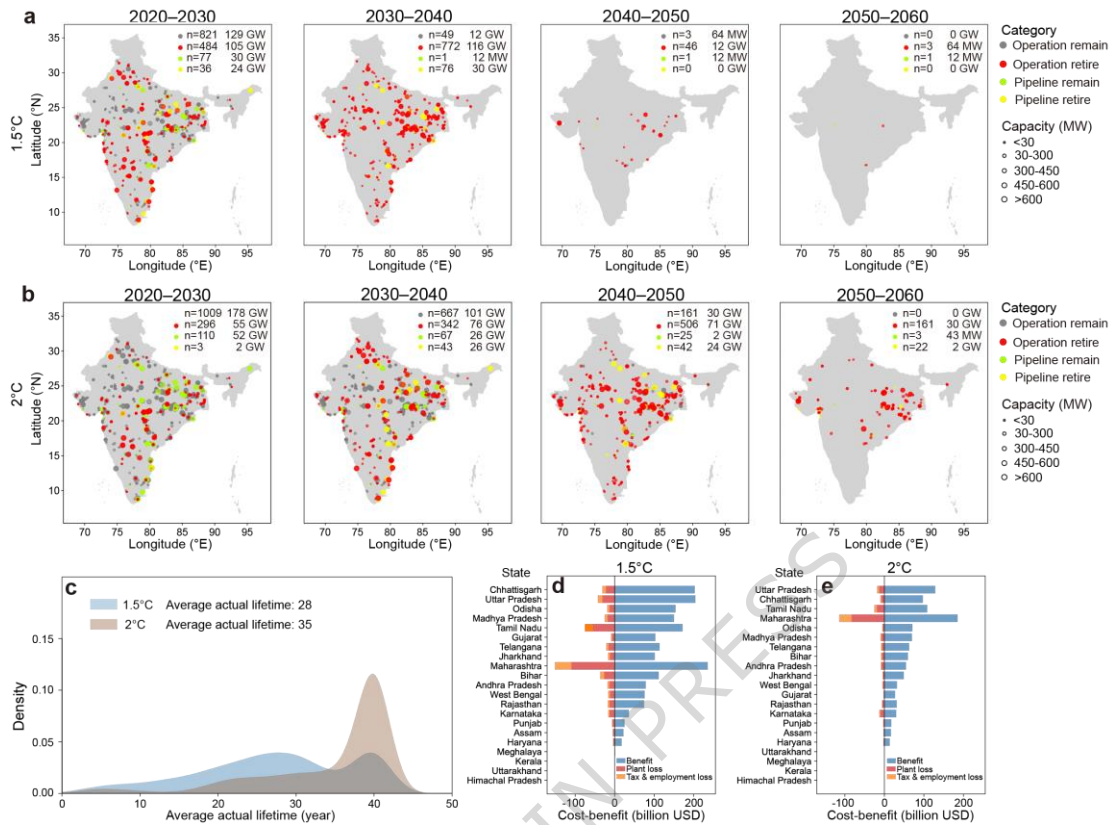

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162 **Fig. 2 | Cost-benefit analysis of coal power units. a, b** Total costs and benefits of all

163 units under the 1.5°C and 2°C scenarios, showing the cumulative values from early

164 retirement to the end of the assumed lifetime. The shaded areas represent the range of

165 uncertainty. **c, d** The cumulative values for each unit across four dimensions, with units

166 sorted from left to right in increasing order. The bar colors represent the installed

167 capacity of each unit (in gigawatt, GW). The four dimensions include carbon benefits,

168 health benefits, plant losses, and tax & employment losses, all measured in billion US

169 dollars (USD). The results include both operational and pipeline units.

170 We conducted a cost-benefit analysis using a dynamic optimization approach,

171 incorporating environmental, economic, and social dimensions. Carbon and health

172 benefits reflect the advantage dimension, while tax & employment and plant losses

173 correspond to the cost aspect. The model determined the optimal retirement year for

174   each unit and the optimal values for each objective. Figure 2a, b illustrate the trade-offs

175   in cost-benefit for operating and pipeline coal units under the 1.5°C and 2°C climate

176   targets. The blue solid lines represent the results for each dimension under the assumed

177   lifetime of 40 years. The shaded areas indicate the uncertainty range results, accounting

178   for an expanded assumed lifetime of 35–45 years, as well as variations in other

179   parameters (see the uncertainty analysis section in Methods). Stricter climate targets

180   result in higher plant losses and tax & employment losses, amounting to 516 billion US

181   dollars (USD) (range: 377–723) under the 1.5°C scenario, and 253 billion USD (range:

182   171–415) under the 2°C scenario. However, these stricter targets also yield

183   substantially higher carbon and health benefits, reaching 1,879 billion USD (range:

184   1,218–2,946) for 1.5°C, and 1,055 billion USD (range: 589–1,906) for 2°C. This

185   highlights the economic advantages of pursuing ambitious temperature goals. Figure

186   2c, d presents the results for individual units across dimensions, with the black line

187   representing the value assumed for the 40-year lifetime. Significant variation exists

188   between different units in all scenarios. Generally, large-capacity units, especially those

189   exceeding 600 megawatts (MW), have a more substantial impact on carbon benefits

190   and losses, consistent with their high emissions and energy consumption. This

191   highlights the critical role of larger plants in impacting overall metrics and guiding

192   decision-making. Additionally, health impacts are influenced by the regional

193   background characterization factors of local pollutants, as measured per disability

194   adjusted life years (DALYs) (Supplementary Fig. 5).

195

Phaseout roadmap for coal power units

Fig. 3 | Phaseout roadmap of coal power units and their actual lifetimes under climate goals scenarios across periods. a, b The retirement year of individual coal power units. Operating units refer to those still in operation in the baseline year 2020, while pipeline represents units that are planned or currently under construction. The grey, red, green, and yellow dots represent operation units that have not yet been retired, operation units that have retired, commissioned pipeline units that have not yet been retired, and retired pipeline units, respectively. The size of the circles indicates the installed capacity (in megawatt, MW). The labels in the upper-right corner of each map indicate the number of retired units by type and their total capacity (in gigawatt, GW). The map is based on factual evidence and displays the non-disputed areas under actual control. **c** The actual lifetime of each unit under the 1.5°C and 2°C scenarios. **d, e** Cost-
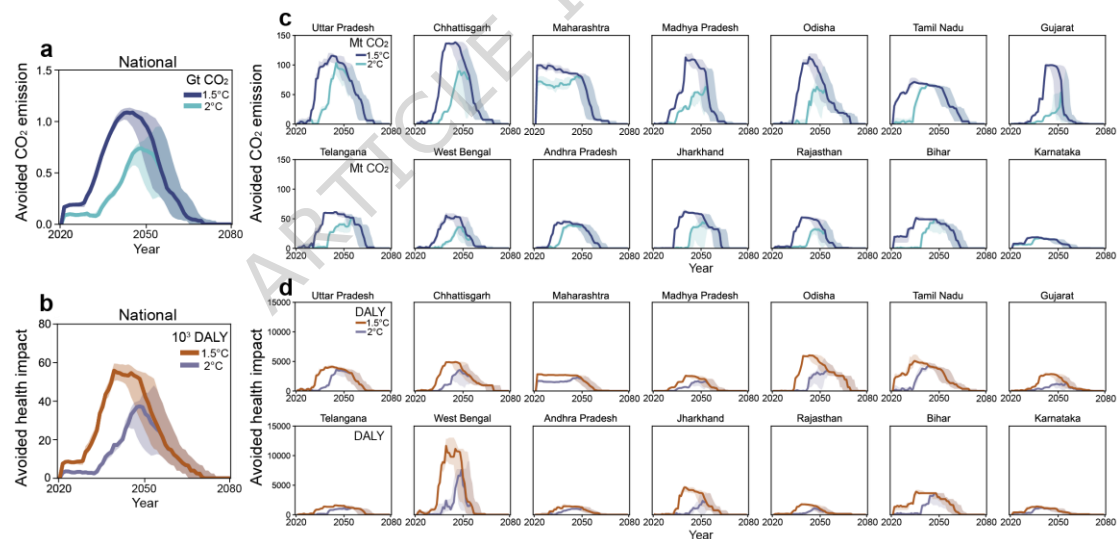
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209 benefit outcomes for each state under two scenarios, ranked in descending order by net

210 value from top to bottom. The benefits include carbon and health benefits, while the

211 costs encompass plant loss and tax & employment loss. The base maps were obtained

212 from Esri ArcGIS 10.8. Map images © Esri and its licensors. Used under license.

