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Modeling coal plant stranded costs for decarbonization pathway analyses

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ABSTRACT

Retiring coal plants as part of a decarbonization strategy has started to become a reality in the last five years and is reflected in the least-cost plans of many countries. However, major issues go beyond the scope of such planning, including commercial contracts, markets and asset stranding. This paper proposes a new model formulation that endogenously calculates stranded assets taking into consideration commercial and market issues. It can be used to develop insights into economic and financial issues surrounding stranded costs of coal retirement. An illustrative example around the existing 209 GW coal fleet, including an aging part of the coal fleet of 100 GW, in India is used to show how the model can be implemented with relative ease. A second case study is constructed for the Philippines, which has a much younger and uniform coal fleet. Comparing and contrasting the two case studies is valuable for understanding the critical drivers of stranded costs.

Introduction

Decarbonization of power systems is a topic that is at least three decades old. However, decisive acts on retiring old coal plants and not replacing them have emerged only in the last five years or so in the UK, Europe, and very recently in the developing world. The task of shutting down more than 2.1 TW of coal globally, in the long run, is critical from a net-zero emission perspective. However, it also throws up significant challenges, including up to $5 trillion needed in new generation investments by 2030 (Birol & Malpas, 2021), dealing with socio-economic issues, stranded coal mines and plant assets, and reneging commercial power purchase agreements for coal generation in place. Reversing the pace of climate change to get to 1.5 °C or even 2.0 °C would require a speed and depth of coal plant closure that needs to be at a global scale which is not only unprecedented but has financial and social dimensions that are far greater and far more complex than the achievements to date. If the development challenges facing the developing nations, including the need to meet rapid electricity growth and capital constraints, are considered, the challenges for these nations are even more formidable.

The scale of the asset stranding problem and the opportunities arising from addressing it are both enormous. The global coal power plant stock accounts for close to 30 % of CO_2 emissions globally and 40 % of electricity generation as the leading user of coal (Carbon Brief, 2021). Coal plant capacity has gone up 62 % since 2000, with as many as 14 countries beginning to use coal for power generation for the first time over this period. Therefore, a significant part of the global coal capacity is relatively new, which raises the issue of stranded costs. Global stranded asset costs for coal plants have been estimated somewhere in the range of a quarter of a trillion dollar by 2030 to a trillion dollars by 2040 (Benn et al., 2018). The challenge is not merely one of compensating the asset owners as (a) a part of the coal plant fleet continues to be economic in some parts of the world, and hence the coal plant owners can justifiably seek economic compensation for forgone profits; (b) majority of the coal plants barring pure merchant plants are under some form of long term financial contracts (e.g., long term power purchase agreements) with assured returns up to 25 years that might set the level of compensation well above stranded capital costs or economic compensation level; and (c) financial compensation in one form or another is only part of the challenge because there are significant social and environmental issues that may include direct and indirect job losses, including ancillary businesses associated with the plant and upstream impact on the coal mining sector, wider economic losses associated with the shutdown, environmental remediation costs, etc., requiring a “Just Transition” (Czyżak & Wrona, 2021).

The present work is motivated by the need to steer decarbonization policies in the developing world, where there is limited data, analysis, and capacity. There is a need to develop practical modeling analysis that can be easily implemented to inform coal retirement strategy, including an estimate of stranded costs of coal plants.

A short summary of key literature

The issue of stranded cost in generation and transmission has been discussed in the context of reliability as the risk of stranded assets

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Nomenclature

Sets

t	Hours/sub-hours of the day
y	Years
g	Coal units
s	Scenarios (BAU or Decarbonization)
p	Price scenarios (market price or PPA)
t	Hours/sub-hours of the day
Parameters	
α	Net revenue minimum threshold to be maintained
$MinGen_g$	Minimum plant load factor below which plant must be shut down
$MaxGen_g$	Maximum plant load factor
$Capacity_g$	Capacity of coal unit g
$Cost_{g,\,y}$	Variable cost of unit g in year y
$FC_{g,\,y}$	Fixed cost of unit in year y
θ_y	Discount rate applied to cost parameters and net revenues
$P_{y,\,p,\,t}$	Hourly price forecast for scenario p
H_t	Number of hours in block t
$Target_{y,\,s}$	Target coal generation in year y
$\Phi_{y,\,s,\,p}$	Minimum load factor
Variables	
NR	Total system net revenue – objective function
$NR_{g,\,s,\,p}{}'$	Net revenue for scenarios (s,p) for coal unit g
$Gen_{g,\,y,\,t,\,s,\,p}$	Generation from coal unit g
$RetireC_{g,\,y,\,s,\,p}$	Retirement (cumulative) of coal unit g
$Cap_{g,\,y,\,s,\,p}$	Remaining capacity of coal unit g
$Retire_{g,\,y,\,s,\,p}$	Retirement of coal unit g $\{0,1\}$

needs to be traded off against that of running out of capacity, i.e., unreliability. Billinton et al. (1997) discuss this trade-off in 1997, noting the difficulty of achieving this in a deregulated environment, especially because customers seek reliability without necessarily being willing to pay for it. The definition of stranded cost of an asset in economics relates to part of the costs/expenditure that cannot be recovered through the market revenue. Such stranding could be for reliability-centric investments that are not compensated adequately by a market or driven by other factors, including market reform and climate/renewable policy that may lead to low/zero utilization of thermal assets. Woo et al. (2003) discuss how 12 electric utilities in the US, most notably in California, faced significant asset stranding costs following the introduction of markets in the nineties. Victoria et al. (2020) show that stranded costs arising from carbon/renewable policies for thermal generators may be very high, representing 12 % of the system cost in the European energy system for a rapid decarbonization scenario. Gerbaulet et al. (2017) also perform a long-term generation capacity expansion model (dynELMOD) to show significant coal asset stranding risk, especially with limited foresight starting as early as the 2020s. Löffler et al. (2019) use a global energy system model to show that globally 260 GW of coal and gas capacity worth more than 200 billion Euro may get stranded by 2025.

The focus of the current work is on carbon policy-induced asset stranding. However, it should be noted that such stranded costs would reflect inter alia market price and reliability issues. In general, existing studies relevant to the underlying work might be grouped into two categories: (a) literature on the identification of candidate coal power plants for retirement and the estimation of associated stranded costs, and (b) power system modeling methodologies evaluating the impacts of coal retirement and renewable penetration. Examples from both of these categories are reviewed below.

