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Article

Clean Coal as a Transitional Buffer: A Critical Study of Livelihood Strategies Amid South Africa's Energy Decarbonisation

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Abstract: As the global momentum toward decarbonisation accelerates, coal-dependent economies face the dual imperative of reducing emissions while safeguarding livelihoods. South Africa, which relies on coal for over 85% of its electricity and employs more than 90,000 individuals directly in coal mining, stands at a critical crossroads. This paper examines whether Clean Coal Technologies (CCTs), including ultra-supercritical combustion, fluidised bed systems, and carbon capture and storage, can serve as a viable transitional solution within a just energy transition framework. Through a multi-dimensional analysis, the paper explores the employment potential of CCTs compared to renewable energy pathways, evaluates the scalability and environmental trade-offs of each approach, and contextualises their socioeconomic impacts, particularly in mono-industrial regions like Mpumalanga and Lephalale. Case studies from global experiences in the United States, China, India, and Australia are used to draw comparative insights. Special focus is given to South Africa's experience with CCT deployment through Eskom and Sasol, including performance, design challenges, and carbon intensity. The paper argues that while CCTs may offer short-term mitigation of job losses and continuity for industrial operations, their long-term viability is constrained by cost, partial emissions reduction, and infrastructure limitations. Conversely, renewable-based transitions, although requiring more systemic restructuring and reskilling, offer higher employment multipliers, decentralised development opportunities, and greater environmental co-benefits. The study concludes with strategic recommendations for South Africa, including defining CCTs as transitional buffers with exit strategies, enhancing retraining programs, leveraging green finance, and fostering international collaboration. Ultimately, a just transition must be guided not solely by technology, but by integrated policies that prioritise both decarbonisation and socioeconomic equity.

Keywords: clean coal technologies; just energy transition; coal-dependent economies; employment and reskilling; renewable energy transition

1. Introduction

As the world intensifies efforts to decarbonise its energy systems in response to the climate crisis, coal, the most carbon-intensive fossil fuel, has become a symbol of both environmental degradation and economic dependency. South Africa stands at a unique and precarious crossroads in this transition [1]. Ranked among the top coal-producing countries globally, South Africa relies heavily on coal not only as its primary energy source but also as a foundational pillar of its economy. Coal accounts for nearly 85% of the country's electricity generation, with the bulk supplied by state-owned utility Eskom [2-3]. Beyond its centrality to power production, coal mining also underpins the livelihoods of hundreds of thousands of workers and supports broader regional economies, particularly in provinces like Mpumalanga and Limpopo [4].

The potential implications of a rapid shift away from coal in such a context are immense. The South African coal sector directly employs nearly a hundred thousand individuals and indirectly supports hundreds of thousands more through local procurement chains, transportation, small-scale

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commerce, and informal sector activities [5-6]. As many of these jobs are concentrated in rural or peri-urban communities with limited economic diversification, the loss of coal-related employment would not only affect individual workers, but entire communities and regions. The threat is not hypothetical. Global investment patterns are already pivoting sharply toward renewables, multilateral lenders are withdrawing support for coal-based projects, and local power procurement plans increasingly prioritise clean energy sources. Consequently, the livelihoods of millions of people, breadwinners and their dependents, are at risk as the coal economy contracts in response to global decarbonisation imperatives.

In light of this, the concept of a Just Energy Transition (JET) has emerged as a cornerstone of national and international climate policy discussions. At its core, JET seeks to ensure that the transformation of energy systems is inclusive, equitable, and does not leave vulnerable communities behind. It aims to balance climate action with social justice by providing support mechanisms such as retraining, economic diversification, and social protection to those most affected by the shift away from fossil fuels [7-8]. In South Africa, JET is particularly salient. The government's Presidential Climate Commission has framed JET as a developmental opportunity, one that must involve public participation, respect for local contexts, and prioritisation of vulnerable populations [9]. Yet, in operationalising JET, a significant debate has emerged over the possible role of Clean Coal Technologies (CCTs).

CCTs refer to a suite of technologies designed to improve the environmental performance of coal utilisation by reducing emissions and increasing efficiency [10]. These include coal washing, integrated gasification combined cycle (IGCC), fluidised bed combustion, and post-combustion technologies such as carbon capture, utilisation, and storage (CCUS). While such technologies do not eliminate the emissions associated with coal burning entirely, they promise substantial reductions in particulate matter, sulphur dioxide, nitrogen oxides, and, most importantly, carbon dioxide. Proponents argue that CCTs could serve as an interim solution that preserves jobs and economic stability in coal-dependent regions while buying time for renewable alternatives to mature and scale [11]. Moreover, given South Africa's substantial investment in coal infrastructure and skilled workforce, clean coal technologies are viewed by some as a pragmatic path to harmonise economic and environmental goals during the transition period [12-13].

