Mitig Adapt Strateg Glob Change (2025) 30:48
https://doi.org/10.1007/s11027-025-10230-z

Circular economy and energy transition: a review of South Africa's 5-year just energy transition investment plan (JET-IP)

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Received: 4 October 2024 / Accepted: 14 May 2025

Abstract
Over the past decade, the term "*circular economy*" has become increasingly important, particularly in the areas of sustainability, resource management, and productivity. This concept is now being actively considered and implemented by national, public, and private organisations worldwide. As concerns about the impacts of climate change increase, so do discussions about mitigating its consequences. An important aspect of this discourse is the shift from fossil fuels to renewable energy sources. Recognising the unacceptable phenomenon of climate change, particularly global warming, the South African government has committed to reducing greenhouse gas (GHG) emissions and promoting green mobility through the Just Energy Transition Investment Plan (JET-IP). This study aims to provide a critical review of South Africa's JET-IP, evaluating the feasibility of the proposed decarbonization of the energy sector by identifying key constraints and opportunities for a successful transition. The approach involved a critical review of South Africa's Just Energy Transition (JET) policy documents, government documents, and related publications, focusing on the 5-year transition plan. The emphasis is on the status and opportunities of the five-year (2023–2027) JET-IP in South Africa, considering the potential of renewable energy sources in the country. The study reveals that South Africa's 5-year JET-IP faces two interconnected challenges that hinder its feasibility and smooth implementation: the slow deployment of renewable energy sources and obstacles to ensuring reliable and affordable energy. These challenges stem from resistance to decommissioning coal-fired power generation and austerity-driven utility policies. The study offers perspectives and proposes strategic pathways to accelerate the integration of renewable energy technologies into the country's current energy mix. The findings provide insights into South Africa's Just Energy Transition, applicable to fossil fuel-dependent countries, particularly in the coal-reliant Global South.

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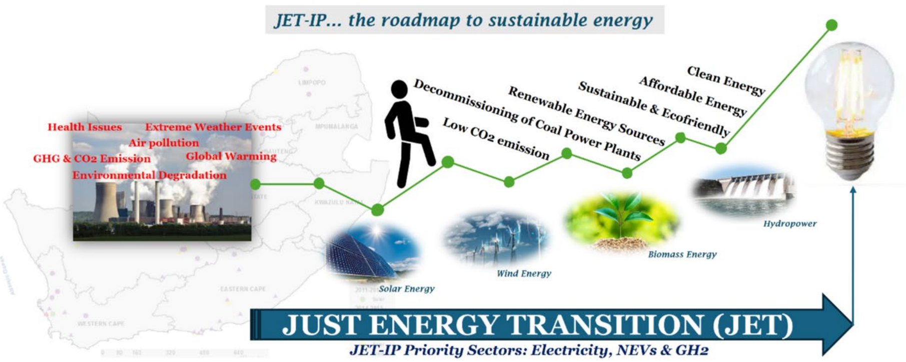
Published online: 23 July 2025

Graphical abstract



Keywords Climate change · Coal · Electricity · Green hydrogen · JET-IP · New energy vehicles · Renewable energy · South Africa

Acronyms

ACT-IP	Accelerating Coal Transition Investment Plan
ADB	African Development Bank
AFD	French Development Agency
CBAM	Carbon Border Adjustment Mechanism
CIF	Climate Investment Fund
COGTA	Cooperative Government and Traditional Affairs
COP29	29Th United Nations Climate Change Conference, or Conference of the Parties
DBSA	Development Bank of South Africa
DFIs	Development Finance Institutions
DMRE	Department of Mineral Resources and Energy
EEPBIP	Energy Efficiency in Public Buildings and Infrastructure Programme
EIA	Environmental Impact Assessment
ERA	Electricity Regulation Amendment Act
ESKOM	Electricity Supply Commission (of South Africa)
EU	European Union
EV	Electric Vehicle
FBE	Free Basic Electricity
FDI	Foreign Direct Investment
G20	Group of twenty of the world's largest economies formed in 1999
GDP	Gross Domestic Product
GH_2	Green Hydrogen
GHG(s)	Greenhouse gas(es)
ICE	Internal Combustion Engine
IDC	Industrial Development Corporation
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producers

IRP	Integrated Resource Plan
JET	Just Energy Transition
JET-IP	Just Energy Transition Investment Plan
JETP	Just Energy Transition Partnership
JTC	Just Transition Commission
MDBs	Multilateral Development Banks
NDC	National Determined Contribution
NECOM	National Energy Crisis Committee
NERSA	National Energy Regulator of South Africa
NEV(s)	New Energy Vehicle(s)
OECD	Organization for Economic Cooperation and Development
PCC	Presidential Climate Commission
PMU	Project Management Unit
PPAs	Power Purchase Agreements
PPCA	Powering Past Coal Alliance
PV	Photovoltaics
RE	Renewable Energy
REs	Renewable Energy Sources
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
SA or ZAF	South Africa
SADC	Southern African Development Community
SAREM	South African Renewable Energy Masterplan
SDG(s)	Sustainable Development Goal(s)
SDZ	Skills Development Zones
SMEs	Small and Medium-sized Enterprises
SSEG	Small-scale Embedded Generation
SWOT	Strengths, Opportunities, Weaknesses, and Threats
TDP	Transmission Development Plan
TES	Total Energy Supply
TFC	Total Final Consumption
UNFCCC	United Nations Framework Convention on Climate Change (UNFCCC)
ZAR	South African Rand

1 Introduction

Despite global efforts to minimise the use of fossil fuels (Jewell et al. 2019), coal continued to make a major contribution to global electricity production in 2021, accounting for more than one-third and leading to record emissions of carbon dioxide (CO_2) (Mirzania et al. 2023). Despite efforts to mitigate climate change (van Voss & Rafaty 2022), 40% of the increase in global CO_2 emissions in 2021 is due to the resurgence of coal (IEA 2022), especially in developing countries, which are responsible for over 60% of greenhouse gas (GHG) emissions. The International Energy Agency (IEA) forecasts a stable trend in coal consumption until 2025 (Renewables 2021), which is due to falling demand in industrialised countries offset by rapid expansion in emerging Asian countries (Jakob et al. 2020). Therefore, the urgency to decrease global coal production is of utmost importance, which has led Australian researchers to call for a Coal Elimination Treaty (CET) (Burke & Fishel 2020). Notwithstanding the importance of global coalitions and treaties for fossil fuel phase-out, the translation of commitments into effective national action faces challenges that go beyond political barriers (Hyun et al. 2023)."Feasibility constraints"provide a way to explore these barriers and serve as a boundary concept for energy policy discussions between different disciplines and stakeholders (Islar et al. 2017).

The European Union (EU) has been at the forefront of advancing technologies and implementing measures to utilise renewable energy sources (REs) and combat climate change (Okpanachi et al. 2022). However, progress in this transition varies across EU Member States (Müller et al. 2021), with the Global North leading the way in these efforts. In contrast, the transition to alternative energy sources in the countries of the global South, particularly in Asia and Africa, is characterised by various approaches. Although there is less available information on the clean energy transition and initiatives in Africa compared to the EU, there is significant focus on this area in academic and policy circles (Koutoudjian et al. 2021). This growing interest is driven by concerns over GHG emissions, aspirations for a fossil fuel-free future, increasing economic uncertainty in the post-COVID era, and the imperative to build post-COVID resilience, all of which have collectively fuelled renewable energy policy initiatives (van der Voorn et al. 2021, 2022). This pressure is fuelled by the need to enhance technological innovation, improve competitiveness and stimulate African economic development. However, just like the EU, Africa's expansion has been uneven due to the several policy objectives of different governments across the continent, with certain regions receiving less scientific interest than others.

Africa's contribution to the global transition to renewable energy is critical, as it has abundant fossil fuel resources and significant reserves of critical minerals that are important for the transition to renewable energy systems that are both equitable and inclusive and based on the principle that no one is left behind. Despite Africa's relatively small share of global investment in the advancement of renewable energy and installed capacity, Africans'current robust economic development and population growth require greater energy resources to support future development. Africa is experiencing significant population growth, with energy demand expected to increase by around thirty per cent by 2040 compared to today, based on anticipated growth in global energy utilisation of 10% (Johnston et al. 2020). While most African countries have commenced the implementation of energy transition initiatives, numerous"clean"energy projects have economic, environmental, and social impacts that jeopardise the well-being of vulnerable communities already susceptible to the effects of climate change. Recent studies show that current low-carbon pathways for phasing out coal that are in line with reducing global warming to 1.5 °C exceed even optimistic ambitions in reality (Bi et al. 2023). To reach the IPCC's 1.5 °C threshold, China, India, and South Africa (SA) would have to phase out coal at a historically unprecedented pace (Muttitt et al. 2023). Reconciling the transition to clean energy with the principles of fairness and equity is a growing challenge, making the feasibility of total decarbonisation in coal-dependent countries, including South Africa, particularly difficult (Baker et al. 2014). The concept of a"just transition"has been discussed since the 1970 s. Originally, it was about supporting workers in heavy industries facing environmental threats (Heffron et al. 2015; Henry et al. 2020; Newell & Mulvaney 2013). In recent years, discussions have become politicised around energy justice and just transition (Carley & Konisky 2020; Healy & Barry 2017; Heffron & McCauley 2022), highlighting the unequal burdens on non-OECD nations, including China and India (Vinichenko et al. 2023). It is increasingly recognised that the formerly colonised countries of the Global South are losing their political autonomy due to the pressures of global climate change (Symons & Friederich 2022).

1.1 Review of the current state of research in JET

There is currently a wave of scholarly interest in SA's path to just transition (Barnes 2022; Hanto et al. 2022; Joshua & Alola 2020), building on extensive literature that has emerged from 2010 to the present day (Baker & Phillips 2019; Bohlmann et al. 2019; McEwan 2017). An important contribution comes from the 2009 study by Winkler and Marquand, who argued in favour of a fundamental shift in industrial policy to enable the transition to a low-carbon economy (Winkler & Marquand 2009). Despite the limited research evaluating the JET 5-year plan, the recent proliferation of just transition research in SA is noteworthy. Haegele et al. (2022) noted that the political impact of Eskom (the national electricity utility) and the trade unions, combined with the economic importance of coal, hindered the adoption of RE and the realisation of Sustainable Development Goals (SDGs) 1, 8, and 10. Research on just transition, both within (Hanto et al. 2021; McCall et al. 2019; Rempel 2023; Sarkodie & Adams 2020; Semelane et al. 2021) and outside South Africa, has predominantly focused on techno-economic factors (McCall et al. 2019; Semelane et al. 2021), which is consistent with trends in the literature addressing feasibility impediments of national energy transitions (Cherp et al. 2021). Mirzania et al. (2023) propose the Just Transition Feasibility Framework (JTFF) to evaluate the interaction between energy justice and feasibility constraints, operationalizing this framework in South Africa through qualitative synthesis of primary and secondary data. Houston and Ruppel (2022) explore the legislative and policy developments in South Africa's energy sector, examining partnerships such as the International Just Energy Transition Partnership between South Africa and the European Union (EU). Ramluckun et al. (2024) assess the energy policies of BRICS member states, providing comparative insights and recommendations for South Africa to leverage best practices in energy policy. While feasibility studies often attempt to determine the effect of technical and economic factors that hinder the adoption of certain technologies (Li & Taghizadeh-Hesary 2022; Odenweller et al. 2022), they often overlook the socio-political aspect of energy transitions (Loftus et al. 2015). According to Burton et al. (2019), much of the policy discourse in SA remains fixated on the feasibility of technological and economic solutions, rather than recognising the need to manage the transition through policy interventions. Consequently, there remains a significant knowledge gap in understanding the viewpoints of major stakeholders and the socio-political dynamics that are actively shaping SA's path to a just transition.

South Africa's energy sector is heavily reliant on coal, which contributes significantly to greenhouse gas emissions and exacerbates climate change. Despite the urgency of transitioning to renewable energy sources, the country faces numerous challenges in implementing its Just Energy Transition Investment Plan (JET-IP). These include resistance to the decommissioning of coal-fired power plants, particularly in economically disadvantaged regions such as Mpumalanga, insufficient funding, weak governance frameworks, and socio-economic disruptions linked to the restructuring of Eskom. Furthermore, while the JET-IP provides a strategic framework for transitioning to cleaner energy sources, its effective implementation is hindered by geographic, political, and logistical complexities. Compounding these challenges is the lack of comprehensive studies that address the multi-dimensional aspects of South Africa's energy transition, including the integration of economic growth, social equity, and environmental sustainability. Despite substantial research on South Africa's energy transitions, critical gaps remain in understanding the intersection of feasibility constraints—technical, socio-political, and economic—and energy justice in the context of the country's JET 5-Year Plan. While frameworks like the JTFF (Mirzania et al. 2023) and comparative analyses of international partnerships (Houston & Ruppel 2022) provide valuable insights, they lack a detailed examination of how South Africa's historical, economic, and social challenges affect the implementation of equitable energy transitions. Additionally, existing studies focus more on theoretical frameworks or comparative evaluations rather than assessing the practicality and effectiveness of specific policy measures (including the 2023–2027 JET plan) in addressing domestic energy transition barriers. Moreover, such research often lacks actionable insights for addressing implementation barriers or providing transferable lessons for similar transitions in other regions.

This study aims to bridge these gaps by offering a comprehensive and critical analysis of South Africa's JET 5-Year Plan within its broader energy transition strategy. Unlike previous works that primarily focus on theoretical frameworks or comparative studies, this research integrates the policy documents of the SA 5-year JET-IP and other secondary sources to provide actionable insights into the feasibility and justice dimensions of energy transition. By critically evaluating the socio-political, economic, and technical barriers to coal phase-out and renewable energy development, the study moves beyond descriptive analyses to propose targeted interventions that address these challenges. Moreover, the study uniquely highlights the environmental, social, and economic trade-offs embedded in South Africa's energy transition policies, providing a nuanced understanding of how feasibility constraints shape the pace and equity of transition. It synthesizes findings from policy documents, academic literature, and real-world developments to evaluate the alignment of the JET 5-Year Plan with global best practices and local realities. This study focuses primarily on South Africa's energy transition, which may limit the direct applicability of the findings to countries with differing socio-economic and energy landscapes.

The paper was organised to address its objectives. The next section outlines the research framework and methodology adopted for this study. Section 2 delves into the historic overview and background of the South African energy landscape, detailing various energy sources and their associated emissions. Section 3 provides a comprehensive review of the 5-year Just Energy Transition (JET) plan in South Africa, examining its priority sectors and cross-cutting areas, while Section 4 provides a critical discussion and deductions from the review. Section 5 explores the challenges and prospects associated with the JET plan and proposes a strategic framework for its successful implementation. Finally, Section 6 summarizes the key findings and offers recommendations for policy development and future research directions.

1.2 Framework and research methodology

The methodological approach adopted in this study was designed to critically evaluate South Africa's Just Energy Transition (JET) 5-Year Plan by integrating the concept of transition feasibility and JET principles. The JET principle, which explores the shift from dependence on fossil fuels and other non-renewable energy sources to reliance on renewable energy, was employed to contextualize South Africa's energy sources and transition. This framework further underscores the significant potential of South Africa's renewable energy resources, serving as a foundation for evaluating the feasibility and equity of the 5-Year JET plan. Additionally, the"eliminate waste and pollution"principle of the circular economy provided a complementary perspective, emphasizing the importance of minimizing pollution from fossil fuel-based energy systems through decommissioning coal-powered plants.

This comprehensive policy review approach begins with an in-depth review of relevant policy documents, including government publications, reports from international organizations, and legislative frameworks guiding South Africa's energy transition. A systematic database search (Scopus, Web of Science, Google Scholar) was conducted using targeted keywords such as "Energy Sources", "Renewable Energy Sources","Just Energy Transition,""South Africa energy policy,"and"coal-fired power plant decommissioning,"with Boolean operators (e.g.,"AND,""OR") and advanced filters to focus on relevant studies from 2000–2024. The review identifies technical, socio-political, and economic barriers to transitioning from coal to renewable energy, focusing on three priority sectors (Electricity, New Energy Vehicles, and Green Hydrogen) and cross-cutting areas (skills development, Mpumalanga JET, and municipalities). Secondary sources, including academic literature and government reports, were synthesized to highlight infrastructure, governance, and financial challenges. The plan's alignment with energy and social justice was assessed, emphasizing its capacity to reduce inequality, ensure equitable energy access, and involve marginalized communities in decision-making.

Finally, the study integrates its findings into a proposed strategic framework that links feasibility constraints with equity outcomes, offering actionable recommendations for policymakers. This framework evaluates the effectiveness of the JET 5-Year Plan and contributes to a broader understanding of how just energy transitions can be achieved in other fossil fuel-dependent economies in the Global South. This approach ensures that the study is both rigorous and grounded in practical relevance, addressing the multifaceted challenges of energy transition in South Africa. This approach facilitates the identification of transferable lessons and policy innovations that could enhance the feasibility and equity of South Africa's energy transition. Figure 1 presents a detailed flowchart describing the methodology.