Carbon Trust et al. (2021) and Czyżak & Wrona (2021) use multicriteria analysis (MCA) to identify and prioritize candidate plants for retirement. The multicriteria framework considers the impact on the power system security, associated retirement costs, emissions, short-run marginal cost (SRMC), incumbent power sales contracts, retrofit history, and governing decarbonization policies. Stranded costs are estimated either based on the opportunity cost or stranded investments in the coal assets. Benn et al. (2018) and Carbon Trust et al. (2021) estimate the stranded cost based on the opportunity costs associated with the additional revenue that could be earned by keeping a plant operating. Johnson et al. (2015) and Korea Energy Economics Institute (2017) estimate stranded investment by forecasting stranded capacity multiplied by annualized CAPEX. This methodology can be considered when the financing period matches the plant's lifetime. Johnson et al. (2015) use the MESSAGE-MACRO model, and Korea Energy Economics Institute (2017) used the METER (Model for Energy Transition and Emission Reduction) model for projecting stranded capacity. Kefford et al. (2018) analyze the impact of early retirements of fossil fuel-fired power units needed to follow a 2 °C trajectory of emissions reduction introduced by the International Energy Agency (IEA) in the 2DS scenario. Authors explore the policy implications surrounding early retirement and make estimates of the potentially stranded power plant assets. Maamoun et al. (2020) identify coal units for early retirement using a new retirement index which, apart from plants' age, used estimated CO_2 emissions and potential health impacts from air pollution. This approach used on a global scale prioritizes the retirement of aging units in the developed world for early retirement rather than newer and efficient plants existing in developing countries. Zhang et al. (2022) investigate the risks associated with coal power units' retirements and their stranded costs in the next decade. They first estimate the needs for the coal power capacity under various scenarios, then forecast needed coal capacity expansion and finally use these outcomes to estimate the stranded coal assets following the retirement process. Mo et al. (2021) use a probabilistic simulation model to estimate the risk of coal units becoming stranded assets under climate policies and uncertainties. The dynamics of uncertain parameters are simulated using a stochastic process that subsequently allows calculating the probability distribution explaining the risks of asset stranding.

Some analyses have been presented in the academic literature around the impact of retiring baseload coal and increased penetration of renewables, e.g., (Rahmani et al., 2016). Olsen et al. (2018) present an excellent example of a sophisticated stochastic programming-based analysis of emissions taxes needed to meet a regulatory standard. Their analysis covers inter alia, a full array of longer-term investment requirements down to commitment and multiperiod constraints to show the emissions tax can be optimized by choosing from cleaner generation as well as demand-side (energy efficiency) measures. Wang et al. (2020) discuss an emissions trading scheme considering the carbon flows associated with a transmission network and full consideration of demand-side alternatives using a two-stage scheduling method in conjunction with a zero-sum game data envelopment analysis. There are also good examples of more conventional least-cost planning that comprehensively analyzes the long-term evolution of demand and technology to come up with a least-cost mix of technologies. Chattopadhyay (2010), for example, presents an Australian case study that showed how different sets of technologies can be analyzed under alternative emissions trading and market-based carbon pricing mechanisms up to the year 2050. Kim et al. (2020) present a chance-constrained equilibrium model for the US system that captures the strategic interaction among the state regulators working in conjunction with the state utilities to meet the decarbonization goal (through a renewable portfolio standard) in the least cost manner. Cui et al. (2019) used detailed worldwide coal plant-level data to investigate different trajectories for the coal power sector using an integrated assessment model. The key metric used for the retirement selection was an operational lifetime limit. In the subsequent work, Cui et al. (2021) used a similar methodology to assess a high-ambition coal phase-out exclusively in China.

Another global integrated assessment model was used by Edwards et al. (2022) to estimate changes in global stranded assets' costs from coal-fired power plants in various regions. Their analysis shows that the risk of asset stranding to meet the Paris Agreement targets remains significant. Shen et al. (2020) present the low-carbon electricity network transition model used to schedule coal units' retirement, develop new renewable capacities, and consider power grid aspects. The model was formulated as a multi-objective structure balancing three conflicting objectives of cost, carbon emission, and system risks. The IEA has been at the forefront of energy sector decarbonization analysis including the *India Energy Outlook* 2021 (International Energy Agency (IEA), 2021), which forms the basis for one of the case studies presented in this paper. IEA's World Energy Outlook comprehensively covers all of the sub-sectors in energy using the World Energy Model (WEM). Liu et al. (2020) discuss how coal asset stranding is becoming a significant issue in markets like China with significant penetration of renewables and propose a methodology to calculate the stranded cost based on market revenue and costs that can be recovered through a subsidy mechanism.

Gap in the literature

The power system economics literature has presented a range of stranded assets and coal retirement evaluation techniques, ranging from cash-flow-based financial estimates to sophisticated planning models accounting for taxes, emissions trades, and renewable standards. However, a few key challenges remain to be addressed.

First, there is an unresolved trade-off in the levels of complexity of the presented approaches. On the modeling side, the problem's scale, the models' complexity, and extensive data requirements often mean that substantial effort is involved in undertaking such an analysis (see, for example, (Löffler et al., 2019)). Even for a single country, forming a strategy on the order in which coal plants should be shut down to achieve a specific decarbonization goal (e.g., net-zero emission by the year 2050 or a softer target) requires significant efforts. This can be particularly challenging in a developing-world context, where addressing the shortcomings in data quality, availability, and adequacy can be laborious (Debnath & Mourshed, 2018). On the other hand, the back-of-the-envelope analysis, while easy to use, maintain and fill with data, often fails to capture the crucial dynamics of power system operation, both on the technological and economic front (see for example, (Carbon Trust et al., 2021)). The shortfalls of these simplified techniques used to formulate policies, which may include providing inadequate retirement schedules or overestimating the economic costs of retirement, might be again particularly damaging in developing countries, where resource endowments prone to stranding are often located (McGlade & Ekins, 2015; Ansari & Holz, 2020). This trade-off is graphically presented in Fig. 1. There is room for a methodology in the middle of complexity scale, capturing the dynamics of conventional units and their dispatch decisions, but reducing the data requirements through simplified system representation.

Second, a myriad of sophisticated long-term capacity expansion models has been utilized to construct long-term power system roadmaps designed to reach specific environmental goals of emission reduction (Debnath & Mourshed, 2018). Therefore, the significant gap

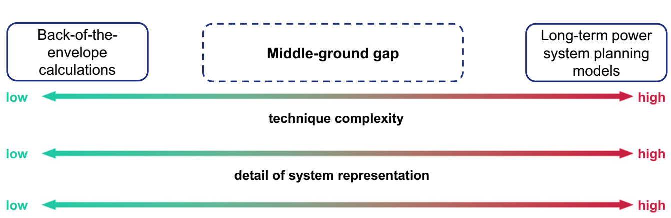

Fig. 1. Trade-off between two extreme methodologies.

lies not within trying to substitute existing planning models but complementing them with analyses focused on coal retirement. This might be achieved, for example, by effectively utilizing the results of the complex planning models, specifically coal generation trajectories, to calculate stranded cost values. A simplified methodology would allow to account for diverse emissions reduction scenarios, each of which may have substantially different price outcomes and probability of occurrence. Such an approach not only exploits already existing analyses but also allows for modeling multiple coal trajectory (and associated price) scenarios or contract conditions, which would be challenging in complex, large-scale models.

