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Identifying coal plants for early retirement in India: A multidimensional analysis of technical, economic, and environmental factors

Nada Maamoun [a], Puneet Chitkara [b], Joonseok Yang [c], Gireesh Shrimali [d], Joshua Busby [e], Sarang Shidore [e], Yana Jin [f], Johannes Urpelainen [b,*]

[a] CAU Kiel, Germany
[b] Johns Hopkins SAIS, United States of America
[c] Sungkyunkwan University, Republic of Korea
[d] Stanford University, United States of America
[e] UT Austin, United States of America
[f] Environmental Defense Fund, United States of America

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ABSTRACT

Coal-fired energy generation is the backbone of India's power sector and considered a driver of its economic development. However, it is associated with detrimental environmental and health impacts in India and its fleet is currently struggling with overcapacity and inefficiency problems. One solution to address these challenges is the early retirement of some of India's coal-fired power plants. In this paper, we introduce multidimensional indices that identify plants for retirement based on comprehensive criteria that include technical and economic characteristics of plants as well as their environmental impacts. We implement an ensemble approach, where we formulate 8008 indices based on all possible combination of seven relevant parameters and rank plants accordingly. This approach facilitates a comprehensive analysis of the plants' performance on different parameters and provides a new outlook on plant retirements that differs from the common approach of retiring plants based solely on technical characteristics such as age, capacity, and heat rate. Our results show that top plants recommended for early retirement are typically 7 years older, 13% more expensive and have around 40% higher population exposure to emissions compared to an average plant in India. We estimate the potential costs saved from the retirement of the worst-performing 50 GW of generating capacity to be $21 billion resulting from shifting ownership towards a cheaper cost of capital and replacing coal by more competitive sources such as solar power.

1. Introduction

Coal-fired electricity is the most significant source of heat-trapping greenhouse gases. In the absence of commercially viable carbon capture, the phaseout of coal power globally will be essential if the goal of keeping temperatures from rising 2°C above pre-industrial levels is to be kept. Given that India is one of the largest coal-fired power producers in the world and is ranked among the top five global emitters of carbon dioxide (CO_2) [1], the decarbonization of its power sector is key for climate stability. Coal is the backbone of India's power sector and over the past two decades India's coal capacity quadrupled; growing from 50 GW in 2000 to reach 209 GW in 2021 [2,3].[1] This expansion does not come as a surprise given India's rapid economic growth. In its Nationally Determined Contributions (NDCs) pledge for the 2015 Paris Agreement, India pledged to increase the share of non-fossil fuel capacity in its energy mix; and the country has set ambitious targets to increase its Renewable Energy (RE) capacity to reach 450 GW by 2030 [4]. However, the projected growth of India's coal fleet coupled with the rise in RE have led to problems of over capacity, under-utilization of plants, and a potential risk of stranded assets [5].

In addition to inefficiency concerns, coal-fired power plants are the biggest contributor to CO_2 emissions, which contributes to global warming. As a result, India's energy policies have a significant impact on global climate change given the size of the Indian coal fleet. Coal-fired plants also contribute significantly to sulfur dioxide (SO_2), Nitrogen Oxides (NOx), and Particulate Matter (PM) emissions, all of which have detrimental health effects. Hence, emissions from Indian coal-fired plants may need to be substantially reduced, in order to

* Correspondence to: Rome Building, 4th Floor. 1619 Massachusetts Avenue, NW. Washington, DC 20036, United States of America.
E-mail address: JohannesU@jhu.edu (J. Urpelainen).

[1] The growth of the Indian coal fleet across the past two decades is not linear though and mostly occurred between 2010 and 2016.

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remain consistent with global climate targets and prevent further negative health impacts. Therefore, early retirement of some of its capacity is one solution that alleviates the problem of overcapacity as well as effectively reduces emissions and negative health and environmental impacts [5–7]. Early retirement is also sensible from an economic point of view. RE generation costs are quickly falling, currently half that of coal-fired energy, making coal-fired generation less competitive with the newer and cleaner sources [3,4].

The early retirement of some of India's coal fleet needs to follow comprehensive criteria that is sound to the local context, technically feasible, and socially beneficial. Previous studies on retirements in India gave priority to technical and economic characteristics such as age, efficiency, and costs [7–9]. While these factors are essential criteria for economically feasible retirement pathways, using them solely has some limitations. Prioritizing age disregards the fact that older plants in India are cheaper to operate even if they are pollution intensive and cheaper to retire [9]. Prioritizing generation efficiency leads to overall fleet improvement and pollution reductions but would lead to the retirement of younger plants that are more expensive to retire [9]. Thus far no study has directly accounted for the environmental impact of coal-fired power plants which is also costly.

In order to have meaningful criteria for retirements in place, we need to consider the public health and environmental impact [9]. In this paper, we provide a comprehensive, multi-dimensional approach that contributes to a sequential retirement "pathway" of the Indian coal fleet which accounts for the technical and economic performance of the plants as well as the environmental impact they have. Our indices rank plants based on their environmental impact, their technical and economic efficiency, and their location. The application of our multi-dimensional approach is not limited to the Indian coal fleet, rather it is relevant for designing multi-dimensional regional retirement pathways across all major coal consumers. For the Indian coal fleet, we use seven parameters that reflect these aspects. Three of those parameters are: population exposure to air pollution, water stress, and carbon emission factors — variables that represent the different facets of coal-fired power plants' impact on the environment. The remaining four parameters are: age, variable operating costs, generation efficiency, and distance to coal source — parameters that reflect the different economic and technical efficiency of a plant. We formulate 8008 indices based on the different weighted combinations of these seven parameters.[2] Using the 50 GW threshold mentioned in the report by the Central Electricity Authority (CEA) [8] and identified in the Council on Energy, Environment and Water (CEEW) study as excess capacity [9], we identify the worst performing 50 GW of installed capacity according to each index. We find that top plants identified for early retirement by our indices are on average 7 years older, 4% less efficient, and 13% more costly than the rest of the fleet not scheduled to be retired early. They also have worse environmental impacts, they suffer from higher water stress levels, are located in areas that suffer from higher water stress levels, and have a 40% higher population exposure to emissions in comparison to the remainder of India's coal fleet.[3]

We compare our results with the plants named by the CEA in their 2018 report [8] for possible early retirements as well as those recommended in the CEEW report [9]. We find that our results are fairly similar, when it comes to the common factors such as age and/or efficiency, but differ because of the diverse parameters we include in our analysis such as distance to coal source and environmental impacts. We investigate the difference between our list and the one named in the CEA report in more detail by separating the plants into two groups: economic and environmental, then we compare them with their respective groups in the CEA report. We compare the results based on the environmental indices (water stress, emission factors, and population exposure) only with those present in the CEA list of potential retirements as "per the new environmental norms". We find that plants named by our indices perform worse on all three parameters compared to those listed by the CEA. As for the economic list, we compare results based on our economic indices with those listed for early retirement by 2022–27 in the CEA report and we do not find a noteworthy differences with regards to age or efficiency but we do find that distance to coal sources is 90% longer and costs are 21% more expensive.

We estimate the cost-saving potential of the early retirement of plants listed by our indices to be \$21 billion, this is ~5 times that of the cost-saving potential of plants considered for potential early retirement in the CEA report and 3.5 times that of plants in the CEEW study. These cost savings are a result of savings from shifting towards a cheaper power source and shifting ownership towards a cheaper cost of capital.

In the sensitivity analysis, we compare the plants recommended for early retirement based on our multidimensional indices with the rankings of other indices that focus solely on each parameter separately. Comparing the worst performing plants (50 GW) of each index, we find that while there are some similarities, top plants according to each index are fairly diverse. This shows that retirement pathways would be sensitive to the parameters' weighting, meaning that prioritizing different parameters would lead to different plants being retired early. This underlines the importance of having a multidimensional approach that reflects the different aspects and impacts of coal-fired power in India.

In the coming section, we provide an overview on the coal industry in India and its role in the energy mix as well as its impacts on the population and environment. The third section introduces the research design and provides details on the data used in the analysis. The fourth section presents the results and the sensitivity analyses, and the final section concludes.

2. Negative externalities from India's coal-fired power plants

2.1. Coal in the power mix

India's coal fleet is the third largest globally and is the backbone of its electricity generation. As of 2021, India's total coal capacity in operation was 208 GW, accounting for 10% of global capacity, 55% of total installed capacity in India, and supplied at least 70% of its total electricity [3,7]. Nevertheless, we can see a slowdown in coal capacity growth as well as a drop in its share of power generation, which fell from 78% in 2018–2019 to 72.9% in 2020–2021 and is projected to reach 54% by the end of this decade [3].

India's coal fleet faces a problem of "overcapacity"; plants are running at capacity factors lower than the ideal level capacity factor, implying a low utilization rate and low efficiency. The Indian government expects that a typical coal plant in normal situations keeps an annual average capacity factor of 85% with some seasonality variations [3,10]. However, in 2021, plants were operating at lower capacity factors; utilization rates were 51% for FY2021 more than 20% less than in FY2011 (75%), and were expected to fall even further to 48% by 2022 [1,11,12]. The fall in the utilization rates may be explained by demand growth that is slower than previously expected coupled with increasing share of RE, which exhibits trends opposite to that of coal [3,7,12].

India has one of the highest growth rates in RE capacity and currently ranks as the fourth country globally in RE power capacity. Current installed RE capacity grew 12% over the past year – compared to a growth rate of 1.9% in coal and lignite capacity – reaching 92.5

[2] Each parameter takes a weight from 0 to 1 in 0.1 increments such that the sum of parameter weights for each index is 1. This results in 8008 different indices consisting of all possible combinations of these seven parameters.

[3] Population exposure (explained in Section 3.1.2) refers to the number of people exposed to a plant's emissions weighted by the plant's $PM_{2.5}$ emission intensity, such that we are able to differentiate between the pollution intensity levels of plants and account for it in our analysis.

GW, and accounting for 24.5% of total capacity and around 11% of generation. It is projected to account for 53% of capacity and 31% of power generation by 2030 [3,13,14]. Generation prices of solar and wind have fallen dramatically over the last few years, reaching ~Rs 2/KWh and Rs 3/KWh, respectively — in some cases, half the cost of coal power [3,14]. And while RE faces some challenges, such as land availability [15], the falling costs of RE as well as the projected falling CO_2 emissions associated with a higher share of RE, makes the shift favorable from an economic perspective [3,16,17]. Nonetheless, coal has strong political support and is expected to remain a significant part of India's power mix. The rise in RE is not expected to substitute coal completely, but reduce how often fossil fuel plants are run leading to cheaper and cleaner energy generation as well as excess coal-fired capacity that would need to be shut down due to its under-utilization [3,5,9,17].

2.2. Water resources, air quality, and climate change

Far beyond a depiction of pure industrial rise and fall, the negative externalities of coal power compose the other major motivation for early retirement of coal fleet on a global level. Compared to other sectors, coal power has unparalleled environmental impact potential in three main aspects: ambient air pollution, water resources depletion, and global climate change.

