Received April 25, 2021, accepted May 7, 2021, date of publication June 7, 2021, date of current version June 18, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3087081

ACT on RE+FLEX: Accelerating Coal Transition Through Repurposing Coal Plants Into Renewable and Flexibility Centers

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This work was supported by the Energy Sector Management Assistance Program (ESMAP) and benefitted from the country level data that was collated from various other ESMAP projects (with the exception of Bulgaria).

ABSTRACT Decarbonizing the power sector forms a critical part of the global combat against climate change. This requires *inter alia* retirement of the global coal power plant fleet of 2,100 GW. Although a significant part of this capacity is aging, there are complex issues that need to be addressed including the economic viability of existing coal plants in some countries relative to renewable projects and barriers to exit of coal. We have used detailed power plant level operational cost data for ten developing countries with significant share of coal and compared these with levelized cost of renewables, to demonstrate that competitiveness of coal varies significantly across different geographies. Countries like India where renewable projects have been highly competitive and there is an aging fleet of coal plants many of which are far away from mines, are already highly uncompetitive. On the other hand, countries like South Africa that have relatively inexpensive coal plants, but the average cost of renewable projects have not yet dropped sufficiently (as of 2020), will require special efforts to phase out coal completely beyond plants that have reached, or gone well past their technical life. Accelerated retirement of coal would require a new business model that allows repurposing some of these sites for alternative usage including generation from renewables, conversion of the incumbent generator into a synchronous condenser coupled with a fly wheel to provide reactive power and inertia; and installation of energy storage systems. As a repurposed coal plant for energy related activities can retain part of the workforce, it can also address some of the complex social issues. In order to develop a comprehensive repurposing program at a national level, the process needs to follow a least-cost planning methodology to identify prospective coal plant candidates for repurposing and then undertake a cost-benefit analysis of individual projects. We have demonstrated this methodology using a case study for Morocco.

INDEX TERMS Climate change, renewable power, coal plant repurposing, least-cost planning.

I. INTRODUCTION

A. CONTEXT

Global CO_2 emissions reached 33.4 billion/giga tonnes (bt or gt) in 2019 with significant contribution from the developing nations over the last two decades, reducing the contribution from US and Europe to approximately a third of total emissions. China had emissions in excess of 10 bt followed by India (2.6 bt). USA, in comparison, had 5.3 bt emissions in 2019 or half of that in China, albeit its cumulative emissions till 2019 of 410 bt is close to double that of China. Coal-fired power generation globally accounts for more than 10 bt of emissions and is the single largest source of emissions. The growth of coal-based generation capacity in the developing world has been very significant including China (1,000+ GW), India (200+ GW), South Africa (40+ GW). There are as many as six developing countries in the top ten coal-based power systems. Reducing emissions

The associate editor coordinating the review of this manuscript and approving it for publication was Zhiyi Li.

from power generation, especially coal-fired power generation, has been extensively discussed over at least past three decades. Yet, the global installed coal-fired capacity has doubled from 1,066 GW in 2000 [1] to 2,125 GW in 2020 despite the falling cost of wind, solar and battery storage, particularly over the past decade. As of May 2021, there is additional 180 GW coal capacity being constructed and another 320 GW in planning stage [2]. A large part of the new capacity is in the developing nations. The number of countries with coal capacity stands at 80 and there are still as many as 13 new countries that may be added to this list [1]. On the bright side, coal-based generation (as opposed to capacity) plateaued over the last five years and even decreased for the first time in 2020, albeit a serious contraction in demand due to COVID-19 contributed to it.

More importantly, retirement of the older fleet has accelerated and nearly 300 GW of coal capacity has shut down over the past five years, mostly in the United States, China, and Europe. There are also voluntary initiatives promoting coal phase out such as the *Powering Past Coal* initiative led by the UK and Canada [3], that promises to phase out coal from 19 countries. This however accounts for less than 5% of the installed 2.1 TW capacity. As the developed nations that account for more than 60% of the cumulative CO_2 emissions, have already started taking actions including phasing out coal, our endeavor here is to focus on some of the coal-heavy developing nations to explore the economics of coal and ways to accelerate the transition in these countries. There are analyses that suggest a large share – somewhere in the range of 65%-80$^+$% will need to be retired by 2030 to contain the global temperature increase to two degree Centigrade. There has been significant optimism that coal capacity will decrease as cleaner generation has reached grid parity *and* this is going to happen rapidly with 42% of the global capacity already making a loss back in 2018 [4]. Others have a more cautious view on grid parity and noted that parity will depend on system and country characteristics [5]. Given that the optimism on coal retirement has been out there for several years but at the same time growth in coal capacity has largely continued unabated over the last decade, there is clearly something amiss about the predictions that heralded a rapid end of coal.

It is also worth noting that there have been multiple policy initiatives not the least of which is a Nationally Determined Contributions (NDC) formulated under the Paris Agreement in 2015 that were submitted by 192 countries worldwide accounting for 96% of the global greenhouse gas emissions. However, a lack of transparency of the NDC targets limited their effectiveness including any discernible trend in reduction of coal capacity. There have been other policy drives like renewable energy targets that have been more effective in pushing fossil fuel out of the generation mix. Policies around energy efficiency initiatives, specific clean technology promotion including battery storage in recent years have also played a role, albeit to a much lesser extent compared to RE targets.

One of the factors contributing to coal plants not shutting down anywhere near as fast as was predicted is that existing coal plants that are 20 years or older have their capital investment largely depreciated and the cost of operating these plants is relatively low in many cases. In several countries that have substantial domestic coal resources, the cost of keeping coal generators online is particularly low (e.g., $10-30/MWh). At the same time, notwithstanding the low winning auction prices for solar/wind celebrated in the media, average solar/wind power purchase agreements (PPA) in many developing countries tend to be significantly higher than those record low prices [6]. There are in fact several factors that might explain the low auction prices [7] and there is routinely a difference found between auction and PPA prices (as well as levelized cost of electricity or LCOE) [6]. If the LCOE of solar/wind is not below the short-run marginal cost (SRMC) of operating an existing plant, the coal plant could economically operate, as long as the gap between LCOE and SRMC is high enough to cover the fixed operation and maintenance (FOM) costs. Our first focus in this paper is to undertake a rigorous comparison of LCOE of renewable projects based on IRENA's 2019 data and realistic cost data for coal plants in a number of developing countries deployed as part of power system planning studies in these countries. As a simple first step, it can provide useful insights into the share of coal fleet and specific power plants that have already become (as of 2020) uncompetitive to renewables. It is important to develop a clear perspective on where coal sits relative to renewable energy so that policymakers can make informed decisions with respect to decarbonization.

Repurposing old coal plants/mines [8] can form a part of such policy decisions because they can support renewable/storage development at the existing coal plant site (e.g., solar PV on ash ponds, battery storage or BESS near the substation, etc) as well as re-use some of the assets (e.g., substation and connection assets, generator, etc). A repurposed coal plant site can accommodate some renewable (**RE**) generation, albeit it may replenish only a small share of the incumbent coal plant generation. More importantly, the site can become a ''flexibility'' (**FLEX**) center to replenish bulk of the reactive power by converting an existing generator into a synchronous condenser (SYNCON) as well as frequency control ancillary service (e.g., through flywheel attached to SYNCON and from a BESS) and inertia (through flywheel). As many power systems make a transition to a high level of RE penetration, such **RE+FLEX** centers on repurposed coal plant sites could be an attractive proposition. This can be a critical part of programs like Accelerating Coal Transition (ACT) [8] because repurposing can make a good business case for plants to shut down well before they complete their technical life [9]. The new project can also re-employ part of the workforce and continue an energy business on the site that can partially address some of the difficult social issues that often prolong the life of coal plants [10].

TABLE 1. Coal-dominated developing countries covered in the analysis.

Country	System Size (MW)	Coal (MW) and %*	Electricity consumption (TWh)**	Coal consumption (mt)***	GDP (B$)****	Population (M)****
India	350,149	226,500 (65%)	1,309	986	2,869	1,366
Turkey	80,353	16,979 (22%)	272	134	761	83
South Africa	56,121	41,674 (75%)	229	196	351	59
Ukraine	52,047	24,663 (48%)	130	51	154	44
Vietnam	41,862	14,491 (35%)	227	74	262	96
Pakistan	34,178	3,045 (9%)	126	21	278	217
Kazakhstan	20,179	12,216 (61%)	101	97	182	19
Uzbekistan	14,455	2,650 (19%)	58	6	58	34
Bulgaria	11,672	4,614 (40%)	35	34	69	7
Bosnia-Herzegovina	4,211	2,050 (49%)	12	9	20	3
Morocco	8,278	2,663 (32%)	35	8	120	36
TOTAL	**673,505**	**351,545 (52%)**	2,534	1,617	5,124	1,965
World	6,303,594	2,007,214 (32%)	2,4739	8,622	87,799	7,674
Global share of selected countries (%)	**11%**	**18%**	**10%**	**19%**	**6%**	**26%**

Source: World Electric Power Plants Database, Platts, 2018; International Energy Agency (IEA); Energy Information Administration (EIA); World Bank

* Share of coal-based capacity ** 2018/19 data from IEA ***2018 data from EIA ****2019 data from World Bank

Identification of coal projects that have become uneconomic is a key first step that can start with a simple LCOE analysis. However, this will need a more extensive planning study to assess the requirements for generation (and ancillary services) from a system perspective, namely: can these coal plants be safely retired and repurposed for the system to meet demand and continue to operate in a secure way? Such a planning analysis may identify *economic retirement* opportunities ahead of reaching the technical plant life, especially as RE costs drop and the O&M costs of an old plant typically rise rapidly towards the end of its life. Once a set of plants is identified to be potential candidates, a cost-benefit analysis for each individual plant will need to be conducted to ascertain if repurposing as a RE+FLEX facility can bring sufficient benefits to warrant the investment and mitigate the coal decommissioning impacts.