Finally, even if an optimal coal plant retirement schedule is obtained, there are still other issues, like stranded assets, that need to be addressed ideally in the same model as an endogenous variable. Although there have been high-level policy analyses (Benn et al., 2018; Carbon Brief, 2021; International Energy Agency (IEA), 2021), there has been little by way of a practical modeling methodology that data can support to capture stranded asset cost calculation in an optimization model with constraints around it for a balanced allocation of these costs across the plants. Therefore, there is room for a technique that builds on existing generation plans and focuses on the coal fleet to answer this question.

Consequently, the specific objectives of this paper are as follows:

- Building on the World Bank's work on coal transition and Electricity Planning Model (Chattopadhyay et al., 2020), it introduces Coal Retirement Model (CRM) as a tool to develop insights into coal retirement pathways.
- Extensively describes two relevant developing countries case studies of India and Philippines, with coal-heavy power systems and the need for support of decarbonization strategies.
- Develops insights into economic and financial issues surrounding coal fleet retirement in the presented case studies, focusing on the evaluation of forgone revenues, stranded costs, and retirement schedules.

Modeling coal retirement

Overall methodology

Fig. 2 presents the high-level structure of the presented methodology. This coal retirement model is designed to complement more detailed long-term planning frameworks, which are usually utilized to produce emission reduction roadmaps for countries or regions. The modeling input is partially shared, and the common parameters include

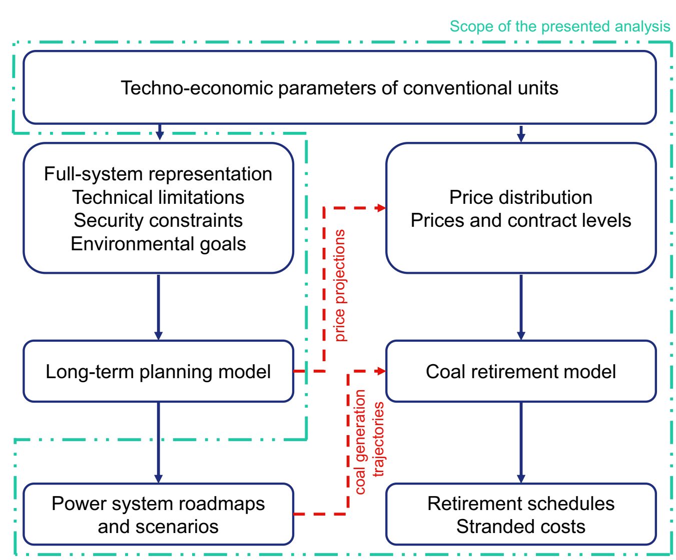

Fig. 2. High-level structure of the presented methodology and its connection with the planning model.

techno-economic properties of the conventional units, such as installed capacity, capacity factors, efficiency, fuel costs, or O&M costs. The planning model may have a substantially more extensive input dataset and internal mathematical structure. Consequently, it will provide a coal generation trajectory, implicitly ensuring that all reserve margin, frequency containment ancillary services (FCAS), transmission constraints, technical limitations, and environmental goals are being honored. Such a two-step process creates an elegant framework for policy discussions around coal retirement, being simple, transparent, and capturing multiple views on coal generation reduction and commercial and market issues. It also utilizes and leverages already existing sophisticated modeling exercises, focusing entirely on the problem of coal retirement, allowing to model multiple coal trajectory (and associated price) scenarios or PPA conditions. Finally, it provides a simple alternative evaluation of stranded costs, allowing to challenge or validate already existing estimates provided by utilities and institutions.

Carbon costs, limits, or other constraints related to environmental policies can be (and often are) implicitly built into the analysis through the emission reduction scenarios of the long-term planning model. If these carbon prices (or other costs related to environmental policies) should be built into the stranded costs calculations is a moot point. If the analyzed countries or regions do not have a carbon pricing policy, the stranded asset values can arguably exclude those. In the case of India and the Philippines, which are analyzed in the further sections–both countries do not have a carbon pricing policy in place or plan to have one. As such, these are not considered in the stranded cost calculation. Furthermore, historical electricity price series are used that do not include a carbon price to be consistent with this approach.

Mathematical model

The core model structure discussed here can be set up as a linear or mixed-integer optimization programming problem depending on the granularity of retirement decisions sought (i.e., unit level or at plant level or a group of plants by vintage/cost/ownership etc.). The key features of the model are as follows: (a) it focuses on the coal fleet only to maximize the fleet's net revenue (NR) in order to meet a targeted generation (Target). The Target may be derived from a systemwide master plan and decarbonization pathway targets; (b) it considers multiple scenarios on generation trajectories as well as economic market-based compensation and longer-term power purchase agreements (PPA); and (c) criteria that limit the level of asset stranding, e.g., below say 50 % of baseline net revenue or plant load factor floor below which the plant cannot be in operation.

The core model presented here can be extended to incorporate additional considerations but is deliberately kept simple so that it can be easily replicated for a number of countries within the limitations of available data and resources.

$$NR = \begin{cases} \sum_{y,g,t,s,p} \left(P_{y,p,t} - Cost_{g,y}\right) \cdot Gen_{g,y,t,s,p} \\ - \sum_{y,g,t,s,p} FC_{g,y} \cdot \left(Capacity_g - RetireC_{g,y,s,p}\right) \end{cases} \tag{1}$$

$$\frac{NR'_{g,s',p'} - NR\}_{g,s\},p\}}}{NR'_{g,s',p'}} \le \alpha \tag{2}$$

$$\sum_t \sum_g Gen_{g,y,t,s,p} \cdot H_t = Target_{y,s,p} \tag{3}$$

$$\sum_t Gen_{g,y,t,s,p} \cdot H_t \ge MinGen_g \tag{4}$$

$$\sum_t Gen_{g,y,t,s,p} \cdot H_t \le MaxGen_g \tag{5}$$

$$Cap_{g,y,s,p} = Cap_{g,y-1,s,p} - Retire_{g,y,s,p} \cdot Capacity_g \tag{6}$$

$$\sum_g Cap_{g,y,s,p} \ge \frac{Target_{y,s,p}}{\varnothing_{s,p}} \tag{7}$$

$$RetireC_{g,y,s,p} = \sum\nolimits_{y' \le y} Retire_{g,y',s,p} \tag{8}$$

The mathematical formulations of the CRM are presented in Eqs. (1)–(8). Eq. (1) shows the fleetwide net revenue calculation based on prices P that may either be a market-based compensation (e.g., projected hourly spot prices as an exogenous input to the model) or commercial PPAs. The difference in systemwide net revenue between the BAU and a decarbonization scenario is used as a measure of forgone revenue, which for retired units may be used to estimate stranded costs [2]. The forgone net revenue is what the generators may be reasonably expected to be compensated for due to a decarbonization policy. Eq. (2) sets a limit on how far a generating unit's net revenue (NR) can deviate from a baseline/business-as-usual (BAU) scenario. This is equivalent to a cap on the maximum regret for individual generators. Eq. (3) requires the fleetwide generation to follow a generation trajectory and may include a decarbonization scenario that drastically reduces coal generation over the years. This, in turn, would reduce NR for units relative to a BAU scenario, but Eq. (2) would require the loss in NR to be limited below a certain limit, which in turn drives the generation allocation (Gen) and hence retirement (Retire) decisions. Eqs. (4)–(6) are the standard min and max generation limits and capacity balance. It should be noted that if Retire is treated as a binary variable, then the generator basically either has to operate above the minimum capacity utilization level or be retired. Eq. (7) requires a minimum level of fleetwide capacity to be maintained, which is a proxy for various considerations, including capacity, spinning reserve, and load shape, both necessary in a long-term planning model like the one presented. Some of these details can indeed be modeled more explicitly, but the principal driver of this model has been an easy and rapid way of calculating coal retirement and associated stranded asset costs for multiple developing countries with limited data. Eq. (8) defines the cumulative retirement in each year.