Ambient air pollution ranks as the fourth cause of death globally and fifth in India specifically. Air pollution's related health impacts are also a worldwide concern [18,19]. Coal-based power generation process produces large amount of SO_2, NOx and primary PM (particulate matter). Without the operation of pollution control measures, they are released into the lower atmosphere and become directly part or precursors of the ambient $PM_{2.5}$. India's power sector is by far the largest contributor to SO_2 emissions (59.1%), the second largest contributor to NOx emissions (25.0%), and the third largest contributor to $PM_{2.5}$. (16.1%) [4,18].[4] These three pollutants, in addition to mercury (Hg) which also is emitted from coal combustion, have severe negative health impacts such as: lung cancer ($PM_{2.5}$), respiratory and cardiovascular problems (SO_2 and $PM_{2.5}$), toxicity (NOx) strokes ($PM_{2.5}$), and brain damage in children (Hg): all leading to premature mortality. It is estimated that in India around 600,000 deaths per year are attributed to ambient air pollution, 50% of which are linked to emissions from the power generation sector. Roughly 11 million years of life is lost annually, equivalent to 268,000 premature deaths [18]. Thus, air pollution and its effect on public health is a major concern and a key policy priority. Given that India's energy sector is one of the main contributors to its air pollution crisis, it presents itself as a critical part of the solution [4].

The extent of absolute health impacts is determined by the population density surrounding the emissions sources. Indian coal-fired plants have the highest absolute pollution exposure risk as plants lack pollution control and the population density in the areas affected by the plants' pollutants is high. Indian coal is also known for its high ash content and low calorific value making Indian plants more emission-intense compared to their global counterparts [19,20]. In 2015, India tightened the national emission standards of coal-fired power plants and they were obliged to comply with the new emission norms by 2017. Those norms entailed cutting down SO_2 and NOx emissions. Prior to these norms, there were barely any emission standards except a very loose one on PM. However, the deadline for these new standards has been extended for the third time to 2025, allowing around 72% of plants to continue pollution for at least 3 more years [9,21].

A second externality resulting from coal-fired energy is water stress. Global water stress levels are increasing mainly due to the increase in demand coupled with a shortage in supply, partly due to the shift in global precipitation patterns as a result of climate change among other factors. Energy production is very dependent on water. Coal combustion particularly is the second most intensive source of energy after oil as it uses significant amounts of water for cooling and to create steam. The situation in India is especially dire as water supplies suffer from high seasonal variability as well as the heavy use of water in agriculture, making India the second most water-stressed country among the world's major coal producing/consuming countries [22,23].

Water scarcity is a major challenge for coal-fired power generation in India as more than 70% of the Indian coal fleet is located in water-stressed areas. Water shortages cause delays as well as limits the ability to operate plants at full capacity, thus eroding plant profitability and sometimes leading to losses. Already, nation-wide blackouts and even plant closures have occurred due to water shortages.[5] Water stress levels are only expected to intensify with the growth of India's coal fleet, and if left unmanaged the risk of inadequate water supplies may have severe financial consequences on the companies operating in India [22,24]. Already, the Indian Ministry of Environment, Forest and Climate Change (MoFECC) has called for stricter water consumption limits for all plants and zero waste water discharge for plants installed after 2017 [4,22].

A third externality is the emission of greenhouse gases (GHG). Coal-fired energy generation is one of the largest contributors to CO_2 emissions globally and by far the largest source in India compared to other fossil fuels [1,11]. It is also a major source of NOx, which contributes to global warming [4,19]. The magnitude of India's CO_2 emissions plays a key role in the global target of climate stability and keeping in line with the Paris Agreement's 2 °C limit. India is considered a demographic power globally given the size of its population and has one of the world's largest coal reserves. Its energy sector relies heavily on fossil fuels (60.9% of total energy generation) and coal in particular (52.6% of total energy generation), thus the size of its fleet and accordingly its emissions plays a major role in the global projection of the future of CO_2 emissions [11,25,26]. Even though, climate change may not be a great concern for most of India's population [27], India does have a significant stake in mitigating climate change given that a large share of India's rural population depend on climate sensitive sectors such as agriculture, fisheries, and forests as well as natural resources such as water, coastal zones, and biodiversity [4,28].

2.3. Technical and financial performance

In addition to the environmental, health, and efficiency concerns, India's coal fleet is still growing — even if at slower rates. Given the rise in RE capacity and problems of under-utilization, unless the growth in electricity demand accelerates beyond the government forecasts, India would end up with more under-utilized and potentially stranded coal-fired plants leading to revenue losses [1,11]. As the results in [5] show, one way to address such a problem would be to retire plants early. The average age of the Indian coal fleet is young and a shorter lifespan per plant would address the problem of overcapacity as well as effectively reduce emissions, helping keep the 2 °C target within reach. In India's 2018 National Electricity Plan, 25 GW were identified as excess coal capacity that could be retired early. In another recent study by CEEW, approximately 50 GW were found to be a surplus to the system requirements [8,9]. This means that the early retirement of some of India's coal capacity may be feasible given the current challenges faced in coal-fired generation, the strides in RE generation, and the environmental damages associated with coal. Thus far, the

[4] Ambient $PM_{2.5}$ pollution is not limited to coal combustion, various other sectors jointly contribute to the ambient $PM_{2.5}$ pollution, such as industry, residential (cooking and heating with solid fuel), transportation, construction dust.

[5] In 2008 shortage in water supply has led to the closure of NTPC's Sipat plant in the state of Chattisgarh.

political and economic environment in India does not seem very eager to replace coal, given India's ample domestic coal reserves which help insulate the country from having to import energy [5,27].

Therefore, to retire some of India's coal-fired plants earlier than their expected life, we need insights from aggregated, national level analysis to set robust criteria upon which we can rank the plants and prioritize which should go first. Meaningful criteria for early retirements need to account for medium and long-term system requirements, address public health concerns and result in efficiency improvements and costs savings [9]. Stakeholders need to be equipped with knowledge on what, how, and when the early retirement of a specific coal plant is most desirable.

2.4. Existing literature on early retirements of coal-fired power

The common approach for addressing coal plants' retirements is to retire older plants first. Such an approach is sensible as the performance of a coal-fired unit deteriorates with age and older plants thus become more emission intensive and less efficient [19,29]. Older plants are good candidates for early retirement as they are not fit to compete with renewable energy and they have lower future value, so the cost of retiring them is much lower than that of younger plants that have longer expected operational life and more returns [30–32]. They are also more pollution intense in comparison to younger plants as they lack the newer anti-pollution controls technology [30–33]. However, older plants in the Indian fleet are comparatively cheaper than younger ones and provide competitive generation, so making a case for retiring more efficient plants is not economically sensible [9]. In addition to retiring older plants, under-utilized plants also make good candidates if they are underutilized on the grounds of efficiency.[6] Plants with smaller capacity are also considered to be good candidates as they produce disproportionately large amounts of pollution compared to their generating capacity [31,32].

Existing literature on the early retirement of coal-fired power plants has been focused primarily on the technical aspects of the plants. The most commonly used criterion for early retirement in previous literature is age. Nace [34] provide retirement pathways for coal-fired power plants globally based primarily on plant's age. Other studies such as [30] recommend plants for early retirement that are old, inefficient and under-utilized. Huetteman [31] study on plants closures in the U.S. and show that plants that are prone to early retirement tend to be older and smaller in capacity. Recent studies on early retirement of some of India's coal fleets have also focused on the technical and economic aspects of the plants. Studies considered cost effectiveness, age [7] and efficiency [9] as the main criteria for early plant retirements. Both studies show that retiring excess coal capacity will not affect regional supply and demand and would lead to cost savings in the long-run [7,9]. In a study by the CEEW, early decommissioning of plants based on efficiency would result in a 1.9% improvement in the coal fleet's efficiency, reduction of GHG, $1.37 billion saved from avoided pollution control retrofits, and annual savings of $1.23 billion compared to retirements based on variable costs [9]. The study also finds that prioritizing plants based on their efficiency would result in a surplus of 50 GW to the system requirements that can be retired early. In another study, it was estimated that the cost of early retirement of 95 GW would actually pay for itself in 5 to 6 years time, covering compensation payouts to the workforce and payouts to debt and equity holders [9].

Considering the negative impacts of coal-fired plants on human health and on the environment in terms of air pollution and water stress, we need to have a more comprehensive approach in identifying coal-fired plants for early retirement that goes beyond the technical characteristics of the plant and considers their impact on the population and the environment. Few studies have considered the health and environmental impacts of coal-fired power plants as relevant criteria for early retirement. Maamoun et al. [35] consider the air pollution and climate change impacts of coal-fired power plants globally and identify plants for early retirements based on these two variables as well as a plant's age. Cui et al. [36] consider a more comprehensive multidimensional criteria covering technical characteristics, profitability, and environmental impact for a plant-by-plant phase-out of the Chinese coal fleet. Thus far, no study on India considered the environmental and public health impacts as essential criteria for early retirement of Indian coal-fired plants. Given the severe environmental impacts of coal-fired power on the environment and public health in India [37], in this paper, we aim to introduce a multidimensional index that accounts for the plants' environmental impact in terms of population exposure, emission intensity, and water stress levels, in addition to technical and economic efficiency, which include age, operating costs, and generation efficiency.

3. Research method

To identify plants for early retirement and formulate our retirement indices, we have two main attributes guiding our research design. First, we use quantitative measures for every one of the index aspects that reflect their magnitude and how they vary within India's coal fleet. Second, none of the above single aspects is sufficient to solely dominate the decision making process, thus we use a comprehensive, multi-dimensional approach to end up with realistic pathways of early retirement.

The indices are formulated by using seven different variables addressing two aspects: the economic soundness and the environmental impact. First, we include four variables that reflect the economic and technical efficiency; these variables are age, variable operating costs, generation efficiency, and distance to coal source. Additionally, we include three variables that reflect the environmental impacts of the plant; these are population exposure to plants' emissions in India, carbon emission factors, and water stress level. The relevance of each of those variables to plants' early retirement depends on several factors including – but not limited to – stakeholders' point of view, the plant's location, and its characteristics. For this reason, we identify retirement pathways based on an ensemble approach, where we formulate all potential combinations of the seven variables by assigning weights to each variable ranging from 0 to 1 in 0.1 increments. This results in different retirement indices covering all possible weighting schemes and thus, a comprehensive multidimensional identification of worst-performing plants for early retirement.

3.1. Measuring relevant dimensions

3.1.1. Economic and technical efficiency

We use four variables to represent key characteristics of the plants: age, variable operating costs, generation efficiency, and the distance to coal source. Our data covers 142 operating coal-fired power plants, representing more than 98% of current installed capacity [26]. Data on the Indian plants and units are primarily from the Global Coal Plant Tracker (GCPT) covering the capacity, commission year, and locations of coal plants and their units.[7] The age of the plant is measured in years

[6] To clarify, if a plant is under-utilized because of a costly fuel supply agreement, or because the plant does not have a power purchase agreement, then it is not a candidate for retirement on grounds of under-utilization.

[7] The data is complemented with other sources: Climate Analytics, Enipedia, The Global Energy observatory, and Carbon Monitoring for Action (CARMA). More on the sources can be found in the Appendix A.1.

Table 1
Summary statistics on the plant characteristics and their environmental impact covering 142 operating coal-fired plants in India, values are per plant. *Age* measured in years as of 2021, weighted by units' capacity. *Efficiency* is the net electricity generated per heat input by coal units. *VOM* is the variable operations and maintenance costs in $/MWh. *Distance* the most frequent distance (modal distance) traveled from this coal plant to the coal source in kilometers. *EF* is the amount of CO_2 emissions per net electricity generated; emission factors of plant i equals 0 when it has no CO_2 emissions resulting from its electricity generation. *Population exposure (pop. exp.)* is the population-weighted exposure to emissions in millions; it represents the number of people exposed to plant i's emissions weighted by its $PM_{2.5}$ emission intensity. *WS* is baseline water stress metric; it is a measure of the ratio of fresh water demand to its supply and it ranges from 0 (no stress) to 5 (high stress).