213 Based on the optimization, we developed an optimized retirement schedule for

214 each unit and mapped it spatially. Panels a and b of Figure 3 show the spatial

215 distribution of operating and pipeline units in different states across four time periods

216 (2020–2030, 2030–2040, 2040–2050, 2050–2060) under the 1.5°C and 2°C scenarios.

217 Grey or red dots represent operational units that continue operating or retire within each

218 period. In contrast, green or yellow dots indicate new pipeline units that start operation

219 or quit shortly after. The 1.5°C target requires higher retirement rates, with 484

220 operation units (105 GW) and 36 pipeline units (24 GW) phased out between 2020 and

221 2030, even for larger plants, especially in the Eastern Coal Belt. This trend continues

222 to increase between 2030 and 2040 (gradually increasing numbers of red and yellow

223 dots). New units are also expected to retire before 2050, thereby increasing the risk of

224 stranded assets. In contrast, the 2°C target allows for a more gradual retirement process,

225 with more early retirements concentrated after 2030 (represented by more red dots).

226 Moreover, the units have average lifetimes shortened to 28 and 35 years (Fig. 3c). These

227 results highlight that achieving the 1.5°C target demands faster emissions reductions

228 and large-scale early retirements, while the 2°C target allows more time for adjustment.

229 From a state-level perspective (Fig. 3d, e), our retirement strategy reveals that

230 Chhattisgarh could achieve the net benefits of 171 billion USD in the 1.5°C scenario,

231 retiring 83% of its installed capacity (25 GW) between 2030 and 2040. Similarly, Uttar

232 Pradesh demonstrates the net benefits of 110 billion USD in the 2°C scenario, retiring

233 48% of its installed capacity (15 GW) between 2040 and 2050. In addition, Maharashtra

234 yields the most significant benefits in both scenarios but also incurs the highest costs.

235 Specifically, under the 2°C scenario, plant losses, and tax & employment losses are

236 estimated at 83 and 31 billion USD, respectively, increasing to 110 and 42 billion USD

237 under the 1.5°C scenario (the results for each state are summarized in Supplementary

238 Table 8 and Fig. 6). These findings underscore the need for each region to adopt a

239 flexible and tailored transition plan to effectively manage the risks associated with the

240 transition to a low-carbon economy.

241 **National and state-level environmental benefits**

243 **Fig. 4 | Annual avoided carbon emissions and health impacts. a**, **b** National results.

244 **c**, **d** Results for the top 14 states ranked by installed capacity. The solid lines show

245 results under the 40-year lifetime assumption, while the shaded areas indicate the range

246 across lifetime scenarios (35–45 years). CO_2 emissions are expressed in gigatonnes (Gt)

247 at the national level and in million tonnes (Mt) at the state level. Health impacts are

248 measured by disability-adjusted life years (DALYs).

249 We developed unit-level retirement pathways based on climate target constraints

250 and cost-benefit optimization. Annual avoided CO_2 emissions and health impacts were

251 calculated for each coal unit under the retirement strategy, with results aggregated at

252 the state level. On a national scale (Fig. 4a, b), the more ambitious 1.5°C scenario

253 achieves significantly higher cumulative avoided CO_2 emissions of 26 Gt (range: 20–

254 33) and health impacts of 1.3 million DALYs (range: 1.0–1.6) compared to the 2°C

255 scenario, which achieves 15 Gt (range: 10–21) and 0.71 million DALYs (range: 0.4–

256 1.0) by the latter half of the Century. Additionally, the 1.5°C scenario achieves a faster

257 emission reduction rate, with the gap between the two scenarios widening over time,

258 highlighting the long-term benefits of more stringent climate goals. Peak annual

259 avoided CO_2 emissions are projected at 1.09 Gt (range: 1.02–1.13) by 2043 (range:

260 2040–2044) under the 1.5°C scenario and 0.74 Gt (range: 0.57–0.95) by 2048 (range:

261 2045–2054) under the 2°C scenario. Beyond these peaks, scenarios assuming a 45-year

262 operational lifetime yield more significant cumulative avoided CO_2 emissions and

263 health impacts than those considering a 35-year operational lifetime, due to the

264 extended service time of coal units, leading to more substantial cumulative reductions.

265 At the state level, the 14 states shown in the figure account for 95% of India's total

266 installed capacity (Supplementary Fig. 4), with notable regional differences in benefits

267 and losses. States with higher capacities, such as Uttar Pradesh, Madhya Pradesh,

268 Chhattisgarh, and Maharashtra (23.7 GW, 22.8 GW, 27.5 GW, and 25 GW in 2020,

269 respectively), show more significant reduction potential, with cumulative avoided CO_2

270 emissions projected to reach 4.6–9.3 Gt (2°C) and 8.4–13.6 Gt (1.5°C) by 2080. In

271 contrast, northern states like Punjab, Haryana, and Rajasthan have lower capacities,

272 resulting in smaller avoided emissions. Additionally, an estimated 53 GW of new

273 capacity expected by 2030 is likely to accelerate emissions reductions across most

274 states thereafter. Avoided health impacts vary with location, population density, and

275 baseline pollution levels. West Bengal, for example, has the highest regional particulate

276 matter health impact factors (Supplementary Fig. 5) and thus the most significant

277 cumulative avoided health impacts, estimated at 182 (range: 116–261) and 65 (range:

278 36–113) thousand DALYs under the 1.5°C and 2°C scenarios, respectively.

279 **Discussion**

280 The low-carbon transition of the power industry is crucial for mitigating climate

281 change. This study demonstrates that, under both the 1.5°C and 2°C scenarios, the

282 benefits of carbon emissions reduction and health improvements generally outweigh

283 the losses in tax revenue, employment, and power units' profitability, with more

284 ambitious climate targets proving to be more cost-beneficial. Based on the MIND-Plant

285 model, the study further proposed the unit-level optimized retirement plan, revealing

286 regional disparities under different climate targets: under the 1.5°C scenario, more units

287 need to be retired between 2020 and 2030, concentrated in the north, west, and east;

288 under the 2°C scenario, the retirement process is more gradual. These regional

289 differences highlight the need for developing differentiated regional policies that

290 provide adequate support and forward-looking planning for the more affected regions

291   during the transition process, thereby mitigating potential resistance.

292   Although India's coal capacity pipeline, including announced, pre-licensed, and

293   licensed projects, has declined by 85% since 2014 (from 250 GW to 36 GW)[22], some

294   regions remain heavily reliant on coal for economic development, employment, and

295   fiscal revenue, particularly in the Eastern Coal Belt[11,35,36]. These areas are therefore

296   more vulnerable to the risk associated with the coal phaseout. For instance, under the

297   1.5°C and 2°C scenarios, Maharashtra is projected to incur combined losses in power

298   plant assets, tax revenues, and employment amounting to 152 and 114 billion USD,

299   respectively (Fig. 3d, e). To ensure a just and sustainable energy transition, the

300   government should prioritize targeted financial compensation, workforce retraining,

301   and employment support for the regions most affected by the transition.