B. SCOPE OF THIS PAPER

In this paper, we present a set of 11 developing country case studies where coal plays a significant role (Table 1). First, we present a set of statistics to compare the relative merit or coal vs RE across 10 of these countries with a large fleet of older coal plants; Second, we provide a more detailed examination of a few key countries where coal retirement is a genuine prospect; Third, we discuss the case for Morocco which is a smaller system with a relatively newer coal power plant fleet. Since Morocco has taken a strategic position to integrate large-scale RE, we show how planning studies should be conducted to identify coal plants that can be retired ahead of their economic life for which repurposing benefits outweigh costs.

Countries covered in this study are **India, Turkey, South Africa, Ukraine, Vietnam, Pakistan, Kazakhstan, Uzbekistan, Bulgaria, Bosnia-Herzegovina, and Morocco**. All of these countries rely on coal for power generation for a significant share of its total generation, but also possess significant renewable resource potential. These 11 countries account for 11% of the global generating capacity but 17% of the global coal power capacity. These countries are home to 26% of the global population but represent only 6% of the global GDP (Table 1) and electricity consumption growth will continue to be higher than their developed counterparts. Economics of coal and renewable assumes special significance when we consider the trade-off between the need for growth to be fueled by low-cost electricity and a disproportionate level of new investments needed in clean technologies. This work is important to establish the relative economics of coal and renewable which vary significantly across geographies – an issue that is surprisingly arcane, but quite fundamental to formulate carbon reduction strategies. We also introduce a methodology to evaluate coal plant repurposing embedded into sophisticated least-cost planning models. Repurposing as we discuss can also be an important part of a strategy to accelerate retirement of coal units *and* support development of renewables in a financially sustainable way.

II. KEY LITERATURE ON COAL VS RENEWABLES

Coal based generation has been under scrutiny since the nineties, but serious intent and action to retire coal generating assets been visible only in a select number of countries over the last decade. Inadequate systematic and detailed evidence of competitiveness of existing coal plants vis-à-vis renewable energy has contributed to significant confusion over the share of coal generation that should be closed down purely on economic grounds. Some predicted that up to 42% of global coal power plants were running at a loss in 2018, which will grow to 96% by 2030 [4]. More than 50% of renewable capacity added in 2019 is considered to cost less than the cheapest new coal plants [6], and 54% of coal-fired power generation in the EU is cash-flow negative after debt servicing, with the US trailing slightly behind at 48% [4]. Other more conservative sources estimate a minimum of 20% of coal power generation (or 400 GW) was uncompetitive in 2018 relative to solar and wind, which will increase to 50% (or 1000 GW) by 2030 [8]. In India, roughly 71 GW of privately-owned coal-fired capacity is expected to soon face potential financial distress [11]. The phaseout of coal power has been claimed for several years in these studies [4], [6], [8], [11], yet a lack of consistency in data and objective analysis makes it difficult to assess when this is likely to occur. Although the genesis of this finding has been in low winning auction prices for wind followed by solar over the past decade, we discuss below several important nuances that would render a direct comparison between auction prices and cost of coal generation difficult.

The decline in solar and wind technology costs and their 'grid parity' is the key reason why many new coal plants around the world are struggling and face delay or are being abandoned. The LCOE of newly constructed coal plants is undercut by the LCOE of new onshore wind, utility-scale solar, and combined-cycle gas turbine generation [11]. Low auction prices and power purchase agreements for solar in UAE (Abu Dhabi and Dubai), Chile, Ethiopia, Mexico, Peru and Saudi Arabia, dropping as low as USD 0.03/kWh [6], reinforced the view that unsubsidized solar will soon overtake fossil fuel-based generation. The average price of auctions and power purchase agreements of solar PV projects that will be commissioned in 2021 in India is currently at USD 0.039/kWh according to IRENA [6].

Winning auction prices, however, represent only a fraction of the total renewable capacity to be commissioned and are heavily influenced by country's resource potential, financing condition, and auction design [12]. The lowest winning auction price of solar/wind in one country/region may not be representative of conditions elsewhere, or representative of the full spectrum of projects in the same country/region. Replicating such promising results in other countries and regions can be challenging, particularly in some developing countries where RE projects continue to be expensive. A close examination of the rapid price decline in UAE and Saudi Arabia points to several factors depressing the price, such as forward-bidding on expected future decline in hardware prices, low operation and maintenance labor costs in the Gulf region, higher utilization via scaling production, extension of PPAs to 25 years as opposed to typical 20 years, favorable financial terms and low or no land costs [7].

LCOE, on the other hand, represents the minimum price that offsets all direct costs associated with generation, including capital expenditures, operational expenditures, and debt service costs, and has generally been higher than winning auction prices. Distinct from winning auction price, LCOE is considered to be a more appropriate metric for economic analysis, as it fully and transparently captures economic costs over the lifetime of generating technology. In the past decade, LCOEs for RE have indeed dropped massively and are poised for further reduction. The global weighted-average LCOE of utility-scale solar PV declined by 82% between 2010 and 2019, followed by concentrated solar power (47%), onshore wind (39%) and offshore wind (29%) [6]. In general, LCOE reflects the substantial lifetime cost of renewable generation better than auction prices.

A comparison between investing in renewable energy and operating coal power based on LCOE of renewable energy is also problematic. This is because the latter rarely, if ever, incorporates indirect costs associated with grid integration. The costs associated with renewable supply intermittency, the higher transmission and transportation costs from geographic locations favorable for renewables to urban areas, and expenses associated with prematurely closed generations [13] increase the societal costs of solar and wind technologies that ultimately need to be borne by customers. Due to such indirect costs, US states that adopted Renewable Portfolio Standards (RPS) incurred 11% higher electricity prices seven years after passage of the policy, compared to states that had not adopted RPS [13].

Retirement of a coal plant, even those that are well below LCOE of solar/wind, has its own challenges. Coal plant decommissioning is expensive and is further constrained by hidden social and political costs. The investment requirement for technical decommissioning of a coal-fired facility can be \$100-200/kW or up to \$200 million for a 1,000 MW coal plant [8]. A basic social program that ensures 'Just Transition' for workers is estimated to add 20% to the decommissioning costs of a project [10].

Once we consider all of the hidden costs that need to be added to the observed low auction prices for solar and the full decommissioning costs of a coal plants – it is not hard to see why coal plants are not shutting down as rapidly as has been promulgated in some of the forums. It often requires a political commitment by countries who can afford to make the transition going beyond economics. While coal-fired generation has decreased in most high-income countries, most notably in the EU and the USA (−19% and −14% in 2019 respectively) [14], coal still reigns in many parts of Asia. Across ASEAN countries, coal-fired generation grew by 14% in 2019 and the region is on its path to become the third-largest coal consuming region by 2025, followed by the US and the European Union [14]. According to a study published in 2020, 90% of the new coal-fired capacity that was built in the first half of 2020 was commissioned in China as China quickly recovered from COVID-19 pandemic with new coal proposals and permits [15]. Coal consumption is expected to increase in the world's most populous country by 2.6% in 2021 [14].

As the discussion so far alludes to, one has to take a sobering view on the speed at which coal plants are likely to be decommissioned. This is not to suggest that the *Great Transition* [16] will not happen, nor to deny a substantial cost advantages of renewables over coal that will emerge [17]. However, we will need to understand far better the economics of coal relative to renewables in different parts of the world and also develop transition trajectories and business models for shutting down coal plants. There is a growing volume on this topic [18]–[42] that we have discussed over the remainder of this paper including the case studies that are presented in subsequent sections.

Coal plant repurposing [8], [9], [18] is a new business model that requires more attention. It is not a ‘‘new’’ technology *per se* as it is more about packaging technologies like converting existing generators into synchronous condensers [19] and using the site for solar PV, BESS, thermal storage, biomass etc. As a recent analysis [20] shows a repurposing project (in India) can pay as much as five times of the cost of decommissioning. This is particularly good news as the significant cost of decommissioning in the US [21] has demonstrated, such costs can be a significant barrier to exit. That said, some countries have also managed the retirement of coal generators well. Canada exploited the existing infrastructure and turned the decommissioned coal plant site into a 44-MW solar power station in Nanticoke, Ontario [22]. Through building solar park projects in coal mining regions, Germany created employment for 80,000 people in Brandenburg, Saxony, and North Rhine-Westphalia, outperforming the employment from coal power industry in these regions [23], [24]. Such models can build optimism towards a faster decline of coal in places like Chile [25] and South Africa [26] where the concept of repurposing is gaining momentum. Wider technology choices are also available for coal repurposing projects such as concentrated solar power (CSP) and heat exchangers, conversion of coal plants to run on biomass, conversion of adjoining coal mines to pumped storage hydro, usage of the site to develop wind projects, etc.

III. ANALYSIS OF COST OF COAL VS RENEWABLES

The first part of our analysis covers an objective comparison of LCOE of renewables with the short-run marginal cost of older coal plants in ten developing nations. This is a stringent but practical test of competitiveness of renewables over coal.

In most power systems around the globe, fossil fuels such as coal have taken a dominant position in electricity generation for decades, and the commercial deployment of large-scale renewable energy projects was not rolled out until the 2010s. As of 2018, 2007 GW of coal plants were operating in the world, 17% of which built in the 1950s∼1970s and have essentially reached, if not gone well past, the end of the design life, given an average age of these plants of 50∼60 years [27]. China, United States, and India are the top three countries in terms of capacity in operating coal plants, contributing to over 70% of the global coal capacity (Figure 1).