Variables	obs.	mean	std. dev.	min.	max.
Age	142	14.69	10.86	3	46.80
VOM	142	29.97	7.449	13.48	46.65
Efficiency	142	0.340	0.0678	0.00617	0.541
Distance	142	560.0	532.6	0	1,700
EF	142	1.016	0.375	0	3.015
Pop. exp.	142	13.43	9.375	0	62.51
WS	142	2.293	1.652	0	5

and it is the weighted age of the units of plant as of the year 2021.[8] The age of the plants reflects the efficiency and pollution intensity of the units of plant; older plants tend to be generally less efficient than newer plants and are expected to be more pollution-intensive, thus they make good candidates for early retirement [19,30]. The age of plants in our data ranges from 3 years old to ~47 years old, with an average age of 14.69 years as shown in Table 1.

The costs of generation are one of the main economic variables that are directly relevant to the retirement discussion. Plants that are more costly to operate are better candidates for early retirements compared to cheaper plants. To reflect the generation costs, we use the variable operations and maintenance (VOM). The data for operating costs is based on 2018–2019 data set from the CEA reports on fuel availability at power plants. Generation costs across India range from $13.5/MWh to $46.64/MWh; on average cost of generation is equal to ~$30/MWh.[9]

The generation efficiency of a coal-fired power plant is also one of the essential economic variables when considering a plant for early retirement. Efficient coal-fired power plants are less likely to be recommended for early retirement compared to inefficient plants. We measure efficiency of a plant as the net electricity generated per heat input by coal, where the heat input is the calorific value of the coal consumed. The data on coal consumption is extracted from CEA's coal consumption report.[10] Data on the calorific value for coal for each plant is an approximate calculation from the transportation dataset managed by the Center for Railway Information System (CRIS) in India. Data on electricity generated per plants is from the CEA's monthly generation report.[11] We use data for the period from 2015 to early 2020 and aggregate it and then compute the five year average efficiency. For a given plant i at month m, we first compute the heat rate:

$$\text{Heat rate}_{im} = \text{coal consumption}_{im} * \text{coal calorific value}_{i}$$

and then we compute the efficiency of plant i at month m:

$$\text{Efficiency}_{im} = \frac{\text{Electricity generated}_{im}}{\text{Heat input by coal}_{im}}$$

and then we get the average efficiency for plant i over the five years:

$$\text{Efficiency}_{i} = \frac{\sum \text{Efficiency}_{im}}{12 \times 5}$$

The distance to coal source (port or mine) is used to proxy the transportation costs borne by the plant. Generally, the further the plant is from the source, the more expensive and the more polluting it is to transport the coal to the plant and so it would more likely be a good candidate for early retirement. We use the most frequently traveled distance between a coal plant and the coal sources (either mine or port or both) in kilometers.[12] The data for railway distances is based on 2018–2019 data set from the Freight Operations Information System (FOIS) managed by the Center for Railway Information System (CRIS) in India.

3.1.2. Environmental impact

We use three variables that reflect the environmental impacts of the plants: the carbon emission factors, the population exposure to plants' emissions in India, and the water stress level. To capture the contribution of the plants to climate change, the CO_2 emission factors per plant are used. The CO_2 emission factors are the amount of CO_2 emitted by plant as a result of the electricity generation process; higher emission factors mean higher pollution. The data on emission factors are from the 2018 National Electricity Plan (NEP) by the CEA [38] and is calculated as:

$$\text{EF}_i = \frac{\text{CO}_{2i}}{\text{Net generation}_i} \tag{1}$$

where EF_i is the emission factors for plant i. CO_{2i} is the amount of CO_2 emitted by plant i measured in tonnes; $Net\ generation_i$ is the net electricity generated by plant i measured in Megawatthours (MWh).

The amount of damage a plant has on the population is determined by the extent of population density surrounding the plant [19]. To capture the impact of each plant on the population exposed to its emissions, we estimate the population exposure to emissions per plant. To do so, we estimate the end location of the pollutants per plant through a HYSPLIT model and use gridded population data to estimate the number of people affected in areas where the pollutants are estimated to end up based on the model's estimations [35].

The estimation of the location of the plants' emissions as well as the extent of the damage it causes is done via the HYSPLIT model that was developed by the National Oceanic and Atmospheric Administration (NOAA). The HYSPLIT model is one of the most commonly used Lagrangian models in the field of atmospheric sciences; it is used to simulate the transport and dispersion of air pollutants [39–41]. This model supports a diverse range of simulations and applications, one of those is the forward trajectory analysis which we use to estimate where the pollutants of each plant end up. The model estimates where and how frequent the polluting particles of each plant end up based on the location of the plants and wind speed and direction.[13] For all plants we set a standard number of simulated particles and then through the model we can track the dispersion of those polluting particles over the course of a year and get an estimation of the location and the frequency of where the polluting particles end up.[14] By using the

[8] Given that plant's units are not always of the same age, we compute plant's age as a weighted average rather than a simple average of the units age. So, the age of a plant is computed as the sum of the weighted age of its units where the weight of each unit is based on its share of the plant's total capacity.

[9] For missing values, data was imputed using plant capacity and a state dummy.

[10] Data on monthly coal consumption can be found on the CEA website here: https://cea.nic.in/fuel-reports/?lang=en.

[11] Data on monthly reports by CEA is found here: https://cea.nic.in/old/monthlyreports.html.

[12] To do so we compute the median value in the modal interval of railway distance between a coal plant and the coal mines/ports. For plants that import coal, we use the highest possible distance in our data set as we do not have accurate data on their route. Plants that use a mix of imported and domestic coal, we get an average of the domestic distance and the highest distance used for the imports.

[13] More information on the HYPLIT model is available in A.2.

[14] Some plants emit more pollutants than others, however, given that lack the data on the exact emissions each plant produces; we weigh the standard number of air pollutants assigned to each plant based on the plant's $PM_{2.5}$ emission intensity from the Global Power Emissions Database (GPED) by Tong et al. [32].

HYSPLIT model, we can identify areas more likely to be affected by emissions of each plant, and by using gridded population data we can estimate the number of people exposed to those emissions.

The data on population count is globally integrated data on the 2015 population count per grid cell (number of people living in a grid cell) with a resolution of 2.5 arc-min (around 5 km at the equator).[15] This data is from the fourth version of the Gridded Population of the World data (GPWv4) produced by the Center for International Earth Science Information Network (CIESIN) at Columbia University [42]. The population exposure to emissions, thus, is the population exposed to pollutants of a plant as estimated by the HYSPLIT model weighted by the $PM_{2.5}$ intensity of the plant.

$$\text{pop. exp.}_{ij} = \frac{PM_{2.5}\ \text{emissions intensity}_i}{\max_{1\le i\le n} PM_{2.5}\ \text{emissions intensity}_n} \times \sum_{j=1}^{N} \frac{\text{population}_{ij}}{N} \tag{2}$$

where i represents a plant emitting j polluting particles [16] and $pop\ exp_{ij}$ measures the average population located in India[17] exposed to j pollutants based on the population count from the GPWv4 data and the estimated end location of the j polluting particles by the HYSPLIT model. $PM_{2.5}$ $emissions\ intensity_i$ represents the $PM_{2.5}$ emissions of plant i divided by its capacity in MW, $PM_{2.5}$ $emissions\ intensity_n$ is the maximum $PM_{2.5}$ emissions intensity of a currently operating plant in India. Thus, the first term in Eq. (2) measures the plant's weighted emissions intensity relative to the largest plant in India and its value ranges from 0 to 1. $population_{ij}$ represents the population inside India exposed to j pollutants based on the GPWv4 data and the estimated location of plant i's pollutants by the HYSPLIT model. N is the total number of polluting particles emitted per plant. So the population-exposure to emissions of plant i is the average population exposure in India to the j pollutants emitted by plant i multiplied by the weighted emissions intensity of plant i.

To capture the water shortage situation per plant, we use a risk metric that measures the ratio of fresh water demanded over its supply in the region where the plant is located.[18] Data on water stress levels is extracted from the World Resources Institute (WRI) Aqueduct Global Water Risk Atlas [43]. Plants located in areas with higher baseline water stress are better candidates for early retirement. The water stress ranges from 0 to 5, where 0 means that there is low (or non-existent) water stress and 5 reflects high water stress (Table 1).

3.2. Index construction

To formulate the retirement indices we standardize each of the 7 variables described above. Generally, the higher the value the better a candidate the plant is for early retirement; either due to its negative environmental impact, or due to economic or cost inefficiency.[19]

In order to adequately address the variation in each variable's importance, we take an ensemble approach where we compute all possible combinations of the 7 variables with weights ranging from 0 to 1 in 0.1 increments. This approach results in 8008 different indices; each index results from a combination of the seven variables with their corresponding weights satisfying the condition that variable weights sum up to 1. The idea behind this approach is to provide a comprehensive picture of all possible plant rankings based on different parameters, such that we formulate a clear and representative idea about which plants perform worse than others according to the different indices. Additionally, such an approach would allow us to identify plants that are consistently performing poorly across all parameters and, thus, would make very good candidates for early retirement.

4. Results

4.1. Main results

We identify plants that are ripe for retirement based on how well they perform on each index. First, we rank plants according to each of the 8008 indices and identify the worst-performing 50 GW of installed capacity for each index. As a second step, we identify the frequency that a plant appeared in the worst-performing 50 GW. We then rank the plants according to their frequency from highest (8008, appeared in all indices) to lowest (0, did not appear in any of the indices). The top 50 GW of those plants are then identified for early retirement. Overall, we identify 42 plants for early retirement located across India (Table 2), frequency of occurrence in the worst 50 GW lists ranges from 8008 (all indices) to 3302; meaning that these plants are considered to be from the worst 50 GW in 3302 indices at the very least.

The mean capacity of plants recommended for early retirement is 1.18 GW, slightly smaller than the average capacity of an Indian plant at 1.4 GW. Table 4 presents a summary of the index variables for plants identified for early retirement. These plants identified for early retirement have consistently higher mean values (Table 4) for relevant index variables compared to the country's mean values (Table 1). The only exception is efficiency, as higher efficiency denotes good performance. This is in line with the general result that plants identified by our indices perform worse than the average plant in India.

Plants recommended for early retirements are typically older than the average Indian plant, averaging around 21 years old compared to the country average of 14.68 years old. They are also ~13% more expensive than the country average, where the variable maintenance and operations costs of a plant identified for early retirement is around \$34/MWh compared to an average of \$30/MWh across India. These plants are also located further away from coal sources, with an average distance of 906 km compared to the country average of 560 Km. Finally, these plants are 4% less efficient than the average plant in India, suffer from higher levels of water stress, and affect around 35% to 40% more people compared to an average plant in India. Fig. 1 depicts a map of the plants recommended for early retirement based on our indices.