302   Regional transition strategies are not only determined by spatial deployment, but

303   also by the timing of interventions. Energy infrastructure, once established, tends to

304   create long-term dependence on pathways. Hence, delayed decisions can reduce the

305   flexibility of the power system and constrain future transition options[29]. India's current

306   operating coal power plants are relatively young, with an average age of 17 years. To

307   align with the 1.5°C and 2°C climate targets, the average retirement age would be

308   brought forward to 28 and 35 years, respectively. Our analysis outlined a structured

309   coal transition pathway that includes the gradual phaseout of existing coal power plants

310   starting in 2020 and the cessation of new coal power construction after 2030. Without

311   such interventions, India's coal capacity is projected to continue expanding. Emissions

312   from these plants could undermine India's NDC target and impede effective long-term

313   climate mitigation. If the power sector continues along its current trajectory, more

314   costly measures, such as the deployment of carbon capture and storage or large-scale

315   carbon dioxide removal technologies, will be required to offset rising emissions[37].

316   Moreover, the construction of proposed coal plants will result in resource lock-in and

317   miss opportunities for potential investment in renewable energy[38]. Hence, cancelling

318   planned coal power projects should be prioritized to prevent carbon lock-in, while

319   simultaneously pursuing a strategic and regionally tailored phaseout of existing coal

320   power plants. This strategy can also promote future technological innovation and policy

321   development, ultimately contributing to the achievement of global climate mitigation

322   goals.

323   Reducing the environmental risks associated with coal power expansion is

324   essential for sustainable development. The continued growth of coal power capacity

325   poses serious threats to environmental quality, including increasing greenhouse gas

326   emissions, worsening air pollution, and depletion of water resources. An early transition

327   away from coal, in line with ambitious climate targets, can substantially mitigate these

328   risks. Increasing urban air pollution and public health issues in India have become

329   important drivers for reducing coal power[39,40]. If the phaseout strategy in this study is

330   implemented, an estimated 1.0–1.6 million DALYs (1.5°C) and 0.4–1.0 million DALYs

331   (2°C) can be avoided. At the same time, cumulative carbon emissions of 1.9–2.3 Gt

332   (1.5°C) and 0.9–1 Gt (2°C) can be reduced by 2030. This strategy will help India

333   achieve its NDC target of reducing carbon emissions by 1 Gt by 2030. As India prepares

334   to update its 2035 NDC, the findings will also help mobilize international support for a

17

more ambitious and actionable decarbonization roadmap, thereby avoiding a lock-in to

a high-carbon development trajectory.

India has introduced policies such as the Production Linked Incentive scheme to

support the renewable energy goals[41]. In parallel, the country aims for non-fossil fuel

sources to account for approximately 50% of total power generation, meeting half of

its energy demand by 2030 and reinforcing its commitment to net-zero emissions by

2070. Among them, wind and solar power exhibit high scalability, maturity, and

commercial viability in India[42], with solar power capacity reaching 92 GW in 2024[43].

While these low-cost renewable energy sources are expected to meet future energy

demand, the transition to renewable energy still faces challenges in technology, finance,

and infrastructure.

This study primarily focuses on the transition and retirement pathways of coal-

fired power units, along with their associated environmental and socioeconomic

impacts, while broader topics such as energy security and renewable energy substitution

are beyond the scope of this paper. It is essential to note that although the model outlines

an framework for coal power retirement, the implementation in the real world is subject

to multiple uncertainties, including renewable energy potential, grid flexibility, social

acceptance, and political will. In particular, regions with weak regulatory capacity or

high fiscal dependence on coal may face stronger political resistance, which could

potentially delay the transition process. These potential barriers and critical

uncertainties suggest that, while this study represents a exploration of power transition,

the actual decarbonization pathway is likely to be more complex than model projections

357   indicate. Future research should adopt interdisciplinary approaches, integrate external

358   variables such as electricity market fluctuations and policy dynamics, and

359   systematically assess the technological potential and feasibility of renewable energy

360   alternatives to provide more comprehensive support for a fair and sustainable power

361   transition.

362   **Methods**

363   **Optimization framework**

364   To determine the optimal retirement schedule for coal-fired power plants in India

365   under the CERP set by the IPCC, this study develops the MIND-Plant model to conduct

366   a cost-benefit analysis of both operational and pipeline coal-fired power plants. The

367   Gurobi Optimizer version 10.0.3 is employed as the solver to achieve dynamic

368   optimization through iterative computation. Specifically, the model assumes that a unit

369   retires before the end of its assumed lifetime, and the avoided carbon emissions and

370    $PM_{2.5}$-related health impacts from the retirement year to the end of its assumed lifetime

371   are considered benefits. However, such early retirement also results in profit loss,

372   stranded assets, tax, and employment losses caused by the premature closure of the unit,

373   which is defined as costs. These costs, together with the avoided carbon emissions and

374   health impacts, constitute the optimization objectives of the model. We monetize the

375   benefits of avoided carbon emissions and health impacts, compare them with the cost,

376   and aggregate these objectives into a single objective function, allowing the model to

377   optimize and solve for the final result.

19

378   Based on these objectives, the model incorporates capacity constraints aligned

379   with climate targets and balances the impacts across multiple dimensions to maximize

380   benefits and minimize costs for all units. During the optimization process, a binary

381   decision variable is assigned to each power unit for each year, indicating whether it

382   should retire. It then iteratively calculates cumulative impacts across the four

383   dimensions, spanning from the retirement year to the unit's assumed end of its lifetime.

384   Through this process, the model aims to maximize the system's cost-benefit and

385   identify the global optimum for this complex nonlinear problem. Ultimately, the model

386   determines the optimal retirement year for each unit, deriving the optimal value for each

387   dimension, and provides the optimal retirement schedule for each power plant.

388   The objective functions are as follows:

389
$$\text{Maximize} \sum_{i \in I, j \in J} \sum_{t=t_{retire}}^{Y_{i,j}+lifetime} \left(CB_{i,j,t} \times \left(x_{i,t} + x_{j,t} \right) \right) \tag{1}$$

390
$$\text{Maximize} \sum_{i \in I, j \in J} \sum_{t=t_{retire}}^{Y_{i,j}+lifetime} \left(HB_{i,j,t} \times \left(x_{i,t} + x_{j,t} \right) \right) \tag{2}$$

391
$$\text{Minimize} \sum_{i \in I, j \in J} \sum_{t=t_{retire}}^{Y_{i,j}+lifetime} \left(TJ_{i,j,t} \times \left(x_{i,t} + x_{j,t} \right) \right) \tag{3}$$

392
$$\text{Minimize} \sum_{i \in I, j \in J} \sum_{t=t_{retire}}^{Y_{i,j}+lifetime} \left(PL_{i,j,t} \times \left(x_{i,t} + x_{j,t} \right) \right) \tag{4}$$

393   Where $x_{i,t}$ and $x_{j,t}$ are binary decision variables indicating whether the

394   operational unit i or pipeline unit j retires in year t. The decision variables $x_{i,t}$

395   =1 or $x_{j,t}$=1 if operation unit i or pipeline unit j begins retire in year t, and it

396   takes the value of 0 otherwise. $CB_{i,j,t}$, $HB_{i,j,t}$, $TJ_{i,j,t}$, and $PL_{i,j,t}$, represent the

397   cumulative carbon benefit, health benefit, tax & employment loss, and plant loss of unit

398   i and j from retirement year (t_{retire}) to the end of the assumed lifetime year

399 ($Y_{i,j} + lifetime$), respectively. $Y_{i,j}$ denotes the online year of the operation unit i and

400 the commission of unit j, respectively. *lifetime* is the assumed lifespan of 40 years,

401 and we conduct an uncertainty analysis by extending the assumed lifetime range to 35–

402 45 years. These benefits or losses occur after the unit retires. I and J represent the

403 fleets in operation and commission, respectively.