However, the narrative of clean coal as a "saviour" of threatened livelihoods is not without contention. Critics question the feasibility, cost-effectiveness, and long-term sustainability of CCTs [11-12][14]. Many projects touted as clean coal initiatives have encountered technical, financial, or regulatory challenges [14-15]. For instance, the much-publicised Kemper County IGCC project in the United States was ultimately abandoned after significant cost overruns, while CCUS facilities have been criticised for underperforming relative to their capture targets. Moreover, some environmental scientists argue that CCTs may serve to delay genuine transformation, locking nations into fossil fuel dependency under the guise of innovation. There is also concern about the socio-political economy surrounding CCTs, namely, that they often favour large industrial players and foreign technology providers, offering limited direct benefits to the communities whose livelihoods are most at stake [15].

Amid these debates, the central question arises: Can clean coal technologies offer a viable and just pathway for safeguarding livelihoods in coal-dependent economies such as South Africa's during the transition to green energy? This paper aims to critically examine this question by exploring the intersection of technological feasibility, economic sustainability, environmental impact, and social justice. It investigates whether CCTs can realistically serve as a bridge to a greener future without perpetuating environmental harm or reinforcing existing inequalities. To do so, the analysis will draw on both international case studies and local empirical realities, assessing South Africa's unique infrastructural, policy, and socio-economic conditions.

By framing the discussion within the broader philosophy of Just Energy Transition, this paper seeks not only to evaluate clean coal on its technical and economic merits but also to consider its role in shaping a transition that is socially inclusive and ethically defensible. The paper will argue that while clean coal may provide temporary relief in terms of job preservation and energy security, it cannot substitute for a long-term commitment to a truly sustainable and equitable energy system.

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Rather than being viewed as an end, clean coal, if pursued, must be situated within a time-bound, strategically managed transition framework that prioritises ultimate decarbonisation, worker empowerment, and community resilience.

The findings and insights from this study extend well beyond South Africa's borders. Nations such as India, China, Indonesia, Poland, Australia, and the United States, all with significant coal production and coal-fired power dependencies, face similar dilemmas in balancing decarbonization with socio-economic stability. The viability of clean coal as a transitional buffer must be evaluated globally within the contexts of local livelihoods, energy security, and climate commitments. Therefore, while this research focuses on the South African context, its conclusions and recommendations contribute to the broader discourse on equitable energy transitions in coal-dependent economies worldwide.

2. The Landscape of Coal Dependency and Vulnerable Livelihoods

South Africa remains one of the most coal-dependent nations globally, both in terms of energy production and economic reliance. Coal constitutes approximately 85% of the country's electricity generation, predominantly supplied to the grid by Eskom, the national utility [5-6]. The country ranks as the seventh-largest coal producer in the world and holds the third-largest proven coal reserves in Africa, following Nigeria and Mozambique. Most of South Africa's coal is mined in the Mpumalanga and Limpopo provinces, where extensive infrastructure and decades-old socio-economic systems have been built around coal exploitation [16-17].

IAs per the U.S. Energy Information Administration, Country Analysis Brief: South Africa issued in 2024, and ESKOM Integrated Report for the year 2023, South Africa produced 224 million tonnes of coal, of which about 70 million tonnes were exported, primarily to India, China, Pakistan, and Europe during the Russian fuel supply crisis. Coal export revenues contribute significantly to the national balance of payments and provide essential foreign exchange earnings. Eskom alone consumes over 100 million tonnes of coal per year, feeding power stations such as Kendal, Matimba, Medupi, and Kusile.

The country's dependence on coal extends to industrial use as well. South Africa's globally unique coal-to-liquid (CTL) technology, developed and commercialised by Sasol, accounts for nearly 30% of the nation's liquid fuel production, further embedding coal in the industrial landscape [18]. Such multi-layered dependence places South Africa in a particularly vulnerable position as global finance, trade, and climate policies increasingly penalize coal-intensive economies [19].

Coal is not merely an energy commodity in South Africa; it is a socioeconomic cornerstone. As of 2022, the coal mining industry directly employed 90,977 individuals, according to the Minerals Council South Africa (Facts and Figures 2022). Beyond these formal jobs, an estimated 170,000 to 250,000 jobs are indirectly supported through value-chain linkages, including coal transport, maintenance services, supplier contracts, small-scale commerce, and informal sector activities [5-6].

According to [20-22], Transnet Freight Rail, the state-owned rail operator, employs thousands of workers to transport coal to domestic power stations and export terminals, including the Richards Bay Coal Terminal (RBCT), which is also a significant employer in KwaZulu-Natal. Local economies, particularly in Mpumalanga towns such as eMalahleni, Ogies, Bethal, and Secunda, have developed around coal mining clusters. These towns largely rely on coal for their economic activities, supporting a range of workers, traders, contractors, and service providers.