Simple illustrative example

This subsection explains the core concept of stranded asset calculation and the working of the underlying model using a small illustrative example. Table 1 shows plant (or it may be viewed as generation company level) data, including PPA price in the last column.

There are only two fleetwide target scenarios considered for three years (say 2025, 2030, and 2050), namely: BAU (100, 110, and 120 TWh targets for 2025, 2030, and 2050, respectively); and Accelerated Decarbonization (AD) (100, 50 and 0 TWh, i.e., the net-zero target must be met by 2050). There is naturally going to be a need to retire all three plants by 2050 in AD while observing the minimum generation needs in the preceding years below which plants cannot feasibly be in operation.

There are two cases constructed with no restriction on how far net revenue can drop in the AD scenario and a second one wherein NR drop for each generator is restricted to 55 % of BAU level (below which there is no feasible solution). As Table 2 shows, Gen1 loses NR the most from 3200 down to 900 (72 %) in the unrestricted case. If the maximum revenue loss (regret) is capped, Gen1 retirement will need to be postponed to 2050, and that for Gen 3 will need to be brought forward to 2030. There will also be a need to adjust Gen2 dispatch. There is

Table 1
Coal fleet data.

	Max TWh	Min TWh	Cost $/MWh	Price $/MWh
Gen1	60	30	30	50
Gen2	40	20	10	45
Gen3	30	15	40	55

Table 2
Net revenue (NR $m) and retirement year (ret).

	No restriction on α			α capped to 0.55		
	Net Revenue			Net Revenue		
	BAU	AD	RET	BAU	AD	RET
Gen1	3200	900	2030	3200	1440	2050
Gen2	4200	2625	2050	4200	1942.5	2050
Gen3	750	450	2050	750	337.5	2030
TOTAL	8150	3975		8150	3719	

	No restriction on α				α capped to 0.55			
	Net Revenue		Loss Rate	RET	Net Revenue		Loss Rate	RET
	BAU	AD			BAU	AD		
Gen1	3200	900	0.72	2030	3200	1440	0.55	2050
Gen2	4200	2625	0.38	2050	4200	1942	0.54	2050
Gen3	750	450	0.40	2050	750	338	0.55	2030
TOTAL	8150	3975			8150	3719		

an overall decrease in system net revenue from $3975 m to $3719 m to accommodate the constraint that limits stranded asset value for the worst case and does a more equitable allocation of asset value losses across the plants/gencos. Although this reallocation can theoretically be worked out manually, it would be ad-hoc, cumbersome and quite possibly lead to a sub-optimal outcome for a more extensive system with more complex side constraints. Therein lies the value of the model.

Case study 1: large and aging coal fleet (India)

The Indian power system has one of the largest coal fleets in the world, comprising 209 GW across 196 plants. Nearly half of the capacity has been built over the past decade, generating over 1000 TWh and accounting for over a billion tonne of annual CO2 emissions. Therefore, any energy transition in the country critically hinges on the displacement of coal-based generation over the next two decades with renewables, including solar, wind, and hydro, among other options. IEA 2021 (International Energy Agency (IEA), 2021), for instance, postulates that India's coal-based generation (including generation from new coal plants that are under construction and planned additions) will need to reduce below 200 TWh by 2040 for an ‘Accelerated Decarbonization’ (“IEA AD”) pathway. This is in sharp contrast with a Business-as-Usual scenario that would increase coal-based generation to over 1300 TWh by the same year. However, an important development that calls into question the ability to sustain coal-based generation is the proposal to introduce a Market-Based Economic Dispatch (MBED) – effectively a gross pool – wherein coal generators will need to compete with cheaper renewables. Market prices to date have been typically lower than the majority of the coal PPAs and may be further depressed due to the proliferation of renewables up to 450 GW by 2030. As such, the market scenario is used to simulate a potentially faster market-driven retirement of coal, resulting in a lower stranded economic cost. Comparing and contrasting the BAU and AD scenarios and stranded asset costs therein can reveal significant insights into the level of compensation that may need to be paid out to the plant owners,

Key inputs and assumptions

The present analysis is set up to evaluate the retirement and dispatch of 196 coal plants for 2021–2040 under a PPA and spot price scenario under a set of decarbonization scenarios. Both PPA and spot prices are assumed not to change across the years, constructing the scenario based on the historical and realistic price levels. Fig. 3 shows the coal fleetwide generation target scenarios (Target), including new coal generators that consider three intermediate scenarios (IS1–3) in addition to BAU and AD. The difference in generation across the scenarios translates into a significant part of the existing fleet that will need to shut down

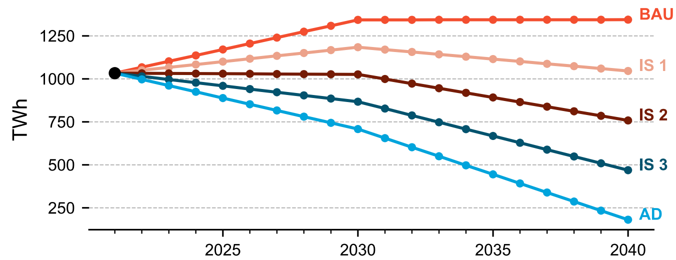

Fig. 3. Coal generation target (TWh) scenarios for India case study.

over the next two decades, including close to 93 GW of capacity that is barely 10-year-old and at risk of getting stranded. This risk will depend both on the cost and sources of revenue for generation (namely, PPA or spot market). The vast majority of the coal plants in India are currently under a PPA arrangement, but as noted, the MBED design scheduled to be implemented in 2023 may usher in a new era of market-based compensation, at least for part of the generation.

Fig. 4 shows the variable cost of the plants by vintage and the fixed costs they are compensated for under a PPA regime. In other words, PPA owners get the weighted average (WA) of fixed cost and variable cost. The fixed cost component is assured for an 85 % utilization level regardless of the actual utilization and hence remains lucrative for generators that lose dispatch but are not retired.

Note: US$1 = Approx. INR 72. Data source: MERIT [11].

