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Socio-technical feasibility of coal transitions in India: Results from stakeholder interviews

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ABSTRACT

Strategizing development-led energy transitions for India would need considerable stakeholder inputs for improved decision-making. While modeling exercises have largely been used for research and policymaking, an increasing need is felt to validate underlying assumptions and model findings based on views of important stakeholders. Particularly, for the coal sector, these stakeholders are present throughout the value chain: mining, end-use (power and industry), regulatory agencies, transport and advocacy. This paper summarizes the key findings of our interviews with $n = 21$ stakeholders across these sectors focusing on evolving coal use, underlying technologies and socio-technical features of this transition. Based on this exercise, interviewed experts largely believe that coal use would continue for the next two decades in the interest of energy security and energy affordability to the consumer. At the same time, they also acknowledged the reduced costs of solar, which makes it a key player in the analysis. We also notice an improved perception of carbon management technologies. Particularly, CO_2 utilization to produce methanol and urea are seen as potential winners as these approaches could facilitate lower imports of petroleum and natural gas products. Geologic CO_2 storage is still somewhat impeded by technical limitations and lack of global exemplars. Other approaches such as recovery of methane from gassy coal mines and biomass co-firing are seen as important but limited in potential. Most stakeholders also pointed to the need for averting job losses in the coal value-chain, which may not necessarily be made up by renewables.

1. Introduction

India is a country with rising energy demands projected over the next several decades. While per-capita energy use in India has doubled since 2000, it is still only a third of China and a tenth of the United States. Around 55 % of India's primary energy consumption and 73 % of electricity generation is supplied by coal. This share is anticipated to decline substantially en route to India's target of achieving net-zero greenhouse gas (GHG) emissions. The Government of India itself has stated a goal of capacity share of 50 % being met by non-fossil sources by the end of this decade. During the same time period, India's renewable capacity is also targeted to reach 500 GW. Indeed, Vishwanathan and Garg [1] estimate that coal will account for only about a quarter of electricity generation by the mid-century in scenarios compatible with the 1.5 °C targets. Other groups have called for an even more aggressive transition with minimal coal use around 2050 [2–4]

These rapid energy transitions will have myriad implications on investment patterns, power and industrial sector operations, employment and revenue generation. Some of these features can be accurately captured by modeling exercises such as those cited above. For instance, Tiwari et al. [5] have found that availability of low-cost CO_2 capture, utilization and storage (CCUS) reduces the need to shift away drastically from coal. However, the feasibility of these wide-ranging changes may not be adequately accounted in modeling exercises. For instance, models show a high penetration of renewables and/or CCUS in the energy mix moving forward. However, it is unclear if these technologies will be able to scale-up consistent with the trajectories shown by these projections. A coal transition may be opposed or promoted by varying advocacy groups

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quite active in the country's discourse. Economic optimality – as targeted in these models – may also not account for regional inequities that may arise due to coal transitions. Moreover, the Indian energy transition would need to be development-led owing to human development goals such as education and health [6].

While modeling studies are useful in establishing techno-economic feasibility, they provide limited insights into factors at the interplay of technology, policy and societal outcomes. As such, a plethora of other literature has also come out on coal (and energy) transitions. Geels et al. [7] have noted that obtaining business and societal support is imperative for gaining legitimacy for transitions. In their work, they have made several suggestions for future research. Most notably, they have indicated that technological innovations would not be sustainable in the long term in the absence of stakeholder engagements. In doing so, they have elucidated the need for policy-oriented research to supplement modeling work.

Alternate methodologies have accordingly been used for researchers to understand support for coal transitions. For instance, Sovacool et al. [8] constructed and studied a dataset of 130 cases of public opposition in seven countries, including India (though their focus was on Northeast India, which accounts for a smaller share of coal production). They noticed opposition to renewables and nuclear was frequent across these cases. One key future direction they pointed to was the impact energy transitions may have on the extent of unemployment caused. This question has been partly addressed by Pai et al. [9] in the context of India where they showed that regions of high coal mining in India were concentrated in districts with high solar insolation. A key limitation mentioned in their study is the readiness from coal workers to transfer their skills to renewable sectors.

Across these studies, some common research directions have emerged. Summarizing insights from six country studies, Sartor et al. [10] called for focused dialogue with stakeholders, labor forces and governments on options for replacing coal in local contexts. Particular emphasis was suggested on diversification avenues for state-owned energy enterprises. This led us to the several key questions for this study: how do stakeholders see the possibility of coal phasedown, and where do stakeholders (particularly in public sector enterprises) see alternative business opportunities in case that happens.

Diluiso et al. [11] carried out a systematic literature review of coal transitions. One of their findings of particular interest was that buildup of CCUS infrastructure was much slower. They indicated that this made the trajectory of coal transitions much more uncertain. This finding was echoed in the subsequent review in this series on coal transitions [12]. This leads us to an additional question we sought to investigate: what is the role CCUS could play in understanding coal continuance in the future energy mix.