In some municipalities, more than 60% of household income is directly or indirectly linked to coal-related activities. In areas like Lephalale, which hosts the Matimba and Medupi power stations, even municipal revenues are tied to coal through taxes and services related to the industry. A study by TIPS (Trade & Industrial Policy Strategies) in 2021 found that the multiplier effect of one coal job in South Africa sustains 2.5–3.0 additional dependents across family and local economic structures. This suggests that job losses in the coal industry can trigger cascading effects on over half a million livelihoods nationwide [5,21,23].

Moreover, as it has been reported by [5,24] and the TIPS (Trade and Industrial Policy Strategies) publication, SOC mandates, outcomes and the COVID-19 pandemic in 2020, the demographic profile of coal workers reveals additional vulnerability. Most are low- to semi-skilled workers, with limited

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post-secondary education. Approximately 87% of coal workers are male, and the majority are in the 35–55-year age group, implying limited prospects for re-employment in other sectors without targeted reskilling. The highly specialised nature of coal-related work, such as dragline operators or underground blasters, does not lend itself easily to rapid transition into green energy sectors like solar or wind.

Multiple independent studies have attempted to model the impact of a coal phase-out in South Africa. The Council for Scientific and Industrial Research (CSIR) forecasts that, under an accelerated energy transition aligned with the country's Nationally Determined Contributions (NDCs), over 50,000 direct coal mining jobs could be lost by 2035 [16, 25-26]. The National Planning Commission projects that by 2050, fewer than 10,000 jobs may remain in coal mining, assuming a near-complete transition to renewables and gas.

According to [27], the regional implications of such transitions are especially concerning. Mpumalanga province, which currently hosts over 75% of all coal-fired generation and coal mining activity, is identified as the most exposed to economic disruption [28]. The province faces not only job losses but also secondary effects such as:

- Depopulation of mining towns
- Declining property values and municipal revenues
- Closure of small businesses and educational institutions
- Erosion of social services and public health infrastructure

A 2023 study by the Presidential Climate Commission reported that certain "mono-industrial towns" in Mpumalanga may face collapse if transition plans do not include comprehensive social cushioning, retraining, and local economic diversification strategies. Furthermore, regional job loss will exacerbate urban migration, pressuring already overburdened metropolitan areas like Johannesburg and Tshwane.

The informal sector, often uncounted in official statistics, is also at risk. This includes informal traders selling food, goods, and services around mining operations, as well as backyard mechanics, recyclers, and subsistence farmers who rely on coal industry residuals such as coal ash or water runoff. The social implications are significant and extend to increased poverty rates, food insecurity, and potential social unrest in regions where coal is the economic lifeblood.

In addition, the planned early decommissioning of coal-fired power plants by Eskom as part of the Just Energy Transition Investment Plan (JET-IP), supported by international partners, is expected to accelerate this decline. Between 8 and 10 gigawatts of coal capacity are slated for retirement by 2035, necessitating immediate strategic planning to cushion affected communities [26, 29].

In brief, the South African coal sector embodies a complex intersection of energy dependence, economic imperatives, and social realities. The transition away from coal, though environmentally urgent, presents a multifaceted threat to livelihoods, especially in rural and peri-urban regions deeply entwined with the industry. Without a robust, equitable, and well-sequenced transition framework, the socioeconomic fallout from the coal phase-out could be profound. Any discussion on clean coal technologies or interim mitigation strategies must be anchored in the realities of these vulnerable communities and the vast employment ecosystem sustained by coal.

3. Clean Coal Technologies: Concepts, Classifications, and Global Experiences

Clean Coal Technologies (CCTs) refer to a suite of technological innovations and operational strategies aimed at improving the efficiency of coal utilization while mitigating its environmental impacts. Contrary to its colloquial use, "clean coal" does not imply a pollution-free fossil fuel, but rather a comparative reduction in harmful emissions such as carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter, relative to conventional coal combustion processes. CCTs encompass both pre-combustion and post-combustion solutions that aim to optimise fuel use, enhance energy output, and reduce the ecological footprint of coal-fired power generation and industrial usage.

The conceptual emergence of clean coal is largely a response to mounting pressure from environmental regulations, carbon pricing mechanisms, and international climate accords. While coal remains abundant and cost-effective in many regions, its environmental liabilities, especially CO_2

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emissions, have placed it under intense scrutiny. Thus, CCTs have been framed as transitional tools that can potentially reconcile the demand for energy security and the imperatives of climate change mitigation.

Clean Coal Technologies can be broadly classified into the following categories:

- Pre-Combustion Technologies: These involve treating coal before combustion to reduce its environmental impact.
- Coal Washing and Preparation: Reduces ash and sulfur content, thus improving combustion efficiency and reducing pollutants.
- Coal Gasification: Converts coal into syngas ($CO + H_2$), which can be used for power generation, chemical synthesis, or hydrogen production. This includes Integrated Gasification Combined Cycle (IGCC) plants.
- Underground Coal Gasification (UCG): In-situ gasification of coal seams underground, reducing surface disruption.