2 Overview of the South African energy sector

2.1 Historical overview

For decades, South Africa has struggled with deep-rooted social and environmental inequalities (Swilling & Annecke 2012). Since the end of apartheid in 1994, the country's heavily fossil fuel-dependent energy system and little or no environmental oversight have exacerbated problems of poverty, inequality, and pollution (Magazzino et al. 2020). Researchers, including Baker et al. (2014) and Barnes (2022) emphasise that South Africa's path to a just transition is hindered by the complex legacy of apartheid, social unrest, poverty, unemployment, and structural instabilities in the energy sector that continue to shape the country's political landscape. These challenges have resulted in a significant portion of the coal industry being economically unviable and environmentally unsustainable (Cock 2019; Hanto et al. 2022; Sarkin 1996). The regional economy has suffered notable setbacks due to

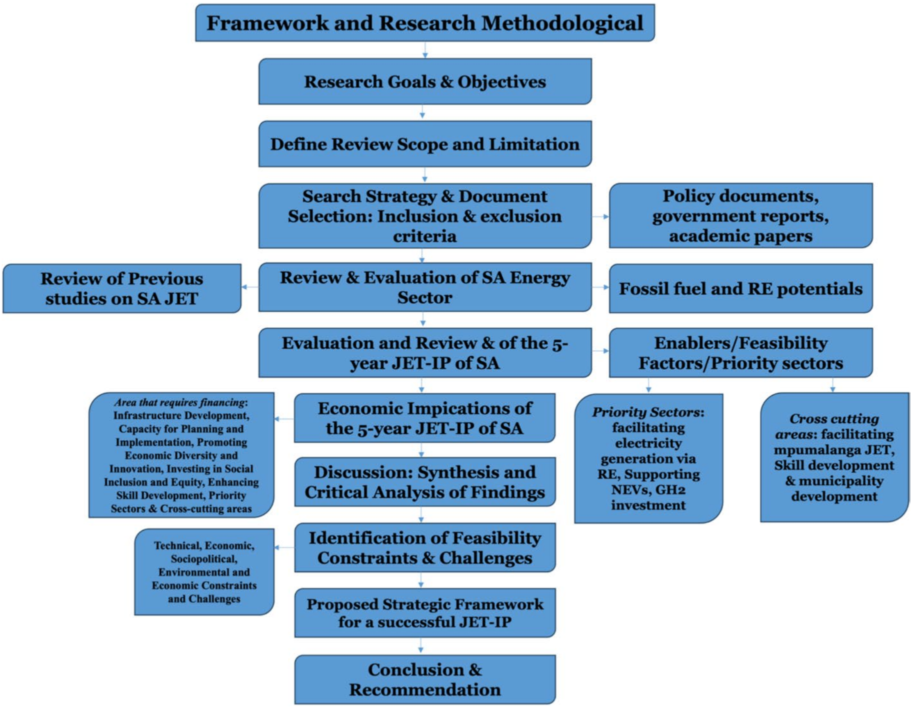


Fig. 1 Flowchart describing the research methodology

the downsizing of mines, which is particularly evident in the Matjhabeng region, about 550 kms southwest of Mpumalanga, the centre of South Africa's mining industry. The closure of mines since the late 1980 s, following a global downturn in the gold markets, has led to significant job losses, the lasting effects of which have not yet been fully remedied (Marais 2013). Similarly, coal-dependent regions such as North KwaZulu-Natal experienced an economic downturn in the 1990 s, bringing communities like Dundee to socio-economic collapse (Nel et al. 2003). These challenges are exacerbated by South Africa's already high unemployment rate of over forty per cent and a Gini coefficient of sixty-three, which the COVID-19 pandemic has further aggravated (Hanto et al. 2022).

Despite numerous hurdles, South Africa remains heavily dependent on coal, a crucial source of foreign exchange reserves (Hanto et al. 2022). The country boasts the largest coal production in Africa, with significant exports and huge coal reserves, making it a leading emitter of carbon dioxide on the continent and globally (Dhansay et al. 2022; Hanto et al. 2022). However, the country also has considerable Renewable Energy (RE) potential and the largest solar capacity in Africa (Adenle 2020). Currently, coal dominates the South African energy mix, accounting for approximately 70% of the total energy supply in 2020, while REs account for only 1.1% (Mirzania et al. 2023). This is in stark contrast to countries including the United Kingdom, which has drastically reduced the use of coal, and the Netherlands, which has successfully phased out coal through strategic industrial and regional revitalisation measures (Nacke et al. 2022). Despite the dominance of coal, the government has set itself the goal of decommissioning a significant proportion of coal-fired capacity by 2030 while expanding renewable energy capacity (Ratshomo & Nembahe 2019; Uhunamure & Shale 2021). To summarise, it can be said that the South African energy sector is still heavily dependent on coal. This places the country alongside major coal-producing nations such as China and India within the G20, but lags behind the leading countries in the introduction of clean energy (Mirzania et al. 2023). Scholars such as Lamb and Minx (2020) define SA as a"coal-dependent developing nation"struggling with feasibility challenges ranging from high emissions to inadequate climate policies. While the country's energy concerns are well documented, it is an important case study for just transition science, illuminating the intricate interplay between socio-economic factors and energy transition imperatives (Adebayo et al. 2021).

2.2 Energy sources, supply, and conversion

The SA energy system is characterised by a heavy reliance on coal, which is dominant in electricity generation and industrial processes. Around 80% of the country's electricity is produced in coal-fired power plants, making it a cornerstone of the national energy supply (Akinbami et al. 2021). This dependence on coal has significant economic and environmental impacts and contributes to greenhouse gas emissions and air pollution (IEA 2021).

2.2.1 Fossil-based energy sources

South Africa has substantial coal reserves, responsible for > 70% of the country's total energy supply (TES), while 18% comes from crude oil and 5.5% from natural gas, and nuclear power (Fig. 2a). Power generation in South Africa is highly dependent on coal (Fig. 2b). It involves the extraction and mining of fossil fuels, which are primarily burnt to generate electricity in coal-fired power stations or used as fuel. Although South Africa is rich in coal, the country is dependent on imports for other energy sources, particularly oil and natural gas. The country's dependence on energy imports makes it vulnerable to supply disruptions caused by external events such as global pandemics or geopolitical conflicts such as the war between Russia and Ukraine (Al-Saadi 2023; Zhang et al. 2023). Conversely, variations in international energy prices can have a significant economic effect on countries that export large quantities of energy. The conversion of energy sources, particularly fossil fuels, into more usable or practical forms is a common practice prior to consumption. In South Africa, crude oil is refined into various fuels and products, while coal, oil, and natural gas are converted into electricity, heat, and feedstock for other processes. Power generation is also an important conversion process, with thermal power plants converting the energy content of fuels or nuclear processes into electricity.

2.2.2 Renewable energy sources (REs) and their potential in SA

REs are becoming increasingly important as nations endeavour to cut CO_2 emissions and reduce reliance on fossil fuels. REs including solar, wind, biomass and hydropower significantly contribute to the electricity supply, even if their share is still lower than coal (Akinbami et al. 2021). Due to South Africa's favourable geographical location, solar energy is the nation's most promising REs. In most regions of South Africa, there are more than 2,500 h of sunshine per year, with daily solar radiation ranging between 4.5 and 6.5 kWh/

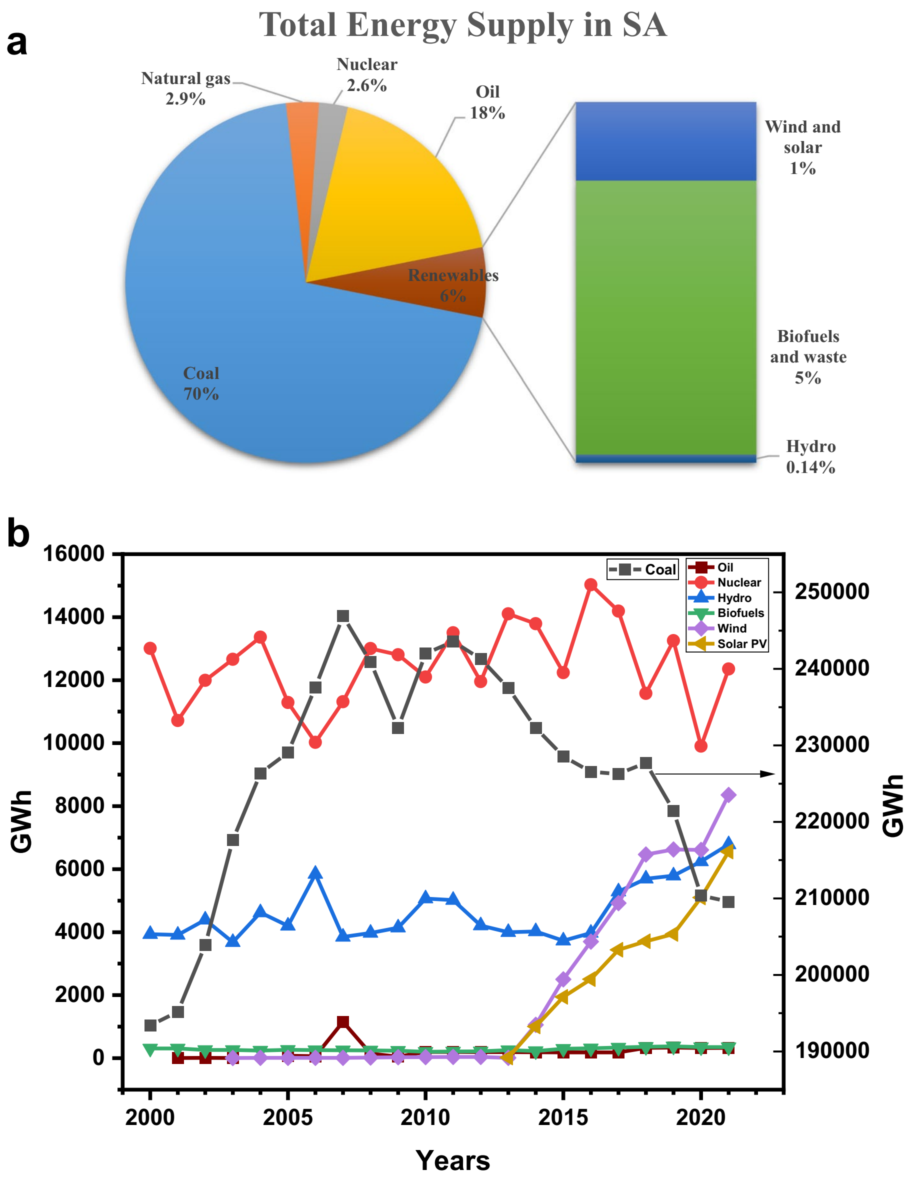


Fig. 2 **a** Total energy supply in SA, which shows an overview of the total energy resources available and consumed in the country, and **b** contribution of different energy sources for electricity generation in SA from 2000–2021. (IEA 2021): this presents a breakdown of the share of various energy sources (e.g., coal, renewables, nuclear, etc.) used for electricity production over two decades, highlighting trends or shifts in energy generation methods

m^2 (Xaba 2023). In southern Africa, the sun shines all year round and provides an average annual 24-h solar radiation of around 220 W/m^2, in contrast to about 150 W/m^2 in the USA and 100 W/m^2 in Europe and the UK. Wind energy also harbours considerable potential in South Africa. The estimated total wind energy capacity is 6,700 GW, comparable to the country's solar potential. Since the early 1990 s, around 30,000 wind turbines have been installed in arid and agricultural areas to supply water, although commercial wind energy for power generation is still underdeveloped (Asamoah 2003). Studies suggest that SA could use around 6 GW of wind energy in mild scenarios, potentially exceeding 50 GW (Akinbami et al. 2021; Smarte Anekwe et al. 2024).

South Africa also has significant untapped energy potential from biomass. Over 42 million hectares of forest and other cultivated land produce more than 1 million tonnes of wood biomass annually (Petrie & Macqueen 2013). South Africa is the continent's largest sugar cane producer, producing over 18 million tonnes yearly (Mandegari et al. 2019). Sugarcane residues and bagasse comprise more than 21% of the total biomass and are often burnt inefficiently, wasting potential energy resources. Proper biomass processing could produce about 400 MW of electricity or 1 tonne of bioethanol (Mandegari et al. 2019). It is assumed that South Africa has considerable untapped hydropower potential (Loots et al. 2015), but the utilisation of this potential is associated with challenges. The projected contribution of hydropower to South Africa's future energy mix is low, around 4%, and its future role in electricity supply remains uncertain. This uncertainty stems from the unclear potential for hydropower development in the country. Despite South Africa's status as a water-scarce nation, there are numerous sites where hydropower could be developed, such as irrigation canals, water distribution systems, wastewater treatment plants, diversion systems, and dams (Bekker et al. 2021). Renewable energies such as solar panels, wind turbines and hydroelectric power stations produce electricity without emitting greenhouse gases or other pollutants. As solar and wind power technologies have fallen drastically, renewable energy has become the cheapest new power generation option in many regions worldwide. Figure 2a shows that REs contribute about 6% of the total energy supply in SA.

2.3 Energy consumption and CO_2 emission

The country's energy demand includes powering automobiles, heating and cooling homes and running factories. Most energy sources come from petroleum products, coal and electricity (Fig. 3a). Total final consumption (TFC) refers to the energy consumed by final consumers, including households and businesses (IEA 2021). It also includes the non-energy use of energy products, such as producing chemicals from fossil fuels. Understanding both TES and TFC is crucial for understanding the energy system. The sectoral breakdown of energy demand in SA is influenced by the country's economy, geography and history. The industrial sector is the main energy consumer with over 38% energy utilisation, as mining and manufacturing require a lot of energy. Household energy consumption is also considerable, accounting for 16%, especially for heating, cooling and lighting. The transport sector depends heavily on petroleum products and contributes (26%) to a considerable proportion of energy demand (IEA 2021) (Fig. 3b). Efforts are underway to diversify the energy mix by including more REs such as wind, solar and hydropower to improve sustainability and minimise the negative environmental impact of coal-based power generation.

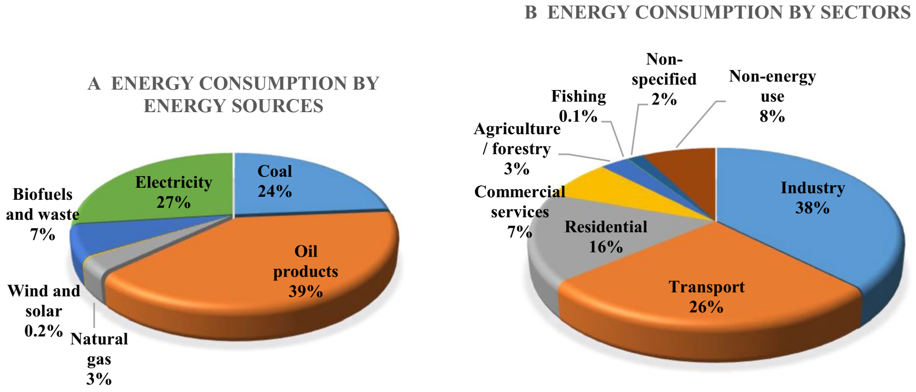


Fig. 3 Energy consumption in SA by **a** energy sources and **b** sectors (IEA 2021)

Energy production is the main contributor to climate change through the emission of GHG, mainly from the combustion of fossil fuels (Anekwe and Isa 2023; Anekwe et al. 2023). Despite global efforts to curb these emissions, CO_2 levels are still significantly higher than necessary to prevent the severe impact of climate change. The GHG Emissions from Energy Data Explorer provides comprehensive estimates for various regions, which show that South Africa leads the way in CO_2 emissions with over 6.5 tCO_2/capita, followed by Libya with 6.1 tCO_2/capita (Fig. 4a). South Africa is a leading CO_2 emitter with 391.74 $MtCO_2$ emissions in 2021, an increase of 40% since 2000 (Fig. 4b), accounting for 1.2% of global CO_2 emissions from combustible fuels (IEA 2021). Most of these emissions come from burning fossil fuels, including coal, oil and natural gas for electricity, vehicle and machinery operation (Fig. 5a and b). The economy and energy systems framework influences the sectoral distribution of CO_2 emissions. Power plants emit CO_2 through the combustion of fuels for electricity and heat generation, while emissions from the transport sector mainly come from the oil-based fuels used by cars. Emissions from private households mainly come from heating with fossil fuels, and emissions from industry result from burning fossil fuels for processes such as producing paper or steel (Ntuli et al. 2022). Direct emissions from certain processes, including cement production, are significant but are not included in these figures.