A. METHODOLOGY

To explore the economic merits of RE displacing coal ‘‘at the margin’’, this study compares the generation cost of coal plants with that of renewable energy technologies at the country level. With the capital investment of extant coal plants considered as sunk costs, the relevant generation cost for a coal plant is limited to its short-run marginal cost (SRMC) including levelized fixed operation and maintenance costs. In contrast, replacement with renewable energy will require

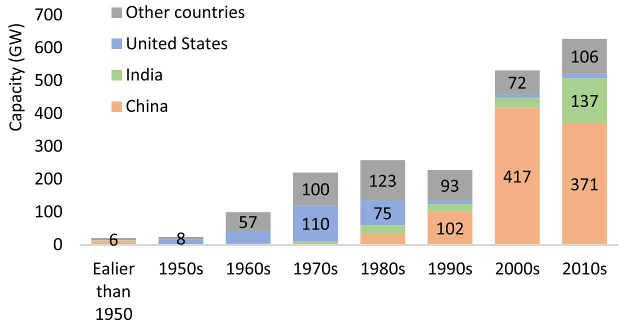


FIGURE 1. Operating coal capacity by commissioning year. Source: World electric power plants database, Platts, 2018.

the construction of additional capacity. Therefore, the cost of renewable electricity is assessed using long-run marginal cost (LRMC). We have used the LCOE as a proxy for LRMC. LCOE is a project-centric metric as opposed to LRMC of supply which is based on the premise of an optimized system to meet incremental demand [28]. We are effectively making an implicit assumption that solar (or wind whichever is cheaper in a system, or more likely a mix of the two) will be the dominant form of supply in the future system.

In other words, the analysis is based on the comparison between SRMC of operating coal capacity and LRMC/LCOE of renewable energy, to see if building new RE capacity to produce a marginal kWh would displace a marginal kWh of coal. This is a more stringent test for renewables as the fixed capital cost of existing coal assets are effectively treated as sunk. It differs from most of the comparisons in the literature that compare LCOE of coal against renewables. We argue that this test, notwithstanding its stringent nature, is a better reflection of reality. A coal plant will continue to be in service as base load as long as it can recover its SRMC given the significant cost of exit (decommissioning costs) and the fact that many of these older coal plants have depreciated fully. A comparison of LCOE of renewables with SRMC of coal can be helpful to identify countries with uneconomic coal capacity that can be shut down to accelerate energy transition, as well as to identify the old coal plants suitable for repurposing.

1) DEFINITION OF COSTS

SRMC of coal generation consists of the fixed operation and maintenance cost (FOM), variable operation and maintenance cost (VOM) proportional to the generation activities, as well as fuel cost. Although the conventional definition of SRMC does not include FOM, a significant part of these ‘fixed’ costs relate to maintaining the dispatch status of coal plants, especially the older coal fleet and as such we have included a levelized component of FOM (for instance, regular maintenance and inspection costs) in our definition that holds significant implications for its relative economics as these plants lose dispatch over the years. SRMC (in \$/MWh) of coal electricity was calculated at the plant level in the study, the formula of which is written below.

$$SRMC = \frac{FOM}{CF * 8760\ hrs} + Fuel\ Cost \times HR + VOM$$

The units of *FOM, Fuel Cost, HR* and *VOM* are respectively \$/MW/year, \$/MMBtu, MMBtu/MWh, and \$/MWh. *CF* stands for the capacity factor of the plants, a ratio of actual annual generation over maximum generation to evaluate the plant utilization. *HR* is the Heat Rate.

LCOE of renewable energy covers capital costs, FOM, VOM, and fuel cost:

$$LCOE = \frac{CC \times CRF + FOM}{CF \times 8760\ hrs} + Fuel\ Cost \times HR + VOM$$

CC is the capital cost to build the solar/wind farm overnight (\$/MW). *CRF*, Capital Recovery Factor, is a rate of repayment that translates overnight capital costs (\$/MW) into annualized costs (\$/MW/year), determined by discount rate and lifetime of the investment. We have used the LCOE of wind and solar PV at the country level from IRENA estimates [6] as a proxy for LRMC.

2) ASSUMPTIONS

Several assumptions were necessary due to data limitations and also to make results comparable across the country case studies: (a) baseline capacity factor is assumed to be 60% for all existing coal plants to maintain comparability; (b) the commissioning year of the plant is determined by the oldest operating unit; (c) additional transmission costs to connect renewable energy and grid balancing costs are ignored that may in fact be quite significant at higher level of renewable penetration [29] – this assumption in a way offsets for the fact that capital costs for existing coal is treated as sunk; (d) no carbon tax is imposed on the generation; (e) all costs are in USD (2020 value).

3) SENSITIVITY ANALYSIS

Sensitivity analysis was also conducted to explore how the relative economics of the older fleet of coal plants would change as maintenance costs increase or as plant availability and efficiency of these plants and hence utilization, drop over the years. On the other hand, renewable energy LCOE is projected to drop sharply. Therefore, relative economics of coal would deteriorate considerably. Important factors to consider in the sensitivity analysis include decreasing renewable energy cost, declining utilization of coal plants, and increasing FOM of coal plants. These factors have been chosen to reflect the policy initiatives that most countries have adopted. As we have alluded to in the introductory section, NDCs per se have been ineffectual due to a lack of transparency, coherence, practical steps to implement and also a lack of sufficient degree of ambition [30]. That said, promotion of renewable energy either as a plank in the NDC in some cases, or as a standalone renewable energy target in significantly more cases, has been a major driver. This has directly and through indirect paths too, led to a reduction in RE technology costs, especially for solar and wind, rapid adoption of these technologies, and these in turn have impacted on utilization of coal in some countries. A drop in utilization of coal also translates into a higher level of cycling, hence more wear and tear, and overall a significant rise in the levelized fixed O&M costs for coal plants.

B. LIMITATIONS OF THE ANALYSIS

The cost comparison analysis makes simplifying assumptions to match available data and keep it transparent, namely:

a. It ignored the utilization difference of coal plants across age groups for all countries, conservatively estimating the SRMC of some old plants with low utilization, while overestimating the SRMC of highly utilized plants. We overcome this limitation to some extent using the sensitivities conducted varying the utilization rate of coal plants. We also recognize that a proper assessment at a system level would ultimately require a planning study to identify the prioritized plants for retirement as we discuss in the next section;
b. We have relied on an average estimate of LCOE of renewables at the country/region level instead of the LCOE of individual projects; and
c. It did not cover the extra costs to integrate renewable electricity from the remote wind/solar farms, the carbon costs associated with coal generation, or systems balancing costs.

C. DATA SOURCES AND ISSUES

Data for coal plants, such as capacity, status, date of commissioning, and fuel type, was extracted from the World Electric Power Plants Database of Platts [27]. Cost data of coal plants, such as FOM, VOM, heat rate, and fuel costs, was extracted from the country-level or regional World Bank - Electricity Planning Model (EPM) database, a least-cost power modeling platform developed by the World Bank to simulate economic dispatch at the plant level [31]. This database is collected from the power system planning reports, or directly from the utilities in the selected countries. LCOE projections of wind and solar were collected from IRENA [6].

As power plant data needed to be merged from Platts and EPM, one challenge we encountered is that individual plant names or even capacity did not always match across these databases. We had to therefore cross-check details through Platts, EPM, as well as WRI[1] datasets for plant name, capacity size, and commissioning year. We also needed to update the status of power plants as plants under construction may have been commissioned and others that have been retired since the databases were last updated. Fuel costs used in EPM represent economic costs that are varied from countries, zones, and coal types – they do not represent the plant specific costs or contract prices.

Our economic analysis using Platts and EPM data focuses on the first ten countries that have significant older coal

[1] Global Power Plant Database, WRI.

capacity noted in Table 1. These countries represented ~349 GW or 17% of the global operating coal capacity in 2018. India is the largest coal country, accounting for 61% of the operating coal capacity. South Africa, Turkey, and Ukraine also occupy a significant share of capacity (Figure 2).

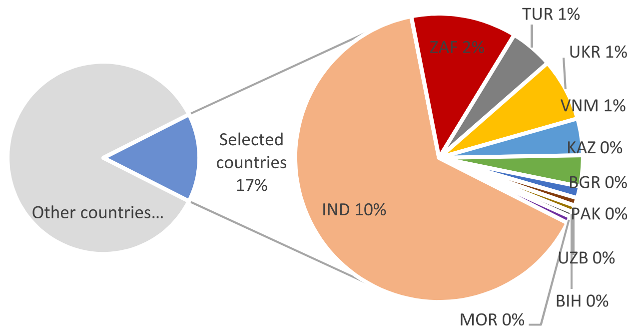


FIGURE 2. **Operating coal capacity in selected countries (2020). Note: IND-India, ZAF-South Africa, TUR-Turkey, VNM-Vietnam, UKR-Ukraine, KAZ-Kazakhstan, BGR-Bulgaria, PAK-Pakistan, BIH-Bosnia and Herzegovina, UZB-Uzbekistan.**

Morocco, with its relatively new fleet of coal plants, represents a special case where there is only one 280 MW unit (or 10% of coal capacity) currently in operation that is relatively old (34 years) compared to the rest of the fleet (less than 20-years old units). Morocco is, however, included in our analysis to demonstrate how a country with significant potential for renewables can accelerate the retirement of its coal capacity and in particular aim to economically shut down the 280 MW unit and repurpose the site. We present this analysis in section V.

IV. RESULTS: COAL VS RENEWABLES ANALYSIS

A. CROSS-COUNTRY ANALYSIS

1) SRMC OF COAL GENERATION BY AGE GROUP

For the purpose of the analysis, three age groups were considered: less than 10 years (new); 10~30 years and over 30 years (old). Of the examined countries, 42% of coal plants are old, especially those in India, South Africa, Ukraine and Kazakhstan. 36% are new with India accounting for 75% of the new units, though Vietnam and Pakistan also have relatively young but small fleets. Countries that have a higher proportion of old coal capacity are South Africa, Ukraine, Kazakhstan, Bulgaria, Bosnia and Herzegovina, and Uzbekistan.

