

South African Industries and Carbon Dioxide Emissions: An Analysis of Key Sectors and Mitigation Strategies

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ABSTRACT

South Africa, a leading economic hub in Africa, significantly contributes to carbon dioxide (CO₂) emissions due to its reliance on carbon-intensive industries. This reliance contributes to emissions across major sectors, including the energy generation sector, the mining sector, which is characterized by significant Scope 2 electricity consumption and Scope 3 value chain emissions, the manufacturing sector, and the transportation sector. This study examines the primary sectors mentioned as the driving force to emissions. The analysis is based on trends, key drivers, and potential mitigation strategies grounded by recent studies and government reports. The broader energy sector is the dominant contributor, accounting for approximately 80% of South Africa's CO₂ total emissions, primarily due to coal-based power generation. Manufacturing, including steel and cement production, contributes significantly due to high energy consumption and process-related emissions. The transportation sector, driven by fossil fuel-dependent road and freight systems, adds to the emissions profile, though to a lesser extent. Emission trends show a steady increase over the past decade, with South Africa's per capita emissions among the highest in Africa. Key drivers include heavy reliance on coal, outdated infrastructure, and limited adoption of renewable energy. Mitigation strategies include transitioning to renewables like solar, wind and hydro power improving energy efficiency, and adopting carbon capture technologies. Policy democratisation is important through engaging communities and engaging industries in decision making to balance economic growth and emissions reduction. Technological interventions, such as green hydrogen and electrified transport, offer further potential. Implementing these measures is critical for sustainable development in South Africa.

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1. Introduction

Coal continues to play a dominant role in South Africa's electricity generation and overall energy sector, making up about 70% of the country's primary energy supply. This strong dependence on coal positions South Africa as the world's seventh-largest per capita emitter of greenhouse gases, (Steed, 2025; Ukoba, 2025). The country is ranked the 1st highest emitter of CO₂ in the African continent, accounting for nearly a quarter of Africa's emissions with amounts and ranks among the top 15 % of emitters globally and as the worst polluter in Africa (Gold & Tregena, 2025). The country relies heavily on fossil fuels, particularly coal which is used primarily in coal-fired power plants operated by ESKOM (Ukoba, 2025). Another cornerstone of the South African economy is the mining industry. It contributes significantly due to its energy-intensive operations and reliance on coal-based electricity though since load shedding it has partnered with private companies in its efforts of being of the grid (Tshinavha & Ukpere, 2025). Manufacturing sectors like steel and cement production further increase emissions through energy use and process-related CO₂ (Ntuli,2022). These industries, while vital for economic growth and employment, create a complex challenge as South Africa seeks to balance development with environmental sustainability.

The environmental and socio-economic impacts of South Africa's carbon-intensive industries are deep. High CO₂ emissions aggravate climate change, leading to rising temperatures, erratic rainfall, and extreme weather events like droughts and floods, which threaten agriculture, water security, and biodiversity in regions such as the Highveld (Igamba, 2023; Nhemachena,2020). Air pollution from coal plants and mining operations also causes health issues, including respiratory diseases, in nearby communities (Ncube, 2019; Mahlangeni, 2024). Transitioning South Africa's economy toward decarbonization involves balancing environmental imperatives with economic stability, particularly in coal-dependent regions like Mpumalanga, where industries such as mining and manufacturing support millions of jobs (Smith, 2023). However, environmental degradation and potential trade penalties, such as the EU's Carbon Border Adjustment Mechanism (CBAM), threaten long-term economic viability (Jones & Brown, 2024).

Strategic interventions are essential to reduce emissions while preserving jobs. South Africa's abundant solar and wind resources can be harnessed through initiatives like the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), which has already facilitated significant renewable energy investments (Eberhard & Naude, 2016). Energy efficiency improvements in mining and manufacturing, coupled with emerging technologies like carbon capture and green hydrogen, provide viable pathways to lower emissions (Mirzania, 2023). Policy measures, including carbon pricing and international collaborations like the Just Energy Transition Partnership (JETP), can attract investment in green infrastructure (International Energy Agency, 2024).

The South African presidency has since launched the presidential PhD programme with key focus areas such as Just Energy Transition (NRF expression on interest document, 2025). This is one of the strategies in trying to mitigate and reducing carbon emissions while addressing energy crisis. Other small emitters are the transport industry and corporate offices. They contribute through energy usage which is not a direct emission and through transportation. To address this and make them accountable, South Africa introduced a carbon tax in 2019 to encourage a shift to cleaner technologies, investments in renewable energy, and better waste management, aligning with the country's national climate goals (Chieh-tse Hou, 2023; Phase two of carbon tax, 2024).