2.4 The need to transition from non-sustainable energy sources in SA

Transitioning to alternative energy is crucial to securing a sustainable and resilient future. Fossil fuels are finite, and their extraction and use have serious environmental consequences, contributing to climate change and air pollution. Clean energy sources, including solar, wind and hydropower, offer renewable, accessible, low-emission alternatives. Switching to these sources increases energy security, reduces GHG emissions and mitigates the impact of climate change. In addition, the clean energy sector offers significant economic opportunities by providing jobs and spurring technological innovation. Investing in clean energy protects our environment, enhances public health, and promotes economic development. This transformation is an environmental imperative and a pathway to a more prosperous, sustainable and equitable society.

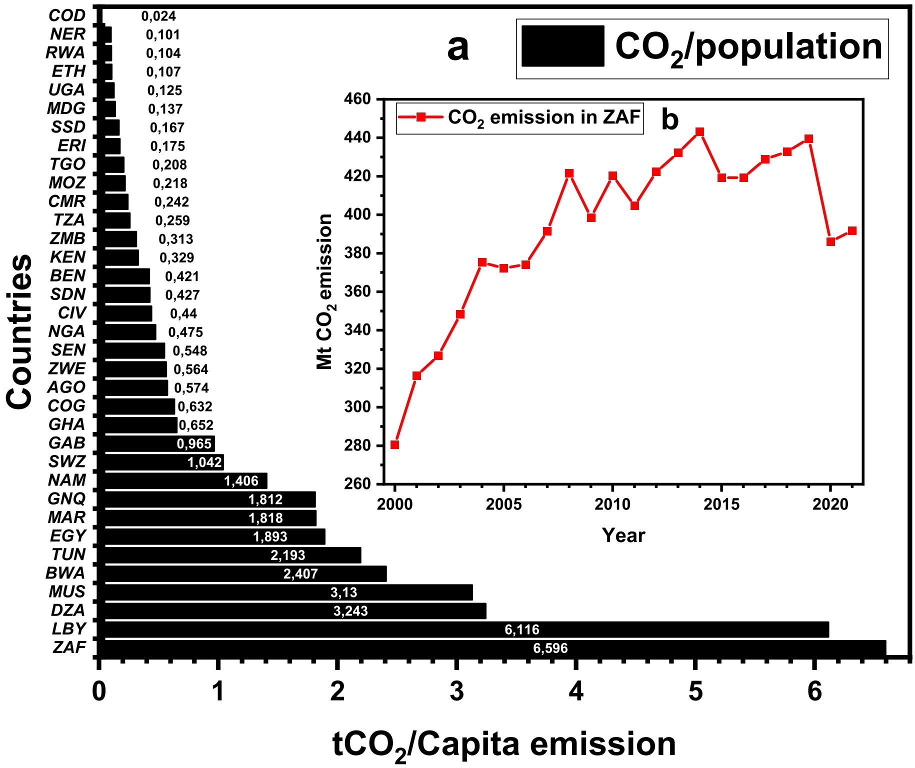


Fig. 4 **a** CO_2 emission per population in Africa and **b** trend in CO_2 emission in South Africa (ZAF) from 2000 to 2021. (IEA 2021)

3 The just energy transition (JET)

The document entitled"Just Transition of the Labour Force and the Creation of Decent Work and Quality Jobs"was published by the United Nations Framework Convention on Climate Change (UNFCCC) in the run-up to COP29 in Marrakesh. These terms were also included in the preamble of the Paris Agreement signed in 2016 (United Nations 2015). From COP21 in Paris to the recent COP27, the"just transition"concept has remained relevant in international climate policy (Dooley 2023; Heffron & McCauley 2022). In a communication to the Powering Past Coal Alliance (PPCA) on 2 March 2021, UN Secretary-General Antonio Guterres emphasised the need to phase out coal-fired power generation to achieve the climate targets and at the same time pointed out the need for a fair and just transition (Mirzania et al. 2023):"Given the speed and scale of the transition, there is a collective and urgent need to address the significant issues involved. To meet the needs of coal communities, we must recognise their requirements and provide tailored solutions at the local level."However, due to criticism from India, China and the United States (Dooley 2023), the terminology changed during COP26 in Glasgow (Burki 2022) from"phasing out coal"to"coal phase down", as discussed in COP28 in Dubai. Numerous nations, particularly in the Global North, have created similar bodies, such as a Just Transition Commission (JTC), as part of their energy transition policies (Heffron & McCauley 2022). South Africa has also taken a

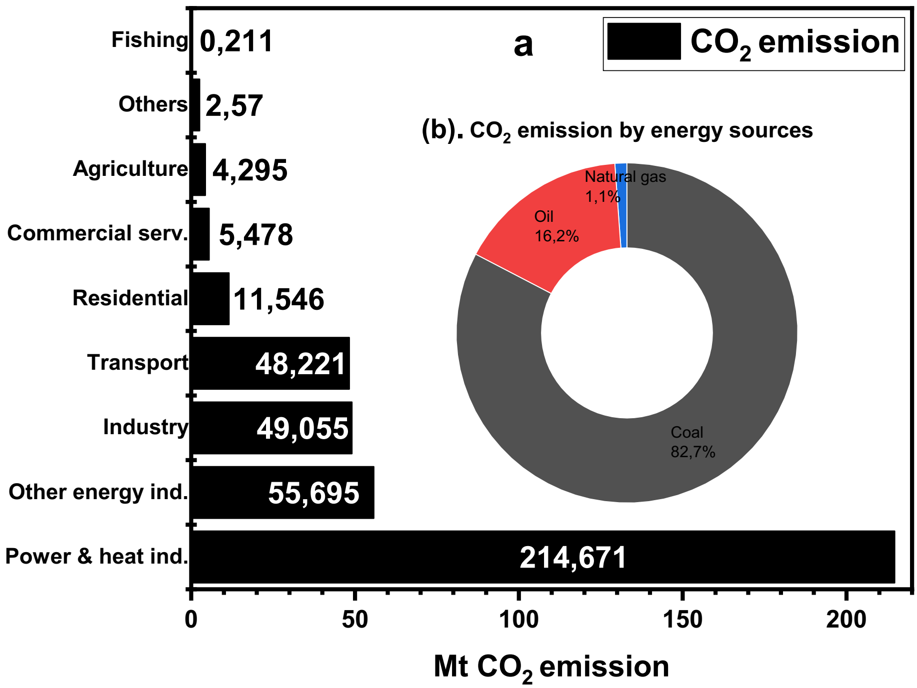


Fig. 5 CO_2 emission by **a** sectors and **b** energy sources in SA. (IEA 2021)

pioneering role in unveiling its Just Energy Transition Partnership (JETP) at COP26, which is sponsored by a consortium of donor nations (Tyler & Mgoduso 2022). Despite the apparent progress in terms of policy trajectory and terminology, concerns have been raised by academics that existing just transition routes perpetuate economic challenges and energy inequities in large coal-producing nations, including SA (Le Billon & Kristoffersen 2020) and regions in Germany, Canada and Australia (Harrahill & Douglas 2019).

3.1 Just energy transition implementation plan (JET-IP) of SA

SA's Just Transition Strategy aims to ensure that all citizens can maintain a good standard of living in the midst of climate change. As the Presidential Climate Commission (PCC) (2022) outlines, a just transition involves creating a secure, affordable, decentralised and diverse renewable energy environment, ensuring equitable access to water, protecting natural resources and promoting sustainable and inclusive land use, especially for vulnerable populations. The South African government recently adopted the National Just Transition Framework, which was established in collaboration with the PCC. This framework, which builds on the Just Transition clause in Chapter 5 of the National Development Plan of the 2011 White Paper, aims not only to achieve fairness in the minerals and energy sectors but also to minimise carbon emissions in the energy sector. On 4th November 2022, South Africa's president instructed the PCC to hold public discussions on the JET-IP as part of the unveiling event of the JET-IP 2023–2027 organised by the PCC. The President then presented the JET-IP to the Heads of Government of the International Partners Group (IPG) at the United Nations Framework Convention on Climate Change (UNFCCC) Congress of the Parties (COP27) in Egypt on 8 November 2022. He also presented it at the G20 meeting in Indonesia. In January 2023, the Presidency established the JET Project Management Unit (PMU) to oversee the implementation of JET intellectual property and develop the JET-IP. In addition, the JET-IP reflects not only the approach to achieving JET-IP but also the results of the extensive stakeholder engagement conducted by the PCC in 2023 with the participation of representatives from various sectors such as organised labour, civil society, youth organisations, business, government and faith-based agencies (Ramluckun et al. 2024; South Africa Government 2022).

SA's JET-IP aims to strengthen the nation's ability to address this transition's social, physical and climate challenges. JET-IP outlines a strategic roadmap for South Africa to meet its decarbonisation objectives in a way that ensures just outcomes for those impacted by the energy transition while promoting inclusive economic growth, energy security and employment. This plan is tailored to SA's socio-economic development pathway and considers the country's specific needs and affordability.

3.2 JET-IP enablers and priority sectors

To ensure the feasibility of the 5-year transition plan, the SA government set short and medium-term targets (enablers or feasibility factors) which are grouped into six specific portfolios: the three priority sectors including energy/electricity generation via REs, adoption of new energy vehicles (NEVs), investment in green hydrogen (GH_2), and cross-cutting areas (Mpumalanga Just Transition – decommissioning of coal-powered plants, skills development and municipality development) (South African Government 2022). In addition, three further portfolios – SA Renewable Energy Masterplan, Energy Efficiency and Road-to-Rail—are supported with JET funding in 2024. Key institutions are assigned leadership roles in specific focus areas, responsible for tasks such as programme and project alignment, resource mobilisation, performance monitoring and stakeholder engagement. The implementation process is iterative, allowing for adjustments as progress is made and momentum builds. The government plays a central role in driving forward the JET. It acts as a regulator, enabler and facilitator to attract private sector investment and international funding for the country's energy transformation. These priority sectors are described below (South African Government 2022). The three priority sectors are discussed below.

3.2.1 Electricity generation, transmission and distribution using REs

The South African government is strongly committed to promoting a low-carbon economy, with a particular focus on the electrical industry. In 2000, electricity production was responsible for 43% of the country's GHG emissions, which will increase by 2020 (South African Government 2022). Most of these emissions come from fifteen coal-fired power stations owned by Eskom, many of which do not comply with air quality emission regulations. Furthermore, nine of these power stations will have reached the end of their lifespan between 2022 and 2034. Achieving SA's decarbonisation goals depends on the effective management of a comprehensive programme that includes four key initiatives: expanding decentralised renewable power generation; upgrading significant parts of the transmission grid; upgrading distribution systems; and strategically decommissioning, repurposing and repowering coal-fired power plants without disrupting energy supply, while actively supporting impacted workers, communities and value chains in the transition to new economic opportunities. Given the ongoing energy supply crisis combined with low economic development, high poverty rates, unemployment and inequality, and financial constraints that hinder large-scale capital projects, effective management of this endeavour is essential.

Electricity generation The 5-year JET-IP forecasts that about 6 gigawatts (GW) of new renewable electricity capacity will need to be fed into the grid annually in the coming years. This is critical to addressing the electricity supply crisis, meeting SA's Nationally Determined Contribution (NDC) targets and achieving long-term decarbonisation goals. The total investment required over five years amounts to approximately ZAR 498 billion (bn), of which approximately ZAR 233.4 bn is for solar power, ZAR 241.7 bn for wind power and ZAR 23.1 bn for battery storage (South African Government 2022). These investments are expected to be primarily made by the commercial sector through the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), as outlined by JET Intellectual Property (Table 1). Due to comprehensive reforms in the South African electricity industry and the prevailing electricity supply crisis, there is potential for large-scale decarbonisation of electricity generation by deploying low-cost renewable energy technologies in the coming years. The cost of photovoltaics (PV) in SA has fallen by 88% to ZAR 0.375/kWh from 2010 to 2021, while the price of onshore wind power has fallen by 68% to ZAR 0.344/kWh. In addition, the share of renewable energies in total electricity production in terawatt hours rose to around 7% by 2022 (Department of Mineral Resources SA 2023).

Electricity transmission The current electricity transmission grid cannot cope with the planned expansion of renewable energy to be integrated into the grid in the coming years. In particular, the grid's capacity to transmit electricity throughout the country is not aligned with the concentration of optimal renewable energy resources (Eberhard et al. 2014), which are mainly located in the Northern Cape and Eastern Cape regions. Over the next ten years, South Africa faces the daunting task of building almost 1,500 kms of new transmission lines yearly (ESKOM et al. 2023). This is significantly more than Eskom's average construction rate over the past three years, which has been ten times lower. Although Eskom has acquired and connected some 4,347 kms of transmission lines and 19 gigavolt transformers over the past decade, this pace is insufficient to address the energy supply crisis or meet South Africa's commitments to minimise carbon emissions. As a result, the REIPPPP bid window for 2022 was severely limited due to insufficient grid connection capacity. Eskom's Transmission Development Plan (TDP) assumes a financial gap of approximately ZAR 250 billion for transmission facilities. With this investment volume, it would be possible to construct 15,000 kms of new power lines by 2032, increasing the annual construction rate from the current 300 kms to 1,500 kms. In addition, there is the potential to install 122,600 megavolt-amperes of new transformation capacity, representing 77% of Eskom's existing installed base (ESKOM et al. 2023; South African Government 2022). However, the TDP faces challenges like Eskom's financial issues, land and equipment procurement delays, environmental approvals, high capital costs, and uncertain NERSA tariffs.

Electricity distribution Over the next five years, a significant investment of more than ZAR 50 bn is needed in the SA distribution network to carter for the expected increase in renew-

Table 1 Key drivers for supporting and scaling up investment in renewable energy generation (adapted from (South African Government 2022))

Factors	Description
Immediate investment in transmission infrastructure	• Over three gigawatts of renewable energy projects were turned down in recent REIPPPP tenders due to inadequate transmission capacity • Insufficient transmission capacity primarily impacts long-distance lines and high-capacity substations • The government is giving priority to addressing this transmission capacity issue
Improving distribution infrastructure	• Small-scale and integrated power generation relies on updated distribution networks • 165 licensed municipalities own half of the distribution grids • JET IP 2023–2027 estimates ZAR 273 billion investment for municipal distribution, detailed in Part 10 of JET-IP • Eskom will manage the rest of the distribution network, requiring ZAR 127.5 billion investment from 2023 to 2035
Creating a wheeling framework	• Establishing a national framework and municipal-level wheeling systems is vital for electricity stakeholders • A draft framework, developed through consultations by NECOM, has been submitted to NERSA
Promoting a competitive electricity market	• The government has presented the Electricity Regulation Amendment Act (ERA) to Parliament to restructure Eskom and foster competition in the electricity market • The ERA aims to establish a competitive market by implementing a market operator, developing a market code, and creating essential systems and platforms • These initiatives will facilitate increased investment in new generation capacity beyond traditional long-term power purchase agreements (PPAs)
Local production of renewable energy technologies	• SAREM oversees the local production of renewable energy technologies and batteries, which is backed by the government and DFIs • SAREM anticipates future funding from international partners, DFIs, and MDBs for JET's intellectual property through its roadmap
Promoting social ownership of renewable energy	• It's essential to ensure renewable energy benefits low-income households • Pilot programs are testing ownership models and microgrid technologies • Expansion plans hinge on obtaining sufficient funding

able energy (RE), including small-scale embedded generation (SSEG) (Bloem et al. 2021; South Africa Government 2022). These investments are critical to strengthen, expand and adapt the infrastructure to cope with the intermittent nature of REs, including wind and solar power. Modern grid management technologies, energy storage solutions and smart grids are required to balance supply and demand effectively. Municipalities face challenges in this context and sustainable financing mechanisms are proposed under the Intergovernmental

Fiscal Relations Act. Eskom manages about 40% of electricity distribution. According to recent estimates, investments totalling ZAR 42.6 bn are required over the next 5 years for necessary improvements, which are closely linked to the TDP (South African Government 2022). The outdated infrastructure contributes to significant technical losses and frequent outages, requiring extensive upgrades and modernisation. Equal access to electricity remains a pressing issue, especially for historically marginalised communities, as more than 20% of households in remote areas still lack a reliable electricity supply. Electricity prices have risen by an average of 8% annually over the last decade, so affordability remains an issue. Grid resilience and cybersecurity are new challenges. Recent reports indicate increased cyberattacks on critical infrastructure (South African Government 2022). The regulatory framework requires further development to support the transition. This includes a coherent policy for electricity trading between Eskom and the municipal grids, aimed at streamlining processes and encouraging private sector participation.