In light of these limitations, the work on coal transitions has benefited through augmentation of modeling results through understanding stakeholder perceptions in India. Initial work in this area carried out by international researchers focused on CCUS feasibility [13,14]. At the time these studies were carried out, Indian policymakers expressed their skepticism to these technologies owing to high costs. More recently, Montrone et al. [15] conducted 28 stakeholder interviews to elicit insights on historic coal continuance in India. They concluded that political economy factors such as revenue, employment generation and energy security make coal transitions difficult in the Indian context. At the same time, they discussed the potential of air pollution reductions as co-benefit cited by some stakeholders.

Since the publication of these results, however, we have noticed substantial policy changes announced by the Government of India. Most prominently, the Prime Minister of India announced at the 26th Conference of Parties that India would target achieving net-zero GHG emissions by 2070. While CCUS technologies are still deemed uncertain, multiple policy documents have been published by various government agencies noticing some low-hanging fruits. Moreover, a combination of geopolitical conflicts, power outages and improving efficiency has led to renewed investments in coal [16]. This includes India's largest power company (NTPC) announcing 4.5 GW additional coal capacity in the ongoing financial year, accompanied by Coal India Limited's goal to increase underground mining by 100 million tonnes of coal by 2027–28 [17,18]. These factors necessitate reviewing stakeholder perceptions on coal transitions in India in a forward-looking context.

Accordingly, this paper seeks to elicit stakeholder perceptions on the realism of coal transitions in India. We try to understand factors that would be essential for scale-up of technologies that influence coal transitions, such as renewables and CCUS. While keeping a technological focus, we also seek to understand the stakeholders' commitment to just transition considerations. Also, contrary to other global studies, we pinpoint some key sectoral insights which are not generally within the forefront of global coal transition discourse. For instance, ~50 % of the revenues of Indian Railways come from coal transport [19]. India's steel industry also depends heavily on imported coking coal [20]. This paper aims to understand the counterfactuals regarding alternative revenue sources for key businesses in such sectors.

2. Methodology

2.1. Pre-interview phase

2.1.1. Topic guide

The methodology entailed carrying out semi-structured interviews with various stakeholders. Most interview research conducted on similar topics has relied on semi-structured interviews as it helps adjust the discussion topics while providing a broad set of boundaries. The topic arc used for these interviews is shown in Fig. 1. The interview begun with a clear set of ethical disclosures (including sponsors of the work, purpose of the interview, anonymity conditions, and recording permissions). Broadly, the interviewees were requested to discuss their role in their organization, how they saw the role of coal in their sector and if low-carbon alternatives were competitive enough. Based on this discussion, they were asked about their personal or organizational projections on coal continuance, as well the barriers in transitioning to lower carbon substitutes.

The first step for the interview was to prepare a list of tentative questions. The first set of questions was prepared by consulting the future directions provided in the literature cited in Section 1. Annual reports and/or sustainability disclosures of individual companies were also consulted in framing questions about mitigation options. This list was distributed to several reviewers for their feedback. After incorporating their feedback, the questions could be divided into three broad categories: policy and regulatory, technological and socio-economic (Table 1). This does not allude to three different questionnaires. Rather, questions to a particular stakeholder included some combination of each of three columns. Broadly, we aimed for 10–12 questions for each stakeholder. These were modified during interview if the stakeholder preemptively provided some insight about a subsequent question. For instance, if a stakeholder mentioned that the costs of solar have come down in a question on limitations to coal demand, we followed that up with a question about the cost-competitveness of solar with coal for baseload generation. Similarly, if a stakeholder mentioned CCUS when asked whether coal could co-exist with net-zero targets, we asked them about their views of the costs of CCUS, particular areas of highest interest to their organization, etc.

2.1.2. Interviewee selection

A key objective of this study was to understand views of experts within the industries, i.e., who are directly involved in the process in question [22]. This is used to validate past studies which focused primarily on researchers and analysts. Such experts also included former officials in such roles as they are more inclined to provide neutral information. Selection of industry 'insiders' may be associated with inherent biases, which are discussed later.

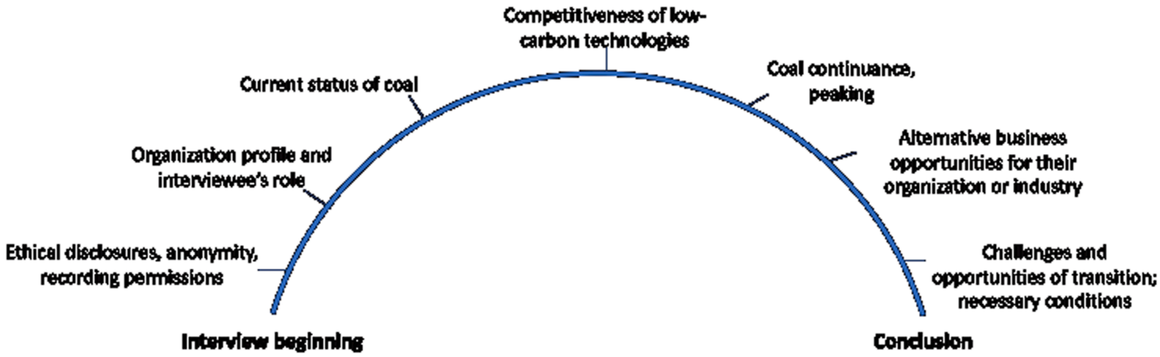

Fig. 1. Topic arc for semi-structured interviews.