Combustion-Based Technologies: These are designed to enhance the efficiency and reduce the emissions during combustion.

- Fluidised Bed Combustion (FBC): Burns coal at lower temperatures to reduce NO_x formation and allows in-bed removal of SO_2 using limestone.
- Low-NOx Burners: Modify flame temperature and oxygen concentrations to reduce NO_x emissions during combustion.
- High-Efficiency, Low Emission (HELE) Plants: Such as supercritical and ultra-supercritical boilers that operate at higher temperatures and pressures to enhance thermal efficiency.

Post-Combustion Technologies: These target the removal of pollutants from flue gases after combustion.

- Flue Gas Desulfurisation (FGD): Removes sulfur dioxide using wet or dry scrubbing methods.
- Electrostatic Precipitators and Fabric Filters: Capture particulate matter.
- Carbon Capture, Utilisation and Storage (CCUS): Captures CO_2 for either underground storage or conversion into useful products like chemicals or construction materials.

The research and development in CCTs aim to address three core challenges:

1. Reducing Greenhouse Gas Emissions: Especially in countries heavily reliant on coal for electricity and industrial processes.
2. Improving Efficiency of Energy Conversion: Enabling greater energy output per unit of coal.
3. Enabling Transition Pathways: Allowing coal-reliant economies to decarbonise gradually while maintaining energy security and economic stability.

The scope of CCTs extends beyond energy systems to include environmental engineering, materials science (e.g., corrosion-resistant alloys for supercritical boilers), and chemical process engineering (e.g., catalysts for syngas conversion).

Several cases and reviews reported elsewhere provide a good insight into the current perspectives of CCTs, as given below.

United States: The U.S. has invested heavily in coal gasification and CCUS. The Kemper County IGCC project in Mississippi was designed to be a flagship CCT facility but suffered severe cost overruns and delays, ultimately being repurposed to run on natural gas. The Kemper project faced significant delays and cost overruns, with expenses exceeding $4 billion, highlighting challenges in implementing clean coal technologies [30].

Meanwhile, the Petra Nova project in Texas was among the few commercial-scale CCUS initiatives but was mothballed in 2020 due to economic challenges and low oil prices. Analysis of Petra Nova's closure reveals financial and operational challenges, including a 16% shortfall in CO_2 capture and reliance on high oil prices for profitability. [31-32].

China: China has been at the forefront of implementing ultra-supercritical coal-fired power plants, which offer higher efficiency and lower emissions compared to traditional coal plants. In this regard, China leads globally in CCT implementation. It has built multiple ultra-supercritical coal plants and is pioneering large-scale CCUS pilots, including the Shenhua CCUS project, which captures over 100,000 tonnes of CO_2 per year, demonstrating China's commitment to integrating

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CCUS with industrial operations to enhance scalability and reduce costs. The country integrates CCTs with industrial parks and chemical facilities to reduce costs and enhance scalability.

According to the Global Energy News Report released in 2024 under the title "China remains world leader in clean coal-fired power generation technologies", China has significantly advanced the deployment of ultra-supercritical (USC) coal-fired power plants. By early 2024, USC plants constituted 32% of China's operating coal-fired thermal power plants (TPPs) and accounted for 93% of those under construction. These plants achieve thermal efficiencies between 44% and 46%, surpassing the 33%–37% efficiency range of subcritical units. Higher efficiency translates to reduced coal consumption and lower greenhouse gas emissions per unit of electricity generated.

A news report released by the Ministry of Ecology and Environment of the People's Republic of China in 2012 (under the title "China's First CCS Project Captures 40,000 Tonnes of CO2"), the Shenhua Group initiated China's first carbon capture and storage (CCS) demonstration project in Inner Mongolia. Between 2011 and 2012, the project successfully captured and stored over 40,000 tonnes of CO_2 in saline aquifers. This project demonstrated China's capability to implement the entire CCS process, from CO_2 capture to underground storage, marking a significant milestone in the country's efforts to reduce carbon emissions from coal-based industries.

As it was reported by [33], China is strategically integrating clean coal technologies with industrial parks and chemical facilities to enhance scalability and reduce costs. The GreenGen project in Tianjin exemplifies this approach. It's a $1 billion initiative aimed at developing near-zero-emissions coal-based electricity generation, hydrogen production, and CCS. By co-locating power generation with industrial processes, China aims to maximize resource efficiency and minimize environmental impact.

India: India has implemented Fluidized Bed Combustion (FBC) and low-NOx burner technologies in several new-generation plants to improve combustion efficiency and reduce emissions. The NTPC Dadri plant has piloted post-combustion CO_2 capture. However, infrastructural and financial barriers continue to hinder widespread adoption.