Decommissioning, repowering and reuse of decommissioned coal-fired power plants The closure of coal-fired power plants has a considerable economic and social impact on the communities and workers who depend on these operations. The recent shutdown of the Komati power station in Mpumalanga emphasises the need for thorough planning to diversify the economy and invest in repowering and repurposing sites long before closure (Vale et al. 2024). In line with the 2019 IRP, Eskom plans to decommission and repurpose 22 GW of coal-fired power stations in Mpumalanga over 15 years. This aligns with South Africa's decarbonisation targets and affects numerous municipalities. However, recent developments are changing this timeline (South African Government 2022):

- Due to the electricity supply crisis, the government and Eskom are reconsidering the timeline for decommissioning and may postpone the closure until 2030.
- An independent study by NT is analysing the technical and financial implications of extending the life of the coal fleet.
- NECOM is using modelling to determine the necessary delays in decommissioning power stations based on the new capacity in the Energy Action Plan.
- The DMRE updated the IRP in 2019.
- Eskom's debt cancellation conditions limit borrowing without exemption from the Minister of Finance.
- The decommissioning of the Komati power station, which preceded the JET IP, was criticised for lacking early investment in reuse and community development. The lessons learnt from Komati are being incorporated into the approach for the Accelerated Coal Transition Investment Plan (ACT IP), which is crucial for future decommissioning decisions.

South Africa's interest in the Climate Investment Fund (CIF) in 2020 focused on financing the decommissioning, repurposing and repowering of Eskom's retiring power plants through the ACT Investment Programme (Lowitt 2021). This plan, developed by Eskom, the DFFE and the CIF, aims to decommission coal-fired power stations, promote renewable energy and create a just transition for affected communities. It is an integral part of the international commitments made at COP26. The ACT IP focuses on the decommissioning of the Hendrina, Grootvlei and Camden power stations between 2023 and 2027, supporting repurposing and repowering with renewable energy, community-driven investment in Mpumalanga's green economy and the Energy Efficiency in Public Buildings and Infrastructure Programme (EEPBIP) (Lowitt 2021; Shrimali & Jindal 2020; South Africa Government 2022). Funding includes concessional loans from MDBs and CIF grants that facilitate partnerships with the private sector to repurpose and replace capacity.

3.2.2 New energy vehicles (NEVs)

The JTF in SA recognises the need for the automotive sector and its link to the decarbonisation of transport fairly and equitably. The transition from internal combustion engine (ICE) vehicles to NEVs presents both a challenge and an opportunity for South Africa and has implications for industry viability and emission reduction targets (Barnes et al. 2022). A growing NEV sector can sustain jobs, reduce transport costs, reduce emissions, create new industrial jobs and maintain access to export markets, all supporting just transition objectives. The JET-IP emphasises the significant investment required for the NEV transition in SA's automotive value chain. Failure to adapt to technical and regulatory changes in key export markets could jeopardise jobs and revenue. To achieve the decarbonisation targets and ensure a just transition, an investment of ZAR 128.1 bn is estimated for the period 2023 to 2027, with further funding required in subsequent phases (South African Government 2022). Several factors will affect the pace of the NEV transition, including the availability of funding, grid conversion to renewables, technological advances and regulatory measures (Pienaar et al. 2023). Collaboration with the private sector and global partners will be crucial due to the scale of resources required. The JET Implementation Plan outlines a framework for the NEV sector that reflects ongoing initiatives by DFIs, municipalities and the private sector. The plan recommends that the IDC lead the coordination efforts to attract funding and accelerate the growth of the NEV industry in SA. The NEV JET portfolio comprises three elements derived from the JET-IP 2023–2027 (South African Government 2022):

1. Using supply-side incentives for the automotive sector will boost production and investment in supply chains for new energy vehicles (NEVs) while safeguarding jobs in automotive production. The funding required for this amounts to about ZAR 26.5 bn for 5 years.
2. The IDC's NEV initiative aims to secure funding and provide project preparation support for various aspects related to NEV car assembly, supplier fleets, component manufacturing, supply chains, battery mineral extraction and associated activities. About ZAR 34.5 bn will be needed for 5 years.
3. The DBSA oversees a programme for NEVs in public transport, which aims to provide grants and project preparation support for public transport, particularly taxis and buses, as well as the necessary electric charging facilities. Around ZAR 10.55 bn will be required for this scheme for five years.

The main objective of the plan is to scale-up existing pilot projects and programmes to evaluate their effectiveness and secure funding through grants and concessional financing, thereby improving their viability and attracting additional investors. Following the implementation of government policy on NEVs, demand and supply channels will facilitate the replication of these innovative projects, leading to the normalisation of NEVs in the SA transport sector. It is crucial to note that the proposed funding does not include an allocation for private end-user NEV incentives, as the government policy on demand-side incentives has not yet been finalised. Table 2 shows the potential measurable impact of NEVs intervention.

3.2.3 Green hydrogen (GH_2)

South Africa can capitalise on its inherent advantages to establish a competitive GH_2 ecosystem in the region, thereby supporting the retention and expansion of a robust industrial framework (Rischer 2023). Under increased demand, South Africa can produce approximately 7 million tonnes per annum (mtpa) of GH_2-based products for the domestic and international markets. If this is realised, it can potentially increase gross domestic product (GDP) by approximately 5.9% or almost ZAR 500 bn in real terms by 2050 (South African Government 2022). In addition, SA's globally competitive GH_2 synthesis provides a low-cost means of reducing carbon emissions in various sectors, including steel, cement, petrochemicals and heavy-duty transport, resulting in emission reductions of around 10–15% in these industries. An economically viable decarbonisation strategy that includes effective final-stage emission reduction measures (such as GH_2) is central for these sectors and their associated industries to be steadfast amid the global transition to a low-carbon economy. This is particularly important given the impact of international regulations, including the EU Carbon Border Adjustment Mechanism (CBAM), which poses a significant risk to around 50% of South African exports (Gu et al. 2023; South African Government 2022). By implementing decarbonisation measures early, these industries can achieve higher prices for

Table 2 Impact of NEVs (JET-IP) intervention

NEVs (JET-IP) Impact	Measurable metrics
Growth in small and medium-sized enterprises (SMEs)	Number of SMEs
Decrease in carbon dioxide (CO_2) emissions	CO_2 grams per kilometre
Employment in the automotive sector	number of jobs retained and newly generated
Enhancement of employment opportunities for young job seekers	number of youth jobs established
Deployment of public charging infrastructure	quantity of chargers installed
Reduction in tailpipe emissions	decrease in internal combustion engine vehicles
Decrease in carbon footprint per investment	CO_2 emissions abated per unit of currency
Wider impact	
Enhancing South Africa's export performance and trade connections with the EU, UK, and the US	export statistics
Drawing foreign direct investment (FDI) into South Africa	FDI per investment
Enhancing air quality	air quality indicators

their products when selling to specialised industries further down the supply chain. While the production cost of green steel before 2030 is projected to be around double that of the existing grey alternative, the integration of green steel into the manufacturing process of an average light vehicle produced in the EU will lead to an average increase of €500 in the cost of a car worth around €30,000 (South African Government 2022).

Four guard rails must be observed to fully utilise the advantages of a local GH_2 company. These guard rails are designed to protect against conflicts with national energy security and other JET objectives. They include:

- Prioritizing localizing value chains where competitive and raising local content requirements to balance sector establishment and socio-economic impact, such as fostering new black-owned businesses.
- Simultaneously grow consumption and export markets to secure new global green value pools and facilitate local downstream business decarbonization, albeit at different rates.
- Prioritize local GHG emissions upcycling into products like green steel and fuels, where the potential exists to enhance the socio-economic effect and long-term energy security.
- Limit GHG-related price increases in areas like steel or electricity to avoid burdening consumers, directing GH_2 towards industry segments capable of bearing the green premium in the first ten to fifteen years. This is because GH_2 is currently offered at an affordable price.

Considering that real GDP growth is expected to be less than 10% between 2012 and 2022, which is lower than population growth, which is expected to be 15% over the same period (South African Government 2022), it is clear that more of the same will not be enough. South Africa must take immediate action to realise the potential of GH_2. Several other countries with competitive GH_2 costs, such as Australia and Chile, have finalized their GH_2 strategy and made great strides in developing an integrated supply base (Lebrouhi et al. 2022). South Africa needs to create and implement rules and regulations to facilitate the development and expansion of the local GH_2 sector. Otherwise, the country will miss the opportunity to increase its GDP by about ZAR500bn or 5.9% (in real terms) by 2050 (World Bank 2022), which would help address the triple challenge of unemployment, inequality and poverty to some extent (Department of Mineral Resources SA 2023). South Africa still has some obstacles to overcome to create its GH_2 sector, although the country has made tremendous progress in its policies, funding, trade relations and projects. Table 3 presents some of the H_2 production projects in South Africa.

3.3 JET-IP cross-cutting areas

The three cross-cutting areas of the JET-IP of SA required for the swift implementation of the priority sectors are discussed below.

3.3.1 Skill development

The main objective of the JET Skills Implementation Plan is to help build a well-coordinated, and adequately resourced skills ecosystem. This ecosystem, which involves various stakeholders such as communities, businesses and government, aims to ensure that SA has a

Table 3 Some H_2 production projects in South Africa for short and medium-term implementation (South African Government 2022)

Project	Description	Developers	Commercial operation date	H_2 yield
IPM/NCP H_2 Refuelling Stations deployment	Commence H_2 Refuelling Stations and 300 fuel cell trucks and buses	Isondo Precious Metals (IPM) NCP	2025	2.5 ktpa GH_2 300 fuel cell trucks/buses
Ubuntu Green H_2: Phase 1	GH_2 and GNH_3 synthesis from REs (solar and wind)	Ubuntu Green Energy	2026	7 ktpa GH_2/3.5 ktpa GNH_3
Green H_2Mobility: Phase 1 Pilot	GH_2 for long haul transport	RRS Investment	2026	1 600 000 Nm^3 GH_2
HySHiFT Secunda	SAF synthesis from existing Sasol Secunda assets with new electrolysers and REs	ENERTRAG, Sasol, Linde	2026	16.4 ktpa GH_2/36.1 ktpa SAF
Atlanthia Green NH_3/H_2: Phase 1	GH_2 and GNH_3 synthesis in from REs (solar and wind)	Atlanthia Green H_2	2027	7.3 ktpa GH_2/36.5 Ktpa GNH_3
Coega Green NH_3 Project: Phase 1	GNH_3 synthesis in the Coega Industrial Development Zone	Hive H_2 South Africa	2028	237 ktpa GNH_3
South African H_2 Valley	Some GH_2 projects to transform selected regions into an H_2 valley	Anglo American, DSI, Bambili Energy, ENGIE	2030	185 ktpa GH_2 by 2030
Phelan Green H_2	GH_2 and GNH_3 production	Phelan Green H_2	2030	85 ktpa GH_2/480.22 ktpa GNH_3
Green H_2 Mobility: N7 Corridor	GH_2 for long-haul transportation	RRS Investment	2031	

skilled and capable labour force to execute JET initiatives and drive economic development in key value chains. The approach for an effective Skills Implementation Plan focuses on three key dimensions identified by the JET-IP (Table 4). This approach requires a comprehensive skills development approach that integrates skills planning processes with the transition of JET sectors and includes short-, medium- and longer-term planning approaches. It requires coordination and strategic support at the national level and adaptation at the local level to emerging skills needs (South African Government 2022). It also extends the traditional role of skills systems beyond skills provision to ensure a seamless transition from education to work and promote suitable skills matching in the workplace. In addition, the provision of resources for the JET's key value chains, including renewable energy, green hydrogen (GH2) and electric vehicles (EVs), requires consideration of all three aspects of the skills system. Coherent anticipation and development of skills will help address anticipated gaps between skills demand and supply and ensure effective workplace skills utilization.

3.3.2 Mpumalanga just transition

The province of Mpumalanga lies at the centre of the'minerals-energy complex', which historically formed the economic backbone of South Africa and revolved around mining, metal refining, petrochemicals and manufacturing (Mohlakoana et al. 2023; Nel et al. 2023). With more than 80% of the country's coal-fired power stations and 111 coal mines (56 of

Table 4 Approaches for effective JET skill implementation (South African Government 2022)

Key Dimensions	Description
Retraining and upskilling of adult workers	• Emphasizes the significance of acknowledging past learning and offering comprehensive labour market data to aid in retraining and upskilling • Stresses the need for forward-looking, enduring strategies for retraining, which incorporate skills enhancement into socio-economic and socio-ecological frameworks
Anticipatory systems and processes for skills	• Enhancing labour market information systems to align with future requirements of industries, communities, and marginalized populations • Implementing diverse skills development strategies, catering to immediate and medium-term needs
Supporting essential skills	• Enhancing the flexibility of the workforce and aiding trainers in fostering fundamental knowledge, skills, and values within the JET framework • Offering various forms of training, such as vocational, workplace, and technical training to meet diverse learning needs

which are still in service), as well as the Sasol coal-to-liquids complex, Mpumalanga is heavily impacted by the transition to low-carbon energy. An estimated 150,000 to 200,000 jobs are at risk, including 80,000 coal miners and 15,000 employees in the transport sector. In addition, there are further risks for formal and informal service professions, some of which are traditionally carried out by women. Around 400,000 people are directly or indirectly at risk (Nel et al. 2023; South African Government 2022). The transition also poses a challenge to municipal revenues and services, especially in areas such as eMalahleni, where coal accounts for about half of local returns. The communities rely on the services provided by Eskom and the coal mining companies, such as water and electricity, which could be jeopardised without additional support. Recognising the need for a just transition in Mpumalanga, the JET-IP outlines a framework for investment and practical measures to diversify the province's economy and attract new skills and capital (Table 5).

3.3.3 Municipalities

Municipalities are pivotal in South Africa's energy transition, enhancing energy security and ensuring reliable, affordable electricity to support socio-economic development. Due to local governments' various challenges, a coordinated effort across national, provincial, and municipal levels is crucial to overcoming substantial financial, technical, and administrative barriers. The Department of Cooperative Government and Traditional Affairs (COGTA), National Treasury (NT), and organized local government bodies lead this intergovernmental collaboration, which is vital for developing sustainable electricity solutions for communities of varying sizes and capabilities. Municipalities have several key roles to play in achieving these goals (South African Government 2022):

- Recent legislative changes allow municipalities to buy electricity directly from independent power producers (IPPs) or to setup their own power generation companies.
- Municipalities can contribute significantly to the decarbonisation of the electricity sec-

Table 5 JET-IP objectives and their alignment with the Mpumalanga just transition

JET-IP Objectives	Green Economy Development Plan Objectives in Mpumalanga
Repurposing coal power plants	• Emphasizing renewable energy generation will expand economic participation in the province • Backing substitute energy sources like GH_2, waste-to-energy projects, and repurposing coal-fired power stations, with Eskom as a partner
Enhancing infrastructural development	• Investing in water facilities aims to enhance drought resilience and create a better environment for industrial growth • Transforming urban areas requires rooftop solar PV systems, circular waste management, and generating electricity from landfills
Diversification of the local economy	• Promoting agricultural skills and agri-processing for a larger share of the value chain • Expanding current tourism businesses and attracting new ones to the province
Youth and future generation investment Capacity building – coal workers	• Mpumalanga aims to become a skills hub for the Green Economy, focusing on the circular economy opportunities in the battery storage supply chain

tor, address national electricity supply bottlenecks and support the energy transition and economic development.

The effectiveness of regulatory innovations, including increased integration of power generation and grid wheeling, to drive SA's energy transition and ensure security of supply is highly dependent on the functionality and resilience of municipal grids and their operations, such as a suitable tariff framework. Many municipal electricity distribution networks have deteriorated over the past two decades, posing a challenge to embedded RE generation, supply security and equitable energy access. The successful introduction of electric vehicles (EVs), especially in public transport, depends on the functionality of municipal distribution grids (Arias et al. 2019). Municipalities are also crucial in facilitating universal electricity access, reducing the electrification gap and ensuring affordability through electricity tariffs and the implementation of measures, including the free basic electricity (FBE) subsidy. The transition to a future energy generation system will require significant investment in municipal electricity systems to enable the increasing penetration of renewables and support new generation models such as Small-Scale Embedded Generation (SSEG). Desired outcomes for municipalities include a higher share of renewables in the electricity mix, functioning distribution networks that support renewable penetration and universal access, tariff structures that align with JET targets, and efficient municipalities that can effectively manage electricity generation and distribution (South African Government 2022). Table 6 presents a summary of JET-IP priority sectors and related programmes.