The criteria for selection of the experts were threefold. First, the ideal interviewee was strongly involved with one (or more) aspects of the coal value chain. This included extraction, use, transport, governance and advocacy. Second, ideal interviewees would have >15 years of experience, and were at least at a senior executive level at the time. This criterion was defined to ensure that they were in a decision-making position in their organization, and not in a purely technical role. Third, stakeholders with experience in more than one sector within the coal value-chain were preferred though this was not an essential criterion.

Designing a stratified sample, i.e., statistically-representative set of interviewees was not possible because of the multiple metrics involved across the coal value-chain (number of employees, revenue, associated GHG emissions). Instead, we opted for purposive sampling where experts were selected based on experience while ensuring a sufficient diversity of perspectives across sectors [23]. It is notable that some past work (e.g., [15]) has focused on stakeholders within a political economy perspective. Thus, they have looked at central government ministries as the key decision-making bodies and other organizations (such as companies, civil society) as influential organizations. Our understanding of the Indian coal sector – instead – points to a distinction in opinions along sectoral lines. Indeed, in public sector enterprises which dominate most of India's coal and power production, there is a direct involvement at the board-level of Government of India employees, and the government retains primary stake in these organizations. Many regulatory agencies involve former executives of these private and public sector companies within their leadership. As such, we ensured a diversity of stakeholders along sectoral lines, as shown in Table 2.

A total of 35 potential stakeholders were identified and contacted over email or phone. Out of this, we received an affirmative response for conducting the interview from 21 stakeholders. Upon them confirming their availability, a tentative list of questions was circulated to the stakeholders 3–7 days in advance. This allowed the stakeholders to gauge their comfort level in addressing these questions, ability in answering them based on institutional constraints and browse through relevant literature.

2.2. Interview phase

The interviews were carried out in a semi-structured way. A subset of 10–12 questions from Table 1 was planned for each stakeholder. Depending on the sectoral background of the stakeholder, the share of questions was adjusted. For instance, a senior executive from the technical side (e.g., I4) was presented with more technological questions while advocacy-based respondents were asked socio-economic questions on priority. Owing to the semi-structured nature of these interviews, related questions not within the main list in Table 1 were also presented.

All the respondents gave their permission to record their interviews. All the interviews were conducted over zoom, barring A1 who was accessible only via a telephonic conversation due to their remote location. Some respondents requested anonymity.

2.3. Post-interview phase

After the interview was conducted, the transcript was prepared either manually or using the captioning feature of the Zoom software. Once the transcript was prepared, it was cross-referenced by at least two authors to ensure accuracy in content and context. Some respondents also requested for a review of the transcripts, which was also agreed to. Relevant portions of selected interviews are being included as part of the Supplementary information and have been published (in part) elsewhere [24]. Some portions are being retracted based on stakeholder requests.

The qualitative data analysis involved understanding the level of agreement on key issues for several stakeholders. In doing so, we highlight some points where the agreement was robust and features of the transition which are more contested. Another point of comparison to the stakeholder perceptions was comparison with the global coal transitions literature, especially within developed economies. Here, we wanted to understand important national and regional features which make coal transitions in India more or less lucrative. As such, features of their responses were prioritized: coal continuance projections, readiness of CCUS and other clean coal technologies, sector-specific bottlenecks, and labor/development issues.

3. Results

This section outlines the key highlights of the interviews, and puts these into context based on the past literature. Relevant excerpts from the interviews – used for arriving at these conclusions – are presented in the Supplementary Information section.

3.1. Coal continuance trajectories

Nearly all the stakeholders agreed that the coal consumption in India would increase in the next 15–20 years. Most stakeholders have currently aligned their business models to this projection. They also agreed that while coal conversion to produce value-added products could make up a tangible market, the primary form of usage would be in the electricity sector. There was a coherent understanding that coal use will increase in gross terms, even as its share in electricity generation comes to 45–50 %. This increase would come through a combination of added power capacity, coal diversification into other sectors, and increased plant load factor (PLF) for existing plants. During the height of the COVID-19 pandemic in 2020–21, the average PLF of Indian power plants had fallen to 53 % [25]. At least four stakeholders suggested that an increase in PLF to 80 % alone would drive demand up by 300 million tonnes.

At the same time, there was some disagreement about the amount of peak coal use in India. Currently, India consumes nearly a billion tonnes of coal annually, when accounting for domestic production and imports.

Table 1
Broad categories of questions for semi-structured interviews.