404 **Set up constraints**

405 For each year t, the total capacity of all non-retired units aligns with the capacity

406 pathway for the 1.5°C or 2°C targets. Each unit may be phased out once during the

407 planning period.

$$408 \qquad \sum_i Cap_i \left(1 - \sum_Y^{Y_i + lifetime} x_{i,t}\right) + \sum_j Cap_j \left(c_{j,Y_j}\left(1 - \sum_{Y_j}^{Y_j + lifetime} x_{j,t}\right)\right) \leq C_t + \mathcal{E}_t \qquad (5)$$

$$409 \qquad \sum_{Y_i}^{Y_i + lifetime} x_{i,t} \leq 1 \quad \forall_i \in I \qquad (6)$$

$$410 \qquad \sum_{Y_j}^{Y_j + lifetime} x_{j,t} \leq 1 \quad \forall_j \in J \qquad (7)$$

$$411 \qquad \sum_{Y_j}^{Y_j + lifetime} c_{j,t} \leq 1 \quad \forall_j \in J \qquad (8)$$

412 Where Cap_i and Cap_j are capacity of unit i and j, respectively. c_{j,Y_j} is the

413 binary decision variable indicating whether the pipeline unit j is commissioned in the

414 year Y_j. C_t is the capacity pathway under the climate targets. $\mathcal{E}_t$ is a non-negative

415 slack variable introduced to allow a certain degree of exceedance. In addition to

416 capacity constraints, it is also necessary to meet assumed lifetime constraints (*lifetime*),

417 meaning units that have operated for their designated lifetime must be retired. Formulas

418 (6) and (7) indicate that each unit in operation and pipeline can only be retired once

419 during its lifetime, respectively. Formula (8) suggests that each pipeline unit can only

420 come online once. Under the capacity constraints consistent with climate targets, the

421   model iteratively solves to determine the optimal retirement year for each unit that

422   achieves the maximum cost-benefit. The cumulative impacts across all dimensions

423   from the optimal retirement year to the end of the assumed lifetime can also be obtained.

424   **Carbon benefit**

425   In our study, we use the avoided CO_2 emissions from coal units to estimate social

426   benefits, which are calculated in terms of the social cost of carbon (SCC). The SCC

427   represents the economic cost associated with climate damage caused by emitting an

428   additional tonne of carbon dioxide[44]. SCC provides a monetary estimate of the marginal

429   damages of climate change.

430   The cumulative carbon benefits of coal power units are as follows:

431    $$CB_{i,j,t} = \sum_{i,j}\sum_t x_{i,j,t}\left(\sum_{t=t_{retire}}^{Y_{i,j}+lifetime}\left(SCC_t \times E_{i,j,t}\right)\right) \tag{9}$$

432    $$SCC_t = SCC \times \left((1+g)/(1+d_{scc})\right)^{(t-t_0)} \tag{10}$$

433   Where SCC_t is the social cost of carbon in year t, adjusted for growth rate and

434   discount rate. $E_{i,j,t}$ is CO_2 emissions of unit i and j in year t, measured in

435   tonnes. The base SCC in 2020 is fixed at 86 USD tCO_2^{-1}, with an annual growth-

436   adjusted rate (g) of 2.2%[17,18]. The carbon benefit is discounted (d_{scc}) at a rate of 3%[17].

437   t_0 represents the base year, 2020.

438   The CO_2 emissions from coal power units primarily depend on the capacity,

439   capacity factor, and the type of coal used. Referring to the calculation methods from ref.

440   45, the annual CO_2 emissions (tCO_2 year^{-1}) for each power unit are calculated as follows:

441    $$E_{i,j,t} = G_{i,j,t} \times HR_{i,j} \times EF_{i,j} \times c \tag{11}$$

442   Among them, $G_{i,j,t}$ is the electricity generation of unit i and j in year t,

443   calculated by unit-level capacity (MW), capacity factor (%), and operating hours. We

444   compiled the electricity generation data from each power plant in India using Central

445   Electricity Authority (CEA) Monthly Generation Reports 2020[46], including annual

446   generation and capacity factor. We matched it with our power unit dataset and used the

447   state average value from the CEA reports for power units that lacked capacity factor

448   data (Supplementary Table 2). $HR_{i,j}$ denotes the heat rate in British thermal unit per

449   kilowatt-hour (Btu kWh^{-1})[47] (Supplementary Table 3), and $EF_{i,j}$ represents the

450   emission factor in kilogram CO_2 per terajoule (kgCO_2 TJ^{-1}), dependent on coal type[48]

451   (Supplementary Table 4). c is a unit conversion constant, equal to 9.2427×10^{-6}.

452   **Health benefit**

453   As air pollution is a major global cause of premature death, its associated human

454   health impacts have garnered extensive attention[49,50]. Air pollution from coal power

455   generation contributes to approximately 80–112 thousand premature deaths annually in

456   India, resulting in substantial economic losses[15,51,52]. Therefore, we further incorporate

457   the avoided health impacts related to air pollution in our assessment, quantifying them

458   as economic benefits.

459   We spatially model the health burden and related economic impact caused by

460   primary air pollutant emissions, including sulfur dioxide (SO_2), nitrogen oxides (NOx),

461   and fine particulate matter ($PM_{2.5}$). Specifically, we estimate the health burden from

462   primary $PM_{2.5}$ pollution at each facility location using the methods described by

463   Oberschelp et al.[53]. We then characterize this burden in terms of DALYs, which measure

464   both the years of life lost due to premature mortality and the years lived in less than full

465   health[54]. We then refer to the methods from Rauner et al.[55] to monetize health effects

466   using willingness-to-pay valuation, thereby converting the health impacts associated

467 with air pollution into monetary terms.

$$DALY_{i,j,t} = S_{i,j,t} \times cf_{SO_2,i,j,t} + N_{i,j,t} \times cf_{NOx,i,j,t} + P_{i,j,t} \times cf_{PM2.5,i,j,t} \qquad (12)$$

$$HB_{i,j,t} = \sum_{i,j} \sum_t x_{i,j,t} \left(\sum_{t=t_{retire}}^{Y_{i,j} + lifetime} \left(DALY_{i,j,t} \times V_{DALY} \times \alpha \right) / \left(1 + d_{hb} \right)^{(t-t_0)} \right) \quad (13)$$

470 Where $HB_{i,j,t}$ is the avoided economic loss in health benefits due to avoiding air

471 pollutant emissions for unit i and unit j in year t. $DALY_{i,j,t}$ is the disability-

472 adjusted life year caused by exposure to primary PM$_{2.5}$. $S_{i,j,t}$, $N_{i,j,t}$, and $P_{i,j,t}$

473 represent the annual primary emissions of SO$_2$, NOx, and PM$_{2.5}$ at the unit level,

474 measured in kg. cf_{SO_2}, cf_{NOx}, and $cf_{PM2.5}$ are the regional characterization factors for

475 each pollutant emission per DALY, derived from high-resolution global

476 characterization factor maps (Supplementary Fig. 5) with a spatial resolution of

477 0.25°×0.25°. These maps are developed using atmospheric transport and chemical

478 models for several major air pollutants[53]. V_{DALY} reflects the amount willing to be paid

479 to mitigate the risk of premature death and non-optimal health for one year of life,

480 valued at 118,421 USD per DALY[55]. α is the regional adjustment factor for India

481 (Supplementary Table 5). Economic impacts due to health impacts are discounted at a

482 rate of 5% (d_{hb})[56].

$$S_{i,j,t}, N_{i,j,t}, P_{i,j,t} = G_{i,j,t} \times HR_{i,j} \times ef_k \times c \qquad (14)$$

484 $G_{i,j,t}$ is the electricity generation of each power unit, measured in kWh; ef_k is the

485 emission factors for pollutant class k, measured in grams per kWh (g kWh^{-1})

486 (Supplementary Table 6). Regional emission factors come from the

487 ECLIPSE_V6b_CLE_base emission scenario dataset developed by the GAINS model[57].

488 c is the constant for converting energy units from Btu to TJ, equal to 1.055×10^{-9}.