Garg et al [34] discussed the adoption of advanced coal technologies in India, including Atmospheric Fluidized Bed Combustion (AFBC) and Pressurised Fluidised Bed Combustion (PFBC). It highlights how these technologies improve combustion efficiency and reduce emissions, making them suitable for India's varied coal quality. The study emphasizes the need for policy support to accelerate the deployment of such clean coal technologies.

Shaw and Mukherjee [35] critically reviewed India's initiatives in carbon capture and storage, focusing on pilot projects like the one at NTPC Dadri. It details the technical aspects of post-combustion CO_2 capture and the challenges faced in scaling up such projects, including high costs and the need for supportive infrastructure.

Luthra et al [36] identify and rank the major barriers to the adoption of renewable and sustainable energy technologies in India. It categorizes barriers into economic, financial, technical, and policy-related challenges, providing a comprehensive overview of the obstacles hindering the widespread implementation of clean energy solutions.

Australia: Australia has supported High-Efficiency, Low-Emission (HELE) technologies, including supercritical and ultra-supercritical plants, through governmental policies aimed at reducing emissions from coal-fired power generation. Despite policy support, CCUS adoption in Australia remains limited due to economic viability concerns and geological uncertainties related to CO_2 storage.

In their report, [37] examine the performance of Australia's supercritical coal-fired power stations, revealing that these newer plants have not demonstrated superior reliability compared to older subcritical units. The findings suggest that while HELE technologies are promoted for their efficiency and lower emissions, their operational reliability in the Australian context has been questionable.

Andrew et al [38] discuss the challenges of investing in CCS hubs in Australia, emphasizing the uncertainties related to sub-surface storage capacities. It highlights the need for comprehensive geological assessments to ensure the viability of long-term CO_2 storage, which is crucial for the success of CCUS projects.

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Michael et al [39] comprehensively evaluate the feasibility of establishing CCUS hubs in Western Australia, considering both technical and economic factors. It identifies potential industrial clusters and suitable geological formations for CO_2 storage, while also discussing the economic challenges and infrastructure requirements for successful implementation.

South Africa: South Africa's reliance on coal, particularly for electricity and liquid fuel production, has led to an interest in CCTs. Eskom, which operates one of the largest coal-fired power fleets globally, has invested in supercritical plants like Medupi and Kusile, though both have faced design flaws and cost escalations [40]. This study investigates the factors contributing to schedule delays and cost escalations in South Africa's major energy projects, specifically Medupi and Kusile. The authors identify key issues such as inadequate project planning, design flaws, and poor contractor performance. The paper emphasizes the need for improved project management practices to mitigate such challenges in future infrastructure developments.

Inglesi-Lotz and Blignaut [41] assess the opportunity cost of water usage by the Kusile and Medupi coal-fired power plants. Given South Africa's water scarcity, the authors analyze the trade-offs between water allocation for power generation versus other potential uses. The study provides insights into the broader economic and environmental implications of large-scale coal-fired power projects in the country.

Sasol, a global pioneer of coal-to-liquid (CTL) technology, operates the Secunda plant, the world's largest CTL facility. While this industrial complex is technologically advanced, it is also one of the largest single-point emitters of greenhouse gases globally. Efforts have been made to integrate energy efficiency and carbon capture initiatives, but scalability and cost remain significant barriers. Looking deep into the matters related to the project, [42] evaluate the potential role of CCS in South Africa's energy sector, highlighting the Secunda CTL plant as a significant point source of CO_2 emissions. The authors discuss the technical feasibility of capturing CO_2 from such facilities and the economic implications of implementing CCS at scale. They note that while CTL plants like Secunda are ideal candidates for CCS due to their high-purity CO_2 streams, the high costs and infrastructural requirements pose substantial barriers.

South Africa's potential for deploying CCUS is currently being explored, particularly in the Lephalale area, where geological formations may support long-term CO_2 storage. However, pilot projects have not yet moved beyond the feasibility stage due to regulatory, financial, and infrastructure constraints.

Clean Coal Technologies, though not a panacea, can play a transitional role in coal-reliant economies seeking to align with global climate targets while maintaining economic stability. As one may get a clear insight into the matter from the above case studies and reviews, it is evident that despite substantial investment, CCTs have faced numerous challenges. Their effectiveness is contingent upon techno-economic viability, institutional readiness, and coherent integration with broader decarbonisation strategies. As global momentum shifts towards net-zero, CCTs should be viewed as interim solutions requiring stringent oversight, clear timelines, and alignment with the principles of a JET.

For easy reference, we summarise below the points that have already been discussed.