Fig. 5 shows the projected spot prices used to calculate the revenue of generators selling all their outputs at the wholesale market under MBED. The price distribution is represented using ten blocks from peak to off-peak for each year. A spot market-based compensation, in comparison to a fixed PPA price regime, has some upsides during peak over INR 6/kWh for the top 5 % of the hours, but spot prices average around INR 3/kWh (USD 42/MWh) with 40 % of the time below that level. Many of the generators – both old and relatively new – are not competitive below the INR 3/kWh level on their variable costs. There is, therefore, a higher chance of these generators being uncompetitive if the fleet is competing for a progressively lower total generation over the years under the AD scenario.

The assumption of a constant spot price is a limitation of the analysis, and it was used due to the lack of reliable long-term electricity price forecasts associated with the AD scenarios for either country case. As depicted in Fig. 2, the methodology allows annual price forecasts to be deployed as an input to the stranded cost allocation that should reflect inter alia fuel price variations, changes to the generation mix, and demand. It was chosen to do the analysis based on a single-year market price projection, notwithstanding the data limitations, which still served a useful purpose. It provides relatively clean benchmark numbers of stranded costs that are free from a host of planning model assumptions. The fact that there is considerable uncertainty on future market design in India (and the Philippines), let alone prices that would require complex modeling puts a proper analysis of spot price

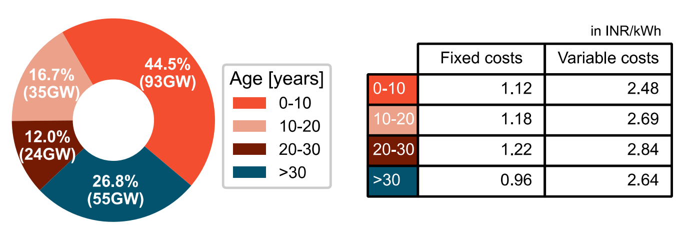

Fig. 4. Coal capacity by vintage and costs (FC = fixed cost, VC = variable cost).
Note: PPA price = FC + VC with minimum FC set at 85 % utilization for first 25 years of life of the plant.

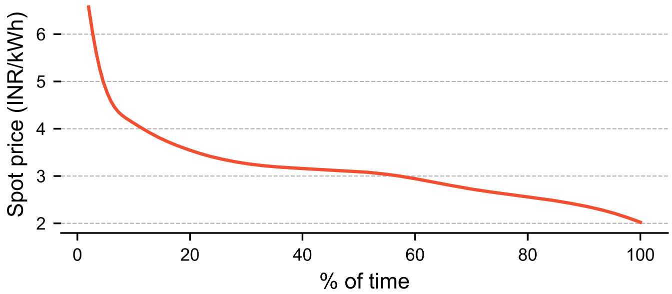

Fig. 5. Spot market price distribution in India.

projections for AD scenarios beyond the scope of the work and could prove to be counterproductive.

Results of the Indian case study

Table 3 summarizes the results for both the PPA and market-based revenue scenarios. The net revenue loss is limited to 50 % for both PPA and market price scenarios, i.e., the difference between BAU and AD for each of the price scenarios is limited to half of the BAU net revenue level.

The stranded cost under the PPA regime ranges from INR 0.4 to 5.8 trillion (USD 6 bn to USD 81 bn), depending on the target level of decarbonization. These compensation figures are significantly reduced under the market regime, ranging from INR 0.1–1.7 trillion (USD 2 bn to USD 23 bn). In other words, if all of the generation moves to a gross wholesale electricity market (MBED) regime to compete on the basis of their costs, ignoring the take-or-pay obligations or fixed costs under the PPA regime, a large part of the coal fleet would be deemed unprofitable. As such, the compensation requirements will drop by at least a factor of three, even under the most stringent AD scenario. As the IS-3 scenario shows, a *market-based assessment of stranded costs* is, in fact, at a relatively low level (INR 0.5 trillion translating to USD 7 billion), suitable to accelerate the retirement of 64 GW of coal relative to BAU at an average compensation of $108/kW.

The IS-2 and IS-3 scenarios present modest to reasonably deep decarbonization pathways with 42 GW and 86 GW of coal capacity being decommissioned, respectively, *under a PPA regime* at an estimated stranded cost of INR 1.4 trillion (USD 19b) and INR 3.1 trillion (USD 43b), respectively. This clearly shows that it may be cheaper to target the group of 42 GW generators with the most expensive operation cost at a stranded cost of $19b or $452/kW on average. While this is four times as expensive compared to the market price scenario, the implied cost of CO_2 reduction is still modest, as the next point discusses. As increasingly more profitable units are shut down, the compensation payable to the PPA-holder generators rises to $536/kW for the next lot of (86–42=) 44 GW capacity. In fact, the stranded cost will be much higher at $81b under the AD scenario, which equates to an incremental cost of $1070/kW *to move from IS-3 to AD* as an additional 37 GW capacity is retired with a forgone (discounted) net revenue of $35 billion. These findings are important to prioritize projects that may be good candidates for accelerated coal transition, subject to meeting other preconditions, including a prudent way of managing social issues.

Although this analysis does not explicitly look at the associated reduction in CO_2 and local pollutants, it is worth noting that IS-2, IS-3, and AD scenarios all represent a massive reduction in coal-based generation of 288 TWh, 568 TWh, and 793 TWh, respectively, by 2040, relative to the BAU generation of 811 TWh in the same year. Even if we consider the higher end of stranded cost and assume the compensation will fully offset the generators at that level, the implied *average* cost of CO_2 reduction for IS-2, IS-3, and AD works out to be approximately $10/t, $14/t, and $22/t, respectively. As IS-3 and AD, in particular, represent deep decarbonization pathways, the average cost of carbon reduction is quite remarkable. It indicates that even at the high end of this range, around 7 billion tons of CO_2 (in the AD scenario in cumulative terms over 2021–2040) is achievable at a (discounted) cost of $81b. Of course, the Market/MBED scenario presents a far cheaper solution with practically zero cost for IS-3 and $23b for AD. While this calls for sweeping reform of the PPA regime to bring all of the generations in the country to be cleared through the market, it also shows the rich reward that such measures entail not only to enhance cost efficiency but the tremendous potential for a market-based mechanism to deliver decarbonization through accelerated retirement of coal units.

Table 3
Summary of results for Case study 1.