489 **Tax and employment loss**

490   Transition away from coal power is likely to have adverse impacts on government

491 tax revenues and local employment. Therefore, tax ($T_{i,j,t}$) and employment losses are

492 incorporated into the optimization model.

493   In this study, the taxes for coal-fired power plants include direct taxes ($T_{direct,i,j,t}$),

494 indirect taxes ($T_{GST,i,j,t}$), and coal taxes ($T_{GST\ Compensation\ Cess,i,j,t}$). The direct taxes primarily

495 consist of income tax, corporate tax, capital gains tax, and securities transaction tax,

496 accounting for 30% of net income. If revenue exceeds Indian Rupee (INR) 10 million,

497 an additional surcharge of 2% is also levied[58]. The indirect taxes consist of Goods and

498 Service Tax (GST), which has replaced the previous State Value-Added Tax, Central

499 Sales Tax, and Service Tax on Transportation[58]. The coal tax is an implicit carbon tax

500 levied on mined coal, also known as the Clean Energy Cess or Clean Environment Cess.

501 Since the introduction of the coal tax, the price of coal has increased from INR 50 per

502 tonne in 2010 to INR 400 per tonne in 2016[59]. With the introduction of GST in India in

503 July 2017, the Taxation Laws Amendment Act 2017 abolished the Clean Energy Cess.

504 In its place, the GST Compensation Cess was introduced at a rate of 400 INR per

505 tonne[60].

506   The formulas for calculating tax revenue are as follows:

507
$$T_{i,j,t} = \sum_{i,j}\sum_{t} x_{i,j,t} \sum_{t=t_{retire}}^{Y_{i,j}+lifetime} \frac{\left(T_{direct,i,j,t} + T_{GST,i,j,t} + T_{GST\ Compensation\ Cess,i,j,t}\right)}{\left(1+d_{tax}\right)^{(t-t_0)}} \quad (15)$$

508
$$T_{direct,i,j,t} = NP_{i,j,t} \times r_{direct} \quad (16)$$

509
$$T_{GST,t} = G_{i,j,t} \times HR/LHV \times C_{coal,cost} \times 5\% \quad (17)$$

25

510
$$T_{GST \text{ Compensation Cess},t} = G_{i,j,t} \times HR / LHV \times r_{cess}$$ (18)

511   Where, $T_{i,j,t}$ is total tax. r_{direct} represents the income tax rate (the value is 32% if

512    $NP_{i,j,t} >=$ INR 10 million, else 30%, assuming 1 USD = 74 INR in 2020). $NP_{i,j,t}$ is the

513   net profit of the unit. r_{cess} represents the GST Compensation Cess rate, which is INR

514   400 per tonne. LHV is the lower heat value, measured in kilocalories per kg (kcal kg^{-}

515   ^{1})[47]. The tax revenue is discounted at a rate of 10% (d_{tax})[61].

516   To assess the losses incurred by India from the gradual phaseout of coal power,

517   the impacts on unemployment are calculated by applying the corresponding

518   employment factors to the installed capacity and electricity generation. The total

519   number of jobs is estimated by multiplying the installed coal capacity by the

520   employment multiplier for the operation and maintenance sector, expressed in jobs per

521   MW[62]. We use the average real wages in the Indian power sector, as reported by the

522   International Labour Organization, to represent the wages of coal power plant workers[63].

523   Employment losses are then monetized and discounted at a rate of 3%[17]. This section

524   mainly focuses on the direct employment losses resulting from the shutdown of coal

525   power plants, specifically the unemployment of operation and maintenance workers. It

526   excludes jobs in construction, installation, manufacturing, coal mining, and

527   transportation[64]. Although the retirement of power plants may generate new

528   employment opportunities, this aspect is not considered in this study.

529   **Power plant loss**

530   To meet climate targets, coal-fired power plants are expected to retire early,

531   resulting in plant losses that include foregone profit opportunities ($PL_{i,j,t}$) and stranded

532   assets ($SA_{i,j,t}$). We first assess the profitability of each unit. Annual profit is estimated

533   as the difference between annual revenues and costs. Revenues are calculated based on

534   electricity prices and the electricity generation of units.

$$PL_{i,j,t} = \sum_{i,j}\sum_{t} x_{i,j,t}\left(\sum_{t=t_{retire}}^{Y_{i,j}+lifetime} NP_{i,j,t} / \left(1+d_{np}\right)^{(t-t_0)}\right) \qquad (19)$$

$$NP_{i,j,t} = EP \times G_{i,j,t} - C_{i,j,t} \qquad (20)$$

537   In this context, $NP_{i,j,t}$ is the annual net profit of unit i and unit j in year t, which

538   is calculated by revenue minus cost ($C_{i,j,t}$). Revenue is measured by electricity prices

539   (EP) and electricity generation ($G_{i,j,t}$), and the value of EP in each state as

540   referenced in the reports published by each State Electricity Regulatory Commission[65].

541   $C_{i,j,t}$ include fuel delivery costs (C_{coal}, USD per tonne), variable operating and

542   maintenance costs ($C_{OM,variable}$, USD kWh^{-1}), fixed operating and maintenance costs

543   ($C_{OM,fixed}$, USD kW^{-1}). The units' profit is depreciated at a discount rate d_{np}, which is

544   10%[47,61].

$$C_{i,j,t} = C_{coal,i,j,t} + C_{OM,fixed,i,j,t} + C_{OM,variable,i,j,t} \qquad (21)$$

$$C_{coal,i,j,t} = C_{coal,cost} \times G_{i,j,t} \times HR_{i,j} / LHV \qquad (22)$$

547   Where the coal cost is measured by the delivered coal price $C_{coal,cost}$, which

548   includes purchase and transportation costs. $C_{OM,fixed,unitary}$ and $C_{OM,variable,unitary}$ are

549   referenced from the research of Mallah et al.[66]

$$C_{OM,fixed} = C_{OM,fixed,unitary} \times Capacity \qquad (23)$$

$$C_{OM,variable} = C_{OM,variable,unitary} \times G_{i,j,t} \qquad (24)$$

552   Second, we explore the risk of stranded assets for units under climate scenarios

553   and consider this as a loss. Unrecovered capital costs are used as a measure of stranded

27

554   assets. The abandonment value of power plants retired prematurely is calculated as the

555   total capital of the assets multiplied by the portion of the expected lifespan that is

556   abandoned due to early retirement[7]. Stranded Assets are calculated using the following

557   formula[10]:

558
$$SA_{i,j,t} = \left(OCC \times Cap_{i,j} \times \left(L - RL_{i,j} \right) / L \right) / \left(1 + d_{sd} \right)^{(t-t_0)} \qquad (25)$$

559   In the formula, $SA_{i,j,t}$ is stranded assets for unit i and unit j in year t; $Cap_{i,j}$

560   represents capacity; L denotes the assumed lifetime; $RL_{i,j}$ stands for retirement age;

561   and OCC represents the overnight capital cost for each power unit (measured in USD

562   per kW), which is estimated based on the research conducted by Dulong et al.[9] And the

563   stranded assets are discounted by 5% to the base year (d_{sd})[9,67]. The retirement of units

564   that have operated beyond their fixed lifespan will not result in any stranded assets, as

565   the initial capital cost has been fully paid[68]. Therefore, we only consider units with

566    $L \geq RL_{i,j}$, otherwise, the stranded assets are zero.