Policy and regulatory	Technological	Socio-economic
Previous indicative policy statements of the Government of India indicate use of 1.5–2 billion tonnes of coal by 2030–40. Do you think that has changed in recent years?	What have the limitations been for India to effective coal production increase to reach the billion tonne target?	What could be the alternative revenue sources for your company?
Could coal co-exist with the net-zero target?	To what extent is solar (or other renewable power) competitive with coal-based generation?	What are some steps that could be followed for ensuring equitable lives for coal workers and their families?
Do you see climate change constraints (such as the coal cess[i]) as becoming a limitation to coal companies at some point?	Would a focus on coal-based alternatives such as coalbed methane and underground coal gasification provide sustainable sources of revenue for coal companies in the future?	Do you see any recent changes in coal businesses that have affected the workers?
What would be the implications on the coal sector if a carbon market or trading scheme is introduced in India?	Are there any key bottlenecks on the coal utilization side (either power or industry) that could be sorted through technology levers?	Do you think that only the Government of India and the mine owners or companies like Coal India have a role to play in the just transition and contribute to the welfare of the workers?
Recently, the government opened up commercial coal mining to the private sector. Do you see a major impact on coal productivity and/or sustainability	As Coal India is entering into the methanol market, do you think that apart from electricity, coal to methanol or hydrogen can have a suitable potential in India, for example into the chemicals or transport sector and can it be competitive?	If coal use is to be stopped in India, what would be the main priorities from coal workers perspective from among the following, for eg: financial security, job security for children, relocation from home towns, mental stress, adjusting and learning new jobs and skills etc.?
What are the key policy reforms that you would wish to see in the Indian coal sector?	What potential do you see for CO2 capture, utilization and storage (CCUS) technology?	What is the possibility of reemployment of skilled and unskilled workers currently in the thermal power plants to renewable plants?
	Could you please talk about the scope of diversification of the Indian power companies into sectors such as green hydrogen?	
	For continuous and reliable power generation, renewable energy requires huge storage and hence its actual cost will be very high. How can India deal with this issue?	

[i] The coal cess, formally the Clean Environment Cess, was a tax on all coal and lignite used in India. This was gradually increased from INR 50 to INR 400 per tonne of coal between 2014 and 2016. The original design was to use the collected proceeds for renewable capacity addition via the National Clean Energy and Environment Fund. This has been merged into the new Goods and Services Tax regime since July 2017 [21].

Table 2
Profile of stakeholders interviewed.

Stakeholder code[#]	Primary sector	Secondary sector (if any)	Level
A1	Advocacy		CEO/Board level
A2	Advocacy	Governance	Senior executive
ER1	Environmental regulation	Mining	Senior executive
E1	Electricity	Electricity market	CEO/Board level
E2	Electricity	Electricity market	Senior executive
E3	Electricity	Governance	CEO/Board level
I1	Cement	Mining	Senior executive
I2	Petroleum	Marketing	Senior executive
I3	Cement		CEO/Board level
I4	Steel	Mining	Senior executive
M1	Mining	Power	CEO/Board level
M2	Mining	Chemicals	CEO/Board level
M3	Mining		CEO/Board level
M4	Mining		CEO/Board level
M5	Mining	Governance	Senior executive
M6	Mining	Electricity	CEO/Board level
M7	Mining		CEO/Board level
M8	Mining	Electricity	CEO/Board level
T1	Transport		Senior executive
T2	Transport		CEO/Board level
T3	Transport	Logistics	CEO/Board Level

[#] Here, the letter denotes the sector while the number denotes the order in which they were interviewed.

Past policy statements of the Government of India indicated the use of 1.5–2 billion tonnes by 2040 [26]. As Table S1 in the SI shows, most stakeholders agreed that the use of 1.2–1.4 billion tonnes in the next ten years would be realistic, with peak use of around 1.5 billion tonnes. Only one stakeholder suggested that consumption of 1.5–2 billion tonnes by 2040 of coal use still remains the most probable outcome.

Several reasons were cited by the stakeholders for the revised projection. The predominant reason here was the reduction in the levelized cost of electricity for solar – and also wind to some extent. Most stakeholders agree that the policy outlook for 1.5–2 BT coal production was overly optimistic and likely would not be needed. That said, they also agree that some increase in coal production and use (by 300-400 MT) may be possible owing to the coal capacity already in pipeline, and increasing plant load factor (PLF).

At the same time, several other factors were cited by stakeholders which are not readily noticeable in the past literature (Table S2 of the SI). Stakeholders pointed to a variety of non-climate reasons for plateauing of coal use in some phases in the past, or possibly in the future. These included a lack of capacity expansion in coal-fired power plants as well as safety and air quality externalities. On the coal production end, stakeholders in the mining sector pointed to the lack of private coal extraction companies as a major deterrent. While this was solved partially with the recent regulation on commercial coal mining with private sector participation [27], stakeholders mentioned that this could be "too little, too late". Similarly, on the end-use, stakeholders lamented the current structure of power distribution companies (DISCOMs). DISCOMs in several states have fallen back on their bills to generation companies that has led to a reduction in their PLF [28]. Finally, lack of point-to-point infrastructure for coal transport was indicated as a key logistical deterrent. Stakeholders in both the shipping and railway sectors noted that despite a robust network of transport networks across various hubs in trunk lines, bottlenecks remained in transport from coal mines and towards power plants from these hubs. Interestingly, policy interventions such as carbon markets were not opposed by any of the stakeholders as long as they were transparent.