With the default assumptions, the average SRMC of each age group mostly falls in between \$30~\$40/MWh, with very few extremes. Older plants (>30 years) generally have higher SRMC (\$41~\$59/MWh) due to higher heat rates, which can be observed for Turkey and Vietnam. However, this cannot be generalized as fuel costs account for vast majority of SRMC and fuel prices vary significantly across geographies. Older coal plants in India tell quite a different story owing to their low fuel costs. In India, the older plants are more likely to use cheaper local coal than some new plants which are fueled by imported coals or are located far away from the mines. The abundance of coal reserves in Kazakhstan and South Africa can also bring down the SRMC to \$25/MWh and \$34/MWh, respectively (Figure 3).

2) COMPETITIVENESS OF COAL GENERATION

Coal generation can gradually lose cost advantages as renewable electricity costs fall. Figure 4 plots the SRMC range of coal generation of each country (in boxes) to compare with the LCOE of renewable generation (in dots). In most countries, the LCOE of solar PV, and to a lesser extent wind, is higher than the SRMC of coal. There are few exceptions, such as India and Turkey, showing overlaps between the LCOE of renewable energy and the SRMC range of coal plants (Figure 4). This implies installing *new* renewable energy capacity can be more economic than operating an *existing* coal unit.

Among all selected countries, India has the lowest average LCOE to produce renewable power, namely, \$49/MWh for wind and \$45/MWh for solar PV [6]. With SRMC of coal power ranging from \$17/MWh to \$51/MWh, India has already showed some uneconomic coal capacity in the country, as operating costs are becoming higher than the average LCOE of renewable electricity.

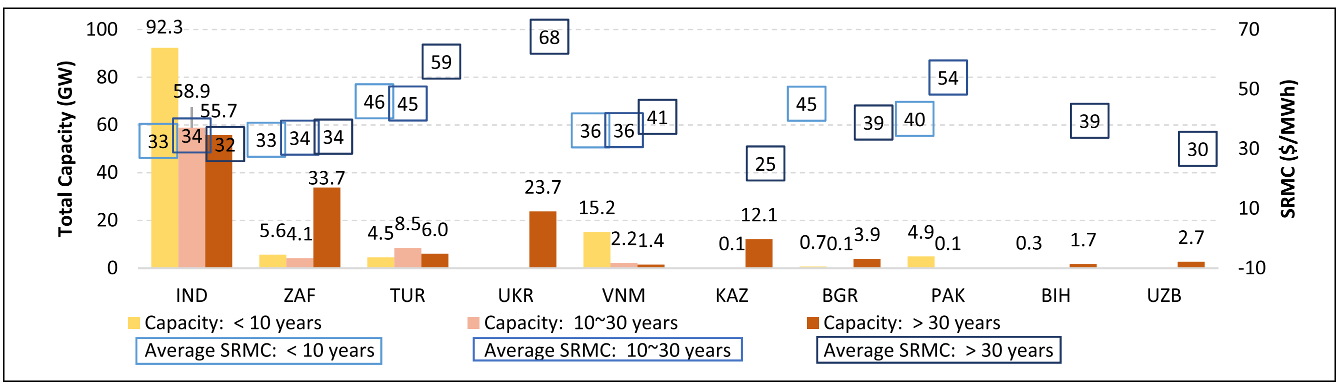
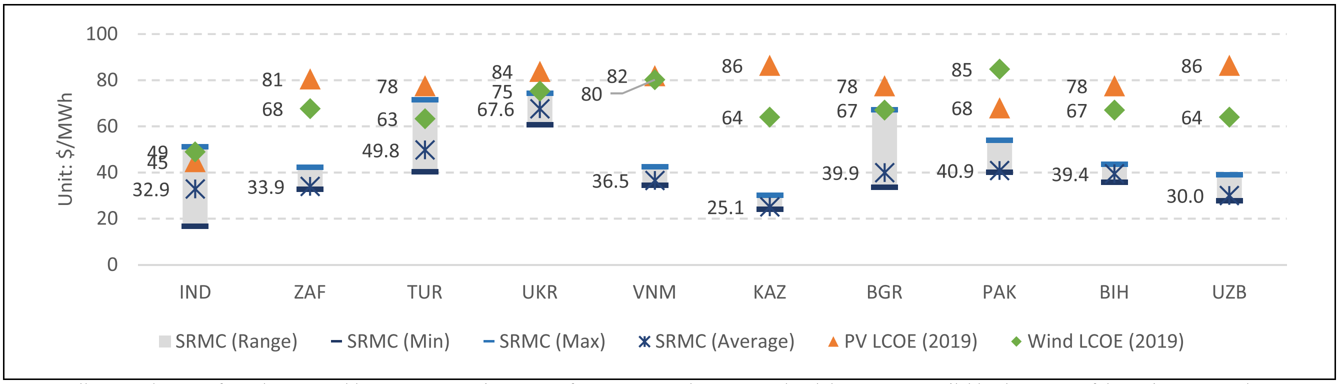


FIGURE 3. **Operating coal capacity and short-run marginal cost (SRMC) by age group. IND-India, ZAF-South Africa, TUR-Turkey, VNM-Vietnam, UKR-Ukraine, KAZ-Kazakhstan, BGR-Bulgaria, PAK-Pakistan, BIH-Bosnia and Herzegovina, UZB-Uzbekistan.**



Note: All LCOE data was from the Renewable Power Generation Costs of IRENA [6]. When country-level data was not available, the LCOE of the region or a nearby country was used for the countries, such as Bulgaria, Pakistan, BIH, and Uzbekistan.

FIGURE 4. Cost competitiveness of existing coal capacity versus local renewable resources. IND-India, ZAF-South Africa, TUR-Turkey, VNM-Vietnam, UKR-Ukraine, KAZ-Kazakhstan, BGR-Bulgaria, PAK-Pakistan, BIH-Bosnia and Herzegovina, UZB-Uzbekistan.

In Turkey and Ukraine, though the LCOE of renewable energy was relatively high in 2019/20 ($63~$84/MWh), but the SRMC of coal generation is even higher in many cases because of the aging nature of these fleets. The SRMC of coal ranges from $40/MWh to $72/MWh in Turkey, and from $61/MWh to $74/MWh in Ukraine (Figure 4). Using 2019/20 data even with relatively high cost of renewable projects, it was economically feasible to repurpose some coal plants that are more costly than wind or solar in both countries. As the cost of renewable projects in these two countries poised to drop sharply, retirement of coal is a distinct possibility in the near future.

The remaining countries have an average LCOE of renewable energy ranging from $68/MWh to $86/MWh, much higher than the coal generation costs, especially for the countries with cheap coal resources. South Africa is one of the most representative countries, where coal generation leads in the power dispatch with an estimated SRMC of $33~$42/MWh (Figure 4). Other countries, such as Vietnam, Kazakhstan, and Pakistan, also follow very similar patterns as South Africa. Although South Africa has already seen 5.4 GW of its retired coal capacity that are under active consideration for being repurposed with solar PV [32] and has extensive plans to retire up to 10.5 GW of capacity over this decade [33], *early* retirement and repurposing of the rest of the fleet will need a close economic scrutiny in the short term given relatively low SRMC of coal in the country. As solar/wind and battery storage cost drop over the years and the remaining fleet loses efficiency, the relative competitiveness of coal will erode in the long term, as discussed further below.