This study synthesises data from peer-reviewed journals, South African government reports and various organisations reports. A systematic review procedure was followed to identify

and select sources. To perform a techno economic analysis of the transportation of CO₂, a study of key sectors or industries and its CO₂ emissions data is required. The objective of the study was to identify and analyse the major sectors contributing to CO₂ emissions in South Africa. The data will assist future research for techno economic assessment of carbon dioxide retro fitment and transportation. There are other sectors that only relies on meeting the emissions standards according to regulations without having appropriate emissions measures. This study boost groundwork of renewable energy studies forming part of motivation why alternative energy sources are important in South Africa. Under the Paris Agreement, South Africa has pledged that the country's GHG will be within the range of 398-510 Mt CO₂-eq by 2025 and between 350-420 Mt CO₂-eq by 2030. Furthermore, a foundation for sustainable development and future research is laid by this work.

2. Data Collection

The systematic review was followed by Data triangulation. To enhance reliability, data from peer-reviewed journals, government reports, and organisational publications were cross-referenced to validate findings. Discrepancies were resolved by prioritising primary data and more recent publications. Only sources directly addressing South Africa or providing global applicable insights with clear relevance to the South African context were included. Under the Paris Agreement, South Africa has pledged that the country's greenhouse gas emissions will be within a range between 398-510 Mt CO₂-eq by 2025 and between 350-420 Mt CO₂-eq by 2030. The agreement was signed in 2016.

A forecast of the amount of CO₂ produced in the sectors was done using Excel FORECAST sheet with the aim of determining if the goal in the Paris agreement will be achieved for sectors with reported values. The tool is a built-in data analysis tool that predicts future trends based on historical and chronological time-series data, using advanced exponential smoothing algorithms. It creates a new worksheet with a chart and table, offering insights into projected values, confidence intervals, and seasonal patterns without complex formulas. Excel trendline was used but the correlation coefficient was 69% which was not considered as a strong correlation according to this study.

3. Key Industries Producing CO₂ Emissions

South Africa's high CO₂ emissions is influenced by various industries or sectors. The contributing factors includes energy production sector, mining sector, manufacturing sector, transportation sector and energy consumers.

3.1 Energy Production Sector

The energy sector is dominated by coal-fired power plants operated by ESKOM and additional plant operated by SASOL. According to the Organisation for Economic Co-operation and Development (OECD) Economic Surveys 2025, coal supplied over 80% of the country's electricity at the power stations, with stations like Medupi and Kusile contributing significantly due to their scale and inefficiencies. The sector's high emission intensity is worsened by aging infrastructures and limited adoption of Carbon Capture and Storage (CCS) technologies (Ko et al., 2021; SurrIDGE & Cloete, 2009). Kusile was designed to have carbon capture technology according to the report prepared by Business Enterprise University of Pretoria (Blignaut et al, 2011). Though it has not been fully implemented, the plant's design includes the necessary physical spaces, connections, and considerations for adding carbon capture technology. South Africa's energy sector is a basis of its economy but remains one of

the largest contributors to carbon dioxide (CO₂) emissions, primarily due to its heavy reliance on coal for electricity generation (Ukoba, 2025). The next section looks at the amount emitted in the various energy industries.

3.1.1. Coal-fired Power Generation

South Africa’s energy sector is dominated by coal as stated earlier. In 2024, South Africa accounted for approximately 1.2% of global CO₂ emissions from fossil fuels, largely driven by coal-based electricity generation according to the World Energy Data, 2025. Coal power plants, primarily concentrated in Mpumalanga, are responsible for the energy sector’s CO₂ emissions, (Department of Mineral Resources and Energy, 2023). Table 1 shows the breakdown of the average CO₂ produced through the coal-fired power generation plants in South Africa from 2020 to 2025. The information is based on available data ESKOM report. The data is reported in financial year which runs from April to March per cycle. The data reflects the production of CO₂ from coal combustion for electricity generation, and a chart in Figure 1 visualises the trend.

Table 1: Historical CO₂ produced Data from power stations (2019–2023)

No	Year	CO ₂ emission (Million Metric ton)	Source
1	2020/2021	151.11	ESKOM CO ₂ data
2	2021/2022	172.51	ESKOM CO ₂ data
3	2022/2023	171.16	ESKOM CO ₂ data
4	2023/2024	190.45	ESKOM CO ₂ data
5	2024/2025	153.47	ESKOM CO ₂ data

CO₂ produced from South Africa’s coal-fired power plants ranged between 151.11 and 190.45 Million Metric tons annually from 2019 to 2023, showing a slight decline in 2020 due to reduced demand during the pandemic and a gradual decline in 2023 as renewable energy adoption expanded. The summary of Table 1 is illustrated in Figure 1. In 2024, load shedding ended in South Africa and most of the ESKOM plant were running to full capacity. The increased to 190.45 Million Metric Ton might have been caused by the increased in energy generation.