3.4 Economic implication of JET-IP

The JET-IP details the investments needed over five years, amounting to ZAR 1.5 trillion, to align South Africa's shift to a low-carbon, climate-resilient economy with the updated Nationally Determined Contribution (NDC) to be submitted to the United Nations Frame-

Table 6 Summary of 5-year JET-IP Portfolios and related programmes to facilitate implementation

JET-IP 5-year Portfolios (Priority areas)	Key Features, programmes and intervention
Electricity	• Private sector-driven RE generation and storage • Expansion of transmission grid led by Eskom/NTCSA • Maintenance and upgrades of distribution systems • Early repurposing of coal plants and support for affected stakeholders
New Energy Vehicles (NEVs)	• Supply-side incentives for NEV production and employment growth • Co-funding for NEV assembly and supply chain investments • Prep for NEV public transport and charging infrastructure • Battery industry investments and charging network planning • Planning for a national charging infrastructure network
Green Hydrogen (GH2)	• Funding: Mobilize GH2 funds for project de-risking • Supply: Access tech and support local manufacturing • Demand: Secure trade deals • Shared infrastructure: Coordinate and accelerate projects • Technology incubation: Fast-track R&D • Policies and regulations: Develop GH2 grid framework • Community engagement: Roll out the benefit strategy
Mpumalanga Just Transition	• JET Funding links finance to community projects for tangible benefits • Accelerating Coal Transition Investment Plan (ACT-IP) facilitates coal transition • Community-led projects empower an economic shift from coal • The Mpumalanga plan is bolstered by national JET efforts focusing on skills and municipal capabilities
Skills	• JET establishes a skills ecosystem that is aligned with the national plan • Skill Development Zones (SDZs) in key regions foster local learning • Assessments guide tertiary education needs • Capacity building targets the government • Teacher training integrates energy concepts
Municipalities	• Municipal JET structures are developed for capability enhancement • Municipal infrastructure financing is structured for funding • Affordable energy access initiatives include efficient appliance distribution

Table 7 JET-IP 5-year funding requirements (South African Government 2022)

JET-IP funding for 2023–2027	USD billion	ZAR billion
Electricity sector	40.67	711.40
New Energy Vehicles (NEVs) sector	7.32	128.08
Green Hydrogen (GH_2) sector	18.24	319.01
Skill development	0.15	2.71
Municipal capacity	18.24	319.06
Total	**84.6**	**1480.26**

Table 8 Breakdown of 2023–2027 financing requirements for each priority sector (ZAR USD) billion

Projects	Electricity	NEV	GH_2	Subtotal
Infrastructure Development	978	83	313	1.374
Capacity for Planning and Implementation	2.14	2	5.5	9.6
Promoting Economic Diversity and Innovation	40.4	43	-	83.4
Investing in Social Inclusion and Equity	9.6	-	-	9.6
Enhancing Skill Development	2.7			2.7
Sub-total	1030.14 (58.9)	128 (7.3)	319 (18.2)	
TOTAL ZAR (USD) billions				1480 (84.6)

1 USD = 17.49 ZAR

work Convention on Climate Change in 2021 (Tables 7 and 8) (South African Government 2022). At the Conference of the Parties (COP26) in 2021, five international partners (including developed nations; private sector investors; Development Finance Institutions (DFIs); Multilateral Development Banks (MDBs); governments; and philanthropies (Fig. 6) pledged to provide South Africa with USD 8.5 bn, approximately ZAR 148.75 bn, consisting of concessional loans, commercial loans and equity, and grants. By 2023, commitments from abroad for JET-IP increased to USD 11.6 bn, approximately ZAR 198.2 billion (Simpson et al. 2023a, b; South African Government 2022). In addition, the reforms introduced by the government in the electricity sector have triggered significant private-sector investment in RE generation in SA. Investment is crucial in three key sectors: electricity, NEVs and GH_2. In addition, cross-cutting sectors such as skills and municipalities require further funding. Mpumalanga, a coal-dependent province, needs targeted investment to diversify its economy and create new opportunities for coal-dependent communities.

3.4.1 Current JET-IP financing status

For five years, the JET-IP 2023–2027 indicates a financial requirement of ZAR 1.5 trillion, about USD 85 bn (South African Government 2022). A significant portion of this is earmarked for decarbonising the electrical industry and mitigating its impact on communities. Donors and investors are invited to join the SA government in funding the JET through the JET Investment Plan 2023–2027. In addition, initial commitments totalling around USD 8.5 bn have been made by the EU, Germany, France, the UK and the US. Table 9 shows the

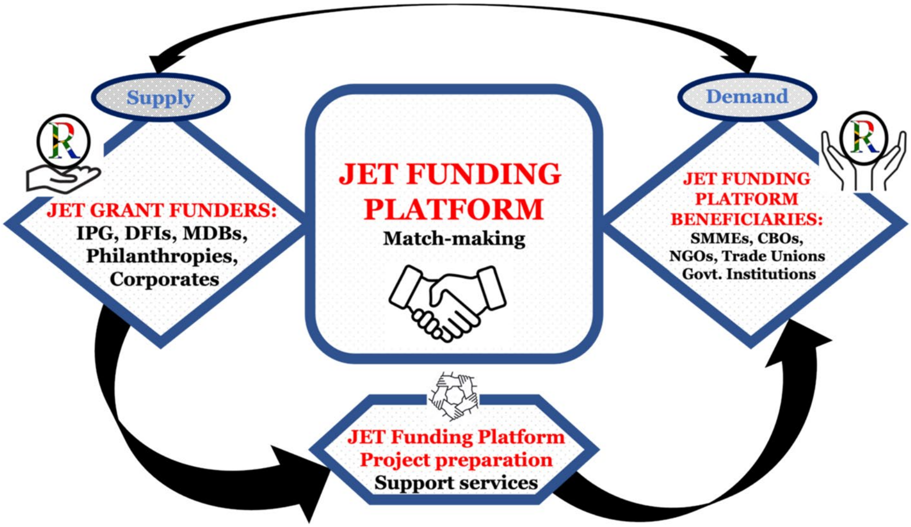


Fig. 6 JET funding platform (adapted from (South African Government 2022))

status of the different financial sources including concessional credit facilities, grants and commercial facilities for the JET implementation plan.

4 Discussion

The high CO_2 emissions, driven by coal combustion, position South Africa as a leading emitter on the continent. Transitioning to renewable energy is critical for addressing climate change, reducing emissions, and promoting sustainability. South Africa's government has set ambitious goals to decommission coal-fired power plants and increase renewable energy capacity by 2030. However, these efforts face feasibility challenges, including inadequate climate policies, socio-economic instability, and international dependency on coal exports. The Just Energy Transition (JET) framework emphasizes the need for equitable solutions to address the socio-economic impacts of phasing out coal, particularly for affected communities. While initiatives like South Africa's Just Energy Transition Partnership (JETP) reflect progress, critics argue that current strategies may perpetuate existing economic challenges and energy inequities. The South African case underscores the complex interplay between socio-economic factors and energy transition imperatives, serving as a critical example for just transition science (Avelino et al. 2024; Loorbach et al. 2017; Wittmayer et al. 2021).

The Just Energy Transition Investment Plan (JET-IP) represents a bold framework for addressing South Africa's energy and climate challenges, with significant implications for electricity transformation, the adoption of new energy vehicles (NEVs), and the development of the green hydrogen (GH_2) sector. In the electricity sector, targeted renewable energy expansion and infrastructure upgrades could address energy poverty and create substantial economic opportunities. However, the existing transmission and distribution infrastructure is inadequate for integrating renewables, and delays in coal decommissioning undermine decarbonization goals. Effective collaboration between the government, Eskom, munici-

Table 9 Current financial status of 2023–2027 JET-1P

JET-IP finance source	Financing progress and status
Bilateral *concessional credit facilities*	• Finance Ministry secured EUR 300 M concessional loans from the German Kreditanstalt für Wiederaufbau (KfW) and AFD for the JET-IP • CIF ACT-IP funding programming postponed until May 2024, awaiting coal plant and borrower decisions • Pending decisions on remaining loans and guarantees due to Eskom's borrowing halt and Northern Territory constraints
Pledged *grants*	• The current status of committed grants shows that around ∘ 50% of the JET IP funding has been made available for approved projects, while ∘ 35% is still in the planning phase • Of the pledged grant ∘ 47% earmarked for technical assistance, ∘ 19% for infrastructure ∘ 11% for community development ∘ 10% for project preparation ∘ 10% for capacity building ∘ Others for studies and communication • 26% of the grant funds are earmarked for initiatives under the Mpumalanga Just Transition Initiative
Pledged *commercial facilities*	∎ The commercial credit facilities promised under the JET IP are yet to be programmed ∎ The private sector is expected to invest a minimum of ZAR 500 billion in the JET initiative in South Africa, particularly in RE technologies, GH_2, and NEVs ∎ Local and international financial institutions are crucial in financing JET projects and driving innovation and competition ∎ The private finance sector's input to the national GDP exceeded ZAR 1 trillion in 2022 ∎ International philanthropy strongly supports South Africa's JET, but its impact must be aligned with other funding for optimal results ∎ The SA government's budgetary commitment to JET remains unconfirmed, while NT continues tagging expenditures for future planning ∎ Contributions from South Africa's DFIs, DBSA and IDC, are pending confirmation ∎ Analysis is needed to gauge international and local contributions to JET, aligning with green finance standards and defining'just transition'elements

CIF: Climate Investment Fund; *ACT-IP*: Accelerating Coal Transition Investment Plan; *AFD*: French Development Agency; *DFIs*: Development Finance Institution; *DBSA*: Development Bank of Southern Africa; *IDC*: Industrial Development Corporation

palities, and private investors is crucial to addressing these challenges, alongside scaling up grid technologies and retraining programs for displaced workers.

Green hydrogen (GH_2) offers a transformative opportunity for South Africa's Just Energy Transition Investment Plan (JET-IP), positioning the country as a global leader in renewable energy while addressing industrial decarbonization in steelmaking, ammonia production, and transportation. However, challenges such as the high cost of electrolysers, limited renewable energy capacity, and insufficient infrastructure for storage and distribution hinder progress. Strategic investments in research and development, international partnerships to boost demand, and phased implementation through pilot projects are critical to overcoming these barriers. Furthermore, systemic issues like grid instability and inadequate renewable energy generation must be addressed to ensure a stable electricity supply for electrolysis. GH_2 development must also align with other JET-IP pillars, such as electricity transition and new energy vehicles, creating a cohesive energy framework. By prioritizing proactive policymaking, substantial infrastructure investment, and collaboration across government, industry, and international partners, South Africa can unlock the potential of GH_2 while ensuring social and environmental sustainability.

The shift to NEVs aims to preserve South Africa's automotive sector competitiveness, reduce transport emissions, and create new industrial opportunities. However, funding gaps, limited public charging infrastructure, and social inequities in NEV access present barriers to widespread adoption. Integrating NEVs with the renewable energy transition, incentivizing private investment in charging networks, and prioritizing affordable ownership models can address these challenges. Meanwhile, South Africa's potential to lead in green hydrogen production faces hurdles, including high costs, limited domestic demand, and infrastructure gaps. Strategic partnerships with global markets, enhanced R&D to lower production costs, and careful project planning to mitigate social and environmental risks are critical for scaling up the sector.

The Just Energy Transition Investment Plan (JET-IP) identifies three cross-cutting areas—skill development, Mpumalanga's just transition, and the role of municipalities—as vital for implementing priority sectors. A robust skills ecosystem is essential for equipping South Africa's workforce to execute JET initiatives across industries like renewable energy, green hydrogen, and electric vehicles. This requires integrated planning, forward-looking retraining strategies, and alignment of education with labour market demands to close skill gaps. With its coal-dependent economy, Mpumalanga faces significant risks, including job losses and declining municipal revenues, but the JET-IP proposes economic diversification through green energy projects, tourism, and agriculture. However, realizing this vision necessitates addressing structural challenges, such as retraining displaced coal workers and improving economic infrastructure to attract investment. Municipalities play a critical role in ensuring energy access and transitioning to renewable energy, yet they face systemic issues like outdated grids and financial constraints. Municipalities must leverage new legislative powers to procure energy from independent power producers, strengthen grid infrastructure, and foster sustainable energy models to succeed. While these initiatives provide a framework for progress, they underscore the need for substantial investment, coordinated policy support, and local capacity-building to overcome logistical and socio-economic barriers and ensure a truly inclusive energy transition.

The investment and financing status of the JET-IP underscores the financial scale and complexity of transitioning South Africa to a low-carbon economy. With an estimated ZAR 1.5 trillion (USD 85 billion) required over five years, the bulk of funding is allocated to decarbonizing the electricity sector, advancing new energy vehicles (NEVs), and green hydrogen (GH_2) technologies. Commitments from international partners, including the EU, US, UK, Germany, and France, amount to approximately USD 11.6 billion, with concessional loans, grants, and commercial credit forming the funding mix. However, these contributions remain fragmented, with many grants still in the planning or approval phase and commercial facilities yet to be fully programmed. Private sector investment is expected to contribute significantly, particularly in renewable energy (RE), GH_2, and NEVs, emphasizing the need for robust public–private partnerships.

Economically, the JET-IP is transformative, aiming to diversify coal-dependent regions like Mpumalanga and stimulate sectors with green growth potential. The plan aligns investment with job creation, skill development, and infrastructure enhancement to mitigate the socio-economic impacts of transitioning from coal. Yet, the financing gap, reliance on private contributions, and pending domestic budgetary commitments highlight vulnerabilities in execution. Successful implementation will require improved financial structuring, alignment with green finance standards, and strategic deployment of resources to ensure long-term sustainability and inclusivity.

5 Feasibility constraints and challenges for the successful implementation of JET-IP

The JET-IP agreement can potentially drive energy transition and unlock access to climate funds. However, as a novel mechanism with ongoing development, there is a risk of it falling short of its potential. Ensuring the successful implementation of the JET-IP is vital for realising a sustainable energy transition in SA. Nonetheless, various obstacles require resolution to ensure the successful execution of the JET-IP (Irene et al. 2023). Todd & McCauley (2021) highlighted critical factors like technological, cost-effectiveness, and market barriers.

5.1 Technical constraints

The nations committed to achieving net-zero carbon emissions by 2050 or 2060 are expanding, with India, SA, Japan, Canada, and China joining the ranks (Scroll 2021). The successful implementation of the JET-IP in SA relies on various technical factors, including the governance and institutional architecture established to oversee the transition. The JET-IP aims to transition the country to a low-carbon and climate-resilient economy, focusing on various sectors such as electricity, NEVs, and H_2 (PCC 2003). A robust policy framework is essential for shifting towards a fair and sustainable energy system. However, these policies are fraught with technical obstacles that hamper the successful implementation of JET-IP. The potential absence of a comprehensive policy framework could challenge the transition towards a fair and sustainable energy system. This framework should encompass legislation, regulations, and detailed policy documents to establish clear objectives, targets, and strategies for a successful and equitable energy transition. Effective governance structures ensure alignment between national energy policies and the goals of the JET-IP (Ramluckun et al. 2024). Another major challenge is building technical capacity in the relevant government agencies, regulatory bodies, and other stakeholders, as this is necessary to effectively implement the plan. This includes training programs, workshops, and knowledge-sharing initiatives to enhance skills in energy planning, project management, policy analysis, and regulatory oversight. In addition, strengthening institutional capacity enables more informed decision-making, improves project execution, and enhances the overall success of the transition.

5.2 Financial constraints

According to the report by (PCC 2003), some of the weaknesses of the JET-IP lie in its lack of comprehensive, transparent, and structured alignment between the projected financial investments required and specific projects. The effective implementation of these projects depends on the availability of financial mechanisms. To facilitate their execution, it is recommended to establish dedicated transition funds and enhance national resources with supplementary financing (Arora and Schroeder 2022). The JET plan lacks the level of detail needed to determine the appropriate financing mechanisms for individual projects, leading to a lack of granularity in project financing. Criticism has been directed at the plan for its perceived lack of"bankability,"indicating a deficiency in presenting a detailed investment case that would attract both public and private sector investors. This includes various sources of capital such as Development Finance Institutions (DFIs), Multilateral Development Banks (MDBs), philanthropic organisations, asset managers, commercial banks, and private equity firms. This absence of detailed project information hinders the immediate preparation and implementation of projects for financial investment across various sectors.

Another significant obstacle pertains to securing concessional finance, a crucial element for the implementation of the JET-IP. Recently, the National Treasury disclosed that SA has entered into bilateral loan agreements with prominent financial institutions such as the World Bank, Kreditanstalt für Wiederaufbau (KfW), and the African Development Bank to bolster the nation's JET endeavours. This concessional financing comprises a $1 billion loan from the World Bank, €500 million from KfW, and an additional $300 million from the ADB. These financial arrangements align with South Africa's funding strategy to diversify its international borrowing portfolio. However, achieving the goal of a just energy transition depends on robust governance structures, effective management frameworks, comprehensive monitoring and evaluation mechanisms and robust risk management protocols, which may be precarious (Hattingh and Maharaj 2023). Financial constraints can impede the adoption of innovative tools and technologies necessary for the implementation of JET. Many developing countries face budgetary limitations for infrastructure development, restricting their ability to invest in advanced planning tools (Badu et al. 2012). Integrating JET-IP into infrastructure planning processes may be challenging without adequate funding, limiting its widespread adoption and effectiveness.

The successful implementation of the JET-IP requires addressing several challenges, including the availability of concessional finance, the need for innovative solutions to JET-IP implementation problems, and the resistance and hurdles faced in the implementation of the JET-IP (Booyens et al. 2024). The JET Funding Platform, provided by the JET Projects Management Unit (PMU), plays a vital role in the JET-IP by facilitating collaboration between grant fund providers and recipients and aiding applicants in preparing their submissions. Consequently, the effectiveness of the JET-IP hinges on solid governance, resilient management structures, comprehensive monitoring, evaluation, learning frameworks, and robust risk management frameworks.