4.2. Comparison with previous reports

The CEA report identified three lists (total of ~50 GW) of plants that would be fit for potential early retirement by 2022 and 2027 based on their age, efficiency, or their inability to comply with the new environmental norms.[20] The CEEW also identified in a recent study 30 GW for early retirements that coincide with those in the CEA list as

[15] The data is based on the 2010 round of the Population and Housing Census that took place between 2005 and 2014 and is then extrapolated so as to provide estimates for the years 2000 till 2020 in five-year intervals, the year used for our analysis is the year 2015.

[16] Power plants emit not only particles but also trace gases, such as SO_2 and NO_x Both gases produce more secondary $PM_{2.5}$ than the primary emitted particles. Polluting particles refers to the polluting air parcels/pollutants.

[17] Some of the polluting particles end up outside the borders of India, these are not included in the analysis presented in this paper.

[18] In cases, where the plants uses sea water for cooling, the water stress level is set as zero as there is no shortage in the sea water.

[19] The only exception is the efficiency measure; higher values reflect higher generation efficiency. Thus, the efficiency variable was reversed before standardization so that 0 reflects operation at maximum capacity and 1 reflects no operation.

[20] The NEP identified plants for potential early retirement by 2022 amounting to capacity of ~22.7 GW (5.9 GW + 16.7 GW). The 5.9 GW are old and inefficient plants and the 16.7 GW were listed for early retirement due to lack of space for installation of FGD (Flu Gas Desulfurization) system to curb SOx emissions. An additional ~25.6 GW were listed for retirement by 2027 as they would have exceeded 25 years and outlived their utility.

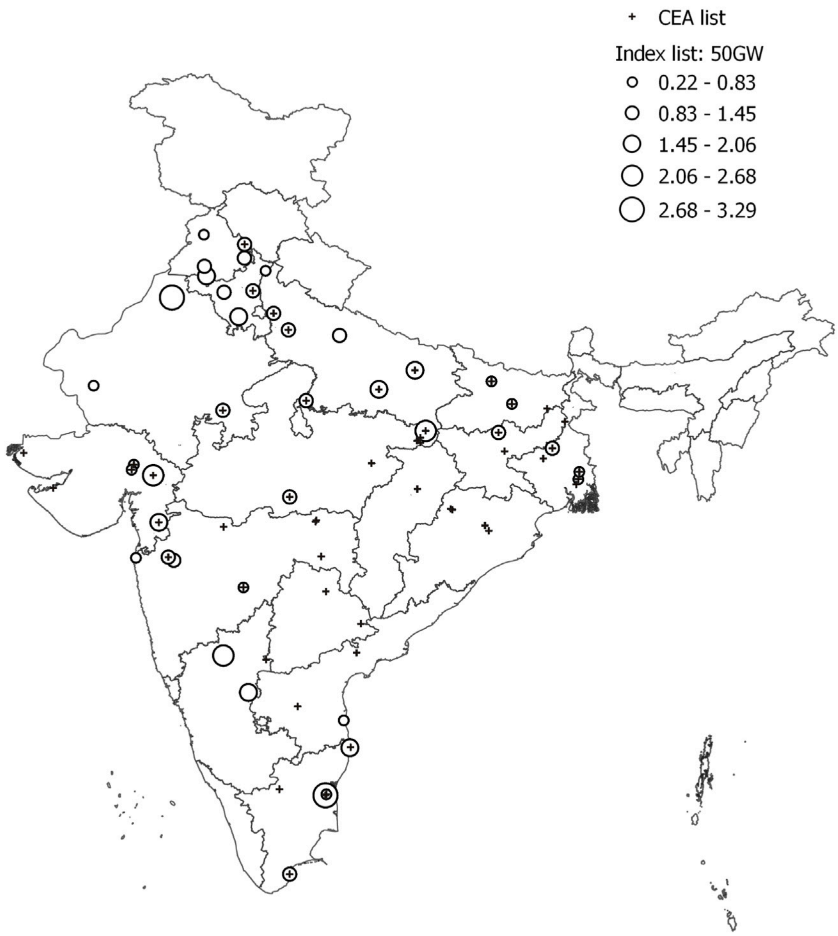

Fig. 1. Plants identified for early retirements (total capacity of 50 GW). The circle size represents the capacity of the plant in GW, each circle size represents a quantile. The plus marks indicate that this plant has been mentioned in the CEA lists [8] for early retirement.

well as an additional 20 GW to be mothballed based on the efficiency of the plants. Both reports depend on the plant's technical characteristics such as age and efficiency to rank the plants and identify the worst-performing plants for early retirements. Unlike our ensemble approach, none of the reports consider a multidimensional approach that combines the technical, economic, and environmental characteristics of the plants simultaneously.

We compare plants identified for early retirement by our multidimensional indices with the CEA and CEEW lists. The aim of this comparison is to highlight the differences in the performance of plants that are identified for retirements by our comprehensive criteria and plants that were identified based on their technical characteristics only. We also compare the differences in potential cost-savings from plants' early retirement in Section 4.3. In Fig. 1, we can see plants recommended by our indices represented by the circles and plants in the CEA lists represented by a plus (+) sign. There is an estimated ~60% similarity between the plants identified by our indices (Table 2) and those presented in the CEA report (Table 3) [8].

Comparing the key statistics of relevant index variables in the top table with the middle (CEA) and bottom (CEEW) ones in Table 4, we can see that plants in the CEA list are on average 4 years older than those identified by our index.[21] Both plants in the CEEW study and CEA list are relatively cheaper to operate and maintain, where their VOM are on average ~$31/MWh compared to an average of $34/MWh for plants identified by our indices. Additionally, they are much closer to coal sources than plants identified by our indices for early retirement, 576 Km and 511 Km respectively compared to 907 Km. Plants in the CEEW and CEA lists face lower water stress compared to plants identified by our indices.[22]

When it comes to harmful emissions and population exposure, we find slightly higher values (12%) in population exposure in our plants list compared to the CEEW plants. We do not find a noteworthy difference in population exposure between our indices and the CEA list. Also, carbon emission factors do not vary across the different lists. This also applies to the difference in plants' generation efficiency. Our results are mainly different because we use different criteria than CEA and CEEW in their reports. As can be seen, differences in the mean values of common variables such as efficiency are trivial.

If we compare plants that are solely identified by our indices with plants identified by the CEA and the CEEW reports, we find that they substantially differ from other plants in several aspects. These plants have an average age of 9.5 years. Their VOM is on average approximately $38/MWh, making them more than 20% more expensive to operate. They are located further away from coal source, where the average distance is 1030 km, and they face severe water stress compared to the plants identified by the other lists (Table 4).

To investigate the differences between our results and the plants listed in the CEA report in more detail, we group the lists into two

[21] This is not surprising as the CEA identified plants that would be at least 25 years old by the year 2022.

[22] Given that the CEEW study [9] identified 30 GW similar to those in the CEA lists, it does not come as a surprise that their summary statistics are very similar to each other.

Table 2
Plants identified for early retirement. *Rank* refers to the order plant's performance (from worst to best) based on their frequency of appearance in the worse 50 GW list of each index of the 8008. *GW* is the plant's capacity in GW. Plant names in **bold letters** are plants that are also listed in either the CEA or the CEEW report.

Rank	Plant name	GW
1	**Ropar power station**	0.844
2	**Sabarmati power station**	0.455
3	**Kota power station**	1.24
4	**Panipat power station**	0.92
5	**National Capital Dadri Thermal Power Plant**	0.84
6	**Gandhinagar power station**	0.61
7	**Harduaganj power station**	1.27
8	**Wanakbori Thermal Power Station**	2.27
9	**Suratgarh Super Thermal Power Station**	2.82
10	**Nasik MAHAGENCO Thermal Power Station**	0.91
11	**Neyveli Thermal Power Station I**	0.77
12	Rajiv Gandhi Thermal Power Project	1.2
13	**Bandel Thermal Power Station**	0.33
14	**Tanda power station**	1.76
15	**Bakreswar Thermal Power Station**	1.05
16	**Guru Hargobind Lehra Mohabbat Power Station**	0.92
17	**Satpura Thermal Power Station**	1.33
18	Deenbandhu Chhotu Ram power station	0.66
19	Goindwal Sahib Thermal Power Plant	0.54
20	Indira Gandhi Super Thermal Power Project	1.5
21	Giral power station	0.25
22	**Ukai Thermal Power Station**	1.91
23	**Neyveli Thermal Power Station II**	3.29
24	**Parli Thermal Power Station**	0.75
25	Dahanu power station	0.5
26	Rajpura Thermal Power Project	1.4
27	**Titagarh power station**	0.24
28	**Parichha power station**	1.14
29	**Obra Thermal Power Station**	2.414
30	**Kolaghat Thermal Power Station**	1.26
31	Kudgi Super Thermal Power Project	2.4
32	Neyveli Zero power station	0.25
33	Talwandi Sabo Power Project	1.98
34	**Thamminapatnam power station (Simhapuri)**	0.6
35	Bellary Thermal Power Station	1.7
36	Vallur Thermal Power Plant	1.5
37	Rosa Thermal Power Plant	1.2
38	**Barauni Thermal Power Station**	0.22
39	**Tuticorin Thermal Power Station**	1.05
40	Nasik RattanIndia Thermal Power Project	1.35
41	**Feroze Gandhi Unchahar Power Station**	1.55
42	**Muzaffarpur power station**	0.61

groups.[23] The CEA lists were divided into three: plants that can be retired by 2022, plants that can be retired by 2027, and plants that can be retired due to new environmental regulations. For the sake of comparison with our indices' results, we divide them into 2 lists. The first list includes plants to be retired for environmental purposes (~17 GW as per the CEA report) and these are to be compared with plants identified based on environmental indices only.[24] The second list includes plants to be retired by 2022 or 2027 (~32 GW as per CEA report) and we compare this list with the plants identified based on economic indices.[25]

[23] We focus the detailed comparison on our results and the plants listed in the CEA report because the CEA report has categorized the retirements into: early retirements due to the new environmental norms and early retirements by 2022 and 2027. In the CEEW study [9], no distinction between environmental and non-environmental retirements was specified.

[24] Environmental indices are indices that are formulated of the 3 environmental variables: population exposure, carbon emission factors and water stress, or any combination thereof. Overall we have 66 environmental indices.

[25] Economic indices are indices formulated of the 4 economic variables: VOM, efficiency, age, and distance, or any combination thereof. Overall, we have 286 economic indices.

Table 3
Plants recommended for early retirement by the CEA. *Rank* refers to the order plant's performance (from worst to best) based on their frequency of appearance in the worse 50 GW list of each index of the 8008.