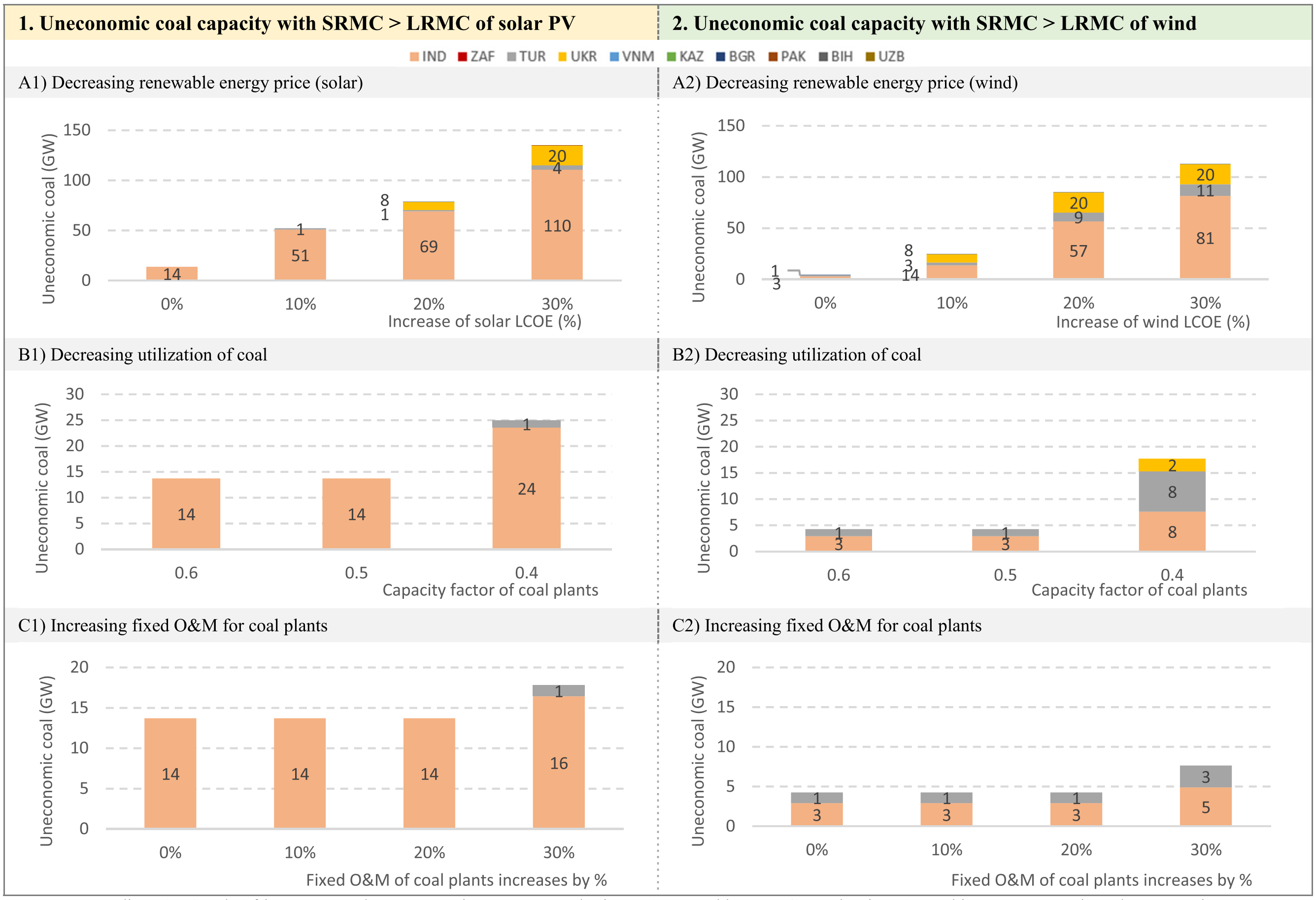
3) SENSITIVITY ANALYSIS

The scale and scope of uneconomic coal capacity can be affected by multiple factors, such as learning curve of renewable energy cost and utilization of coal plants. Sensitivity analysis is helpful to quantify the impacts from some input variables to simulate their trends in the future, including aggressively downward trend of renewable energy cost, decreasing utilization of coal capacity, and rising FOM costs as more plants age. Policy initiatives *inter alia* RE targets that provided the scale up, coupled with technology breakthrough have already lowered solar and wind capital costs significantly. Projections by IRENA among others indicate average annual capital cost reduction from 1%-3% pa or approximately 10%-30% over this decade. Coal plant fleetwide average utilization in countries like India has already dropped significantly from 75% in 2011 down to 50% in 2020 with the advent of cheaper renewables being one of the key drivers. Major RE policy initiatives such as the 450 GW target by 2030 in India would push this utilization further down to 40% [34]. This drop in turn would increase the levelized FOM charges faced by these plants. We have adopted these RE cost and coal plant utilization reduction parameters uniformly across all countries for comparability. The following sections discuss how these results are sensitive to changes in key assumptions driven by the RE policy initiatives:

a: DECREASING RENEWABLE ENERGY COST

By assuming a 10%, 20%, and 30% drop in the capital cost of local PV and wind power from present level, the analysis measured the influence on coal economics from a steeper learning curve of renewable electricity cost in the near term (Figure 5, A1&A2). Given current cost level (0% decrease), India and Turkey have at most 14 GW and 1 GW coal less economic than solar PV and wind, respectively.

If costs of solar generation fall by 30% from the level in 2019, the amount of uneconomic coal capacity, with SRMC higher than solar costs, will reach as high as 135 GW in selected countries, nearly ten-fold of the amount in the base case (Figure 5, A1). If LCOE of wind energy reduces by 30%, the scale of uneconomic coal capacity, with SRMC above wind costs, will increase massively to 113 GW from 4 GW in the base case (Figure 5, A2).



Note: IND-India, ZAF-South Africa, TUR-Turkey, VNM-Vietnam, UKR-Ukraine, KAZ-Kazakhstan, BGR-Bulgaria, PAK-Pakistan, BIH-Bosnia and Herzegovina, UZB-Uzbekistan

FIGURE 5. Sensitivity analysis of unprofitable coal capacity across countries.

Under most circumstances, uneconomic coal capacity will be concentrated in India, Turkey, and Ukraine, with India contributing to at least half of this capacity. Specifically, a drop by 30% in renewable electricity cost from that in 2019 will mean the *average* LCOE of solar PV or wind falls in \$31∼\$34/MWh range in India and \$40∼\$66/MWh in other countries. As renewable cost decreases in the future, both solar and wind can be more competitive than a large proportion of coal in India, while wind has a greater advantage in Turkey and Ukraine. Hence, coal transition can be significantly accelerated in India, Turkey, and Ukraine, especially when costs of renewable generation lower by 30% from the current level.

b: DECREASING UTILIZATION OF COAL CAPACITY

When the capacity factor of all coal plants is reduced to 50% from the base level (60%), uneconomic coal capacity will increase from 14 GW to 25GW across the selected countries, mostly in India (Figure 5, B1). A further decrease of the capacity factor to 40% pushes the SRMC of an additional 10 GW coal capacity in Turkey and Ukraine beyond the LCOE for wind (Figure 5, B2).

c: INCREASING FOM OF COAL PLANTS

Aging coal plants may require higher fixed operation and maintenance expenditures to keep them in working order, which pushes up their SRMC. However, given the relatively small share of FOM in the SRMC calculations, we find that even a 30% increase in the FOM only increases uneconomic coal capacity slightly by 2∼3 GW from the base case, primarily in India and Turkey (Figure 5, C1&C2).

In general, our analysis suggests that a reduction in renewable energy cost may be a bigger driver of global coal transition than costs related to the age and inefficiency of the coal power plants. On average, the difference between the LCOE for RE and the SRMC for coal is the smallest in India, Turkey, and Ukraine making the economic viability of coal plant shutdown in these countries worthy of a deeper investigation. In other countries, such as South Africa, where LCOE of renewable electricity in 2019/20 [6] is almost twice the SRMC of existing coal, accelerating the coal transition, beyond the planned retirement, will rest more heavily on steeply declining costs of renewable energy. It is possible for these countries to achieve such a decline, especially for South Africa, which is naturally endowed with high-quality solar

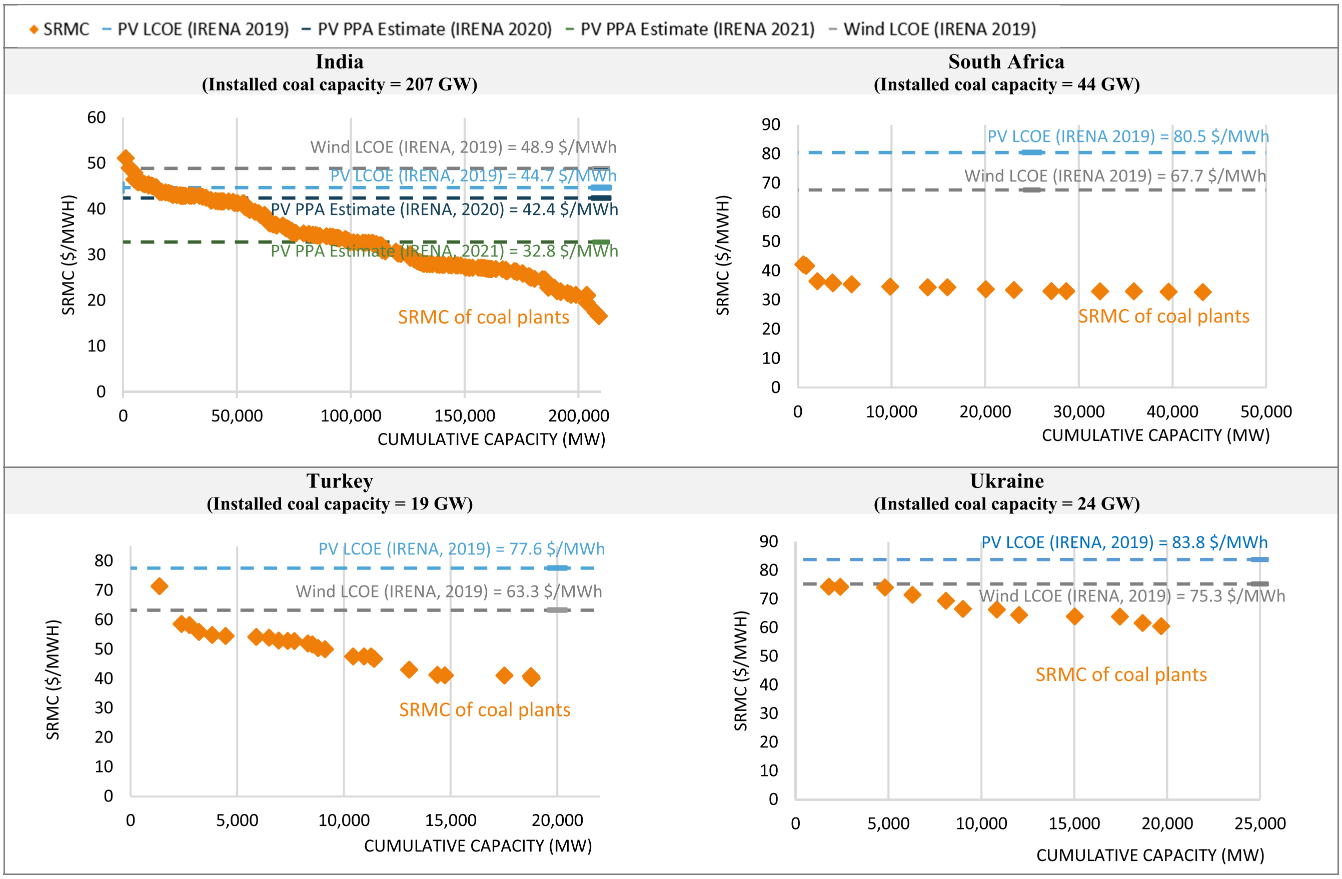


FIGURE 6. **Inverse supply curve of coal capacity (India, South Africa, Turkey, and Ukraine).**

and wind resources. It should be noted that in 2019/20, solar costs in South Africa are 50% higher than in Argentina, 70% more than in Brazil, and about twice the costs in India and China [6], suggesting ample room for improvement.

B. COUNTRY SPECIFIC RESULTS

We have next focused on the four larger systems of India, South Africa, Turkey, and Ukraine and understand the economic retirement opportunity of coal in these systems.