5.3 Cost and availability of energy sources (Coal vs Renewable Energy Sources, REs)

Globally, coal is the primary fuel for power generation, accounting for 36% of total fuel consumption. Forecasts indicate that coal will continue to have a considerable share of the power generation market for the foreseeable future (IEA 2022). The five largest coal consumers—China, USA, India, Japan and SA—utilise 82% of the world's coal resources. SA is the 5 th largest coal producer in the world, with an average annual production of 224 million tonnes of marketable coal (Lloyd 2017). A significant portion, 25%, of this production is exported, making SA the third largest coal exporting nation. Coal has traditionally been a dominant energy source in SA as it is a reliable, readily available and relatively inexpensive source of energy, providing approximately 72.1% of primary energy demand, and this dependence is projected to continue over the next ten years due to the limited availability of viable alternatives (Eskom 2021). This limits the investment, utilisation and application of REs. However, the environmental effects of coal, including high carbon emissions and air pollution, have led to a global push towards cleaner and more sustainable energy sources. REs, including solar, wind, and hydropower, offer cleaner alternatives to coal and contribute to reducing greenhouse gas emissions.

5.3.1 Operational cost of energy source

In the context of the JET-IP, the cost of transitioning from coal to REs is a significant factor. While coal-fired power plants may have lower operational costs in fuel procurement and maintenance compared to certain RES technologies, such as solar and wind, they also incur additional costs associated with environmental compliance, pollution control, and carbon emissions. Although coal is abundant and offers a low-cost energy source, the implementation of emissions reduction measures, including carbon pricing or carbon taxes, can further increase the operational costs of coal-fired power generation. In contrast, REs technologies benefit from minimal fuel costs and relatively lower operational and maintenance expenses over their operational lifetime. Transitioning to REs involves initial investment in infrastructure and technology, but over time, RE can be more cost-effective and sustainable, especially considering the decreasing costs of renewable technologies.

5.3.2 Availability of alternative energy sources

Availability is another critical factor in the transition from coal to REs. SA has abundant coal reserves, historically supporting the country's energy needs. However, the finite nature of coal reserves and the environmental impact of coal combustion necessitate a shift towards more sustainable energy sources. REs, on the other hand, are abundant and inexhaustible, particularly in solar and wind resources, offering a long-term and sustainable solution to SA's energy needs. Economic concerns and environmental and social factors drive the transition from coal to REs. Coal combustion is associated with negative externalities, including air and water pollution, land degradation, and public health impacts. In contrast, REs technologies offer cleaner and more sustainable energy alternatives with minimal environmental footprint and reduced GHG emissions. The transition to REs aligns with South Africa's commitments under international climate agreements, including the Paris Agreement and contributes to mitigating climate change and improving air quality.

The JET-IP aims to address the cost and availability challenges related to transitioning from coal to renewable energy sources by promoting investment in RE infrastructure, supporting the development of clean energy technologies, and creating a conducive policy environment for RE deployment (Caprotti et al. 2020). By prioritising renewable energy investments and phasing out coal-fired power plants, the JET-IP seeks to achieve a JET that balances economic, social, and environmental considerations for a sustainable future in SA. While coal may have been historically favoured for its affordability and availability, the JET-IP in South Africa emphasises the need to transition towards cleaner and more sustainable energy sources, including REs. Despite potential challenges related to cost and availability, the declining costs of RE technologies and the environmental and economic benefits they offer make them increasingly attractive options for investment and deployment under the JET-IP (Merven et al. 2022).

5.4 Decommissioning coal power plants

One of the primary objectives of the JET-IP in SA is to oversee the retirement of the nation's coal-fired power plants, improve the transmission grid facilities, enhance the electricity distribution system, transition the automotive sector value chains, build new energy vehicle supply chain localisation, promote new growth in sustainable manufacturing, and set SA in becoming a world-leading exporter of green hydrogen (Manika 2023; Suharsono and Maulidia 2023). However, decommissioning coal power plants presents several challenges, which are highlighted below:

5.4.1 Concentration and location of coal power plants

One of the challenges is the geographical concentration of coal plants and mines in a single region in South Africa, which could lead to a negative multiplier effect from the decommissioning of plants (StatSA 2021; Seiler et al. 2023). This concentration could lead to economic instability in the affected regions. A significant hurdle is the potential disagreement over electricity planning and the execution of the energy transition. Despite declarations and objectives, numerous policies fail to materialise, resulting in a disconnect between policy and implementation (Suharsono and Maulidia 2023). This gap could hinder the successful decommissioning of coal power plants and the transition to REs.

5.4.2 Extending the service life of coal-fired power plants

The ongoing electricity supply crisis in South Africa is fuelling calls for extending the life of coal-fired power plants, which could prolong the development of coal infrastructure and delay the implementation of JET. This scenario is at odds with the plans for a rapid phase-out of coal-fired power generation outlined in the JET IP and highlights the controversial nature of electricity planning and the implementation of the energy transition.

5.4.3 Technical challenges

Decommissioning coal power plants requires careful planning and coordination to ensure the safe shutdown and dismantling of infrastructure, including power generation units, transmission lines, and associated facilities. Technical challenges may arise from the need to manage hazardous materials, such as asbestos and heavy metals, as well as the disposal of coal ash and other waste products generated during operation. Additionally, transitioning to alternative energy sources may require upgrades to grid infrastructure and integration of renewable energy systems, presenting technical complexities.

5.4.4 Increase in the unemployment rate

Coal power plants often serve as significant sources of employment and revenue in coal-dependent regions, making their closure economically disruptive (Mathu & Chinomona 2013). Decommissioning coal plants may result in job losses for coal miners, power plant workers, and communities reliant on the coal industry. Moreover, the transition to alternative energy sources entails investment in new facilities and technologies, which can involve substantial upfront costs. Balancing the economic impacts of coal plant closures with the long-term benefits of transitioning to cleaner energy sources is a major challenge for policymakers and stakeholders. The closure of coal power plants can have profound social implications for affected communities, including disruptions to livelihoods, loss of tax revenue for local governments, and social unrest.

5.4.5 Socio-economic issues of the decommissioning of coal plants

Communities dependent on coal mining and power generation may face socio-economic challenges, such as poverty, lack of jobs, and social dislocation (Mirzania et al. 2023). Addressing the social consequences of coal plant closures requires comprehensive support measures, including retraining and job placement programs, economic diversification initiatives, and community development projects. The decommissioning of coal power plants is often subject to political and regulatory dynamics, influenced by factors such as energy policy objectives, stakeholder interests, and public opinion. Policymakers must navigate complex political landscapes and engage with diverse stakeholders, including industry representatives, labour unions, environmental advocates, and local communities. Regulatory frameworks governing coal plant decommissioning, environmental remediation, and transition planning are crucial in shaping the pace and scale of the energy transition.

5.4.6 Environmental concerns

Although decommissioning coal power plants minimizes GHG emissions and mitigates climate change, it also raises environmental considerations. Coal ash disposal, land remediation, and air and water quality management are key ecological challenges associated with coal plant closure. Ensuring proper environmental remediation and transitioning to cleaner energy sources that minimise environmental impact are essential for decommissioning.

5.5 Sociopolitical constraints

The JET-IP in SA faces various sociopolitical constraints that can impact its successful implementation. These constraints arise from the complex interplay of social, political, and economic factors within the country (Hanto et al. 2022). Some of these constraints include social equity concerns, labour issues, community engagement and participation, political dynamics, and policy uncertainties. Some of the sociopolitical constraints include:

5.5.1 Social equity and justice

One of the primary sociopolitical constraints of the JET-IP is ensuring social equity and justice throughout the energy transition process. SA's energy sector is deeply intertwined with historical patterns of social inequality, particularly along racial lines. The transition away from fossil fuels, including coal, may disproportionately impact vulnerable communities dependent on coal mining and power generation for employment and livelihoods. The plan aims to transition to REs and phase out coal-fired power plants, which can have significant social implications, particularly for communities reliant on the coal industry. Ensuring the transition is fair and does not disproportionately impact vulnerable communities is a critical sociopolitical challenge (Arora and Schroeder 2022). The transition from coal to renewable energy sources may lead to job losses in the coal industry, affecting workers and their families. Resistance to the energy transition may stem from fears of unemployment and economic instability among workers in coal-dependent industries. Addressing the potential displacement of workers and providing support for reskilling and transitioning to new employment opportunities is a key sociopolitical challenge for the JET-IP (Mohlakoana et al. 2023). Some of the social difficulties include:

5.5.2 Lack of stakeholders'engagement and participation

Engaging and involving local communities in the decision-making processes related to the energy transition is crucial for its success (Lennon et al. 2019). There has been a lack of effective community engagement in the JET program. Ensuring that communities impacted by the transition have a voice in the planning and implementation of the JET-IP is essential to address sociopolitical challenges and build support for the transition (Steadman et al. 2024). Meaningful engagement with local communities affected by the energy transition is crucial for building trust, fostering cooperation, and addressing community concerns. However, community resistance or lack of buy-in can hinder the implementation of renewable energy projects and infrastructure development. Effective communication, participatory decision-making processes, and community consultation mechanisms are essential for navigating sociopolitical tensions and ensuring community support for the JET-IP initiatives.

5.5.3 Conflicting political interests and ideologies

Energy transition policies and initiatives are often subject to political contestation and ideological debates. In South Africa, political interests, including those of coal industry stakeholders and labour unions, may influence government decision-making and policy implementation regarding the energy transition. Political fragmentation and competing priorities within the government can slow the adoption of ambitious renewable energy targets and the allocation of resources to support clean energy investments. The successful implementation of the JET-IP requires strong political will and alignment among various stakeholders, including government entities, industry players, civil society organisations, and local communities. Overcoming political differences and ensuring collaboration among stakeholders is a significant sociopolitical challenge that can impact the plan's effectiveness.

5.5.4 Policy framework, regulatory and implementation uncertainties

Uncertainty surrounding energy transition policies, regulations, and incentives can create barriers to investment and hinder the growth of renewable energy markets. Inconsistent policy frameworks, regulatory gaps, and changing government priorities may deter private sector involvement and undermine investor confidence in clean energy projects. Establishing and enforcing policies that support the goals of the JET-IP, such as promoting renewable energy adoption and phasing out coal, requires a robust regulatory framework. Ensuring that policies are effectively implemented and enforced transparently and in an accountable manner is essential to address sociopolitical constraints and build trust in the energy transition process. Figure 7 presents a SWOT diagram outlining the economic, social, technical, and environmental strengths, opportunities, weaknesses, and threats associated with successfully implementing South Africa's 5-year Just Energy Transition Investment Plan (JET-IP).

6 Wayforward for a successful implementation of the 5-year JET-IP

The successful implementation of South Africa's Just Energy Transition Investment Plan (JET-IP) requires a comprehensive and strategic approach that takes into account governance, financing, infrastructure, workforce development, social equity, research and innovation, environmental sustainability, monitoring and international collaboration, which are

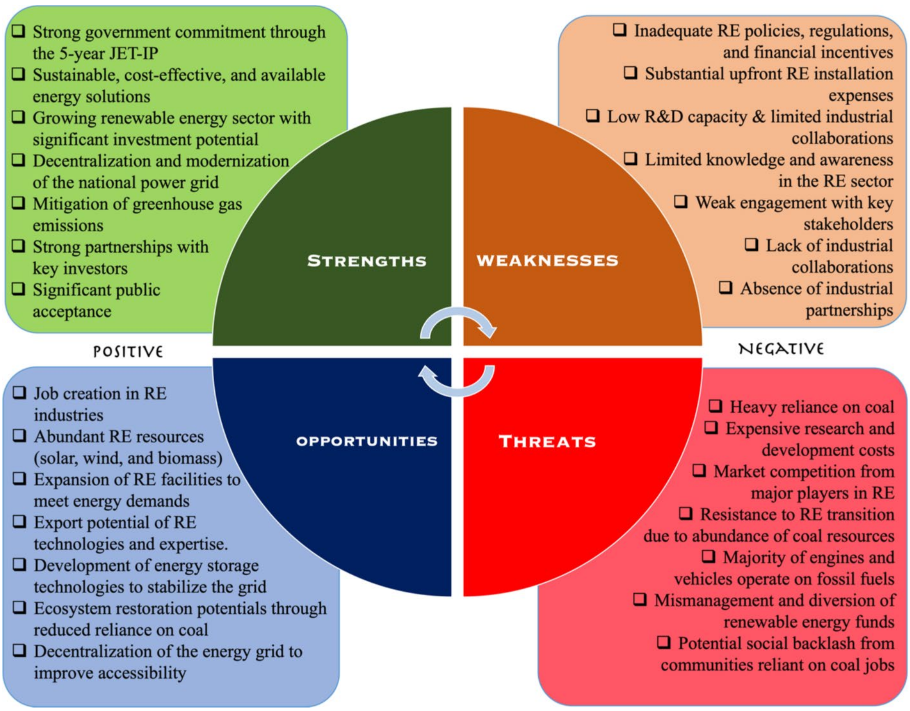


Fig. 7 SWOT diagram showing the technical, economic, social, political and environmental benefits, potentials, limitations and constraints of the 5-year JET-IP of South Africa

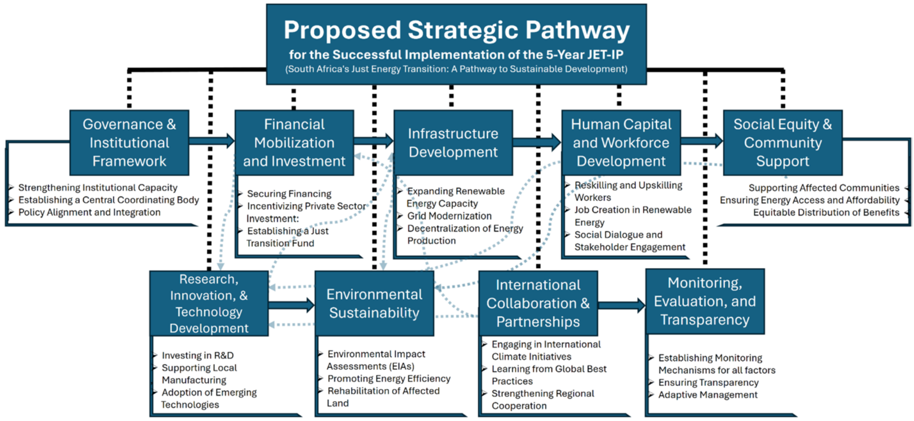


Fig. 8 Proposed strategic pathway for the successful implementation of the 5-year JET-IP, showing the relationship between these factors. The thick blue arrows in the strategic framework illustrate the dependence of one factor on another, highlighting the sequential or causal relationships that drive the overall process. In contrast, the faint blue dotted lines represent the interconnections and relationships among the various elements, emphasizing their dynamic interplay and mutual influence within the framework. These lines highlight how different factors are interconnected and influence one another. The directional arrows within the framework illustrate the causality or progression, indicating that one factor can contribute to or result in another. This design underscores the dynamic nature of the framework, where the interactions between elements form a cohesive structure to address the complexities of the energy transition

discussed in the sections below. Figure 8 illustrates the proposed strategies essential for successfully implementing the SA's 5-year JET Investment Plan. This diagram illustrates the intricate relationships between these factors and how they interact and reinforce each other. The visual representation not only highlights the interdependencies between the different elements but also emphasises their joint role in promoting the energy transition in South Africa. By understanding these interdependencies, stakeholders can ensure a coordinated and coherent approach to achieving the country's energy transition goals that balance economic growth, social equity and environmental sustainability.

6.1 Governance and institutional framework

Firstly, strengthening governance and the institutional framework is critical. Effective implementation depends on strengthening the capacity of key institutions such as the South African Department of Mineral Resources and Energy (DMRE), Eskom and the regulatory authorities. These institutions must be empowered to manage and monitor the transition to renewable energy. Strengthening a central coordinating body such as the PCC, possibly reporting to the SA Presidency, will ensure coordination between all stakeholders, including government agencies, the private sector, labour unions and civil society. This centralised body would oversee the implementation of the plan, monitor progress and mediate any conflicts between the different sectors. Furthermore, it is important to harmonise and integrate the SA's JET-IP with existing national policies, such as the National Development Plan (NDP) and the Integrated Resource Plan (IRP), to ensure coherence and avoid contradictory measures.

6.2 Financial mobilisation and investment

The mobilisation of financial resources is another important aspect. South Africa needs to secure substantial financial resources to support the transition. This includes access to international climate finance and the mobilisation of private-sector investment. The Green Climate Fund (GCF) and the Just Energy Transition Partnership (JETP) are potential sources of such finance. The government should introduce tax breaks, subsidies, and a favourable regulatory environment to incentivize private sector investment. Public–private partnerships between the SA government and private actors in the energy sector will play a key role in developing renewable energy infrastructure (Ngwadla et al. 2023). A dedicated Just Transition Fund should be established to support communities and workers affected by the transition, fund retraining programmes, support small and medium-sized enterprises (SMEs) and provide social protection measures for vulnerable groups. In addition, the SA JET funding platform should connect grant providers with potential recipients, offer support services for project preparation and ensure transparent data and analyses on the use of grant funds for JET projects (Coffee 2020).