Number	Plant
1	Ropar power station
2	Sabarmati power station
3	Kota power station
4	Panipat power station
5	National Capital Dadri Thermal Power Plant
6	Gandhinagar power station
7	Harduaganj power station
8	Wanakbori Thermal Power Station
9	Nasik MAHAGENCO Thermal Power Station
10	Neyveli Thermal Power Station I
11	Bandel Thermal Power Station
12	Tanda power station
13	Bakreswar Thermal Power Station
14	Satpura Thermal Power Station
15	Ukai Thermal Power Station
16	Neyveli Thermal Power Station II
17	Parli Thermal Power Station
18	Titagarh power station
19	Parichha power station
20	Obra Thermal Power Station
21	Kolaghat Thermal Power Station
22	Tuticorin Thermal Power Station
23	Barauni Thermal Power Station
24	Feroze Gandhi Unchahar Power Station
25	Muzaffarpur power station
26	Khaperkheda power station
27	Mettur Thermal Power Station
28	Kahalgaon Super Thermal Power Plant
29	Bhusawal Thermal Power Station
30	Sanjay Gandhi power station
31	Talcher power station
32	Raichur Thermal Power Station
33	Southern CESC power station
34	Farakka power station
35	Dr Narla Tata Rao power station
36	Rayalaseema Thermal Power Project
37	Kutch GSECL power station
38	Singrauli Super Thermal Power Station
39	Chandrapur Thermal Power Station
40	Anpara power station
41	Tenughat power station
42	Sikka Thermal Power Station
43	Ramagundam power station
44	North Chennai Thermal Power Station
45	Korba Super Thermal Power Station
46	Kothagudem Thermal Power Station
47	Jharsuguda Ind-Barath power station
48	Talcher Kaniha Super Thermal Power Station
49	Ib Valley power station
50	Mejia power station
51	Vindhyachal power station
52	Koradi Thermal Power Station
53	Rihand power station

4.2.1. Environmental indices

Looking at the environmental variables: population exposure, emission factors and water stress, we can see that values in Table 5 exhibit higher values compared to those in Table 4. We can also see that the mean values of the three environmental variables are relatively higher for plants that are identified by the indices compared to plants in the CEA list. Population exposure to emissions emitted by plants identified by our indices is 15% higher than that of the plants in the CEA list. Water stress levels are also higher for plants identified by our indices compared to those in the list.

For economic variables in Table 5 such as age and VOM costs we do not see a noteworthy difference. However, efficiency is 3% lower for plants identified by our indices and distance is ~24% longer. While these variables do not play a role in the environmental indices ranking, this shows that parameters are not completely isolated from each other.

Table 4
Summary statistics for plants that appear frequently in worst-performing 50 GW across the 8008 indices (Indices list), plants that are mentioned in the CEA report (CEA list), plants recommended in the CEEW report [9] (CEEW list), and plants that are identified solely by our indices and are not commonly identified by either the CEA or the CEEW (Index only). *Age* is measured in years as of 2021, weighted by units' capacity. *Efficiency* is the net electricity generated per heat input by coal units. *VOM* is the variable operations and maintenance costs in \$/MWh. *Distance* is the most frequent distance (modal distance) traveled from this coal plant to the coal source in kilometers. *EF* is the amount of CO_2 emissions per net electricity generated; emission factors of plant i equals 0 when it has no CO_2 emissions resulting from its electricity generation. *Population exposure (pop. exp.)* is the population-weighted exposure to emissions in millions; it represents the number of people exposed to plant i's emissions weighted by its $PM_{2.5}$ emission intensity. *WS* is baseline water stress metric; it is a measure of the ratio of fresh water demand to its supply and it ranges from 0 (no stress) to 5 (high stress).

Variables	obs.	mean	std. dev.	min	max
Indices list					
Age	42	21.72	12.44	3.500	46.80
VOM	42	34.81	6.005	23.38	45.58
Efficiency	42	0.300	0.0706	0.00617	0.431
Distance	42	907.2	511.1	30	1,700
EF	42	1.108	0.481	0	2.197
Pop. exp.	42	18.44	13.69	0.313	62.51
WS	42	3.707	1.577	0	5
CEA list					
Age	53	25.56	9.333	4	46.80
VOM	53	31.07	7.087	18.21	40.61
Efficiency	53	0.308	0.0665	0.00617	0.441
Distance	53	512.0	446.5	0	1,516
EF	53	1.084	0.409	0.271	2.197
Pop. exp.	53	18.28	12.19	2.578	62.51
WS	53	2.404	1.634	0	5
CEEW list					
Age	63	22.04	10.36	5.5	46.8
VOM	63	30.57	7.36	18.21	46.64
Efficiency	63	0.316	0.067	0.00617	0.540
Distance	63	576.37	486.4	0	1700
EF	63	1.076	0.323	0.270	2.197
Pop. exp.	63	16.1	11.5	1.86	62.5
WS	63	2.330	1.692	0	5
Index only					
Age	14	9.44	5.76	3.5	25
VOM	14	37.9	4.71	29.58	45.58
Efficiency	14	0.336	0.059	0.219	0.431
Distance	14	1029.2	559.659	30	1700
EF	14	0.934	0.441	0	2.070
Pop. exp.	14	11.7	7.47	0.31	29.8
WS	14	4.28	1.11	0.76	5

Plants identified for early retirement in the CEA list are geographically more widespread as illustrated by Fig. 2. Unlike the CEA list, our indices do not identify any plants in Bihar, Andhra Pradesh, Odisha, Telangana, and Karnataka. However, all states that have plants identified for early retirement by our indices also come up on the CEA list.

4.2.2. Economic indices

In Table 6, summary statistics for the relevant index variables are presented. Comparing the values of the index list with those of the CEA list in Table 6, we can see that the difference in age and efficiency across both tables is very minor. On the other hand, distance and costs are 90% and 21% higher respectively for plants identified by our indices. This shows that our results are mainly different because we use different criteria and variables that are common (age and efficiency) exhibit relatively similar values.

Similar to the environmental indices, plants in the CEA list are geographically more widespread than those identified by our indices as illustrated in Fig. 3. Unlike the CEA list, our indices do not identify any plants in Bihar, Andhra Pradesh, Jharkhand, Madhya Pradesh, Odisha, and Telangana. On the other hand, our indices identify plants in Rajasthan, Haryana, and Karnataka, which were not in the CEA lists for possible early retirement by 2022 or 2027.

Table 5
Summary statistics for plants that appear frequently in worst-performing 17 GW across the 66 environmental indices (top) and plants in the CEA list of retirements due to the new environmental norms (bottom). *Age* is measured in years as of 2021, weighted by units' capacity. *Efficiency* is the net electricity generated per heat input by coal units. *VOM* is the variable operations and maintenance costs in \$/MWh. *Distance* is the most frequent distance (modal distance) traveled from this coal plant to the coal source in kilometers. *EF* is the amount of CO_2 emissions per net electricity generated; emission factors of plant i equals 0 when it has no CO_2 emissions resulting from its electricity generation. *Population exposure (pop. exp.)* is the population-weighted exposure to emissions in millions; it represents the number of people exposed to plant i's emissions weighted by its $PM_{2.5}$ emission intensity. *WS* is a baseline water stress metric; it is a measure of the ratio of fresh water demand to its supply and it ranges from 0 (no stress) to 5 (high stress).

Variables	obs.	mean	std. dev.	min.	max.
Environmental indices					
Age	16	24.87	11.11	5	45
VOM	16	32.78	6.199	23.38	39.87
Efficiency	16	0.271	0.0847	0.00617	0.351
Distance	16	648.7	576.6	27.15	1,516
EF	16	1.493	0.666	0.501	3.015
Pop. exp.	16	25.40	16.03	5.540	62.51
WS	16	3.755	1.564	0	5
CEA list					
Age	25	26.87	11.10	4	46.80
VOM	25	32.86	7.210	18.21	40.61
Efficiency	25	0.303	0.0904	0.00617	0.441
Distance	25	521.4	458.5	21.41	1,516
EF	25	1.174	0.491	0.271	2.197
Pop. exp.	25	21.97	15.93	2.578	62.51
WS	25	2.302	1.825	0	5

Table 6
Summary statistics for plants that appear frequently in worst-performing 32 GW across the 286 economic indices (top) and plants in the CEA lists for retirements before 2022 or 2027 (bottom). *Age* is measured in years as of 2021, weighted by units' capacity. *Efficiency* is the net electricity generated per heat input by coal units. *VOM* is the variable operations and maintenance costs in \$/MWh. *Distance* is the most frequent distance (modal distance) traveled from this coal plant to the coal source in kilometers. *EF* is the amount of CO_2 emissions per net electricity generated; emission factors of plant i equals 0 when it has no CO_2 emissions resulting from its electricity generation. *Population exposure (pop. exp.)* is the population-weighted exposure to emissions in millions; it represents the number of people exposed to plant i's emissions weighted by its $PM_{2.5}$ emission intensity. *WS* is a baseline water stress metric; it is a measure of the ratio of fresh water demand to its supply and it ranges from 0 (no stress) to 5 (high stress).

Variables	obs.	mean	std. dev.	min.	max.
Economic indices					
Age	26	24.71	13.51	3.500	46.80
VOM	26	36.90	5.412	23.38	46.65
Efficiency	26	0.294	0.0721	0.00617	0.391
Distance	26	1,089	449.3	30	1,700
EF	26	1.099	0.504	0	2.197
Pop. exp.	26	17.88	13.62	0.313	62.51
WS	26	3.125	2.019	0	5
CEA list					
Age	34	25.29	8.604	12.59	45
VOM	34	30.30	7.028	18.21	39.87
Efficiency	34	0.307	0.0662	0.00617	0.441
Distance	34	572.9	477.2	0	1,516
EF	34	1.051	0.411	0.271	2.197
Pop. exp.	34	16.14	7.754	2.578	34.61
WS	34	2.652	1.500	0	5

4.3. Cost-saving potential

An essential part of the discussion of early retirements is economic costs. We estimate the potential cost savings for our indices'

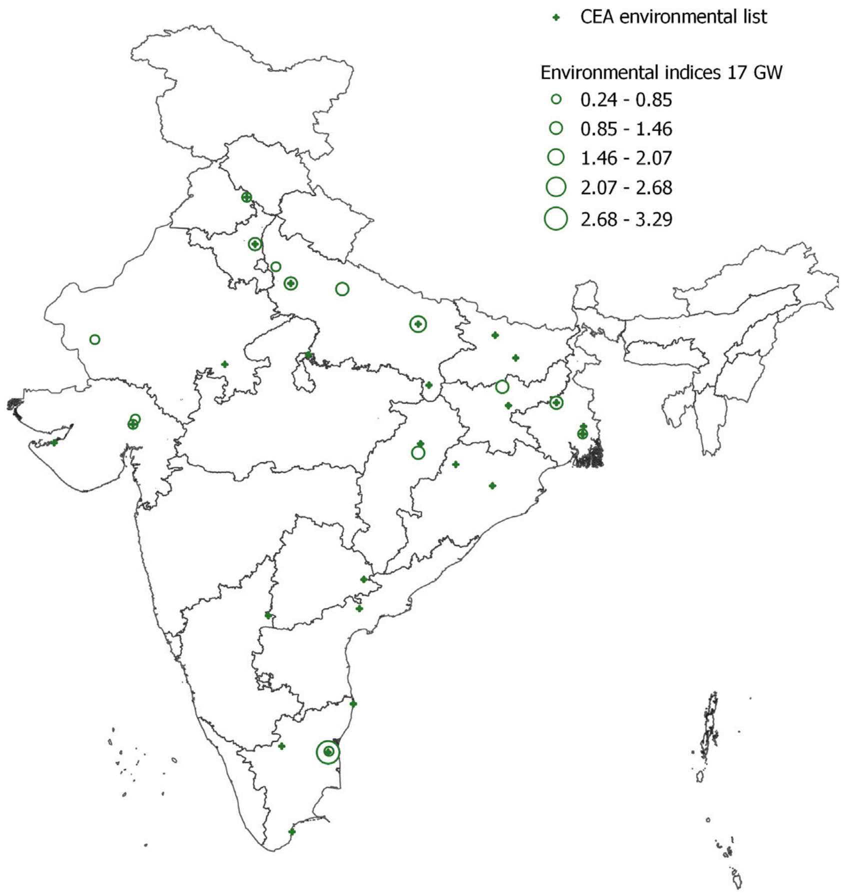

Fig. 2. Plants identified for early retirements based on environmental indices. The circle size represents the capacity of the plant in GW, each circle size represents a quantile. The plus marks indicate that this plant has been mentioned in the CEA report [8] for early retirement.

list (Table 2), the CEA's list of plants (Table 3), and the CEEW study following the methodology in [44]. The cost estimation is basically a quantification of the value created if a coal plant is retired and replaced with solar. Thus, the cost savings would be from two sources. The first source of saving would be from buying a cheaper source of power, namely solar. The second source would be through the reduction in liabilities resulting from the early retirement of expensive plants and shifting ownership towards a cheaper cost of capital.