1) COMPARATIVE COSTS OF COAL AND RE

To identify the uneconomic coal capacity, we ranked coal plants in a reverse order of merit and considered the LCOE of solar/wind as the cost ceiling for economic plants in each country. Specifically, in Figure 6, SRMC in the order from the highest to the lowest can be regarded as the supply curve of uneconomic coal, while the LCOE of renewable electricity is represented by a horizontal line to determine the highest possible SRMC for economic coal plants.

a: INDIA

Though a coal-dominated country, India is leaping ahead in renewable energy development with the third fastest capacity volume additions around the globe in recent years [35]. Coal remains of course by far the largest generation resource in India, with an installed capacity of about 207 GW and contributing to over 60% in the domestic capacity mix. Meanwhile, economies of scale in the manufacturing and installation of utility-scale solar and wind projects have pushed down the cost of renewable energy.

With the average LCOE of wind ($49/MWh) and PV ($45/MWh) in 2019 as benchmarks, the country has around 14 GW coal plants already unprofitable, that is, 6% of the operating coal capacity with an SRMC higher than LCOE of PV (Figure 6). At a weighted average SRMC of $46.4/MWh for this 14 GW coal, it is around $4/MWh higher than the LCOE of PV in 2020. This translates into a *negative* cost of carbon reduction of (-)$4.46/t. The cost of CO_2 reduction of course turns positive when we look at the cheaper end of coal plants up to $27.8/t for the cheapest coal plant but on average below $10/tCO_2e across the entire fleet. Furthermore, if compared with the solar power purchase agreement (PPA) pricing estimates, $42/MWh in 2020 and $33/MWh in 2021, more coal plants will be rendered uncompetitive increasing the share to 16% and 43%, respectively, of the existing coal capacity (Figure 6).

Around 30% of the coal capacity being operated in India has an SRMC falling in the range of $30~$40/MWh.

If LCOE of renewable generation drops to about \$30/MWh, over half of the existing coal plants, or more than 110 GW, will be no longer economic in power generation, especially the ones fueled by expensive imported coals. Two thirds of these plants were built after 2005 and are in fact far away from the planned retirement year, such as Bellary Thermal Power Station with an estimated SRMC of \$49/MWh, due to cost of coal transportation. Therefore, as costs of renewable energy are further reduced in the next few years, there is plenty of potentials for India to repurpose a greater number of existing coal plants. This conclusion is also supported by the recent IEEFA analysis [20].

It should be noted that the choice between coal and renewables in any location is far more complex than a simple comparison of SRMC of coal and LCOE. The situation in India underlines these complexities. The cost of integrating renewables that we have alluded to before, requires attention by system planners. Even at a relatively low 9.13% penetration in terms of generation mix in 2019/20, it was estimated (in July,2020) that the cost of integrating renewable is around \$15/MWh (Rs., 1,110/MWh) [36] which considers the additional transmission and balancing costs, but not storage costs. This cost is expected to go up as the penetration of variable renewable increases over the years. On the other hand, due to the nature of the legacy generation contracts, there is a ''fixed cost'' component for coal that is akin to capital cost and can be in the range of \$10-26/MWh. From the perspective of a buyer (distribution company in India), the ''capital cost'' is therefore not sunk. It has been argued that shutting down 54 coal plants that are older than 20 years would save the distribution companies a massive \$7.2 billion (Rs 530 billion) [37]. However, there are other views e.g., Tongia [38] that aptly note that a more holistic comparison of the options needs to be made to account for integration including storage costs that might make a case for a combination of renewable and coal to be economic. The debate around coal in India [36] also noted a need for substantial reform to tariff paid to coal generators that often include a significant ''fixed cost'' payment that would allow coal generators to continue to be in existence even if its utilization drops.

b: SOUTH AFRICA

Despite high-quality renewable resources, the renewable generation for South Africa according to IRENA [6] data is still costly, with an average LCOE of wind and solar between \$68/MWh and \$81/MWh. The low price of local coal resources makes thermal coal electricity more affordable for the country, with a relatively low SRMC falling somewhere between \$33/MWh and \$43/MWh, almost half of the current wind or solar costs. Hence, in terms of the existing price gap, coal plants will still stay prioritized in the power dispatch because of lower costs (Figure 6).

As of 2020, South Africa has 44 GW coal capacity in operation, accounting for three quarters of the installed generation capacity in the country. About 18 GW of existing coal capacity was built before 1980 and is gradually approaching the end of technical life (50∼60 years) in this decade. Hence, South Africa also envisioned the renewable energy development in the Integrated Resource Plan (2019) [33] to replace 10.5 GW of coal by 2030 and 35 GW by 2050. The economic and business case of coal retirement would hinge critically on how fast cost of solar and wind projects drop over the coming years. When LCOE of renewable generation drops by at least 40% in the country, some coal plants will become uneconomic to operate. Such a degree of cost reduction within the next 10 years is equivalent to a minimum cost reduction rate of 3.8% per annum which is in the projected range of cost decline. Given that global weighted average LCOE of newly commissioned solar PV and onshore wind has dropped by about 13% and 9% year-on-year in 2019 [6], it is foreseeable that coal plants will potentially turn uneconomic in the next 10 years.

c: TURKEY

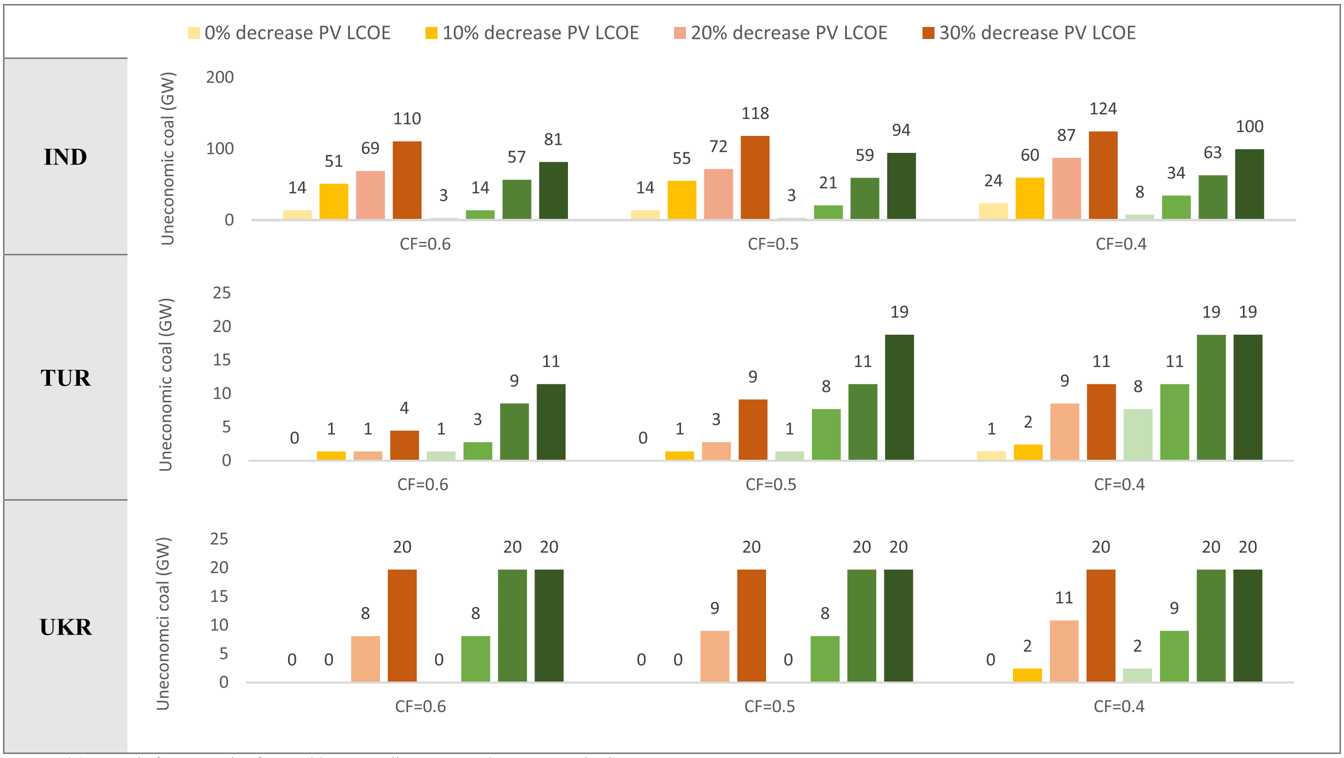
The capacity mix of Turkey is diverse, with hydro, gas, and coal as three main generation sources in terms of capacity size, accounting for 80% of the installed capacity. Coal accounts for more than 20% of the generation capacity in Turkey (Table 1) and 37% of generation in 2019. As of 2020, the operating coal capacity is around 19 GW. The coal produced in Turkey is predominantly lignite, which is powering over half of the coal plants in capacity terms. Lignite is less efficient in generation, so the rest of the coal power stations are also fueled by imported bituminous coal. Thus, the SRMC of coal electricity is generally high in Turkey, ranging from \$40/MWh to \$72/MWh (Figure 6). Generation from Afşin-Elbistan - a power station, which was commissioned in 1984, is estimated to be the most expensive, while the other coal plants have SRMC ranging from \$40/MWh to \$60/MWh.

Given present cost level of renewable electricity in Turkey, the average LCOE of wind (\$63/MWh) has already dropped below the upper bound of the SRMC of coal generation, indicating that wind resources already have some cost advantage. Generation from solar PV also has a competitive LCOE (\$78/MWh), close to the SRMC of some coal capacity. To sum up, considering the generally high cost of coal generation in Turkey, as renewable energy industry further develops, it is economically feasible to expand renewable capacity to substitute the uneconomic coal.

d: UKRAINE

There is currently 24 GW of coal power plants in the Ukraine that account for around 40% of installed power generating capacity (Table 1) and 30% of the annual generation in 2018 [39].