3.2. Coal competitiveness with other sources of energy

Notwithstanding the projections regarding increasing coal production, all the stakeholders acknowledged the increased role of solar in the energy mix. Nearly all the stakeholders mentioned that solar is viable as a source of electricity. Some also noted that the reduction in solar costs by 7–8 times in the last ten years greatly exceeded their expectations. They did, however, note that the variable nature of solar and wind meant that they do not directly compete with coal and other baseload sources such as nuclear. From a consumer perspective, it was noted that the electricity price in solar-rich grids was probably still high. Several stakehokders familiar with grid operation (e.g., E1) noted that the actual electricity price in such grids was not easily elucidated owing to large subsidies that solar receives. This was most clearly summarized by stakeholder E1 with other responses noted in Table S3 of the SI:

> *"When we start comparing the cost, we find that the cost of RE (Renewable Energy) has certainly come down over a period of time starting from Rs. 15/*kWh *to around Rs. 2/*kWh *in 2021 and it is slated to further go down. As of today, coal based electricity costs around Rs. 3.75/*kWh *rupees. However, the costs which are coming out in the market are not the real costs. It is to be noted that solar is getting a lot of subsidies which is in turn loaded into traditional kinds of power generation such as thermal and others. As per a study conducted, the price of around Rs. 1.3/*kWh *is getting subsidized from thermal power plant side to solar side. So, we cannot say that solar is cheaper or thermal is costly because the real price is not coming out in the market."*

In this sense, stakeholders validated modeling findings by Garg et al. [29] who noted that presence of baseload power in the form of coal reduces the electricity price incurred at the consumer end. Stakeholders viewed the costs of grid storage as exorbitantly high, while also conveying that there was a low chance of reducing appreciably before 2050. This is probably somewhat at odds with the academic literature in an international context [30,31]. Large construction times for pumped hydro storage were cited as a key deterrent. Only one stakeholder considered that balancing supply and demand in microgrids could be a possibility, while others were either not optimistic or not familiar with the prosumer concept.

3.3. Technological pathways

3.3.1. Improved understanding of the role of CCUS

Stakeholders reinforced modeling projections that large shares of coal use – if not all – will be in consonance with CCUS. This reflects a marked evolution from stakeholder surveys carried out in the previous decade, where CCUS was met with considerable skepticism [13,14]. Even as some concerns remain, CCUS is no longer seen as a "no go" technology. This may ostensibly be due to several policy roadmaps on this topic by the government [32], emergence of indigenous technologies in this space, and analytical findings pointing to several low-hanging fruits [33,34]. Most stakeholders from the power and mining sectors made it clear that they perceived CCU and CCS separately. Broadly, CCU was viewed positively while there were some apprehensions associated with CCS.

The concerns associated with CCS were associated with large costs and limited technological experience in India and internationally. Power sector stakeholders (E1-E3) identified practical difficulties associated with retrofitting coal-fired power plants older than 10 years. Space limitations and high-ash content of Indian coal would, in their view, make such concepts infeasible. At least five other stakeholders pointed that if CO_2 capture processes are retrofitted on existing coal-fired power plants, the cost of electricity would increase substantially. As such, they saw the need for two drivers if CCS technology is to take off even in high efficiency power plants. First, an upper-bound on CO_2 emissions for a power plant could necessitate deployment of CCS in baseload power plants. Such examples exist for criteria air pollutants and have been illustrated in India with moderate-to-high success for different pollutants [35]. Second, there was a consensus among these stakeholders that the incremental costs associated with CCS could not be solely borne by the consumers. Instead, international financing would have to be made available [36]. Stakeholders also pointed to the limited geologic CO_2 storage potential in India after engineering constraints are incorporated.

Contrary to CCS, stakeholders viewed CCU much more favorably. They identified production of methanol and urea as the two primary pathways here. Both these pathways are consistent with the National Green Hydrogen Mission, under which 5 million tonnes of clean hydrogen is targeted by 2030 [37]. Both methanol and urea require hydrogen and CO_2 as feedstock. The primary driver of the CCU pathways was reduced import dependence for petroleum and natural gas products, with GHG emission reductions being seen as an important co-benefit.

Stakeholder E1, who was most familiar with this topic, indicated that methanol could replace light diesel oil (LDO) in the short-term. LDO is an important industrial fuel emerging from petroleum refining. India's LDO consumption in the fiscal year 2023–24 was 783,000 tonnes [38]. Stakeholder E1 mentioned that current pilot plants are equipped to produce nearly 3000 tonnes of methanol per year by capturing CO_2 and reacting it with low-carbon hydrogen. This can be replicated at other facilities or scaled up to supplement replace India's LDO requirements. In the longer term, methanol is targeted to replace diesel as an electrofuel or e-fuel. This aligns with business models of the power sector as well as the coal mining companies, which seek to produce methanol via surface coal gasification. This technology has also progressed considerably with BHEL developing coal gasifier equipped with CO_2 capture for both coal and lignite producing companies [39].

The CCU pathway for urea production is also anticipated to target import dependence. Urea is used as an important fertilizer and the government has targeted to eliminate direct urea imports by 2025. That said, current fertilizer plants are run using natural gas as a feedstock, for which import dependence is high. Stakeholder M3 pointed out that retired fertilizer plants actually used coal-based gases as feedstock which was later phased out due to higher costs. Accordingly, key companies in the coal and fertilizer sectors are now trying to renew this approach using a joint venture concept. The current cost of syngas production as a feedstock for fertilizers is $5.5/MMBTU. According to stakeholder M3, this would need to reduce to $3.5/MMBTU for cost-competitiveness with natural gas feedstock. Stakeholder M4 agreed with this position and further implied that the government has planned investments of $3.6 billion for such coal-to-fertilizer plants.