The estimation covers the replacement of the energy contract and the refinancing of the remaining payment on capital. It does not cover other relevant challenges such as: unmet demand, workers compensation, legal aspects of the contracts, and so on (see [44]). To estimate savings from the replacement of coal with solar we assume a solar cost of INR 1.99/KWh based on the Ministry of New and Renewable Energy (MNRE) report [14] and the variable costs of each plant are the ones used in our indices. To estimate the total cost savings we use the following formula as done by Shrimali [44]:

$$\text{Cost saved}_i = \text{X}_i \times \text{Y}_i \times (\text{VOM}_i - \text{SC}_i) \tag{3}$$

where $Cost\ saved_i$ are the total costs saved from replacing coal-fired plant i with solar, X_i is the annual generation of plant i (KWh), Y_i is the remaining life of plant i in years, VOM_i are the variable costs of plant i (INR/KWh) and SC_i is solar cost of INR 1.99/KWh.

Our estimations of annual savings resulting from replacing the 50 GW recommended by our indices with solar are equivalent to INR 126 billion ($1.7 billion) and a total savings of INR 1230 billion ($16.73 billion), assuming a lifetime of 25 years. For the plants listed in the CEA report and the CEEW study, we estimate annual savings of INR 55.9 billion ($760 million) and INR 65.8 billion ($890 million), respectively, and a total savings over plants' lifetime equivalent to INR 229 billion ($3.115 billion) and INR 306 billion ($4.16 billion), respectively.

Table 7
Cost savings from the retirement of plants (50 GW). *Index* represent savings estimates based on our indices' list. *CEA* represent estimates based on the retirement of the plants listed in the CEA report. *CEEW* represent the estimates based on the retirement of plants listed in the CEEW. *Total variable costs* refer to the total savings over the plants' lifetime resulting from replacing coal with solar. *Annual variable costs* are the annual savings resulting from replacing coal with solar. *Fixed costs* refer to savings from capacity contracts, which cover financial expenditure, capital expenditure, and fixed costs. *Total costs saved* are total savings of variable and fixed costs.

Savings	Index	CEA	CEEW
Total variable costs	$16.71 billion	$3.11 billion	$4.16 billion
Annual variable costs	$1.7 billion	$760 million	$890 million
Fixed costs	$4.3 billion	$845 million	$2.04 billion
Total costs saved	$ 21 billion	$ 3.95 billion	$ 6.2 billion

Additional cost savings come from capacity contracts, which cover financial expenditure, capital expenditure, and fixed costs. We estimate savings to be approximately INR 321.143 billion (∼$4.3 billion) compared to an estimated cost savings of INR 62.863 billion (∼$845 million) if plants in the CEA lists are retired early and INR 306 billion (∼$4.16 billion) for the CEEW plants (Table 7). The cost savings are driven by the retirement of younger plants as older plants (>25 years old) are expected to be fully paid for already and thus have no costs to be saved [44]. Potential savings from retirement of 50 GW recommended by our indices would be a total of $21 billion, compared to an estimated ∼$4 billion from CEA list and $6.2 billion from the CEEW list. Thus, our results estimate at least 5 times more savings than the CEA list and 3.5 times more than the CEEW recommended list. Our cost-savings estimates do not cover system level impacts such as reliability nor do they cover other relevant costs such as worker compensation.

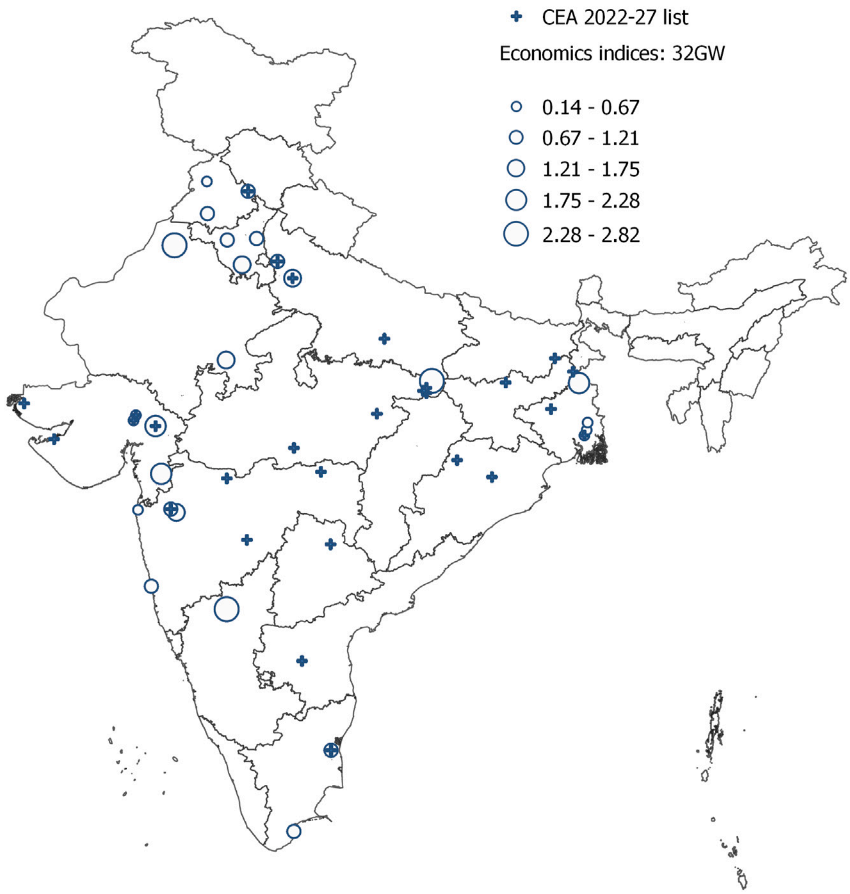

Fig. 3. Plants identified for early retirements based on economic indices (total capacity 17 GW). The circle size represents the capacity of the plant in GW, each circle size represents a quantile. The plus marks indicate that this plant has also been mentioned in the CEA report [8] for early retirement.

As a result, the cost estimates presented here are not exhaustive, but they do shed light on how altering the criteria for early retirements and going beyond the technical and economic characteristics would lead to higher costs savings.

The differences in the age and variable costs distribution across the lists (Table 4) may explain why the potential cost-savings (Table 7) resulting from the early retirement of plants identified by our indices are 5 times more than that of plants in the CEA list and 3.5 that of plants in the CEEW list. While the mean age of plants identified by our indices is not that much lower than those in the CEA list and CEEW study, the capacity of younger plants to be retired from the CEA and CEEW lists (~10 GW and 18.5 GW) represent less than 40% and 70%, respectively, of capacity identified by our indices (~26 GW).

4.4. Sensitivity analysis

To check the sensitivity of the indices to the different weighting schemes, we compare the results of each 100% index with one another. The plants names per each index are found in Tables 8 and 9. We can see some similarities across the plants, however, top plants according to each index are fairly diverse.

In Fig. 5, we can see the rank correlation between the indices; this is measured by calculating the Kendall rank correlation of the worst 50 GW installed capacity according to each index. Overall, the indices are not highly correlated with each other, yet some of them are highly significant even if the correlation are weak. The largest positive correlation (35.5%) is between the VOM costs and the distance. The correlation between costs and distance is statistically significant at 1%. This is not surprising as the cost of coal transport is affected by the distance between the plant and coal source, thus it is expected to be positively correlated with the variable operations costs of a plant.

The positive and significant correlation between a plant's age and population exposure (28.2%) and between age and efficiency (27.2%) is not surprising either given that older plants tend to be less efficient, more pollution intense and less likely to have pollution control technologies. Water stress and VOM costs exhibit a significant correlation of 21.1%, same for water stress and distance, where the correlation is ~20%. This may be explained by the fact that most power plants that were identified for retirement are in Rajasthan, Haryana, and Punjab, which suffer from water stress. Additionally, power plants on mine mouths are in states like Chhattisgarh, Bihar, and Jharkhand, which receive a good amount of rainfall, have rivers flowing through them, and have a good forest cover. In Fig. 4, the location of plants, their corresponding water stress levels, and the location of coal fields are illustrated. We can see that plants that are close to coalfields have relatively lower water stress levels.

5. Conclusion and policy implications

In India, coal-fired generation is the main source of energy and is the backbone of the Indian economy. However, coal-fired generation in India is facing technical and financial challenges given the falling utilization rates, the declining prices of RE, as well as coal's negative effects on the environment and public health. It is estimated that around 300,000 deaths in India are attributed to the power generation sector, not to mention the harmful impact on children development and overall health of the population. Under the 2015 Paris Agreement, India pledged to increase its share of non-fossil energy generation. One way to address these challenges and keep in line with the emission

Table 8
Top plants to be retired according to a 100% weight assigned to each of the 3 environmental variables: *Population Exposure (pop. exp.)* is the population-weighted exposure to emissions in millions; it represents the number of population exposed to the plant *i*'s emissions weighted by its $PM_{2.5}$ emission intensity. *WS* is baseline water stress metric; it is a measure of the ratio of fresh water demand to its supply and it ranges from 0 (no stress) to 5 (high stress). *EF* is the amount of CO_2 emissions per net electricity generated; emission factors of plant *i* equals 0 when it has no CO_2 emissions resulting from its electricity generation.