In Ukraine, the cost of coal generation is also relatively high. This is due to the high cost of coal itself, being sourced from inefficient mining facilities, as well as old coal plants with high operations and maintenance costs. The SRMC of coal plants ranges between \$61/MWh and \$74/MWh (Figure 6).



Note: *CF stands for "capacity factor. ** IND-India, TUR-Turkey, UKR-Ukraine.

FIGURE 7. Sensitivity analysis of unprofitable coal capacity in India, Turkey, and Ukraine (over LCOE of VRE and CF of coal).

Currently, the cost of renewable energy is also high, although the LCOE of wind resources ($75/MWh) comes close to the upper bound of the SRMC for coal plants. It is only a matter of time before wind and solar will provide more affordable power than coal plants in Ukraine. For example, if the LCOE of these renewable technologies were to drop by more than 20% (from current levels of $84/MWh for local solar PV, and $75/MWh for wind), it would fall below the average SRMC of all coal power plants ($68/MWh).

2) SENSITIVITY ANALYSIS: COMBINED EFFECT OF RE COST REDUCTION AND O&M COST INCREASE OF COAL

In fact, the scale of uneconomic coal capacity will be more likely to simultaneously influenced by the decreasing cost trend of renewable energy and hence lower utilization of aging coal plants. Figure 7 displays the sensitivity analysis conducted for India, Turkey, and Ukraine, which clearly demonstrates that even absent any carbon price, relative economics of renewable coupled with rising costs of inefficient older coal fleet, would make a strong case for natural transition away from coal. The combined sensitivity analysis evaluated the amount of uneconomic coal capacity under decreasing LCOE of RE (by 0%, 10%, 20%, and 30%) as well as decreasing capacity factor of coal power (60%, 50%, 40%).

a: INDIA

Approximately 60% of the existing coal capacity, or 124 GW will be rendered uneconomic when LCOE of PV reduces by 30% and capacity factor of coal drops to 40%. This is a 13% increase over 107 GW, relative to the scenario where we considered the baseline capacity factor of 60% (Figure 7). Capacity factor of Indian coal plants has been dropping steadily over the years from ~78% in 2009/10 to 60% in 2019 and an estimated 51% in 2020/21 [40]. It is therefore envisaged that a drop in solar/wind costs coupled with increasing cost of coal plants could potentially make a stronger case for repurposing coal plants in India.

b: TURKEY

With costs of wind generation dropping by 30%, another 8 GW Turkish coal capacity will become uncompetitive if capacity factor of coal generation is reduced from 60% to 40% (Figure 7). In other words, when renewable energy cost and coal utilization decreases at the same time, all existing coal capacity (about 19 GW) will be uneconomic making a strong case for several of these projects to be repurposed to provide flexibility services.

c: UKRAINE

As renewables and coal generation costs are relatively close at present, we find a very striking change in balance as we make coal more expensive while dropping cost of renewable projects. If renewable generation costs drop by 30% together with a drop in utilization of coal plants, almost all 20 GW operating coal capacity in Ukraine is rendered to be more expensive than renewables (Figure 7). Even when LCOE

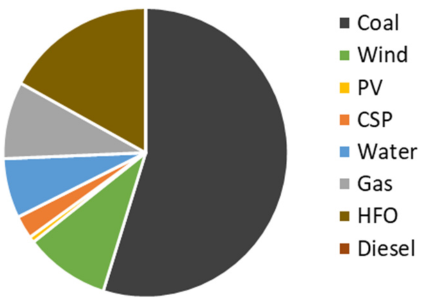


FIGURE 8. Current generation mix in Morocco.

of solar/wind drops by only 10%, a capacity factor of 40% of coal plants will increase the level of SRMC and make some coal capacity uneconomic. Given the aging coal fleet in Ukraine and relatively high average cost of renewable projects observed to date, this sensitivity is deemed to be realistic and once again should make a resounding case for coal plant repurposing.

V. COAL PLANT REPURPOSING: PLANNING AND COST BENEFIT ANALYSIS

While the cost analysis of coal plants provides insights into the competitiveness of coal at a high level, identification of coal plants that can be retired and repurposed requires:

a. A least-cost planning analysis that decides both new entry and retirement of plants in the system to meet projected demand over next several years; and
b. A cost-benefit analysis of retired coal plants that may potentially be repurposed.

In this section, we present such an analysis for Morocco, which currently has more than 50% of its generation (Figure 8) coming from four coal power plants (Table 2). It is a relatively new coal fleet with only 3 units that are older than 25 years including Mohammedia (280 MW unit, 33 years old and has 34% thermal efficiency). Morocco also has nearly 2 GW of heavy fuel oil (HFO) capacity that is very expensive to run with SRMC ranging from \$140-177/MWh. Coal plants in comparison are far cheaper with SRMC between \$38-53/MWh. LCOE of wind and solar for Morocco are estimated at \$47/MWh and \$43/MWh, respectively using data collected for planning analysis.

TABLE 2. Major coal plant derated capacity in Morocco (2019).

Plant Name		Comm. Year	Capacity (MW)	Fixed O&M ($/MW-year)	Var. O&M ($/MWh)	Heat Rate (MMBTU/MWh)
Jerada		2016	320	32,490	2.90	8.76
Mohammedia		1987	280	32,490	2.90	9.91
Jorf Lasfar	Units 1&2	1994	630	25,850	0.99	8.27
	Units 3&4	2000	624	25,850	0.99	8.24
	Units 5&6	2013	626	35,200	1.30	8.76
Safi		2018	1,283	55,000	0.83	8.25

Morocco has significant RE resources and has the largest concentrated solar plant (510 MW) in the world at Ouarzazate. There is significant policy development in the country to increase the share of RE going forward to more than 50% by 2030. Demand is projected to grow rapidly from ~40 TWh pa to somewhere between 65-100 TWh by 2035 according to the official "Low" and "High" demand projections. Morocco is also currently a net exporter of electricity to Spain and has aspiration to increase its exports. The high demand growth presents a challenge to any coal retirement as the system needs to increase its capacity from 10 GW at present to 25-35 GW by 2035 depending on the demand growth.

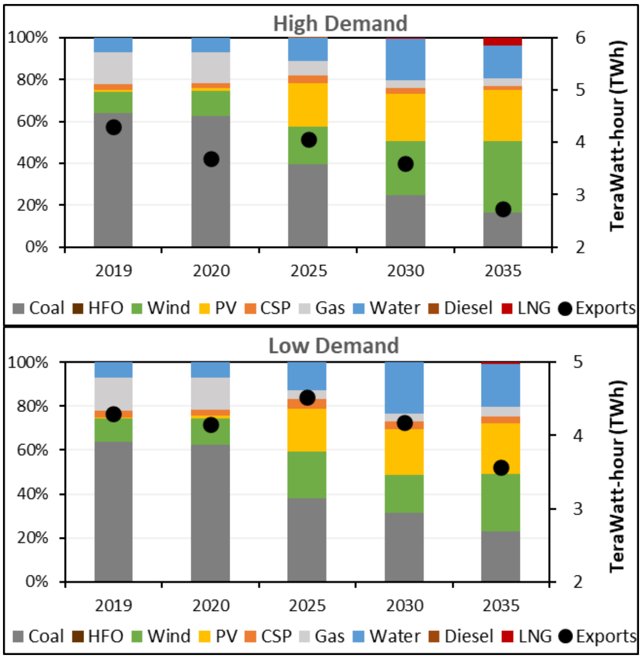


FIGURE 9. Generation mix and export (TWh – secondary axis).

A. LEAST-COST PLANNING ANALYSIS

The least-cost planning analysis is conducted to check if one or more of the older coal (and HFO) generating units are likely to be economically retired and yet for the system to build sufficient cleaner/cheaper capacity that meets the operating reserve and reliability standards. We used the Electricity Planning Model [31] developed at the World Bank to assess the optimal capacity expansion and retirement strategy for High and Low demand scenarios for 2019-2035. The model is a state-of-the-art planning tool that has been deployed for more than 80 countries.

As the results of the planning analysis in Figure 9 show, the coal generation share for both low and high demand scenarios, drops significantly to 20% or below by 2035 even without considering a carbon limit/price. In absolute terms, both scenarios decrease coal-based generation from 27 TWh at present to 16-17 TWh by 2035. Solar and wind generation, on the other hand, increase to 52%-61% by 2035 suggesting Morocco's 52% renewable target by 2030 may be eminently achievable. A significant share of the existing coal generation will become uncompetitive compared to RE over the next 15 years relative to solar and wind.

Mohammedia (280 MW) is found to have a low capacity factor in 2019 and is deemed to be retired economically from 2022 as its fixed O&M is not justified from a further drop in dispatch. A significant part of the HFO capacity (1,590 MW) is also retired economically over the planning period. In total 1,870 MW of thermal capacity is retired in line with a drop in thermal share that saves $221 million.

B. COST-BENEFIT ANALYSIS OF REPURPOSING MOHAMEDDIA (280 MW) COAL PLANT

Cost-benefit analysis (CBA) compares the incremental benefits and costs of one or more alternative scenarios versus a *status quo* (business as usual or BAU). Mohammedia (280 MW) is retired in 2022 in our alternative scenario (repurpose scenario) as per the least-cost analysis. The BAU keeps Mohammedia running until 2031 or 9 more years after the economic retirement year found in the least-cost planning analysis. The time horizon of the CBA is aligned with the power system study and considers the next 15 years (up to 2035). Benefits and costs are discounted at a 6% discount rate. Further details of the BAU and our alternative repurpose scenario are given below.

1) BAU (MOHAMMEDIA CONTINUES TO BE IN OPERATION)

a. Coal plant is used at 50% capacity factor (CF) until 2031;
b. Plant is decommissioned as from 2032; and
c. 150 workers are laid off in 2032.