- High capital and operating costs: Technologies like IGCC and CCUS are often not competitive with renewables, especially as the price of solar and wind power continues to fall.
- Technical complexity: High-pressure and high-temperature systems require specialised materials and skilled maintenance, often lacking in developing countries.
- Limited carbon mitigation: Most CCTs reduce, but do not eliminate, carbon emissions. Even CCUS has an average capture rate of 80–90%, which still allows for considerable CO_2 release.
- Economic risk: Several high-profile projects (e.g., Kemper, Petra Nova) have been shelved due to cost overruns and inability to secure long-term revenue streams. This may be due to an inadequate cost-benefit analysis of implementing clean coal, along with its capital intensity and operational costs. Additionally, one should consider the potential for job creation in the value chain, such as logistics for CCUS and plant retrofitting.

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- Risk of technology lock-in: Prolonged dependence on CCTs may delay deeper transitions to zero-carbon technologies and infrastructure. Concerns also exist regarding the TRLs of key technologies, grid compatibility, retrofitting challenges, and the gaps in required skills and capacity-building.
- Environmental considerations: CCTs still have residual emissions and an environmental footprint. Long-term impacts of CCUS are leakage, land use, and water consumption. It is recommended to conduct a comparative study on renewables regarding LCOE and lifecycle emissions for improved understanding.
- Policy and institutional readiness: National policies may or may not be in favour of CCTs (e.g., Integrated Resource Plan 2019). Global and domestic financing options exhibit similar trends, such as the Just Energy Transition Investment Plan (JET-IP). Furthermore, regulatory uncertainty, vested interests, and slow adoption remain significant barriers to deployment.

4. Comparative Analysis: Clean Coal Technologies vs. Renewable-Based Job Transition

The global shift toward decarbonization presents both a challenge and an opportunity for economies heavily dependent on fossil fuels, particularly coal. Two major pathways often debated for managing this transition while safeguarding livelihoods are: (1) the continuation of fossil fuel use through Clean Coal Technologies (CCTs), and (2) transitioning to renewable energy sources with accompanying job creation strategies. Each path offers unique implications in terms of technology, economics, environmental impact, and employment. This section critically evaluates the relative merits and limitations of both, with a particular emphasis on their ability to preserve or create livelihoods in coal-dependent regions like South Africa.

CCTs, by design, aim to sustain existing coal-based infrastructures and workforce structures. Their primary employment advantage lies in preserving jobs in existing coal mines, thermal power plants, and related industries (e.g., transportation, maintenance, procurement). For example, the implementation of flue gas desulfurisation (FGD) units, carbon capture, utilisation, and storage (CCUS), or fluidised bed combustion systems typically requires skilled technical maintenance and retrofitting teams, often drawn from the existing workforce. In South Africa, the immediate retention of such positions through CCT deployment appears socio-politically appealing.

In contrast, renewable energy, particularly solar photovoltaic (PV), wind, biomass, and small hydro, offers higher employment multipliers per installed megawatt (MW). According to IRENA (2021), solar PV creates 1.5–2.0 jobs/MW, wind energy 0.7–1.0 jobs/MW, compared to 0.3–0.5 jobs/MW for coal. Moreover, renewables drive job creation across diverse stages: manufacturing (e.g., solar panel and wind turbine assembly), installation, operations and maintenance (O&M), and decommissioning. Several countries, including India, Germany, and the USA, have demonstrated that investment in renewables leads to net positive employment effects even after accounting for fossil fuel job losses.

However, renewable-based job creation typically requires reskilling, geographical relocation, and infrastructure changes, which pose significant transitional barriers for older, semi-skilled coal workers. This challenge is acute in mono-industrial towns, where both job mobility and industrial diversification are limited.

CCTs have a lower barrier to workforce integration because they rely on technologies closely aligned with existing thermal power processes. For example, plant operators trained in subcritical systems can, with minimal upskilling, manage supercritical or ultra-supercritical units. Similarly, coal gasification or CCUS operations share many engineering parallels with conventional chemical and combustion systems.

On the contrary, the renewable energy sector demands a restructured skill portfolio, electrical and electronics knowledge, IT-integrated system operation, and remote sensing for diagnostics. Many coal sector employees, particularly in countries like South Africa, India, and Indonesia, possess limited post-secondary qualifications, making this shift difficult without extensive retraining programs. Furthermore, younger workers are better suited to such transitions, while workers aged 45 and above, who constitute a significant proportion of coal sector employees, are more vulnerable to displacement.

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Nevertheless, international evidence suggests that proactive skills planning can ease this shift. For instance, in Spain's Asturias region, the phased retirement of coal mining was supported by a comprehensive worker transition program, offering early retirement, retraining grants, and relocation assistance.

CCTs, especially those involving CCUS and IGCC, are capital-intensive and often commercially uncompetitive without substantial subsidies. Projects like Kemper County IGCC (USA) and Petra Nova CCUS (USA) were either abandoned or mothballed due to cost overruns, low ROI, and technological complexity. Retrofitting older coal plants with CCTs can cost USD 500–1,200 per kW, while operational costs, especially energy penalties from CO_2 capture, can raise the levelized cost of electricity (LCOE) significantly.