567   **Scenario description**

568   We conducted a bottom-up assessment of environmental emissions and economic

569   characteristics for each coal power unit, while retirement decisions were guided by top-

570   down climate target trajectories. Phaseout strategies consistent with 1.5°C and 2°C

571   pathways were designed to evaluate the cost-benefit of coal power units.

572   We compared the future pathways of coal power capacity under the 1.5°C and 2°C

573   targets with the actual operational capacity for each year. This process identifies the

574   surplus capacity exceeding the climate target, which is then sequentially deducted from

575   the actual operational capacity based on cost-benefit maximization decisions. This step

576 is repeated iteratively to ensure that the operational capacity aligns with climate-

577 compatible targets for specific years. The raw data in climate scenarios were obtained

578 from the IPCC Sixth Assessment Report (AR6) Working Group III (WGIII) Scenario

579 Database, hosted by the International Institute for Applied Systems Analysis[34], which

580 provided coal power capacity pathways under 1.5°C and 2°C scenarios. We use

581 categories C1 (no or limited overshoot) and C2 (high overshoot) for 1.5°C consistent

582 pathways, and Categories C3 (likely below 2°C) and C4 (below 2°C) for 2°C pathways

583 (see Supplementary Table 1 for descriptions). Power scenarios from seven major

584 integrated assessment models (GCAM, AIM/CGE, MESSAGE-GLOBIOM, IMAGE,

585 REMIND, WITCH, and POLES) were employed to analyze coal power pathways

586 across 379 recent scenarios, encompassing trajectories aimed at limiting average global

587 warming to 1.5°C and 2°C by the end of the Century. Since each model generates

588 parameter outputs at 5- or 10-year intervals, we employed second-order polynomial

589 interpolation to derive annual data. The median and range of the results are presented

590 in Fig. 1c, d. We assumed the current operational and pipeline coal fleet would not

591 transition to units equipped with Carbon Capture, Utilization, and Storage, biomass

592 energy, or natural gas.

593   Additionally, India's coal power units are relatively new, with an average

594 operational lifetime of about 17 years. We adopt a typical coal power plant assumed

595 lifetime of 40 years[1,69,70], and conduct an uncertainty analysis by extending the assumed

596 lifetime range to 35–45 years. The analysis encompassed the operational capacity in the

597 baseline year of 2020 and the pipeline capacities for the years after that.

Characteristics of coal plants

We utilized unit-level data from the World Electric Power Plants (WEPP) database by S&P Global Platts[71], which was cross-validated with the Global Energy Monitor database[72], to analyze currently operational coal-fired power plants in India. The unit-level information includes the vintage year, installed capacity, coal type, and location. For units without online years, we estimate the median value of all fleets. Since the WEPP database does not include latitude and longitude information for power plants, we used Google Earth to map each unit's location based on the physical addresses provided in the WEPP database (Supplementary Fig. 2). And for a few small units that were not visible on satellite imagery, we approximated their location using the geographical coordinates of the respective administrative district. Besides, our unit-level inventory includes 1,305 operations (operating in the baseline year of 2020) and 113 pipelines (planned or under construction before 2030) in India, with a combined installed capacity of 233 GW and 53 GW, respectively (Supplementary Fig. 3).

Uncertainty analysis

Since the model includes multiple key parameters, we conducted a quantitative uncertainty analysis of them and their impacts on multidimensional outcomes, including assumed lifetime, SCC, capacity factor, and discount rate. The assumed lifetime range was extended to 35–45 years, and the capacity factor was conducted with a ±5% variation. Discount rates were applied to convert future benefits and costs into present values, enabling comparability of cost-benefit outcomes over time. In our model, the discount rate applies to multiple dimensions, including carbon benefits, health

620 benefits, taxes, employment, plant profits, and stranded assets. By defining parameter

621 ranges and performing iterative simulations, we explored the extent to which variations

622 in assumptions influence the results. The specific ranges for each parameter are

623 provided in Supplementary Table 9. Additionally, we performed a comprehensive

624 assessment based on the assumed lifetime range of 35–45 years, incorporating the

625 uncertainty of various parameters. The results of the uncertainty analysis are presented

626 in Supplementary Figs. 9–12.

Data Availability

628 The unit-level data are collected from the World Electric Power Plants database

629 (https://www.spglobal.com/marketintelligence/en/)[71] and the Global Energy Monitor

630 database (https://globalenergymonitor.org/zh-CN/projects/global-coal-plant-tracker/)[72].

631 Raw data for climate scenarios are from the IPCC AR6 WGIII Scenarios Database[34].

632 The base maps used in this study were generated using Esri-standardized datasets

633 within ArcGIS 10.8. All geospatial processing and visualization were performed by the

634 authors. Map images © Esri and its licensors. Used under license. Source data are

635 provided with this paper. The data that support the other findings within this article can

636 be obtained from the author upon request.

Code Availability

638 The code used to process all modeling results and create all related images is

639 publicly available on Zenodo: https://doi.org/10.5281/zenodo.14229510[73]. The model

640 was written in Python (version 3.11.7), and optimization modeling was performed using

641 the Gurobi solver (Version 10.0.3): https://www.gurobi.com/. Spatial data analysis was

642 carried out using the Geopandas package (Version 0.14.3):

643 https://geopandas.org/en/v0.14.3/.

644 **References**

645 1. Yang, J. & Urpelainen, J. The future of India's coal-fired power generation

646   capacity. *J. Clean. Prod.* **226**, 904–912 (2019).

647 2. Crippa, M. *et al.* Fossil CO_2 emissions of all world countries-2020 report.

648   *Luxembourg: European Commission*, 1–244 (2020).

649 3. Chakravarty, S. & Somanathan, E. There is no economic case for new coal plants

650   in India. *World Dev. Perspect.* **24**, 100373 (2021).

651 4. Climate   Action   Tracker.   Country   summary   India.

652   https://climateactiontracker.org/countries/india/ (2024).

653 5. Cui, R. Y. *et al.* Quantifying operational lifetimes for coal power plants under the

654   Paris goals. *Nat. Commun.* **10**, 4759 (2019).

655 6. India's just energy transition: Political economy challenges across states and

656   regions. *Energ. Policy* **179**, 113621 (2023).

657 7. Binsted, M. *et al.* Stranded asset implications of the Paris agreement in Latin

658   America and the caribbean. *Environ. Res. Lett.* **15**, 044026 (2020).

659 8. Pfeiffer, A., Hepburn, C., Vogt-Schilb, A. & Caldecott, B. Committed emissions

660   from existing and planned power plants and asset stranding required to meet the

661   Paris Agreement. *Environ. Res. Lett.* **13**, 054019 (2018).

662 9. von Dulong, A. Concentration of asset owners exposed to power sector stranded

663   assets may trigger climate policy resistance. *Nat. Commun.* **14**, 6442 (2023).

664 10. Edwards, M. R. *et al.* Quantifying the regional stranded asset risks from new coal

665   plants under 1.5 °C. *Environ. Res. Lett.* **17**, 024029 (2022).

666 11. Montrone, L., Ohlendorf, N. & Chandra, R. The political economy of coal in India

667   – evidence from expert interviews. *Energy Sustain. Dev.* **61**, 230–240 (2021).

668   12. Aldy, J. E., Kotchen, M. J., Stavins, R. N. & Stock, J. H. Keep climate policy

669   focused on the social cost of carbon. *Science* **373**, 850–852 (2021).