These results point to the need for improved representation of CCU technologies in equilibrium models. To date, most studies have focused on CCS as the end-of-pipe decarbonization approach in such models. CCU cannot directly replace CCS in a modeling framework as the net emission reductions may be lower and it entails much higher inputs from other sectors of the economy [36]. Considering the higher favorability by Indian stakeholders for CCU, it is imperative to incorporate these features into modeling exercises.

3.3.2. Limited deployment of other technological approaches linked with coal

In addition to CCUS, other technological opportunities have been suggested to supplement the revenue of coal companies. These include coal mine methane recovery from underground coal mines and underground coal gasification. All the stakeholders in the mining sector (M1-M8) had mixed responses to these approaches.

Stakeholders indicated that CMM recovery opportunities in India are limited and concentrated to Raniganj, Jharia and East Bokaro coalfields. Several gassy coal mines and unmined coal blocks in these coalfields have total CMM resources of the order of 30 billion cubic metres [40]. This could meet roughly 2–3 % of India's natural gas demands assuming a 25-year project lifetime. Other coalfields do not have adequate gas concentration to set up a viable CMM recovery project – as also evidenced by technical studies. Stakeholder E1 also noted that lack of pipeline infrastructure near these coalfields as a major bottleneck. This would inhibit methane transport even if successful recovery operations were to come online.

Underground coal gasification (UCG) was seen much less favorably by stakeholders. UCG deployment in India has come in the form of two phase of trials by ONGC [41]. While some policy formulation took place in the last decade, currently the Government of India has no targets for UCG. Stakeholders, particularly, in the coal mining sector echoed this view. Stakeholder M7 informed us that NLC had initiated a project and auctioned operations to a bidder. However, cost overruns and environmental risks such as groundwater contamination inhibit such plans at the moment. Similar to CCS, most stakeholders pointed to the lack of global success in UCG as another point of concern.

On the coal utilization end, stakeholders E1-E3 all spoke favorably about biomass co-firing with coal. They indicated that current biomass blending of up to 10 % has been established by NTPC, which could theoretically be increased to 20 % without major retrofits. The key driver of biomass co-firing was to reduce stubble burning in agricultural fields and reduced emissions of criteria air pollutants. That said, both technical and logistical challenges were cited. From a technical perspective, stakeholder E1 identified issues such as the hygroscopic nature of biomass, the handling and mixing problems, effect on safe operation of milling systems, and issues related to grindability, combustion rate and slagging propensity. Logistically, stakeholder E2 noted that waste biomass utilization already happens in rural economies. As such, steady supply of biomass for co-firing would be a challenge.

3.4. Socio-technical issues

Nearly all the stakeholders placed social issues, as they interfaced with the coal sector, front and center of their key priorities. They pointed out that both public and private sector companies have a long history of corporate social responsibility. For instance, Coal India Limited provides full tuition awards to children of its workers selected in engineering and medical colleges. The nature of employment has changed as well – with increasing trend towards contractual employment. Even so, the Indian coal sector has a robust trade union structure and stakeholder A1 advised us that these trade unions often consult with each other. As a result of the strong trade union structure, wages for workers are periodically revised as part of the National Coal Wage Agreements [42]. Currently, the minimum wage for coal miners substantially exceeds the minimum wage for other sectors.

In the short-term, the key priority for mining stakeholders was stated as increasing underground mining production. Coal India has targeted surface mining deposits over the last several decades due to higher miner safety, lower costs of production and lower fugitive methane emissions. However, number of near-surface deposits have been depleted. As such, there is a policy thrust toward having a quarter of the incremental coal production over the next five years come from underground mining [43]. Underground mining has labor requirements of 5–10 times per tonne of coal extracted compared to surface mines [44].

In the longer term, however, stakeholders engaged in worker advocacy, power sector and mining noted that a coal phaseout plan could drastically affect well-being of the workers and their safety. They noted that the scope of employing unskilled workers was much lower in solar or wind power plants. Even if renewable power plants employed comparable number of people as a coal-fired power plant, they acknowledged that the job losses in other parts of the value chain would be an order of magnitude higher. As an illustration, NTPC (India's highest power producing company) employs close to 16,000 people while CIL employs >250,000 people. This is largely due to the nature of work itself. Stakeholders E2 and E3 further noted that solar and wind power plants would largely require electrical and electronics engineers as skilled workers. Here, a large skilled workforce of mechanical and electrical engineers would deal with some job aberrations. Given the uncertainty around CCUS, stakeholders did not provide major insights for its role in aiding just transitions.

Our understanding was that formulating a just, sustainable energy transition policy would have to take a highly regional perspective. Stakeholders such as A1 and M4 mentioned three major considerations for just transitions in India. First, the nature and magnitude of funding required would have to be much larger than what has emerged in the international discourse around just transition. This is because of the large and diversified nature of the Indian coal sector. Second, just transitions would have to take regional equity into account as well. Large coal producing states in India are towards the eastern part of the country. Contrarily, the southern and western parts of the country are rich in variable renewable resources. As many eastern states have a lower human development index, concerns were raised on coal transitions further exacerbating their well-being. Third, stakeholders mentioned – in both an organizational and a personal perspective – that coal transitions might be seen more amenably if the next generation could be trained in skills relevant to renewables. Development-led energy transitions would need to account for these intergenerational factors.