Rank	pop. exp.	WS	EF
1	Panipat power station	Feroze Gandhi Unchahar Power Station	Marwa power station
2	Barauni Thermal Power Station	Panipat power station	Ropar power station
3	Tanda power station	Suratgarh Super Thermal Power Station	Neyveli Thermal Power Station II
4	Titagarh power station	National Capital Dadri Thermal Power Plant	Giral power station
5	Harduaganj power station	Giral power station	Sabarmati power station
6	Lanco Amarkantak Thermal Power Project	Indira Gandhi Super Thermal Power Project	Neyveli Thermal Power Station I
7	Neyveli Zero power station	Harduaganj power station	Tuticorin Thermal Power Station
8	Obra Thermal Power Station	Rajiv Gandhi Thermal Power Project	Panipat power station
9	Ropar power station	Rosa Thermal Power Plant	Kutch GSECL power station
10	Sabarmati power station	Rajpura Thermal Power Project	Sanjay Gandhi power station
11	Kahalgaon Super Thermal Power Plant	Guru Hargobind Lehra Mohabbat Power Station	Tenughat power station
12	Budge Budge Generating Station	Barsingsar Thermal Power Project	Barauni Thermal Power Station
13	Kolaghat Thermal Power Station	Vallur Thermal Power Plant	Ratija Power Project
14	Talcher power station	Talwandi Sabo Power Project	Baradarha power station
15	National Capital Dadri Thermal Power Plant	Thamminapatnam power station (Simhapuri)	Mutiara Thermal Power Plant (Coastal Energen)
16	Bandel Thermal Power Station	Gandhinagar power station	Guru Hargobind Lehra Mohabbat Power Station
17	Singrauli Super Thermal Power Station	Sabarmati power station	Budge Budge Generating Station
18	Tenughat power station	Deenbandhu Chhotu Ram power station	Tanda power station
19	Southern CESC power station	Kalisindh Thermal Power Station	Neyveli Zero power station
20	Muzaffarpur power station	Kota power station	Surat Lignite Power Plant
21	Anpara power station	Chhabra Thermal Power Station	Bhavnagar power station
22	Talcher Kaniha Super Thermal Power Station	Kawai Thermal Power Project	Satpura Thermal Power Station
23	Rosa Thermal Power Plant	Neyveli Thermal Power Station I	Wanakbori Thermal Power Station
24	Simhadri Power Station	Neyveli Thermal Power Station II	Dr Narla Tata Rao power station
25	Feroze Gandhi Unchahar Power Station	Neyveli Zero power station	Gandhinagar power station
26	Barh II power station	Bellary Thermal Power Station	Southern CESC power station
27	Maithon Right Bank Thermal Power Station	Ropar power station	Ukai Thermal Power Station
28	Rajpura Thermal Power Project	Rayalaseema Thermal Power Project	Harduaganj power station
29	Farakka power station	Goindwal Sahib Thermal Power Plant	Meenakshi Energy Thermal Power Project
30	Kota power station	Simhadri Power Station	Shree Singaji Thermal Power Project
31	Raghunathpur Thermal Power Station	Parli Thermal Power Station	Nasik MAHAGENCO Thermal Power Station
32	Dahanu power station	Nasik RattanIndia Thermal Power Project	Raichur Thermal Power Station
33	Bokaro A Thermal Power Station	Nasik MAHAGENCO Thermal Power Station	Tamnar power station
34	Bakreswar Thermal Power Station	Bina Thermal Power Project	Jojobera Power Plant
35	Sanjay Gandhi power station	Parichha power station	Chhabra Thermal Power Station
36	Nabinagar Thermal Power Project	Mettur Thermal Power Station	Wardha Warora Power Plant
37	Kutch GSECL power station	Muzaffarpur power station	North Chennai Thermal Power Station
38	Bara Thermal Power Project	Kudgi Super Thermal Power Project	Kasaipalli power station
39	Koderma Thermal Power Station	Surat Lignite Power Plant	Dr. Shyama Prasad Mukherjee Thermal Power Station
40	Jojobera Power Plant	Wanakbori Thermal Power Station	Goindwal Sahib Thermal Power Plant
41	Mahadev Prasad Super Thermal Power Plant	Jhabua Power Seoni power station	Muzaffarpur power station
42	Dr Narla Tata Rao power station	Satpura Thermal Power Station	Bellary Thermal Power Station
43			Santaldih Thermal Power Station
44			Nabinagar Thermal Power Project

targets set in Paris is through the early retirement of some of India's worst-performing coal-fired plants.

In this paper, we provide a multidimensional approach that identifies plants which make good candidates for early retirement in India based on a comprehensive assessment of their technical and economic performance as well as their negative impacts. By constructing 8008 different indices from the different combinations of seven parameters, we identify plants that perform poorly across all parameters and thus would make ideal candidates for early retirement. The results presented in this paper show that plants ranking higher on the index are older, less efficient, located farther away from the nearest coal source, and are also more expensive to operate. In addition, these plants negatively affect a larger share of population and suffer from higher water stress levels. We estimate that the early retirement of the plants identified by our indices would save approximately $21 billion.

We compare the results of our indices with the plants listed in the CEA report and the CEEW study and find that the plants identified by our indices have higher population exposure, water stress, and are located farther away from the coal sources. Additionally, they are more expensive to operate, are less efficient, and thus would be better candidates for early retirements from both an economic as well as environmental perspective. Estimated cost-savings from the early retirement of the 50 GW capacity listed in the CEA report and the CEEW study represent only 20% and ~30%, respectively, of the costs saved if the worst 50 GW of installed capacity according to our indices are retired.

While our modeling work has shown the financial benefits of coal phaseout, implementation may be subject to a number of political economy constraints. State governments that make decisions about closure of old plants and construction of new plants may not yet be convinced of the viability of replacing coal with renewables, given concerns about intermittency, balancing the load of electricity demand, and the costs of battery storage. Many distribution companies that make decisions about power purchase agreements are highly indebted and will not be able to take advantage of these opportunities which may require yet another injection of central government resources. Though the main plants we identified for closure tend not to be located close to the pit heads and zones of high coal employment, coal continues to provide wider public benefit through cross subsidization of passenger rail travel and social service funds, which may inspire caution by decision makers [45]. Not to mention, that in some areas, the decline in coal demand that would result from plant closures would have implications on local employment and income generation. The government's own plans to impose air pollution standards and equipment retrofits or

Table 9
Top plants to be retired according to 100% weight assigned to each of the 4 economic indices: *Age* is measured in years as of 2021, weighted by units' capacity. *VOM* is the variable operations and maintenance costs in $/MWh. *Efficiency* is the net electricity generated per heat input by coal. *Distance* is the most frequent distance (modal distance) traveled from this coal plant to coal source in kilometers.

Rank	Age	VOM	Efficiency	Distance
1	Bandel Thermal Power Station	Ratnagiri Power Plant	Sabarmati power station	Salaya power plant
2	Talcher power station	Bellary Thermal Power Station	Neyveli Thermal Power Station II	Udupi power station
3	Sabarmati power station	Talwandi Sabo Power Project	Barauni Thermal Power Station	Cuddalore IL&FS power station
4	Obra Thermal Power Station	Sagardighi Thermal Power Station	Kudgi Super Thermal Power Project	Thamminapatnam power station (Simhapuri)
5	Nasik MAHAGENCO Thermal Power Station	Raichur Thermal Power Station	Ratija Power Project	Ratnagiri Power Plant
6	Neyveli Thermal Power Station I	Guru Hargobind Lehra Mohabbat Power Station	Bandel Thermal Power Station	Tata Mundra Ultra Mega Power Project
7	Titagarh power station	Indira Gandhi Super Thermal Power Project	Giral power station	MIHAN Power Project
8	Barauni Thermal Power Station	North Chennai Thermal Power Station	Neyveli Thermal Power Station I	Muthukur Mandal power station (Painampuram)
9	Tuticorin Thermal Power Station	Rajiv Gandhi Thermal Power Project	Titagarh power station	Kudgi Super Thermal Power Project
10	Singrauli Super Thermal Power Station	Harduaganj power station	Wardha Warora Power Plant	Talwandi Sabo Power Project
11	Wanakbori Thermal Power Station	Mettur Thermal Power Station	Sagardighi Thermal Power Station	Ropar power station
12	Gandhinagar power station	Mutiara Thermal Power Plant (Coastal Energen)	Kolaghat Thermal Power Station	Rajpura Thermal Power Project
13	Ropar power station	Panipat power station	Nasik MAHAGENCO Thermal Power Station	Indira Gandhi Super Thermal Power Project
14	Kolaghat Thermal Power Station	Nasik RattanIndia Thermal Power Project	Obra Thermal Power Station	Dahanu power station
15	Ramagundam power station	Rajpura Thermal Power Project	Southern CESC power station	Guru Hargobind Lehra Mohabbat Power Station
16	Southern CESC power station	Kota power station	Jojobera Power Plant	Goindwal Sahib Thermal Power Plant
17	Anpara power station	Ropar power station	Bakreswar Thermal Power Station	Gandhinagar power station
18	Korba Super Thermal Power Station	Gandhinagar power station	Sanjay Gandhi power station	Rajiv Gandhi Thermal Power Project
19	Kothagudem Thermal Power Station	Kahalgaon Super Thermal Power Plant	Bhusawal Thermal Power Station	Sabarmati power station
20	Tanda power station	Bongaigaon power station	Farakka power station	Panipat power station
21	MP Amarkantak power station	Jharsuguda Ind-Barath power station	Muzaffarpur power station	Ukai Thermal Power Station
22	Ukai Thermal Power Station	Goindwal Sahib Thermal Power Plant	Satpura Thermal Power Station	Wanakbori Thermal Power Station
23	National Capital Dadri Thermal Power Plant	Dahanu power station	Paras power station	Harduaganj power station
24	Satpura Thermal Power Station	National Capital Dadri Thermal Power Plant	Bongaigaon power station	National Capital Dadri Thermal Power Plant
25	Dr Narla Tata Rao power station	Sri Damodaram Sanjeevaiah Thermal Power Station	Tenughat power station	Nasik RattanIndia Thermal Power Project
26	Kota power station	Tuticorin NTPL power station	Chandrapur Thermal Power Station	Nasik MAHAGENCO Thermal Power Station
27	Ib Valley power station	Suratgarh Super Thermal Power Station	Khaperkheda power station	Mutiara Thermal Power Plant (Coastal Energen)
28	Panipat power station	Thoothukudi IBTPL power station	Tuticorin Thermal Power Station	Kalisindh Thermal Power Station
29	Chandrapura power station	Sikka Thermal Power Station	Indira Gandhi Super Thermal Power Project	Chhabra Thermal Power Station
30	Tenughat power station	Deenbandhu Chhotu Ram power station	Ropar power station	Suratgarh Super Thermal Power Station
31	Dahanu power station	Sabarmati power station	Parli Thermal Power Station	Kota power station
32	Neyveli Thermal Power Station II	Tuticorin Thermal Power Station	Bellary Thermal Power Station	Solapur power station
33	Farakka power station	Wanakbori Thermal Power Station	Parichha power station	Deenbandhu Chhotu Ram power station
34	Raichur Thermal Power Station	Vallur Thermal Power Plant	Marwa power station	Bhusawal Thermal Power Station
35	Kutch GSECL power station	Kutch GSECL power station	Raigarh Power Project (TRN/ACB)	
36	Mettur Thermal Power Station	Jhabua Power Seoni power station	Tanda power station	
37	Parli Thermal Power Station	Muthukur Mandal power station (Painampuram)	Kahalgaon Super Thermal Power Plant	
38		Kudgi Super Thermal Power Project	Vindhyachal power station	
39		Akrimota Power Project		
40		Bakreswar Thermal Power Station		

closures have been delayed several times, suggesting this agenda will face challenges of implementation. Finally, the land requirements for scaling up renewables may increasingly become contentious as easily accessible sites for utility scale solar are already tapped.