In contrast, the cost of renewable energy technologies has plummeted. Solar PV and onshore wind now have LCOEs below that of new coal in most regions. Moreover, renewables offer scalable deployment, small-scale solar or wind farms can be built in low-infrastructure zones, decentralising power access and stimulating rural employment.

However, initial capital mobilisation for large renewable transitions, including grid upgrades and energy storage, remains a bottleneck. Financing for such transformations is more readily accessible in high-income nations. In developing countries, concessional finance mechanisms (e.g., South Africa's USD 8.5 billion Just Energy Transition Partnership) become crucial to support renewable transitions and social cushioning.

From an environmental perspective, CCTs offer only partial mitigation. While SO_x, NO_x, and particulate emissions can be reduced significantly, CO_2 capture rates average 80–90%, and the downstream handling of CO_2 (especially secure storage) remains a concern. Moreover, reliance on CCTs may lock nations into continued coal dependence, delaying full decarbonisation.

Renewables, by contrast, offer near-zero operational emissions. The primary environmental concerns, land use, resource mining (e.g., lithium, rare earths), and recycling, are increasingly being addressed through lifecycle management and circular economy strategies. Thus, from a sustainability standpoint, renewable energy provides a more enduring solution.

CCTs enjoy greater political acceptability in coal-reliant regions because they present a pathway to "retain jobs while reducing emissions." They offer an illusion of continuity, which is often favoured by local unions and communities wary of abrupt economic shocks. However, this also results in policy inertia, where governments delay necessary structural reforms under the pretext of technological transition.

Renewable energy transitions demand more proactive policy frameworks, including social dialogue, labour market planning, and just transition policies. Countries like Germany (coal commission model) and Canada (federal Just Transition Task Force) have successfully implemented policy architectures that include worker voice and long-term vision.

In South Africa, the Presidential Climate Commission has recognized the value of both approaches, but ultimately leans toward renewables as the end goal, with CCTs playing a bridging role in areas with high socio-economic coal dependency.

The comparative advantage of renewable energy technologies, particularly wind, solar, and green hydrogen, extends beyond emissions reduction into the domain of inclusive economic development. These sectors have demonstrated high employment multipliers, generating more jobs per unit of energy produced than coal. Solar PV and wind alone are estimated to create 1.5 to 2 times more employment opportunities per megawatt compared to conventional coal-fired systems. Moreover, while some level of reskilling is required, many roles in renewable operations, such as electrical installation, mechanical maintenance, and logistics, offer a moderate skills overlap with existing coal sector competencies, facilitating smoother workforce transitions.

Socioeconomic inclusion is another critical advantage of renewables. Their decentralised nature allows for rural deployment, which can empower historically marginalised regions and reduce energy poverty. Innovative ownership models, such as community energy cooperatives and energy commons, enable local populations to participate in and benefit directly from energy production, creating shared prosperity. These participatory structures not only distribute wealth but also foster social cohesion and local governance.

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From a deployment perspective, solar and wind projects offer shorter lead times and modular scalability, enabling quicker implementation in contrast to long-lead clean coal retrofits or CCS infrastructure. This readiness can bridge the energy gap without delaying the overarching imperative of decarbonisation. Moreover, renewables bring significant environmental and health co-benefits. Improved air quality, reduced particulate emissions, and the potential for land rehabilitation on former mining sites collectively contribute to ecosystem recovery and public health improvements. These cumulative advantages make renewable energy not only a viable but a socially and environmentally superior alternative to coal-based technologies in just transition contexts.

In summary, while CCTs offer a practical, short-term solution for preserving jobs in coal-dependent regions, they have significant limitations regarding cost, scalability, environmental impact, and long-term viability. In contrast, renewable energy requires more substantial structural changes and proactive workforce policies, but it has greater potential for job creation, long-term sustainability, and alignment with global decarbonization goals. Therefore, this analysis suggests that CCTs should be viewed as transitional measures rather than final solutions. It's essential to focus on facilitating a fair and inclusive transition toward a renewable energy future.

5. Recommendations in General for Future Work

To maximise the utility of CCTs without undermining long-term decarbonisation goals, several research and policy pathways are recommended:

4. Focus on Hybrid Integration: Combining CCTs with renewable energy (e.g., co-firing biomass with coal) to lower net emissions.
5. Targeted Application in Industry: Reserve CCUS and coal gasification for hard-to-abate sectors such as cement, steel, and chemical manufacturing rather than electricity generation.
6. Improve Cost-Effectiveness: Through modular design, local manufacturing of components, and technology localisation.
7. Accelerate R&D on Low-Cost Capture Methods: Such as membrane separation and solid sorbents for CO_2 capture.
8. Develop Legal and Regulatory Frameworks: For CO_2 storage, monitoring, liability, and ownership rights.
9. Invest in Workforce Transition Programs: To reskill coal workers for roles in clean energy sectors, maintaining social cohesion and labour productivity.
10. Enhance International Collaboration: Especially among countries like South Africa, India, and Indonesia that share similar energy challenges and socioeconomic structures.