	BAU	IS1	IS2	IS3	AD
Revenue based on Power Purchase Agreements					
Coal capacity in 2040 (GW)	124	121	82	38	3
Total retirement by 2040 (GW)	85	88	127	171	206
Total generation in 2040 (TWh)	811	799	523	243	18
Disc. revenue (Trillion INR)	14.9	14.4	13.5	11.8	9.1
Stranded cost (Trillion INR)	0	0.4	1.4	3.1	5.8
Revenue based on wholesale market spot prices					
Coal capacity in 2040 (GW)	125	124	99	61	10
Total retirement by 2040 (GW)	84	85	110	148	199
Total generation in 2040 (TWh)	811	805	601	302	23
Disc. revenue (Trillion INR)	10.1	9.9	9.7	9.2	7.6
Stranded cost (Trillion INR)	0	0.1	0.2	0.5	1.7

Case study 2: small and young coal fleet (Philippines)

Since the late 1990s, coal-based generation saw a staggering increase in the Philippine power system. Its share in the electricity mix experienced a steep increase from just over 6 % in 1995 to 58 % in 2020 (Delina, 2021). The remaining share was attributed to natural gas (19.2 %), which also underwent a significant upsurge since 2000 but leveled off after 2010. The rest of the generation was covered by hydro (10.6 %) and geothermal (7.1 %), as presented in Fig. 6. Although coal mining exists in the Philippines, it is primarily a legacy of the colonial past (Camba, 2015). In fact, domestic coal production is predominantly exported to China, while 85 % of the coal used in the power sector is imported, mainly from Indonesia and partially from Australia.

As of 2022, the total installed coal power capacity in the on-grid areas is 10.6 GW comprising 58 individual, mostly subcritical, units. Most of the capacity has a unit size between 100 and 400 MW (6943 MW in total) and was commissioned between 2010 and 2020 (7983 MW in total). Furthermore, the current coal construction pipeline is likely to intensify the role of coal in the electricity mix and deepen its fuel consumption. An additional 2.7 GW is currently in the pre-permit or permitted stage, and 1.6 GW more is under construction.

Coal continues to be a core power source in the state energy policy. The Philippine Energy Plan 2018–2040 (Department of Energy,

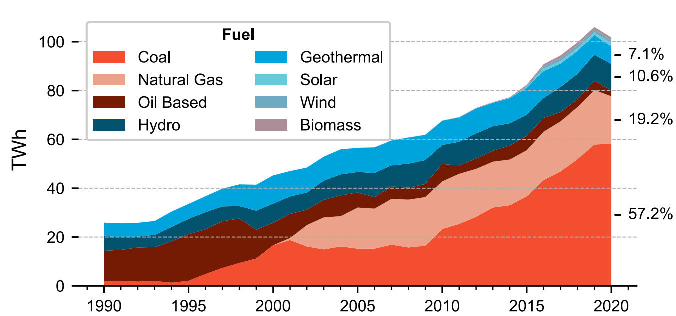

Fig. 6. Historical generation mix (TWh) in Philippines.

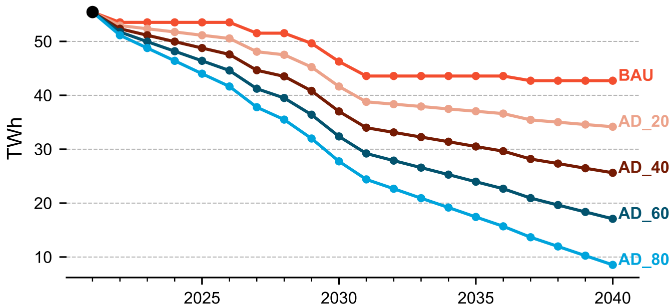

Fig. 7. Coal generation target (TWh) scenarios for Philippines case study.

2018b), which is the primary blueprint outlining the long-term energy priorities, continues to place coal as a decisive resource. The Plan assumes over 50 % share of coal generation in 2040 with over 22GW of coal additions (in the reference scenario). This vision is further extended in the Coal Roadmap 2017–2040 (Department of Energy, 2018a), which assumes an increase in the country's domestic production. Despite the direct coal reliance in most of the strategic documents, on 27 October 2020, the Department of Energy announced a moratorium on endorsements for new coal power plants, declaring a stop to the new coal deployments (Department of Energy, 2020). Nevertheless, the moratorium does not account for any existing units, and the push toward new renewable energy policies was sluggish to a significant extent.

Key inputs and assumptions

The present analysis investigates the retirement and dispatch of existing Philippine coal plants for 2021–2040 under two different price regimes and a set of decarbonization scenarios. Fig. 7 presents coal generation targets for BAU and various decarbonization scenarios. BAU scenario assumes that the annual coal generation from the existing coal capacity is based on the constant capacity factor of 59.8 % (observed historically in 2021). The target generation is calculated considering the natural retirement of specific units after the 30 years of operations (hence it is declining). Accelerated decarbonization (AD) scenarios are modeled as 20 %, 40 %, 60 %, and 80 % generation target in 2040 compared to BAU (AD_20-AD_80), with the reduction happening linearly between 2021 and 2040. The generation targets trajectories are presented in Fig. 7.

As in Case Study 1, two price scenarios are considered: PPA and market prices. The PPA scenario assumes that generators are under PPA contracts, with their revenues calculated based on the existing and available details of 2021 contracts. Fig. 8b presents the assumed PPA structure of the nation's fleet, divided by the capacity and level of the payments. The market prices scenario assumes that the entire fleet of generators participates in the spot market. The price duration curve approximation was based on the 2016–2021 Philippines day-ahead market data and was split into ten representative price segments, similarly to Case Study 1 (Fig. 8a).

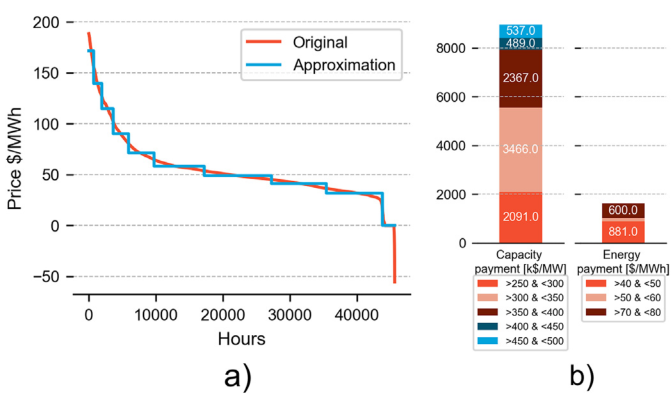

Fig. 8. Coal generation targets (TWh) for BAU and decarbonization scenarios.

Results for the Philippine case study

Table 4 summarizes the results for both the PPA and market-based revenue scenarios for the Philippine case study. The net revenue loss is unconstrained for both price regimes.

The results reveal that no additional capacity is retired for both price regime scenarios in the 20 % generation cut. In both cases, target production is reached through an overall decrease in the fleet's generation. While for the market price scenario, the discounted revenue decreases by 4 % due to forgone profit from the spot market participation, for the PPA scenario, it marginally increases following additional generation from units receiving energy base PPA contracts (revenue from the capacity-based contract remains unchanged without any retirements). A 40 % cut for the market price scenario and 60 % for the PPA scenario see additional retirements and stranded costs turn positive. Furthermore, PPAs largely based on the fixed capacity payments disincentivize capacity retirements, resulting in significantly lower additional retirement values than the market price scenario (0.98 GW vs. 3.29 GW for AD 60 and 4.27 GW vs. 5.65 GW for AD 80).