4. Discussion

This interview exercise enabled us to shed light on some of the ways in which stakeholders within Indian coal value chain are looking at the viability of coal transitions. The key findings and points of disagreements are summarized in Table 3.

4.1. Future directions for modelers

The findings reveal several directions for modelers. The first insight is in terms of scenario design for studying coal transitions. Scenarios in modeling parlance refer to illustrative variants of the future, that may or may not have probabilities associated with them. Scenarios are often categorized on the basis of future temperature rise, preferential investment in one or more technologies, or the drivers of GHG emissions such as energy efficiency. In the Sixth Assessment Report of the IPCC, the use of 'delayed' scenarios was employed [45]. Such scenarios assumed that optimal climate action was undertaken after a decade of delay after 2020. In a similar vein, studies for coal transitions in India could incorporate a 'delay' element to understand the feasibility of reaching net-zero emissions subject to the views of the stakeholders here.

The greater preference for CCU as compared to CCS offers another important insight for modelers. CCS is generally much better modeled than CCU. This is ostensibly because incorporating CCU-derived products would require much more detailed parameterization of sectors such as chemicals and materials. To our knowledge, very few papers have done this globally [46] with none in the Indian context. There is, accordingly, a need to understand the potential products and their characteristics that could be viably produced using CCU. This bottom-up information could be used to supplement existing top-down modeling efforts.

Finally, a key issue echoed by power sector stakeholders was the lack of information around the cost to the consumers. They pointed out that while the levelized cost of electricity for solar and wind had indeed come down, it was not possible to gauge the impact on the cost to the consumer. This points to the need for estimation of such metrics at the system level by combining the costs of system integration.

4.2. Insights for stakeholders' engagement

We noted several interesting communication patterns with stakeholders. Most notably, the awareness or engagement of stakeholders was marked by a stark difference in the interviews before and after the Prime Minister's speech at the Glasgow Climate Conference of Parties. Several

Table 3
Summary of key questions, number of respondents, findings with high agreements, and points of disagreement.

Question	Number of respondents	Key findings with high agreement	Any points of disagreement
Previous indicative policy statements of the Government of India indicate use of 1.5–2 billion tonnes of coal by 2030–40. Do you think that has changed in recent years?	18	High familiarity with these policy statements Growth from the present day predicted by all, with peaking not expected in next decade	The peak coal use expected by stakeholders varied by a factor of two. Three stakeholders mentioned that coal use will not increase to 2 billion tonnes because of reduced demand while two pointed to the depletion of near-surface deposits.
What have the limitations been for India to effective coal production increase to reach the billion tonne target?	13	Land acquisition and/or costs present a key challenge Lack of commercial coal mining regime cited as another key issue	Three respondents pointed to low demand from the power sector but others felt this was more related to extractability.
What could be the alternative revenue sources for your company?	15	Alternative revenue for transporters could be other bulk goods such as iron ore. For cement and steel producers, other sources of energy and feedstock both have to be looked into. CMM and UCG have very localized potential.	Alternative sources of revenue are seen much more positively by transport sector stakeholders, followed by industry and then mining.
Could coal co-exist with the net-zero target?	7	With CCS or afforestation initiatives, coal could co-exist in a net-zero context.	Lack of consensus around the meaning of net-zero (i.e., whether CO_2 or all GHGs, Scope 1 or Scope 1–3, etc.)
To what extent is solar (or other renewable power) competitive with coal-based generation?	19	All stakeholders agreed that the levelized cost of electricity for solar has come down. There was broad agreement around increased role of solar but intermittency was cited as a key issue.	Interpretation of the reducing costs of solar/renewables vary. Particularly, electricity-sector stakeholders pointed to the fact that system costs where difficult to estimate and levelized costs do not convey full picture.
As Coal India is entering into the methanol market, do you think that apart from electricity, coal to methanol or hydrogen can have a suitable potential in India, for example into the chemicals or transport sector and can it be competitive?	12	While theoretical potential was agreed upon, safety issues around hydrogen were cited as a key concern. Methanol was seen as a more promising way to go.	The scale at which coal to chemicals or methanol (as a fuel) could be useful was contested.
What potential do you see for CO2 capture, utilization and storage (CCUS) technology?	13	High potential for CCU (particularly for products like methanol and urea. Higher skepticism around CCS, while lower than studies done a decade back.	Demand for CCU-based products was more contested.
What is the possibility of reemployment of skilled and unskilled workers currently in the thermal power plants to renewable plants?	17	Good possibility, particularly with reskilling.	Number of reemployment roles was highly variable.

stakeholders interviewed clearly stated that they did not understand what net-zero was. Similarly, they echoed lack of awareness of terms like decarbonization or CCUS. After the release of India's long-term decarbonization strategy and the Prime Minister's commitment to reach net-zero by 2070, we did not see such a response. This might allude to the fact that climate discourse is somewhat driven top-down. Contrary to some other environmental issues, climate change policy is largely governed by the central government and then delegated to state/local governments as evidenced by launch of state action plans on climate change aligned with the national action plan [47].