6. Strategic Recommendations for South Africa

Realistic role of clean coal in a just transition: CCTs should be positioned not as a long-term solution but as a short-term transitional buffer to protect critical livelihoods during the initial phases of energy decarbonisation. South Africa must clearly define exit strategies for CCTs, specifying timelines for decommissioning or repurposing coal infrastructure to avoid technological lock-in and ensure alignment with national net-zero commitments. These timelines must be transparent and embedded in integrated resource plans.

Furthermore, the role of CCTs should be strategically embedded in hybrid energy models, for instance, co-firing biomass in ultra-supercritical plants or coupling Integrated Gasification Combined Cycle (IGCC) systems with renewable hydrogen. Additionally, low-carbon industrial clusters, such as in Mpumalanga, can be developed where CCTs (e.g., gasification or partial CCUS) support hard-to-abate sectors like steel, cement, and chemicals while maintaining industrial activity and employment during the transition phase.

Institutional and workforce measures: To enable labour continuity and transformation, the government must establish formal retraining programs tailored to future energy needs, solar PV installation, wind turbine maintenance, battery systems, green hydrogen, and energy efficiency retrofits. These must be geographically localised to areas of coal dependency and developed in collaboration with TVET colleges, industry associations, and unions. Emphasis should be placed on recognising prior learning (RPL) and modular certification to accelerate workforce readiness.

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Simultaneously, local economic diversification is critical. Municipal Integrated Development Plans (IDPs) should embed initiatives such as agro-processing hubs, digital infrastructure deployment, and ecotourism development to provide alternative employment anchors, particularly in mono-industrial towns like eMalahleni, Lephalale, and Ogies.

Policy and Financial Instruments: South Africa should establish conditional public funding for CCT deployment, tying financial support to measurable job preservation or creation benchmarks, as well as emission reduction thresholds. This ensures that any investment in clean coal does not become a subsidy for stagnation but a driver of managed transformation. Criteria for such conditionality could include minimum capture efficiency for CCUS projects, use of local labour, and timelines for technology phase-out.

In parallel, green financial instruments, such as climate-aligned bonds, Just Transition-linked loans, and concessional climate finance, should be mobilised for dual transition investments. These include co-financing retraining programs, expanding transmission infrastructure for renewables, and repurposing brownfield sites for clean energy or industrial retooling. Partnerships with the Development Bank of Southern Africa (DBSA), IDC, and global green finance institutions can de-risk these investments.

International collaboration: Given the high capital cost and technological complexity of CCTs and renewables alike, South Africa must deepen international partnerships for technology access and capacity building. Bilateral and multilateral arrangements should prioritise technology transfer agreements under the UNFCCC framework and intellectual property sharing for scalable applications such as low-cost post-combustion CO_2 capture or gasification-coupled hydrogen synthesis.

Research partnerships with institutions in Germany, China, the U.S., and Japan, countries with active CCT and CCUS programs, should be leveraged to build South Africa's local R&D capacity. Additionally, mechanisms like Article 6 carbon markets under the Paris Agreement should be utilised to monetise verified emission reductions from clean coal retrofits and carbon-neutral renewable expansions

7. Conclusions

South Africa's heavy reliance on coal for electricity generation and industrial applications has created a socio-economic structure deeply interwoven with fossil fuel dependence. The threat of widespread job losses in the coal sector as the country transitions toward low-carbon energy sources presents not only a technological challenge but a moral imperative for social justice. Clean Coal Technologies (CCTs) have been positioned by some policymakers and technologists as a transitional mechanism to preserve livelihoods while decarbonising energy systems. This paper critically examined the practicality, limitations, and socio-economic implications of such an approach.

While CCTs, such as supercritical boilers, fluidised bed combustion, and carbon capture and storage, can moderately reduce emissions and retain a portion of the existing workforce, they are capital-intensive, operationally complex, and ultimately only a partial solution to climate change. Their deployment should be viewed as a short-term buffer, not a long-term pathway. Comparative analysis with renewable energy transitions reveals that the latter offer greater job creation potential, broader socio-economic inclusivity, and superior environmental and health co-benefits—albeit with higher requirements for institutional readiness, workforce reskilling, and infrastructure investment.

The South African context demands a balanced, phased strategy. Clean coal can serve a limited role in bridging the energy and employment gap, particularly in vulnerable regions like Mpumalanga, but it must be accompanied by clearly defined exit strategies. Simultaneously, proactive investment in renewable energy, skills development, economic diversification, and local empowerment is critical. International collaboration and green finance must support this dual transition.

In sum, a just energy transition must prioritise people alongside technology. It must ensure that no community is left behind, and that South Africa's energy future is not only cleaner, but also fairer and more resilient.

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