670   13. Wang, *et al.* Estimates of the social cost of carbon: A review based on meta-

671   analysis. *J. Clean. Prod.* **209**,1494–1507 (2019).

672   14. West, J. J. *et al.* Co-benefits of global greenhouse gas mitigation for future air

673   quality and human health. *Nat. Clim. Change* **3**, 885–889 (2013).

674   15. Cropper, M. *et al.* The mortality impacts of current and planned coal-fired power

675   plants in India. *Proc. Natl. Acad. Sci. USA* **118**, e2017936118 (2021).

676   16. The World Bank. World Bank Country and Lending Groups.

677   https://datahelpdesk.worldbank.org/knowledgebase/articles/906519 (2025).

678   17. Ricke, K. *et al.* Country-level social cost of carbon. *Nat. Clim. Change* **8**, 895–900

679   (2018).

680   18. Richard S.J., T. Social cost of carbon estimates have increased over time. *Nat. Clim.*

681   *Change* **13**, 532–536 (2023).

682   19. Government of India, Ministry of Power. 500 GW Nonfossil Fuel Target.

683   https://powermin.gov.in/en/content/500gw-nonfossil-fuel-target (2023).

684   20. Renewable Energy Policy Network for the 21st Century. Renewables 2024 Global

685   Status Report India. https://www.ren21.net/gsr-2024/ (2024).

686   21. Ministry of Coal, Government of India. Production and annual consumption of

687   coal in the country.

688   https://pib.gov.in/pib.gov.in/Pressreleaseshare.aspx?PRID=1908840 (2023).

689   22. Global Energy Monitor. India Enters an Unnecessary Coal Plant Permitting Spree

690   in 2023. https://globalenergymonitor.org/wp-content/uploads/2023/08/India-

691   New-Coal-Permits-August-2023.pdf (2023).

23. Vinichenko, V., Vetier, M., Jewell, J., Nacke, L. & Cherp, A. Phasing out coal for 2 °C target requires worldwide replication of most ambitious national plans despite security and fairness concerns. *Environ. Res. Lett.* **18**, 014031 (2023).

24. Maamoun, N., Kennedy, R., Jin, X. & Urpelainen, J. Identifying coal-fired power plants for early retirement. *Renew. Sust. Energ. Rev.* **126**, 109833 (2020).

25. Fofrich, R. *et al.* Early retirement of power plants in climate mitigation scenarios. *Environ. Res. Lett.* **15**, 094064 (2020).

26. Cui, R. Y. *et al.* A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nat. Commun.* **12**, 1468 (2021).

27. Muttitt, G., Price, J., Pye, S. & Welsby, D. Socio-political feasibility of coal power phase-out and its role in mitigation pathways. *Nat. Clim. Change* **13**, 140–147 (2023).

28. Figueira, J., Greco, S. & Ehrogott, M. *Multiple Criteria Decision Analysis: State of the Art Surveys*. vol. **78** (2005).

29. Malik, A. *et al.* Reducing stranded assets through early action in the Indian power sector. *Environ. Res. Lett.* **15**, 094091 (2020).

30. Kefford, B. M., Ballinger, B., Schmeda-Lopez, D. R., Greig, C. & Smart, S. The early retirement challenge for fossil fuel power plants in deep decarbonization scenarios. *Energ. Policy* **119**, 294–306 (2018).

31. Lu, Y., Cohen, F., Smith, S. M. & Pfeiffer, A. Plant conversions and abatement technologies cannot prevent stranding of power plant assets in 2 °C scenarios. *Nat. Commun.* **13**, 806 (2022).

32. Yan, X. *et al.* Cost-effectiveness uncertainty may bias the decision of coal power transitions in China. *Nat. Commun.* **15**, 2272 (2024).

33. Diakoulaki, D. & Karangelis, F. Multi-criteria decision analysis and cost-benefit

717   analysis of alternative scenarios for the power generation sector in Greece. *Renew.*

718   *Sust. Energ. Rev.* **11**, 716–727 (2007).

719   34. Byers, E. *et al.* AR6 scenarios database. Zenodo:

720   https://doi.org/10.5281/zenodo.5886912 (2022).

721   35. Steckel, J. C., Edenhofer, O. & Jakob, M. Drivers for the renaissance of coal. *Proc.*

722   *Natl. Acad. Sci. USA* **112**, E3775–E3781 (2015).

723   36. Steckel, J. C. & Jakob, M. To end coal, adapt to regional realities. *Nature* **607**, 29–

724   31 (2022).

725   37. Luderer, G. et al. Residual fossil CO_2 emissions in 1.5–2°C pathways. *Nat. Clim.*

726   *Change* **7**, 626–633 (2018).

727   38. Zhang, W. *et al.* Quantifying stranded assets of the coal-fired power in China under

728   the Paris Agreement target. *Clim. Policy* **23**, 11–24 (2023).

729   39. Gao, M. *et al*. The impact of power generation emissions on ambient $PM_{2.5}$

730   pollution and human health in China and India. *Environ. Int*. **121**, 250–259 (2018).

731   40. Venkataraman, C. *et al*. Source influence on emission pathways and ambient $PM_{2.5}$

732   pollution over India (2015–2050). *Atmos. Chem. Phys.* **18**, 8017–8039 (2018).

733   41. Ministry of New and Renewable Energy, Government of India. Production Linked

734   Incentive (PLI) Scheme: National Programme on High Efficiency Solar PV

735   Modules. https://mnre.gov.in/en/production-linked-incentive-pli/ (2024).

736   42. Umamaheswaran, S. & Rajiv, S. Financing large scale wind and solar projects—

737   A review of emerging experiences in the Indian context. *Renew. Sust. Energ. Rev.*

738   **48**, 166–177 (2015).

739   43. Ministry of New and Renewable Energy, Government of India. Physical

740   achievements India. https://mnre.gov.in/physical-progress/ (2025).

741   44. Pizer, W. *et al*. Using and improving the social cost of carbon. *Science* **346**, 1189–

742   1190 (2014).

743   45. Global Energy Monitor. Estimating carbon dioxide emissions from coal plants.

744   https://www.gem.wiki/Estimating_carbon_dioxide_emissions_from_coal_plants

745   (2023).

746   46. Central Electricity Authority, Government of India. Monthly reports archive.

747   https://cea.nic.in/monthly-reports-archive/?lang=en (2024).

748   47. Central Electricity Authority, Government of India. CDM-CO_2 Baseline Database.

749   https://cea.nic.in/cdm-co2-baseline-database/?lang=en (2024).

750   48. Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. 2006 IPCC

751   Guidelines for National Greenhouse Gas Inventories. (2006).

752   49. Southerland, V. A. et al. Global urban temporal trends in fine particulate matter

753   ($PM_{2.5}$) and attributable health burdens: Estimates from global datasets. *Lancet*

754   *Planet. Health* **6**, e139–e146 (2022).

755   50. Burnett, R. et al. Global estimates of mortality associated with long-term exposure

756   to outdoor fine particulate matter. *Proc. Natl. Acad. Sci. USA.* **115**, 9592–9597

757   (2018).

758   51. Deshmukh, R. & Chatterjee, S. Toward a low-carbon transition in India. *Science*

759   **378**, 595–596 (2022).

760   52. Diaz, D. & Moore, F. Quantifying the economic risks of climate change. *Nat. Clim.*

761   *Change* **7**, 774–782 (2017).

762   53. Oberschelp, C., Pfister, S. & Hellweg, S. Globally regionalized monthly life cycle

763   impact assessment of particulate matter. *Environ. Sci. Technol.* **54**, 16028–16038

764   (2020).

765   54. Anand, S., Hanson, K. Disability-adjusted life years: a critical review. *J. health*

766   *econ.* **16**(6): 685-702 (1997).