6.3 Infrastructure development

Developing renewable energy capacity is essential to achieve the targets set out in the JET-IP. South Africa must accelerate the development and approval of renewable energy projects, particularly in the wind, solar and hydropower sectors. In parallel, the national energy grid must be modernised to accommodate the increasing feed-in from renewable sources. This includes modernising the transmission and distribution grids, integrating smart grid technologies and ensuring grid stability and reliability. Decentralising energy generation by promoting initiatives such as rooftop solar and community-based renewable energy projects will reduce the strain on the national grid and improve access to energy, especially in rural areas.

6.4 Human capital and labour development

The SA energy transition will inevitably lead to workers'redundancy, especially in sectors dependent on fossil fuels. Therefore, comprehensive retraining programmes must be implemented to equip these workers with the necessary skills for employment in the renewable energy sector (Chidzungu and Wafer 2023). Collaboration with educational institutions and industry stakeholders will be essential in developing appropriate curricula. At the same time, job creation in the SA renewable energy sector should be prioritised. This includes direct employment in energy production and related industries such as manufacturing, installation, maintenance and research and development. Social dialogue and the continued involvement of trade unions, communities and other stakeholders will be crucial to address concerns, build consensus and ensure the socially inclusive transition.

6.5 Social equity and community support

Supporting communities in SA heavily dependent on coal and other fossil fuels is essential for a just transition. Targeted initiatives should be introduced to help these communities, such as economic diversification programmes, SME development and infrastructure investments to create alternative livelihoods. It is also important to ensure that energy remains affordable and accessible for all during and after the transition, especially for low-income households. This may require subsidies or special tariff structures to protect vulnerable groups from potential price increases. The benefits of the energy transition, such as job creation and economic opportunities, should be fairly distributed across different SA regions and communities, especially those marginalised in the past.

6.6 Research, innovation and technology development

Investment in research and development (R&D) is key to driving innovation in renewable energy technologies, energy storage solutions and energy efficiency. South Africa should encourage collaboration between universities, research organisations and the private sector to drive innovation. In addition, developing local manufacturing capacity for renewable energy components such as solar panels and wind turbines will reduce dependence on imports, create jobs and stimulate economic growth. The introduction of new technologies such as hydrogen, battery storage and smart grids should be prioritised to improve the efficiency and reliability of renewable energy systems.

6.7 Environmental sustainability

Environmental sustainability must be a key concern for all renewable energy projects. This includes conducting rigorous Environmental Impact Assessments (EIAs) to ensure that these projects do not have a negative impact on biodiversity, water resources, or local communities in SA. Promoting energy efficiency in industry, buildings and transport is crucial to reducing overall energy demand and carbon emissions. In addition, land affected by coal mining and other extractive industries should be rehabilitated to restore ecosystems and create opportunities for new economic activities such as agriculture or tourism.

6.8 International cooperation and partnerships

International cooperation and partnerships with relevant stakeholders, including main actors in RE generation, will be key to the success of SA's JET (Project 90 by 2030 2020; Libala et al. 2023; Simpson et al. 2023a, b). The country should continue to participate in international climate initiatives and agreements to align its transition efforts with global best practices and benefit from international support mechanisms. Learning from successful examples in other countries that have made a just transition to renewable energy will provide valuable insights. In addition, strengthening regional cooperation within the Southern African Development Community (SADC) can enhance regional energy security and promote the development of regional renewable energy markets.

6.8.1 Monitoring, evaluation and transparency

Finally, establishing a sound monitoring and evaluation (M&E) framework is essential for tracking the implementation of the SA's JET-IP. This includes setting clear milestones and performance indicators and ensuring regular reporting. Transparency in decision-making, financial flows and project implementation is critical to maintain public trust and ensure accountability. Regular public consultations and disclosures can improve this transparency. In addition, the plan should be flexible enough to adapt to changing circumstances, such as technological advances, economic changes or social dynamics. Continuous feedback from stakeholders and regular plan reviews allow for necessary adjustments (Nwanekezie et al. 2021).

7 Conclusion

The South African energy sector is characterised by a heavy dependence on coal, extensive energy conversion activities and a wide range of energy consumption sectors. The consumption of these fossil energy sources contributes to GHG emissions, exacerbating climate change. To ensure a sustainable and secure energy future, the country needs to diversify its energy sources, improve energy efficiency, modernise the power grid, implement supportive policies and engage the stakeholders in energy conservation efforts. JET-IP provides a reliable strategy for achieving these goals and successfully transitioning to clean energy sources. However, JET also faces resistance and hurdles to its implementation. The decommissioning of coal-fired power plants in South Africa under the JET IP presents several challenges, including geographic concentration, potential controversies related to energy planning and implementation, and the need for sufficient funding, strong leadership and sound management arrangements. The phasing out of these coal-fired power plants, particularly in the less affluent areas of Mpumalanga Province, and the restructuring of Eskom are critical components of the JET-IP due to their socio-economic impact. Addressing these challenges requires a holistic approach that includes technical expertise, economic planning, social support mechanisms and a sound governance framework. The JET Implementation Plan 2023–2027 highlights the importance of finding innovative approaches to overcome implementation barriers and effectively mobilise various funding sources to meet the requirements of the JET IP. If South Africa carefully manages the transition from coal to cleaner energy sources, it can achieve its energy transition goals while minimising the negative effects on communities, the economy and the environment. The findings of this study highlight that the successful implementation and feasibility of South Africa's 5-year JET-IP requires a coordinated, multi-faceted approach. This approach must effectively balance economic growth, social equity and environmental sustainability to ensure long-term success. By focusing on these strategic areas, South Africa can ensure a just and effective transition to renewable energy sources and secure a sustainable and equitable future for all its citizens. This study provides actionable insights for policymakers, investors, and communities to balance economic growth, social equity, and environmental sustainability during the transition. In addition, it contributes to the global dialogue on energy transitions by offering valuable lessons from South Africa's case for other regions facing similar challenges.

Author contribution *IMS. Anekwe* – Conceptualization, Methodology, Software, Formal Analysis, Validation, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization, Supervision, Project Administration.

D. Ashiegbu—Formal Analysis, Investigation, Data Curation, Writing—Original Draft.

YM. Isa – Supervision, Writing—Review & Editing.

H. Potgieter—Supervision, Writing—Review & Editing.

Funding Open access funding provided by University of the Witwatersrand.

Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

Adebayo TS, Awosusi AA, Bekun FV, Altuntaş M (2021) Coal energy consumption beat renewable energy consumption in South Africa: developing policy framework for sustainable development. Renew Energy 175:1012–1024

Adenle AA (2020) Assessment of solar energy technologies in Africa-opportunities and challenges in meeting the 2030 agenda and sustainable development goals. Energy Policy 137:111180

Akinbami OM, Oke SR, Bodunrin MO (2021) The state of renewable energy development in South Africa: an overview. Alex Eng J 60(6):5077–5093

Al-Saadi N (2023) Russian-Ukrainian War's effects on the world economy. J Explor Stud Law Manage 10(1):8–21

Anekwe IMS, Isa YM (2023) Catalytic conversion of low alcohol to hydrocarbons: challenges, prospects, and future work considerations. Int J Energy Res 2023:1648449. https://doi.org/10.1155/2023/1648449

Anekwe IMS, Isa YM, Oboirien B (2023) Bioethanol as a potential eco-friendlier feedstock for catalytic production of fuels and petrochemicals. J Chem Technol Biotechnol 98(9):2077–2094

Arias NB, Hashemi S, Andersen PB, Træholt C, Romero R (2019) Distribution system services provided by electric vehicles: Recent status, challenges, and prospects. IEEE Trans Intell Transp Syst 20(12):4277–4296

Arora A, Schroeder H (2022) How to avoid unjust energy transitions: insights from the Ruhr region. Energy, Sustain Soc 12(19):1–13. https://doi.org/10.1186/s13705-022-00345-5

Asamoah J (2003) Greening electricity generation in South Africa through wind energy. In: Greenhouse gas control technologies-6th international conference

Avelino F, Wijsman K, van Steenbergen F, Jhagroe S, Wittmayer J, Akerboom S, Bogner K, Jansen EF, Frantzeskaki N, Kalfagianni A (2024) Just sustainability transitions: politics, power, and prefiguration in transformative change toward justice and sustainability. Annu Rev Environ Resour 49(1):519–547. https://doi.org/10.1146/annurev-environ-112321-081722

Badu E, Edwards DJ, Owusu-Manu D, Brown DM (2012) Barriers to the implementation of innovative financing (IF) of infrastructure. J Financ Manag Prop Constr 17(3):253–273. https://doi.org/10.1108/13664381211274362

Baker L, Phillips J (2019) Tensions in the transition: the politics of electricity distribution in South Africa. Environ Plan C: Polit Space 37(1):177–196. https://doi.org/10.1177/2399654418778590

Baker L, Newell P, Phillips J (2014) The political economy of energy transitions: the case of South Africa. New Polit Econ 19(6):791–818

Barnes J (2022) Divergent desires for the just transition in South Africa: an assemblage analysis. Polit Geogr 97:102655. https://doi.org/10.1016/j.polgeo.2022.102655

Barnes J, Analysts B, Montmasson-Clair G, Moshikaro TL, Ndlovu TM (2022) Recommendations to advance south africa's new energy vehicle market and domestic supply chain

Bekker A, van Dijk M, Niebuhr CM, Hansen C (2021) Framework development for the evaluation of conduit hydropower within water distribution systems: a South African case study. J Clean Prod 283:125326. https://doi.org/10.1016/j.jclepro.2020.125326

Bi SL, Bauer N, Jewell J (2023) Coal-exit alliance must confront freeriding sectors to propel Paris-aligned momentum. Nat Clim Chang 13(2):130–139

Bloem S, Swilling M, Koranteng K (2021) Taking energy democracy to the streets: Socio-technical learning, institutional dynamism, and integration in South African community energy projects. Energy Res Soc Sci 72:101906

Bohlmann HR, Horridge JM, Inglesi-Lotz R, Roos EL, Stander L (2019) Regional employment and economic growth effects of South Africa's transition to low-carbon energy supply mix. Energy Policy 128:830–837. https://doi.org/10.1016/j.enpol.2019.01.065

Booyens I, Hoogendoorn G, Langerman K, Rivett-Carnac K (2024) Path creation for an electricity transition in South African tourism. Tour Geogr 26(2):194–213. https://doi.org/10.1080/14616688.2023.2274836

Burke A, Fishel S (2020) A coal elimination treaty 2030: fast tracking climate change mitigation, global health and security. Earth Syst Gov 3:100046

Burki TK (2022) "Phasedown" of coal use after COP26 negotiations. Lancet Respir Med 10(1):10

Burton J, Marquard A, McCall B (2019) Socio-economic considerations for a Paris Agreement-compatible coal transition in South Africa. Energy Research Centre, University of Cape Town: Cape Town, South Africa. https://lifeaftercoal.org.za/wp-content/uploads/2020/05/Burton-Marquard-McCall-JT_Paris_South-Africa-Final.pdf. Accessed 23 May 2024

Caprotti F, Essex S, Phillips J, de Groot J, Baker L (2020) Scales of governance: translating multiscalar transitional pathways in South Africa's energy landscape. Energy Res Soc Sci 70. https://doi.org/10.1016/j.erss.2020.101700

Carley S, Konisky DM (2020) The justice and equity implications of the clean energy transition. Nat Energy 5(8):569–577

Cherp A, Vinichenko V, Tosun J, Gordon JA, Jewell J (2021) National growth dynamics of wind and solar power compared to the growth required for global climate targets. Nat Energy 6(7):742–754

Chidzungu T, Wafer A (2023) Can social impact assessments (SIAs) be a sustainable strategy to address the skills development gap and community sustainability challenges in just energy transition (JET) policy decision-making? Evidence from the South African mining communities of Kriel and Carolina in Mpumalanga. S Afr Geogr J 106(1):89–108. https://doi.org/10.1080/03736245.2023.2214537

Cock J (2019) Resistance to coal inequalities and the possibilities of a just transition in South Africa. Dev South Afr 36(6):860–873

Coffee J (2020) Financing resilient infrastructure. Optimizing Community Infrastruct 101–121. https://doi.org/10.1016/B978-0-12-816240-8.00006-9

Department of Mineral Resources SA (2023) South African Renewable Energy Masterplan (SAREM). R. o. S. Africa. https://www.dmr.gov.za/Portals/0/Resources/Renewable%20Energy%20Masterplan%20(SAREM)/South%20African%20Renewable%20Energy%20Masterplan%20(SAREM)%20Draft%20III.pdf. Accessed 03/02/2024

Dhansay T, Maupa T, Twala M, Sibewu Z, Nengovhela V, Mudau P, Schalenkamp M, Mashale N, Muedi T, Ndou C (2022) CO2 storage potential of basaltic rocks, Mpumalanga: Implications for the Just Transition. S Afr J Sci 118(7–8):1–7

Dooley K (2023) A Fair COP. AQ: Aust Quarterly 94(2):28–35

Eberhard A, Leigland J, Kolker J (2014) South Africa's renewable energy IPP procurement program: success and factors and lessons. World Bank Publications. Washington DC, USA

Eskom (2021) Coal in South Africa. https://www.eskom.co.za/wp-content/uploads/2021/08/CO-0007-Coal-in-SA-Rev-16.pdf. Accessed 02/05/2023

Eskom, Sawea, Sapvia (2023) South African renewable energy grid survey. S. ESKOM. https://www.eskom.co.za/wp-content/uploads/2023/06/RE_Survey_202304rev0_Pub.pdf

Gu R, Guo J, Huang Y, Wu X (2023) Impact of the EU carbon border adjustment mechanism on economic growth and resources supply in the BASIC countries. Resour Policy 85:104034

Haegele R, Iacobuţă GI, Tops J (2022) Addressing climate goals and the SDGs through a just energy transition? Empirical evidence from Germany and South Africa. J Integr Environ Sci 19(1):85–120

Hanto J, Krawielicki L, Krumm A, Moskalenko N, Löffler K, Hauenstein C, Oei P-Y (2021) Effects of decarbonization on the energy system and related employment effects in South Africa. Environ Sci Policy 124:73–84. https://doi.org/10.1016/j.envsci.2021.06.001

Hanto J, Schroth A, Krawielicki L, Oei P-Y, Burton J (2022) South Africa's energy transition–unraveling its political economy. Energy Sustain Dev 69:164–178

Harrahill K, Douglas O (2019) Framework development for 'just transition'in coal producing jurisdictions. Energy Policy 134:110990