2) REPURPOSE SCENARIO (SOLAR PV, BESS AND SYNCON)

a. Coal plant is retired in 2022;
b. New RE plant reuses the site (50 MW Solar PV +50 MW 3h battery storage (150 MWh)) leading to a 15% reduction in CAPEX relative to using a greenfield site for the RE;
c. New plant converts coal generator into a SYNCON (synchronous condenser);
d. New plants provide ancillary services through SYNCON (Reactive power), BESS (frequency control) and new flywheel (inertia);
e. 50 workers retain employment at the new plant; 100 people are laid off in 2022;
f. Avoided CO_2 benefits from reduced coal power generation from the site is attributed to the repurposed project if generation from the incumbent coal plant can be displaced by cleaner forms of generation including renewable power generated on the repurposed site and also elsewhere in the system. This is estimated as part of the planning optimization; and
g. Since the Mohammedia coal power plant is only a small part of the Moroccan power system we assume no change in generation costs vs. BAU.

TABLE 3. Key assumptions on repurposing.

IMPACT	Parameters
GHG emissions	1) CO_2 cost: $41/ton (2020) - $56/ton (2035) [41]
Decommissioning costs	1) Land surface: 2 km2 2) No ash disposal area (recycled by cement companies) 3) Coal storage area: 0.032 km2 4) Coal cleanup cost: ~ 0.1 M$ (estimate based on [9]) 5) Other decommissioning costs*: ~ 11 M$ (estimate based on [9])
Social costs	1) 150 workers employed at coal plant 2) 50 workers re-employed at PV plant 3) Average cost of support program for laid-off workers: ~$12k/worker (one-off) (estimate based on [10])
Ancillary services provision	1) Reactive power value: 5$/Mvarh (used 8760h/year) [42] 2) Frequency control services: 3$/MWh (4h of storage)
Salvage value of coal plant	1) CAPEX of old coal plant: 2.5 M$/MW 2) Scrap value: 10% of initial CAPEX 3) (estimate based on [9]) 4) 5% of initial CAPEX of old plant is reused for repurposing (estimate based on [9])
Change in CAPEX with new plant	1) ~15% savings in CAPEX of PV plant (estimated CAPEX of PV plant is 1 m$/MW) 2) CAPEX of SYNCON + Flywheel: 0.1 M$/Mvar 3) CAPEX of BESS: 200$/kWh with 3h of storage (150 MWh)

* Other decommissioning costs include (i) employee, station overheads and O&M expenses incurred from pre-decommissioning to the completion of the decommissioning phase; (ii) Pre-demolition environmental regulation costs (i.e. asbestos removal); (iii) demolition costs. For more details see [9].

There are incremental benefits and costs of the repurposing option relative to the BAU scenario, namely: (a) Benefits that include avoided carbon emissions over a 9-year period, some of the jobs are retained on the site, the RE+FLEX site can provide substantial ancillary services, reduced cost of site and connection costs for the repurposed project, and the salvage value of the assets that are decommissioned is collected earlier; vs (b) Costs that include new investments in RE+FLEX, decommissioning costs need to be incurred early and a larger share of the employees will need to be retrained/relocated early. As the World Bank [9] study discusses in greater detail, there are reasons to believe that benefits can outweigh cost by a significant margin, especially if there are avoided carbon emissions due to the fact that economic retirement not only reduces system costs from uneconomic fixed O&M costs, but also avoids CO_2 emissions that have a significant cost as reflected in available estimates of the shadow price of carbon used in project analysis [41]. Ancillary services from the RE+FLEX center even after the coal plant is retired may also have significant benefits and enhances the ability of the system to integrate higher volume of variable RE generation. There are other important issues such as retention of part of

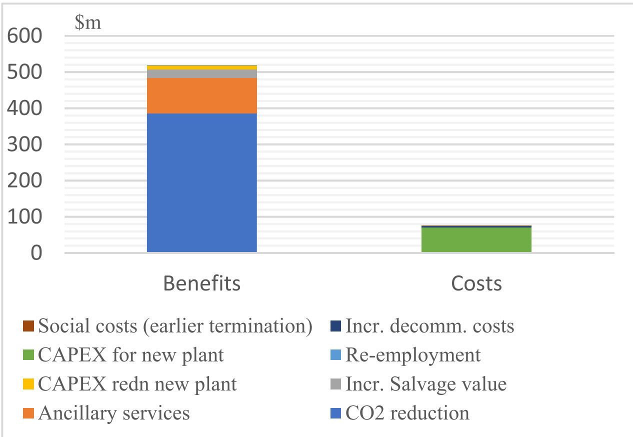


FIGURE 10. **Benefits vs costs of repurposing (inc. CO_2 benefits).**

the workforce. Table 3 lists the assumptions that are used in this analysis.

Figure 10 shows how the benefits and costs stack up for the Mohammedia (280 MW) early retirement in 2022. Total discounted benefits of $518m over 2022-2031 far outweigh the costs of $74.5m, i.e., a benefit-cost ratio of nearly 7. Avoided CO_2 emissions valued at the World Bank social costs render the highest component of benefit ($385m or 74% of total benefits). Bulk of the costs of the project are due to the investments in solar, BESS and SYNCON of $67m. It should be noted that even if the avoided CO_2 benefits are completely ignored, benefits remain at $133m which still yields a healthy benefit-cost ratio of 1.8. A potentially significant source of benefits for the repurposed plant can be the provision of frequency control and dynamic reactive power services. The incremental benefit for such services is estimated at $98m using international market price and can by itself justify the cost of the project.

VI. CONCLUDING REMARKS

There have been countless discussions on reducing the role of coal in power generation since the nineties, but these have become increasingly intense only in the last decade as cost of renewables followed by that of storage, plummeted. These discussions have started being translated into policy actions in some countries – most notably in the UK in recent years. However, the lack of actions outside a limited number of developed nations through focused policy actions is also conspicuous. A casual comparison of winning auction prices of solar and wind in some part of the world, with the levelized cost of a new coal plant, would suggest that coal is vastly unprofitable and should retire. Indeed, a number of studies in the recent years have been making this claim heralding the death of coal. This is, however, a complex subject that requires detailed data at country/system level to see the competitiveness of *existing* coal based on its short-run costs with the levelized cost of renewables which is also very specific to each geography depending on project costs and resource quality.

The answer on economic attractiveness of renewables in the short term can be surprisingly different across geographies as a comparative analysis we have constructed for ten developing countries demonstrates. Countries like India where renewable projects have been highly competitive and there is an aging fleet of coal plants many of which are far away from mines, are already highly uncompetitive. On the other hand, countries like South Africa that have relatively inexpensive coal plants, but the average cost of renewable projects have not yet dropped sufficiently (as of 2020), will require special efforts to dislodge coal completely beyond plants that have reached or gone well past their technical life. There are still other countries like Ukraine and Turkey where both renewable projects as well as coal tend to be expensive, making them "competitive" to each other. As renewable costs are projected to go down over this decade and older coal fleets continue to incur higher maintenance costs and lose efficiency – the situation will change rapidly in all three categories as we have tested using a set of sensitivity cases. We find that countries like India will see solar and wind costs that can be built at prices that challenge the economics of 124 GW of operating coal plants, or 60% of its coal fleet. Ukraine and Turkey where coal is only marginally competitive will see a more drastic switch for coal to become uncompetitive in the coming years. The transition process will require policies like carbon pricing to ensure coal is phased out. However, as the preceding discussions suggest, a relatively low cost of carbon will be adequate in most cases as coal in several systems are only marginally more expensive than the LCOE of renewables. The process can in fact start in the developing world immediately and gain momentum as costs of renewables and storage continue to fall. As we have alluded to in the context of India's transition to clean energy, the first 14 GW of old and expensive coal plant has a negative cost of carbon reduction and on average the entire fleet has an average cost of CO_2 reduction below \$10/ tCO_2e. As costs of solar, wind and storage fall, the cost of CO_2 reduction in the long term will be negative making it a "win win" situation to get cheaper *and* cleaner electricity. It is well worth noting that the cost of carbon reduction in India from coal based generation that we have presented is competitive relative to those that prevail internationally, e.g., \$16/tCO_2e in Spain carbon tax, \$12/tCO_2e in Beijing pilot ETS, \$10∼\$30/tCO2e in EU ETS, and \$15/tCO_2e in California Cap and Trade [43].

As the reality suggests, in the near term, coal will not pave the way for renewables without a policy intervention notwithstanding the potential low cost of carbon. More importantly, such policies also need to address some of the complex issues around the integration of renewables including very real cost of such integration and removing the barriers to exit for coal. The latter includes significant local development, social, and environmental issues as well as significant cost of decommissioning. There is an acute need for development of innovative business models to remove the exit barrier. Repurposing old coal plant sites and equipment can be a formidable option that not only enhances the business case for exit including recovery of decommissioning costs, but also partially addresses social and environmental ones. Development of RE and flexibility (RE+FLEX) centers on old coal plant sites can also be part of the solution to integrate large-scale renewables at a modest cost. It is an opportunity to reduce the barriers to coal retirement and to propel the low-carbon development. There are wider benefits of coal plant repurposing to further boost utilization of renewable energy, stimulate new employment, and strengthen the grid. Such efforts are only at a nascent stage and will need to be scaled up quickly and efficiently to accelerate coal transition.

ACKNOWLEDGMENT

The authors would like to take this opportunity to thank the IEEE Access Editor and two reviewers for the comments provided on the original submission. The team would also like to thank their two internal reviewers from the World Bank, Rahul Kitchlu (Senior Energy Specialist) and Phillip Hannam (Energy Economist), for their comments. The opinions and views presented in this paper are those of the authors own and do not necessarily represent the views of the International Bank for Reconstruction and Development/World Bank or its affiliated organizations.

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