We also noticed that not all stakeholders were equally well-versed with difference between CCS and diverse CCU approaches. CCU can comprise long-term storage when CO_2 is converted into durable products like plastics or concrete. However, other forms of CO_2 utilization may be short-lived, such as conversion to e-fuels, or directly interact with natural environment, such as CO_2-to-urea [48]. The dearth of understanding across these approaches could be concerning and should be prioritized by experts as it may lead to an overestimate of the mitigation potential. This is particularly the case as international financing of carbon management technologies is considered contingent on robust life cycle scrutiny [39].

We also noted another limitation. While lack of pipeline connectivity was cited as an issue for CMM project expansion, it is probably not adequate. The volume and gas purity may mean lower capacity factors and the need for additional gas upgrading, that could potentially make the process cost-prohibitive [49,50]. Instead, onsite use as an industrial feedstock (e.g., in fertilizer plants) or small-to-mid scale power generation could be seen as the likelier alternatives. This is another area which workshops and capacity building events could target.

4.3. Limitations of the study

This paper relies on stakeholder perspectives for understanding the future of coal in India. While several of the insights are useful, such studies can often accompany inherent biases [51]. Notably, most of the respondents are industry 'insiders' and not researchers/analysts in the field. While insiders can provide useful information not immediately apparent to us as researchers, it may be associated with a somewhat constrained outlook. Part of this bias may simply be what is known as the 'ostrich effect' which tends to view negative outcomes to their industry with low likelihood [52]. This is visible as most stakeholders in this study agree that coal would remain in the Indian energy mix for two to three decades. While the risk of such bias remains, we offer two reasons as to why we think it is countered. First, the results broadly enforce many national modeling studies (by analysts with no inherent conflict of interest) which indicate that the role of coal is likely to continue, even if its share declines. Second, several stakeholders clearly acknowledge that renewables have gotten cheaper and have discussed alternative business opportunities. This points to the broader changes that even coal industry insiders are accounting for. Of course, both industry stakeholders and modelers could be wrong as in the case of reducing solar costs [53] or availability of large, accessible unconventional gas reserves in the United States post-2005 [54]. This often happens in the case of disruptive technological change.

Another potential source of biases may potentially occur in the case of technologies such as CCS. Our findings here echo previous work around the skepticism to CCS even as views towards CCU are more positive [55]. This could potentially be due to loss aversion, where individuals/organization tend to weigh negative consequences more heavily than positive ones [56]. In the case of CCS, while the higher costs are alluded to by all the stakeholders familiar with it, they do not mention its role in reducing stranded assets or improving air quality.

5. Conclusions

The literature of coal transitions, or fossil fuels in transition in general, has increased considerably using both integrated assessment modeling and social science methods. Increasingly, practitioners have felt a need to increase the realism of these findings based on regional considerations and socio-technical features.

Despite large number of modeling studies showing a decline of coal, respondents overwhelmingly pointed to the inevitability of coal continuing in the energy mix. Most respondents agreed that the peak coal use in India will be 1.2–1.4 billion tonnes. This is consistent with the aggressive increase in coal production over the previous two fiscal years and Coal India Limited's plan to increase underground mining capacity. This is not to say that respondents viewed renewables pessimistically. In fact, all the respondents acknowledged the reduction in cost of electricity generation for solar by a factor of 7–8. The increase in both coal and solar simultaneously could very well be needed for India to meet its human development index (HDI) targets. Currently, India's per-capita final energy consumption is 21 GJ/year while it would need to increase by 2.5–3.5 times to reach HDI levels above 0.9 [29,57]. This has been termed as development-led energy transition in the Indian context.

An increase in coal use will have to be accompanied with an increase in end-of-pipe mitigation approaches in the form of CCUS. The literature indicates a substantial addition of CCS (relying on geologic storage). In contrast, Indian stakeholders showed a much more positive outlook towards CCU in view of the additional revenue streams. This is, in fact, consistent with studies in the European Union. CCU pathways are inherently different from CCS in the fate and durability of carbon storage. As such, we recommend better representation of CCU pathways (particularly methanol) in equilibrium models to understand overall investment requirements. At the same time, establishing life-cycle scrutiny protocols should be undertaken at priority.

Finally, coal transitions in India will occur at the interface of technological and societal change. It is imperative to understand these two evolutions in parallel. Respondents generally acknowledged that the workforce will have to change in some way as the energy transition accelerates. Financing just transitions would be crucial, particularly as coal mining workers are well paid. Employee reskilling would need to be a priority area for corporations even as they search for alternative business models.

CRediT authorship contribution statement

Udayan Singh: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Saritha Sudharmma Vishwanathan:** Writing – review & editing, Validation, Software, Investigation. **Amit Garg:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Ajay K. Singh:** Writing – review & editing, Resources, Project administration, Methodology. **Srinath Haran Iyer:** Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

A.G. reports financial support was provided by Federal Ministry for the Environment Nature Conservation Nuclear Safety and Consumer Protection. S.H.I. reports a relationship with GE Vernova that includes: employment. A.G., U.S., S.S.V., and A.K.S. are editorial board members and/or guest editors of this journal but are not associated with handling of this manuscript.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2025.100188.

Data availability

Excerpts from stakeholder responses that formed that basis of our findings are appended in the Supplementary Information section. Other study details are available from the authors upon reasonable request.

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