767   55. Rauner, S. et al. Coal-exit health and environmental damage reductions outweigh

768   economic impacts. *Nat. Clim. Change* **10**, 308–312 (2020).

769   56. Haacker, M., Hallett, T. B. & Atun, R. On discount rates for economic evaluations

770   in global health. *Health Policy Plann.* **35**, 107–114 (2020).

771   57. International Institute for Applied Systems Analysis. GAINS south Asia online.

772   https://gains.iiasa.ac.at/gains/docu.INN/index.menu?open=none (2024).

773   58. International Institute for Sustainable Development. India's energy transition:

774   Mapping subsidies to fossil fuels and clean energy in India.

775   https://www.iisd.org/system/files/publications/india-energy-transition.pdf (2017).

776   59. International Institute for Sustainable Development. The evolution of the clean

777   energy cess on coal production in India.

778   https://www.iisd.org/system/files/publications/stories-g20-india-en.pdf (2018).

779   60. Ministry of Finance, Government of India. Climate watch India country platform.

780   https://indiaclimateexplorer.org/climate-policies/CEC/overview (2024).

781   61. Prakash, V., Ghosh, S. & Kanjilal, K. Costs of avoided carbon emission from

782   thermal and renewable sources of power in India and policy implications. *Energy*

783   **200**, 117522 (2020).

784   62. Pai, S., Emmerling, J., Drouet, L., Zerriffi, H. & Jewell, J. Meeting well-below

785   2°C target would increase energy sector jobs globally. *One Earth* **4**, 1026–1036

786   (2021).

787   63. International Labour Organization. Towards an India wage report 2017.

788   https://ilo.primo.exlibrisgroup.com (2017).

789   64. Sasse, J.-P. & Trutnevyte, E. A low-carbon electricity sector in Europe risks

790   sustaining regional inequalities in benefits and vulnerabilities. *Nat. Commun.* **14**,

791   2205 (2023).

792 65. Central Electricity Authority, Government of India. Domestic Electricity LT Tariff

793   Slabs   and   Rates   for   all   states   in   India   in   2016.

794   https://www.bijlibachao.com/news/domestic-electricity-lt-tariff-slabs-and-rates-

795   for-all-states-in-india-in.html (2017).

796 66. Mallah, S. & Bansal, N. K. Allocation of energy resources for power generation

797   in India: Business as usual and energy efficiency. *Energ. Policy* **38**, 1059–1066

798   (2010).

799 67. Johnson, N. *et al.* Stranded on a low-carbon planet: Implications of climate policy

800   for the phase-out of coal-based power plants. *Technol. Forecast. Soc. Change* **90**,

801   89–102 (2015).

802 68. Tong, D. *et al.* Committed emissions from existing energy infrastructure

803   jeopardize 1.5°C climate target. *Nature* **572**, 373–377 (2019).

804 69. Shearer, C., Fofrich, R. & Davis, S. J. Future CO_2 emissions and electricity

805   generation from proposed coal-fired power plants in India. *Earth's Future* **5**, 408–

806   416 (2017).

807 70. Shrimali, G. Managing power system flexibility in India via coal plants. *Energ.*

808   *Policy* **150**, 112061 (2021).

809 71. S&P   Global.   World   Electric   Power   Plant   Database.

810   https://www.spglobal.com/commodity-insights/en/commodity/electric-power

811   (2020).

812 72. Global   Energy   Monitor.   Global   Coal   Plant   Tracker.

813   https://globalenergymonitor.org/projects/global-coal-plant-tracker/ (2025).

814 73. Long, X. et al. Codes for "Ambitious climate targets can make the phaseout of

815   India's   coal-fired   power   plants   cost-beneficial".   Zenodo.

816   https://doi.org/10.5281/zenodo.14229510 (2025).

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Author Contributions

Y. W., J. M., B. C., X. L., and P. C. developed the research idea and framework. X. L., B. C., H. X., and J. M. developed models, provided guidance on methods, and managed the estimation process. X. L. did coding, analyzing, and visualization. X. L., Y. W., J. M., B. C., M. D., and P. C. reviewed the results and manuscript. X. L., B. C., M. D., H. X., P. C., J. M., and Y. W. contributed to the development of the manuscript and had final responsibility for the decision to submit for publication.

Competing Interests

The authors declare no competing interests.

Figure Legends

Fig. 1 | Characteristics of India's coal power units and climate target pathways. a Geographic locations and the installed capacities of individual operating units in India. The map is based on factual evidence and displays the non-disputed areas under actual control. **b** Total installed capacity and age structure of operating units in each state (the baseline year is 2020), as well as the capacity of units under construction or planned (Pipeline). Capacity is expressed in megawatts (MW) at the unit level and in gigawatts

839   (GW) at the state level. **c, d** India's coal power capacity pathways consistent with

840   limiting warming to 1.5°C and 2°C. The dark lines indicate median pathways, with

841   shaded areas representing the 5th–95th percentile range (light shading) and the 25th–

842   75th percentile range (dark shading). The raw scenario data is sourced from the Sixth

843   Assessment Report (AR6) Scenario Database[34]. The base map was obtained from Esri

844   ArcGIS 10.8. Map images © Esri and its licensors. Used under license.

845   **Fig. 2 | Cost-benefit analysis of coal power units. a, b** Total costs and benefits of all

846   units under the 1.5°C and 2°C scenarios, showing the cumulative values from early

847   retirement to the end of the assumed lifetime. The shaded areas represent the range of

848   uncertainty. **c, d** The cumulative values for each unit across four dimensions, with units

849   sorted from left to right in increasing order. The bar colors represent the installed

850   capacity of each unit (in gigawatt, GW). The four dimensions include carbon benefits,

851   health benefits, plant losses, and tax & employment losses, all measured in billion US

852   dollars (USD). The results include both operational and pipeline units.

853   **Fig. 3 | Phaseout roadmap of coal power units and their actual lifetimes under**

854   **climate goals scenarios across periods. a, b** The retirement year of individual coal

855   power units. Operating units refer to those still in operation in the baseline year 2020,

856   while pipeline represents units that are planned or currently under construction. The

857   grey, red, green, and yellow dots represent operation units that have not yet been retired,

858   operation units that have retired, commissioned pipeline units that have not yet been

859   retired, and retired pipeline units, respectively. The size of the circles indicates the

860   installed capacity (in megawatt, MW). The labels in the upper-right corner of each map

indicate the number of retired units by type and their total capacity (in gigawatt, GW).

The map is based on factual evidence and displays the non-disputed areas under actual

control. **c** The actual lifetime of each unit under the 1.5°C and 2°C scenarios. **d, e** Cost-

benefit outcomes for each state under two scenarios, ranked in descending order by net

value from top to bottom. The benefits include carbon and health benefits, while the

costs encompass plant loss and tax & employment loss. The base maps were obtained

from Esri ArcGIS 10.8. Map images © Esri and its licensors. Used under license.

Fig. 4 | Annual avoided carbon emissions and health impacts. a, **b** National results.

c, **d** Results for the top 14 states ranked by installed capacity. The solid lines show

results under the 40-year lifetime assumption, while the shaded areas indicate the range

across lifetime scenarios (35–45 years). CO_2 emissions are expressed in gigatonnes (Gt)

at the national level and in million tonnes (Mt) at the state level. Health impacts are

measured by disability-adjusted life years (DALYs).

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889 **Editorial Summary:**

890 This study develops a plant-level dynamic optimization model outlining India's coal power

891 phaseout pathways aligned with climate targets. The results show that ambitious goals are

892 more cost-beneficial, and social benefits can enhance the feasibility of the transition.

893 **Peer Review Information:** *Nature Communications* thanks the anonymous, reviewer(s) for

894 their contribution to the peer review of this work. A peer review file is available."

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