The average stranded cost under the PPA regime ranges from $0.21 m to $0.32 m per MW, depending on the extent of the generation cut. These compensation figures are relatively similar to the market price scenario, ranging between $0.14 m and $0.35 m per MW. It may be cheaper to target the most expensive group of 1-2GW at a low stranded cost of $0.1–0.2 m per MW, as the oldest, most inefficient, and least profitable units are retired as a priority. Clearly, the stranded costs increase with the deeper decarbonization targets as more profitable and cheaper units are retired to meet the technical constraints.

Forgone revenue is another useful metric as it accounts not only for the prematurely retired units but also for the reduction in the net revenue of units that continue to be online. In both relative and absolute terms, the market price scenario indicates the higher value of the discounted forgone revenue, with a 24 % reduction from BAU (−$2.92 billion), compared to only 4 % with PPA regime (−$1.30 billion). These differences are clearly visible in Fig. 9, which illustrates annual additional forgone revenue and retired capacity between the scenarios. When units are compensated based on the fixed contracts, an increase in both forgone revenue and retirements is delayed toward the second half of the modeling horizon but rapidly accelerated afterward. On the other hand, in the case of the market price scenario, forgone revenue stabilizes post-2030, while additional retirement demonstrates a stable rate (once it begins in 2028).

Table 4
Summary of results for Case study 2.

	BAU	AD20	AD40	AD60	AD80
Revenue based on Power Purchase Agreements					
Coal capacity in 2040 (GW)	8.16	8.16	8.16	7.18	3.89
Additional retirement by 2040 (GW)				0.98	4.27
Total generation in 2040 (TWh)	42.70	34.16	25.62	17.08	8.54
Discounted revenue (billion USD)	31.77	31.82	31.87	31.68	30.47
Forgone total net revenue (billion USD)		−0.05	−0.10	0.09	1.30
Stranded cost (million USD per MW)				0.21	0.32
Revenue based on wholesale market spot prices					
Coal capacity in 2040 (GW)	8.16	8.16	5.96	4.87	2.51
Additional retirement by 2040 (GW)			2.20	3.29	5.65
Total generation in 2040 (TWh)	42.70	34.16	25.62	17.08	8.54
Discounted revenue (billion USD)	12.14	11.66	10.93	10.12	9.22
Forgone total net revenue (billion USD)		0.49	1.21	2.03	2.92
Stranded cost (million USD per MW)			0.14	0.24	0.35

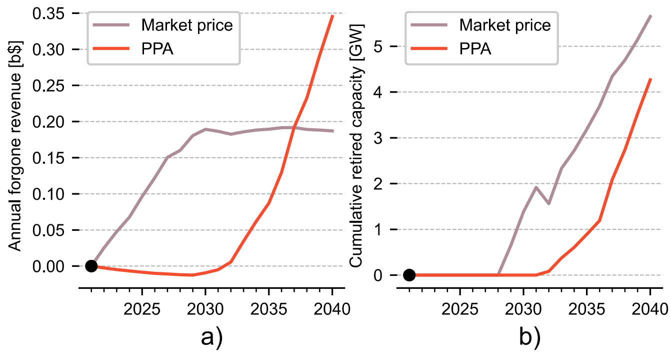

Fig. 9. Annual forgone revenue (graph a) and cumulative additionally retired capacity (graph b) in PPA and market price scenario.

An interesting sensitivity of the case study is the incorporation of Eq. (2) from the main model for varying values of α parameter. Values between 10 %–50 % were evaluated for both PPA and market price scenarios. The impact of this constraint on the total forgone revenue is presented in Fig. 10. Market price scenario sensitivity reveals that the individual forgone revenue might be limited to as low as 28 % with only negligible impact on the total loss in discounted net revenue (below that value model becomes infeasible). For the PPA regime, the value of α might be decreased to 24 %, keeping the same level of cumulative forgone revenue. This is a significantly positive outcome because it means business losses across the retiring units can be kept relatively uniform without increasing the total forgone revenue (or compensation) amount. Past this value, however, forgone revenue increases up to 29 % at α of 18 %, and the model becomes infeasible below that.

While in the PPA regime, the fuel costs are passed through and do not affect discounted revenue of the coal units, it is a crucial determinant of the profitability and eventual compensation in the market price scenario. This impact is presented in Fig. 11. Sensitivity analysis reveals that there is a direct, nearly linear, relationship between coal price and stranded costs (assuming constant market prices). With decreasing

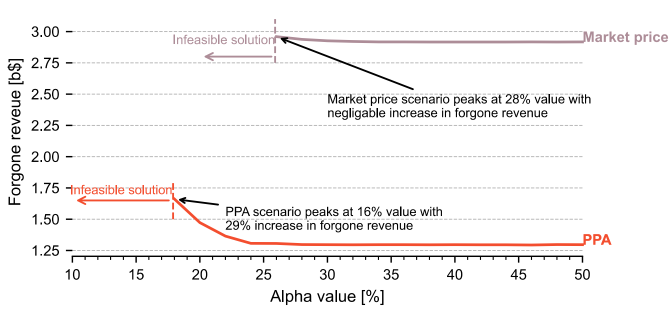

Fig. 10. Impact of the individual forgone revenue limitation on the total forgone revenue.

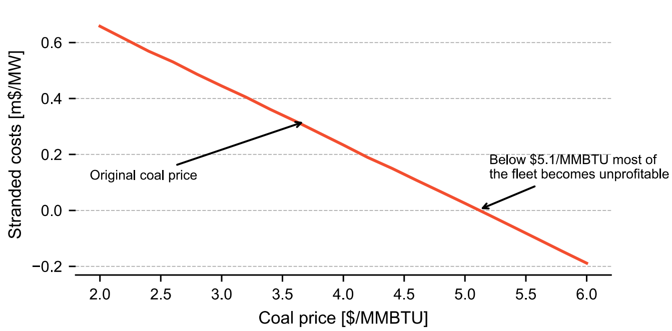

Fig. 11. Relationship between coal price and stranded costs valuation for market price scenario.

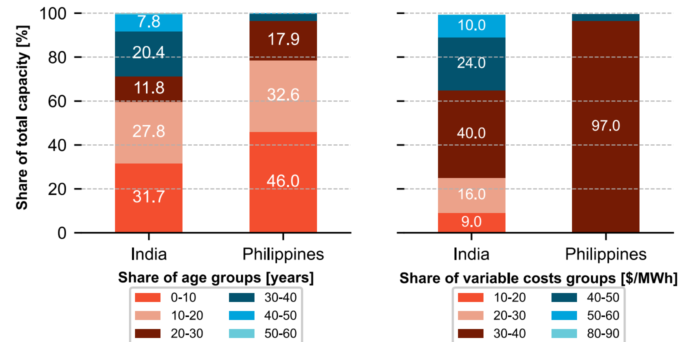

Fig. 12. Individual units' stranded costs for India (AD scenario) and Philippines (AD_80 scenario) for both price regimes.

coal prices, compensation increases up to $0.6 m/MW for a price of $2/MMBTU. Above price of $5.1/MMBTU, stranded costs become negative, as most of the units become unprofitable, and a more stringent generation target reduces losses instead of limiting profits.