Hattingh A, Maharaj P (2023) South Africa's Cabinet has approved the just energy transition implementation plan. https://hsfnotes.com/africa/2023/11/29/south-africas-cabinet-has-approved-the-just-energy-transition-implementation-plan/. Accessed 22 Apr 2024
Healy N, Barry J (2017) Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition." Energy Policy 108:451–459
Heffron RJ, McCauley D (2022) The 'just transition'threat to our energy and climate 2030 targets. Energy Policy 165:112949
Heffron RJ, McCauley D, Sovacool BK (2015) Resolving society's energy trilemma through the energy justice metric. Energy Policy 87:168–176
Henry MS, Bazilian MD, Markuson C (2020) Just transitions: Histories and futures in a post-COVID world. Energy Res Soc Sci 68:101668
Houston LJ, Ruppel OC (2022) Just energy transitions in progress? The partnership between South Africa and the EU. J Eur Environ Plan Law 19(1–2):31–54. https://doi.org/10.1163/18760104-19010004
Hyun M, Cherp A, Jewell J, Kim YJ, Eom J (2023) Feasibility trade-offs in decarbonising the power sector with high coal dependence: the case of Korea. Renew Sustain Energy Trans 3:100050
IEA I.E.A. (2021) South African energy supply and emissions. I. E. Agency. https://www.iea.org/countries/south-africa/emissions. Accessed 12/05/2024
IEA (2022) Global energy review: CO2 emissions in 2021. In: International Energy Agency (IEA). https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2. Accessed 23 May 2025
International Energy Agency (2022) Coal in Net Zero Transitions: strategies for rapid, secure and people-centred change. https://www.iea.org/reports/coal-in-net-zero-transitions/executive-summary. Accessed 02/05/2023
Irene JO, Kelly M, Irene BNO, Chukwuma-Nwuba K, Opute P (2023) Exploring the role of regime actors in shaping the directionality of sustainability transitions in South Africa. Energy Res Soc Sci 99:103068. https://doi.org/10.1016/j.erss.2023.103068
Islar M, Brogaard S, Lemberg-Pedersen M (2017) Feasibility of energy justice: exploring national and local efforts for energy development in Nepal. Energy Policy 105:668–676
Jakob M, Steckel JC, Jotzo F, Sovacool BK, Cornelsen L, Chandra R, Edenhofer O, Holden C, Löschel A, Nace T (2020) The future of coal in a carbon-constrained climate. Nat Clim Chang 10(8):704–707
Jewell J, Vinichenko V, Nacke L, Cherp A (2019) Prospects for powering past coal. Nat Clim Chang 9(8):592–597
Johnston CJ, Andersen RK, Toftum J, Nielsen TR (2020) Effect of formaldehyde on ventilation rate and energy demand in Danish homes: development of emission models and building performance simulation. In: Building simulation, vol 13. Tsinghua University Press, pp 197–212
Joshua U, Alola AA (2020) Accounting for environmental sustainability from coal-led growth in South Africa: the role of employment and FDI. Environ Sci Pollut Res 27(15):17706–17716
Koutoudjian G, Diniz L, Cespedes R, UNDP VG (2021) Renewable Readiness Assessment PARAGUAY. The International Renewable Energy Agency (IRENA(24). https://energycentral.com/system/files/ece/nodes/504304/irena_rra_paraguay_2021.pdf. Accessed 23 May 2024
Lamb WF, Minx JC (2020) The political economy of national climate policy: architectures of constraint and a typology of countries. Energy Res Soc Sci 64:101429
Le Billon P, Kristoffersen B (2020) Just cuts for fossil fuels? Supply-side carbon constraints and energy transition. Environ Plan A: Econ Space 52(6):1072–1092
Lebrouhi B, Djoupo J, Lamrani B, Benabdelaziz K, Kousksou T (2022) Global hydrogen development-A technological and geopolitical overview. Int J Hydrogen Energy 47(11):7016–7048
Lennon B, Dunphy NP, Sanvicente E (2019) Community acceptability and the energy transition: a citizens' perspective. Energy, Sustain Soc 9:35. https://doi.org/10.1186/s13705-019-0218-z
Li Y, Taghizadeh-Hesary F (2022) The economic feasibility of green hydrogen and fuel cell electric vehicles for road transport in China. Energy Policy 160:112703
Libala N, Boraine A, Wilson J (2023) Getting from good intentions to effective action: a proposal for a just transition partnering implementation model in South Africa. AFD Research Papers, 1–36. https://www.cairn-int.info/journal--2023-288-page-1.htm. Accessed 03/02/2024
Lloyd PJ (2017) Coal — The "dirty" fuel? International Conference on the Industrial and Commercial Use of Energy (ICUE), Cape Town, South Africa, pp. 1–6. https://doi.org/10.23919/ICUE.2017.8068006
Loftus PJ, Cohen AM, Long JC, Jenkins JD (2015) A critical review of global decarbonization scenarios: what do they tell us about feasibility? Wiley Interdisc Rev: Clim Change 6(1):93–112
Loorbach D, Frantzeskaki N, Avelino F (2017) Sustainability transitions research: transforming science and practice for societal change. Ann Rev Environ Resour 42(Volume 42, 2017):599–626. https://doi.org/10.1146/annurev-environ-102014-021340
Loots I, Van Dijk M, Barta B, Van Vuuren S, Bhagwan J (2015) A review of low head hydropower technologies and applications in a South African context. Renew Sustain Energy Rev 50:1254–1268

Lowitt S (2021) A just transition finance roadmap for South Africa: a first iteration. https://justtransitionforall.com/wpcontent/uploads/2022/12/TIPS_UK_PACT_A_Just_Transition_Finance_Roadmap_for_South_Africa_First_Iteration_December_2021.pdf. Accessed 23/05/2024

Magazzino C, Bekun FV, Etokakpan MU, Uzuner G (2020) Modeling the dynamic Nexus among coal consumption, pollutant emissions and real income: empirical evidence from South Africa. Environ Sci Pollut Res 27:8772–8782

Mandegari M, Petersen AM, Benjamin Y, Görgens JF (2019) Sugarcane biofuel production in South Africa, Guatemala, the Philippines, Argentina, Vietnam, Cuba, and Sri Lanka. In: Sugarcane biofuels: status, potential, and prospects of the sweet crop to fuel the world. Springer Nature, Switzerland AG, pp 319–346

Manika C (2023) South Africa's Just Energy Transition faces resistance, hurdles. The Africa Report. https://www.theafricareport.com/323694/south-africas-just-energy-transition-faces-resistance-hurdles/. Accessed 22/04/2023

Marais L (2013) The impact of mine downscaling on the Free State Goldfields. In: Urban forum, vol 24. Springer Netherlands, pp 503–521

Mathu K, Chinomona R (2013) South African coal mining industry: socio-economic attributes. Mediterr J Soc Sci 4:337–357. https://doi.org/10.5901/mjss.2013.v4n14p347

McCall B, Burton J, Marquard A, Hartley F, Ahjum F, Ireland G, Merven B (2019) Least-cost integrated resource planning and cost-optimal climate change mitigation policy: alternatives for the South African electricity system. Energy Res. https://www.saippa.org.za/Alt_IRP_final_07022019_ERC-1.pdf. Accessed 23 May 2025

McEwan C (2017) Spatial processes and politics of renewable energy transition: land, zones and frictions in South Africa. Polit Geogr 56:1–12. https://doi.org/10.1016/j.polgeo.2016.10.001

Merven B, Burton J, Lehmann-Grube P (2022) Assessment of new coal generation capacity targets in South Africa's 2019 integrated resource plan for electricity. https://cer.org.za/wp-content/uploads/2021/09/Annexure-A_ESRG_New-coal-plants-SouthAfrica.pdf. Accessed 03/02/2024

Mirzania P, Gordon JA, Balta-Ozkan N, Sayan RC, Marais L (2023) Barriers to powering past coal: implications for a just energy transition in South Africa. Energy Res Soc Sci 101:103122. https://doi.org/10.1016/j.erss.2023.103122

Mohlakoana N, Lokhat M, Dolšak N, Prakash A (2023) Varieties of just transition: public support in South Africa's Mpumalanga coal community for different policy options. PLOS Climate 2(5):e0000205. https://doi.org/10.1371/journal.pclm.0000205

Müller F, Neumann M, Elsner C, Claar S (2021) Assessing African energy transitions: renewable energy policies, energy justice, and SDG 7. Polit Gov 9(1):119–130

Muttitt G, Price J, Pye S, Welsby D (2023) Socio-political feasibility of coal power phase-out and its role in mitigation pathways. Nat Clim Chang 13(2):140–147

Nacke L, Cherp A, Jewell J (2022) Phases of fossil fuel decline: diagnostic framework for policy sequencing and feasible transition pathways in resource dependent regions. Oxford Open Energy 1:oiac002

United Nations (2015) Adoption of the Paris agreement. United Nations Framework Convention on Climate Change (UNFCCC), Paris. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf. Accessed 03/02/2024

Nel EL, Hill TR, Aitchison KC, Buthelezi S (2003) The closure of coal mines and local development responses in Coal-Rim Cluster, northern KwaZulu-Natal, South Africa. Dev Southern Africa 20(3):369–385

Nel E, Marais L, Mqotyana Z (2023) The regional implications of just transition in the world's most coal-dependent economy: the case of Mpumalanga, South Africa. Front Sustain Cities 4:1059312

Newell P, Mulvaney D (2013) The political economy of the 'just transition.' Geogr J 179(2):132–140

Ngwadla X, Athanasiou T, Holz C, Hussein F, Kartha S, Klinsky S, Rajan C (2023) Negotiator briefing: a needsbased approach to climate finance. United Nations Climate Change. https://unfccc.int/sites/default/files/GST/2023-05/A%20Needs-Based%20Approach%20to%20Climate%20Finance.pdf. Accessed 07/07/2024

Ntuli M, Dioha M, Ewim D, Eloka-Eboka A (2022) Review of energy modelling, energy efficiency models improvement and carbon dioxide emissions mitigation options for the cement industry in South Africa. Mater Today: Proc 65:2260–2268

Nwanekezie K, Noble B, Poelzer G (2021) Transitions-based strategic environmental assessment. Environ Impact Assess Rev 91:106643. https://doi.org/10.1016/j.eiar.2021.106643

Odenweller A, Ueckerdt F, Nemet GF, Jensterle M, Luderer G (2022) Probabilistic feasibility space of scaling up green hydrogen supply. Nat Energy 7(9):854–865

Okpanachi E, Ambe-Uva T, Fassih A (2022) Energy regime reconfiguration and just transitions in the Global South: lessons for West Africa from Morocco's comparative experience. Futures 139:102934

PCC (2003) A critical appraisal of South Africa's just energy transition investment plan. https://pccommissionflow.imgix.net/uploads/images/PCC-analysis-and-recommenations-on-the-JET-IP-May-2023.pdf. Accessed 22/04/2023

Presidential Climate Commission (PCC). (2022). Just transition framework – final report and recommendations. https://www.climatecommission.org.za/publications/design-addition-andamendment-to-just-transition-framework-with-dedication-to-pcc-secretary. Accessed 05 May 2024
Petrie B, Macqueen D (2013) South African biomass energy: little heeded but much needed. In: IIED briefing paper-international institute for environment and development, p 17165. https://pubs.iied.org/pdfs/17165IIED.pdf. Accessed 23 May 2024
Pienaar, P., Zuidgeest, M., & Robinson, A. (2023). Challenges facing South African road authorities in the transition to new energy vehicle technology.
Project 90 by 2030 (2020) JET: SA's need for more renewable energy. https://90by2030.org.za/2020/02/25/just-energy-transition-sas-need-for-more-renewable-energy/. Accessed 07/07/2024
Ramluckun R, Malumbazo N, Ngubevana L (2024) A review of the energy policies of the BRICS Countries: the possibility of adopting a just energy transition for South Africa. Sustainability 16(2):703. https://doi.org/10.3390/su16020703
Ratshomo K, Nembahe R (2019) South African energy sector report. 2018. Department of Energy, pp 1–38. https://www.dmre.gov.za/Portals/0/Energy_Website/files/media/explained/2018-South-African-Energy-Sector-Report.pdf. Accessed 23 May 2024
Rempel A (2023) An unsettled "Stranded Asset Debt"? Proposing a supply-side counterpart to the "Climate Debt" in a bid to guide a just transition from fossil fuels in South Africa and beyond. Antipode 55(1):243–267
Renewables I (2021) Analysis and forecast to 2026. International Energy Agency: Paris, France. https://iea.blob.core.windows.net/assets/5ae32253-7409-4f9a-a91d-1493ffb9777a/Renewables2021-Analysisandforecastto2026.pdf. Accessed 23 May 2024
Rischer M (2023) The political ecology of green hydrogen from the global South: an analysis along the socioecological fix framework. In. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1812065&dswid=5971. Accessed 23 May 2024
Sarkin J (1996) The trials and tribulations of South Africa's truth and reconciliation commission, South African. J Human Rights 12(4):617–640
Sarkodie SA, Adams S (2020) Electricity access and income inequality in South Africa: Evidence from Bayesian and NARDL analyses. Energy Strat Rev 29:100480. https://doi.org/10.1016/j.esr.2020.100480
Scroll (2021) In the global race to net-zero emissions, finishing just is more important than finishing first. https://scroll.in/article/992717/in-the-global-race-to-net-zero-emissions-fnishing-just-is-more-important-than-fnishing-frst. Accessed 25/4/2024
Seiler A, Brown H, Matthews S (2023) The JETPs of South Africa and Indonesia: a blueprint for the move away from coal? Centre for Global Development. https://www.cgdev.org/sites/default/files/jetps-south-africa-and-indonesia-blueprint-move-away-coal.pdf. Accessed 24/04/2023
Semelane S, Nwulu N, Kambule N, Tazvinga H (2021) Economic feasibility assessment of manufacturing solar panels in South Africa–A case study of Steve Tshwete Local Municipality. Sustain Energy Technol Assess 43:100945
Shrimali G, Jindal A (2020) Cost-benefit analysis of coal-plant repurposing in developing countries. Available at SSRN 3646443. https://doi.org/10.2139/ssrn.3646443. Accessed 23 May 2024
Simpson NP, Gilmour A, Jacobs M (2023a) Taking stock of just energy transition partnerships. ODI Policy Brief. London: ODI. www.odi.org/en/publications/taking-stockof-just-energy-transition-partnerships. Accessed 7th June 2024
Simpson NP, Jacobs M, Gilmour A (2023b) Taking stock of just energy transition partnerships
Smarte Anekwe IM, Akpasi SO, Mkhize MM, Zhou H, Moyo RT, Gaza L (2024) Renewable energy investments in South Africa: potentials and challenges for a sustainable transition-a review. Sci Prog 107(2):00368504241237347
South Africa Government (2022) Just Energy transition implementation plan 2023–2027. R. o. S. A. The Presidency. https://www.stateofthenation.gov.za/assets/downloads/JET%20Implementation%20Plan%202023-2027.pdf. Accessed 03/02/2024
Statistics South Africa (2021) Quarterly labour force survey quarter 4: 2020 Department: Statistics South Africa, South Africa (2021). https://www.statssa.gov.za/publications/P0211/P02114thQuarter2020.pdf. Accessed 03/02/2024
Steadman S, Colenbrander S, Simpson N, McKechnie A, Cole M (2024) Putting the 'just' in Just Energy Transition Partnerships: what role for the MDBs? ODI working paper. London: ODI. https://odi.org/en/about/our-work/country-platforms. Accessed 17/04/2024
Suharsono A, Maulidia M (2023) What Can Indonesia Learn from South africa's experience of the just energy transition process? Int Inst Sustain Dev. https://www.iisd.org/system/files/2023-07/indonesia-south-africa-jetp-lessons.pdf. Accessed 24/04/2023
Swilling M, Annecke E (2012) Just transitions: explorations of sustainability in an unfair world. UCT Press, an imprint of Juta and Company (Pty) Ltd, Claremont, South Africa

Symons J, Friederich S (2022) Tensions Within Energy Justice. Hist Soc Res/historische Sozialforschung 47(4):303–326
Todd I, McCauley D (2021) Assessing policy barriers to the energy transition in South Africa. Energy Policy 158:112529. https://doi.org/10.1016/j.enpol.2021.112529
Tyler E, Mgoduso L (2022) Just energy transitions and partnerships in Africa: a Aouth African case study. In: Meridian Economics. https://euagenda.eu/upload/publications/202211-ukama-jetpszaf.pdf. Accessed 23 May 2024
Uhunamure SE, Shale K (2021) A SWOT Analysis approach for a sustainable transition to renewable energy in South Africa. Sustainability 13(7):3933
Vale B, Karanja Y, Bikitsha P (2024) Powering the future: amplifying youth in South Africa's low-carbon transition. A Green and Inclusive Future for Youth in the Global South" in partnership with e Broker, the African Studies Centre Leiden African Economic Research Consortium and supported by the International Development Research Centre (IDRC). Netherlands Ministry of Foreign Affairs in 2012, the Netherlands.https://includeplatform.net/wp-content/uploads/2024/04/EmPowering-the-Future-South-Africa-Case-Study.pdf. Accessed 12 June 2024
van der Voorn T, van den Berg C, Bhattacharya P, Quist J (2021) Never waste a crisis: drawing first lessons from the COVID-19 Pandemic to tackle the water crisis. ACS ES&T Water 1(1):8–10. https://doi.org/10.1021/acsestwater.0c00041
van der Voorn T, van den Berg C, Quist J, Kok K (2022) Making waves in resilience: Drawing lessons from the COVID-19 pandemic for advancing sustainable development. Curr Res Environ Sustain 4:100171
van Voss BH, Rafaty R (2022) Sensitive intervention points in China's coal phaseout. Energy Policy 163:112797
Vinichenko V, Vetier M, Jewell J, Nacke L, Cherp A (2023) Phasing out coal for 2° C target requires worldwide replication of most ambitious national plans despite security and fairness concerns. Environ Res Lett 18(1):014031
Winkler H, Marquand A (2009) Changing development paths: from an energy-intensive to low-carbon economy in South Africa. Climate Dev 1(1):47–65. https://doi.org/10.3763/cdev.2009.0003
Wittmayer J, Loorbach D, Bogner K, Hendlin Y, Hölscher K, Lavanga M, Vasques A, von Wirth T, de Wal M (2021) Transformative research: knowledge and action for just sustainability transitions. https://pure.eur.nl/en/publications/transformative-research-knowledge-and-action-for-just-sustainabil. Accessed 23 May 2024
World Bank (2022) South Africa Country climate and development report. In: World Bank. https://www.worldbank.org/en/news/infographic/2022/11/01/south-africa-country-climate-and-development-report#:~:text=South%20Africa's%20ambition%20is%20to,unequal%20society%20in%20the%20world. Accessed 23 May 2025
Xaba N (2023) Whose just energy transition? A South African perspective. Wiley Interdisc Rev: Energy Environ 12(5):e478
Zhang Q, Yang K, Hu Y, Jiao J, Wang S (2023) Unveiling the impact of geopolitical conflict on oil prices: a case study of the Russia-Ukraine War and its channels. Energy Economics 126:106956

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