This analysis suggests the early retirement of some of India's coal fleet is not a straightforward process and subject to varying economic, technical and political considerations. To be politically feasible, retirement pathways in India should address major policy concerns instead of

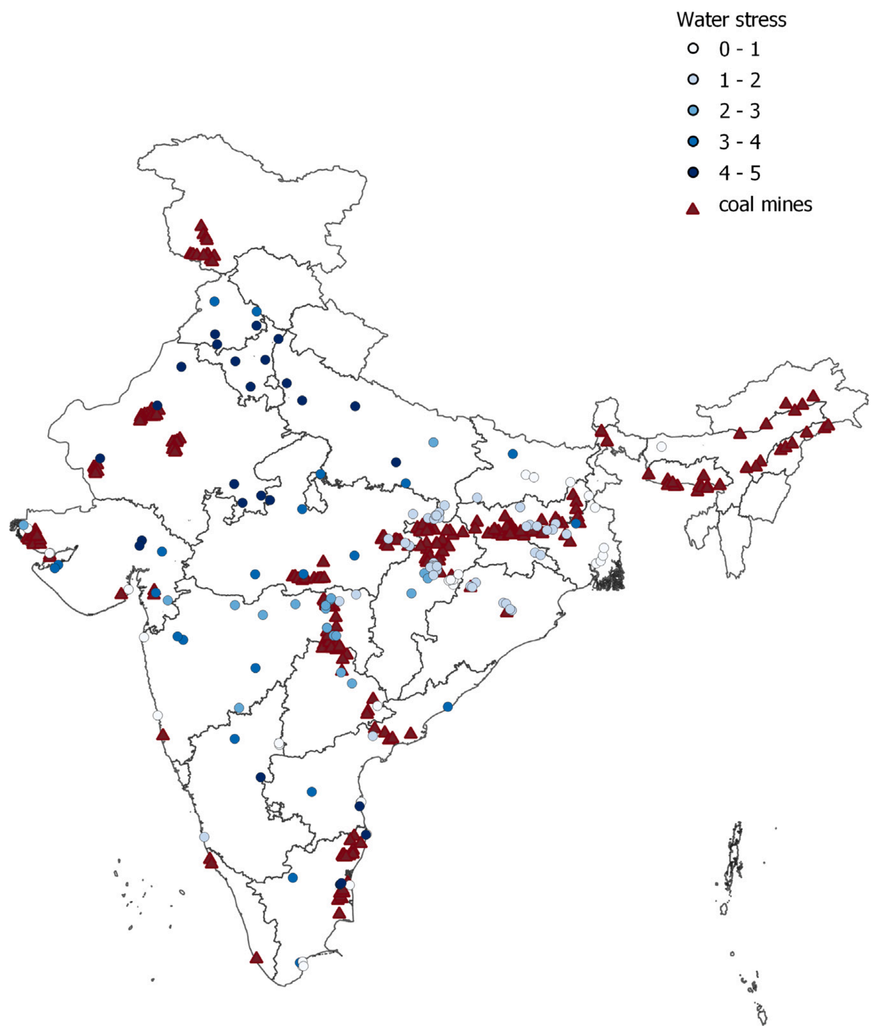

Fig. 4. Map depicts water stress levels of plants and the location of coal fields. Water stress levels range from 1 until 5. 1 represents low water stress levels (light blue) and 5 represents high water stress levels (dark blue). Coal fields are represented by red triangles.

evaluating plants solely on their technical and economic characteristics. Given the salience of pollution problems as well as its public health costs, prioritizing air pollution and accounting for the environmental impact of plants is essential in setting retirement schedules. Our results show that factoring in the environmental impact leads to prioritizing more polluting plants than looking at technical and economic aspects only. This not only leads to higher cost savings but also addresses air pollution, a key policy concern in India. It is also important to consider that generally India's state-level political economies can act as barriers to shutdowns. For example, land is expensive and hard to find in Punjab, potentially making shutdowns more challenging than other states, like Rajasthan, where the situation is less dire. While our seven variables provide a comprehensive way to identify plants for early retirement, another way for identifying plants for early retirement is to give highest priority for plants based on what is more feasible from a political economy perspective.

Our approach faces several data limitations. First, the lack of some plant-level characteristics like the coal type per plant and the sulfur content prevented us from identifying the amounts of each pollutant emitted per plant. Accordingly, the HYSPLIT model produced less detailed estimates of the amount of each pollutant emitted per plant and their concentration levels. We address these limitations by weighing the polluting particles with the plants' $PM_{2.5}$ emission intensity. While this assumption is reasonable, having data on the exact number of pollutants per plant would have enabled us to have more accurate estimates of the population-exposure to emissions. Second, the data on heat rate is an approximate calculation. We understand that oil consumption also contributes to the heat in the boiler but data on oil consumption by each power plant is not reliably available. Although we do not expect that having more accurate data would change our current results, having reliable data on the heat rate that accounts for all relevant parameters would enable us to have more accurate results. Third, our data accounts for the economic, technical, and environmental aspects of coal-fired power in India; however, it does not take into consideration social impact of such retirements, such as labor market effects. Further research accounting for such effects would be an insightful addition and crucial to the applicability of coal power retirements in India. Fourth, our cost estimates do not account for system level impacts nor workers compensation; for more accurate cost estimates, the inclusion of those factors is crucial. Our analysis provides a broad picture of potential benefits of early retirements of India's coal fleet; however, more rigorous analysis that takes into account state level differences and political economy considerations is needed for more feasible retirement schedules.

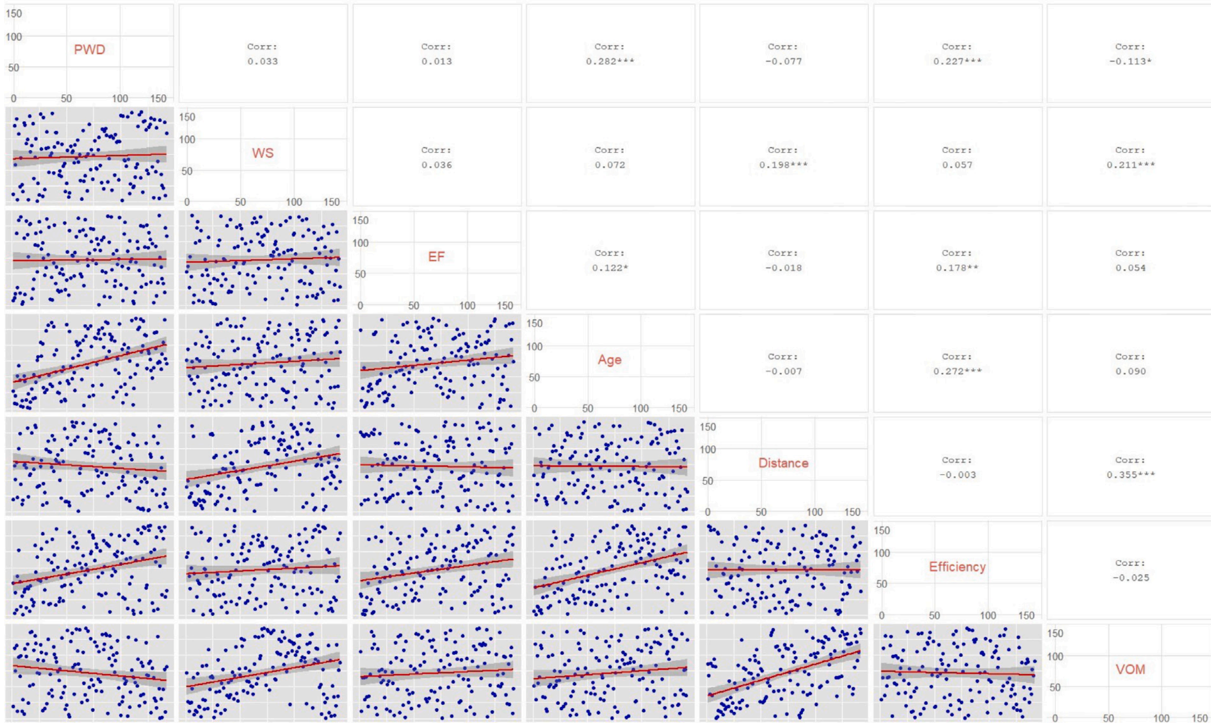

Fig. 5. Rank correlation between the different indices. Each index is based on 100% weight of one of the seven index variables. From top left: population exposure (PWD), water stress (WS), emission factors (EF), age, distance, efficiency and variable operations and maintenance costs (VOM).

CRediT authorship contribution statement

Nada Maamoun: Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Puneet Chitkara:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Joonseok Yang:** Data curation, Writing – review & editing. **Gireesh Shrimali:** Formal analysis, Methodology, Writing – review & editing. **Joshua Busby:** Writing – review & editing. **Sarang Shidore:** Writing – review & editing. **Yana Jin:** Data curation, Writing – review & editing. **Johannes Urpelainen:** Conceptualization, Methodology, Project administration, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

A.1. Data sources for coal plants

The Global Coal Plant Tracker (https://endcoal.org/global-coal-plant-tracker/) produced by CoalSwarm (http://coalswarm.org), a wiki that has more than 9,000 articles about coal housed on SourceWatch.[26] The Global Coal Plant Tracker, provides information on global coal plants that are larger than 30 MW of capacity.

Climate Analytics (https://climateanalytics.org) is a non profit institute for climate science and policy based in Berlin aiming at advancing scientific knowledge in the area of climate change and accordingly provide support and capacity building to stakeholders.

Enipedia was started by the Energy and Industry Group at the department of Technology, Policy and Management at the Delft University of Technology in the Netherlands. It explores the application of wikis in issues related to energy and industry.

The Global Energy observatory (http://globalenergyobservatory.org/) is a project providing a set of free interactive databases, aiming at promoting the global understanding of energy systems, their emissions impacts, as well as accelerating the transition to globally affordable carbon-neutral energy systems.

Carbon Monitoring for Action (CARMA) (http://carma.org/) is a database that includes information on more than 60,000 power plant and their carbon emission as well as 20,000 power companies globally. It is produced and financed by *Confronting Climate Change Initiative* at the Center for Global Development, an independent and objective think tank in Washington, DC.

A.2. HYSPLIT model

We use the HYSPLIT model to estimate where the emissions of the coal-fired plants end up and how frequently they end up in one area so that we can determine the degree of harm they cause to those areas and thereby determine the pollution damage attributed to each plant. To clarify, running the HYSPLIT model, does not give directly the frequency. Each run of HYSPLIT model only gives one trajectory, then the frequency is calculated by combining hundreds of runs, summing how many times the trajectory passes through a given location. For this paper, we ran the models four times a day, every other 8 days for 2013. We assume the lifetime for major air pollutants is around 4 days, and therefore the trajectory was computed for 96 h. The HYSPLIT models were originally run for operating coal plants globally and so we have about 180 trajectories generated for each plant. In total, we have about $180 \times 2143 = 385{,}740$ trajectories. Since this paper focuses only on

[26] Sourcewatch is an open-source encyclopedia sponsored by the Center for Media and Democracy.

India, we exclude all other plants that are not in India, which makes the total number of trajectories around $180 \times 247 = 44{,}460$.

To compute the population weighted damage for India, we consider only the number of people affected by the plants emissions trajectory in India and not outside such as in Bangladesh.

The HYSPLIT model does not come without limitations. It does not provide information on the absolute concentration of the air pollution, it only estimates where the air pollution ends up based on historical wind data. However, while HYSPLIT cannot estimate the absolute concentration of air pollutants, it is more useful for source-receptor analysis; identifying regions where air quality may be affected by emissions from a given plant. That is by far the biggest limitation of applying HYSPLIT in this paper; that we lack information on the contribution of each power plant. To address such a limitation, we weigh the contribution of the plant's pollutants based on the $PM_{2.5}$ emission intensity of the plant so as to reflect the pollution intensity of the plant. Given that we aim at finding out where the pollutants of each plant ends up, the benefit of using the HYSPLIT in this case overcomes the cost.

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