Insights from a comparative case study

The findings from the two case studies are compared and contrasted in this section, providing useful insights into how coal transition pathways are influenced by the core drivers of age, cost of generation, and revenue model.

Fig. 12 shows the relative age and cost structure of the coal fleets for India and Philippines. It reveals that India's massive 209 GW coal fleet is also highly diverse in terms of the spread of age and cost of generation compared to the 10.6 GW fleet in the Philippines. The latter fleet is much younger and also almost entirely in the mid-cost range of $30–40/MWh.

Fig. 13 shows the optimal coal plant trajectories for market price (MP) and PPA scenarios. The presence of an older and high-cost share of the Indian fleet implies the process of economic retirement is already underway and will steadily continue through the next two decades. Retirement of the young coal fleet in Philippines starts late but, under an 80 % Accelerated Decarbonization scenario, needs to ramp up around 2030. Although a market price-led scenario leads to a slightly more accelerated retirement of coal plants in India, Philippines might see a significant divergence among the two revenue models with (past) market prices not supporting more than 40 % of the fleet as early as 2030. In comparison, the incumbent PPAs will reach 40+ % retirement by 2035.

Figs. 14 and 15 show the stranded cost for individual units and in cumulative terms, respectively. The market price (MP) scenarios in both countries lead to significantly lower stranded costs well below $1 m/MW relative to a PPA regime that may exceed the $1 m/MW mark for many plants in India. This shows the need for a push toward a market

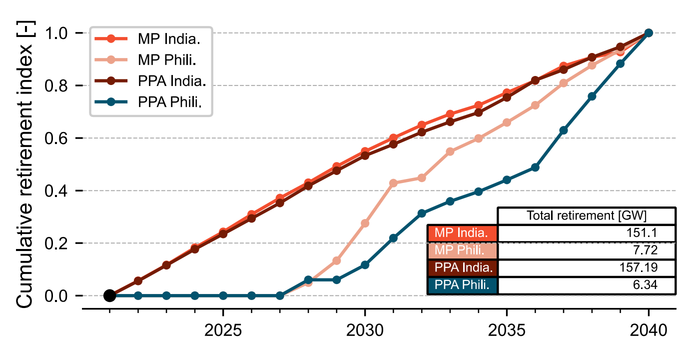

Fig. 13. Cumulative retirements in different price scenarios and case studies.
Note: The AD scenario was used for India, while AD_80 for the Philippines.

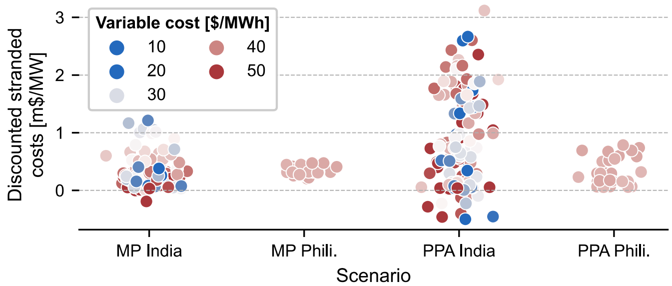

Fig. 14. Individual units' stranded costs for India (AD scenario) and Philippines (AD_80 scenario) for both price regimes.

regime as PPAs for older plants expire to accelerate the decarbonization process.

Concluding remarks

Decarbonizing power systems will require shutting down coal plants before their technical, commercial, or economic life ends. A critical task to achieve this goal is to find an equitable estimate of stranded coal plant assets. The proposed model provides a practical way for policymakers, regulators, and planners to assess stranded costs using an explicit endogenous criterion to limit the loss in net revenue relative to a business-as-usual scenario to drive the plant/unit retirement decisions. The model provides a reasonable trade-off between simpler back-of-the-envelope calculations and complex full-scale power system models, leveraging most essential system aspects from the valuation of stranded assets. The model can be built off the country/utility generation expansion plan and views/scenarios around alternative decarbonization pathways. As both case studies demonstrate, the model could be implemented rapidly using the available generation expansion plan, cost and PPA information available in the public domain, simplified spot market results, and various decarbonization scenarios. An exclusive focus on the existing coal fleet eases the calibration process and substantially limits data requirements, concentrating on the crucial determinants of the resulting costs and revenues. This simplicity also allows capturing multiple views on coal generation reduction through the representation of multiple coal trajectories (and associated price) scenarios or PPA conditions.

For India, the insights from the modeling analysis are significant in that it conclusively demonstrated the stranded asset costs even under a case of compensating the asset owners of the full cost of PPA is USD 19 billion for 42 GW of capacity, or $0.45 m/MW. More importantly, the costs can be drastically lower if India can implement a more liquid wholesale electricity market. For the Philippines, the generous PPA tariffs may delay the fleet's retirement and incentivize a decrease in capacity factor to keep units online. On the other hand, it amplifies the

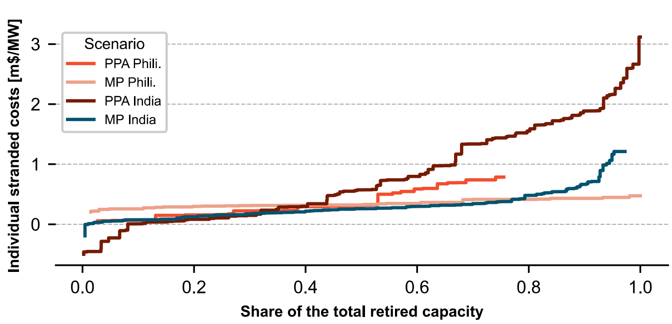

Fig. 15. Individual units' stranded costs merit curves.
Note: Due to the substantial difference in system sizes of the two case studies, retired capacities have been normalized by cumulative retirement values (61,798 MW for India and 5649 MW for Philippines). The AD scenario was used for India, while AD_80 for the Philippines.

compensation costs relative to the retired capacity. With active participation in the spot market, retirement happens earlier, with lower stranded costs for the initial GWs that are shut down. In both price regimes, stranded costs do not exceed $0.4 m/MW, which is a fraction of other available estimates (for example, conducted by ADB's Energy Transition Mechanism (Carbon Trust et al., 2021)). By obtaining more reasonable estimates of stranded costs, this analysis provides essential guidance on how markets can accelerate retirement and facilitates a discussion about the potential compensation levels.

The data requirement and modeling are not onerous and can neatly complement existing master plans and other national/international studies. It is envisaged that the model can be replicated for other countries to assess coal retirement strategy and stranded costs, which is an increasingly important aspect in the world aiming for rapid and just decarbonization. Furthermore, considering attractive computational performance, the model might be extended and cast as a stochastic linear/integer programming problem to incorporate uncertainty in price levels, fuel prices, or the probability of various coal generation trajectories to provide additional insights and policy guidance.

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.

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