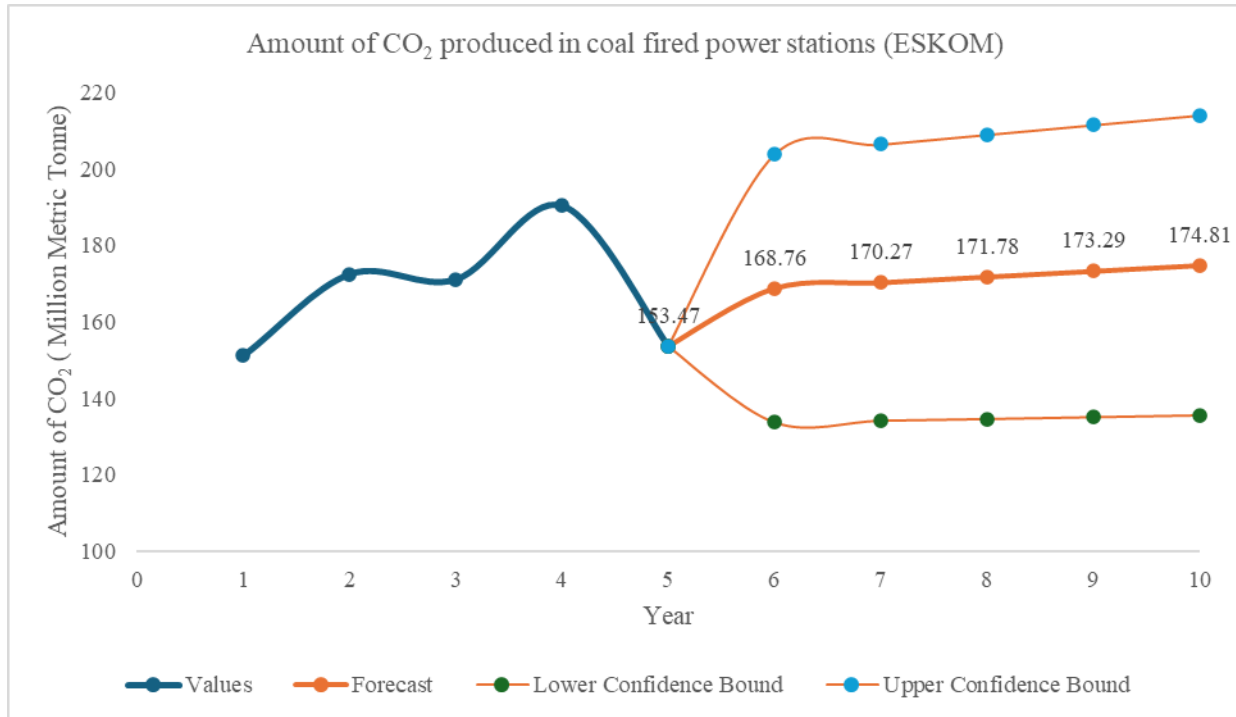


Figure 1: CO₂ produced from the coal-fired plant in South Africa from 2019-2023 as cited in Table 1.

By using FORECAST sheet, the graph was further expanded to 2030. Where the year 2030 is represented by year 10. The forecast is valid provided that the current infrastructure remains the same without changes and the capacity for generation is not adjusted. In year 2030, the plants will be producing an estimated amount of 174.81 Million Metric ton of CO₂.

There are 2 power stations in Limpopo namely Medupe and Matimba power station. Majority are situated in Mpumalanga namely Arnot Power Station, Camden Power Station, Duvha Power Station, Hendrina Power Station, Kendal Power Station, Kriel Power Station, Kusile Power Station, Majuba Power Station, Matla Power Station, Tutuka Power Station and Grootvlei power station. There are one operational power stations in Free state namely Lathabo power station. These are the only operational power stations of ESKOM. Figure 2 is geographical maps of the location of ESKOM power stations in South Africa that are operational in 2025.



Figure 2: Maps pinpointing the locations of ESKOM power stations in South Africa with majority in Mpumalanga, [Adopted from Mail & Guardian, John McCann, 2019]

3.1.2. Synthetic Fuel Production

South Africa’s synthetic fuel industry, led by Sasol’s Secunda coal-to-liquid facility, produces 3.3 million tonnes of refined products annually, making it a significant CO₂ emitter (Enerdata, 2025). This process relies on coal as a feedstock, contributing to high emissions intensity. The synthetic fuel sector emits approximately 60 Million Metric tons of CO₂ annually, accounting for a substantial portion of industrial emissions (Department of Mineral Resources and Energy, 2023). The high energy intensity of coal-to-liquid processes and limited gaseous feedstock for alternative facilities, such as PetroSA’s Mossel Bay gas-to-liquid plant, hinder decarbonisation efforts (Enerdata, 2025). The following data presented in Table 2 represent CO₂ produced from synthetic fuel plants in South Africa.

Table 2: Historical CO₂ produced Data from synthetic fuel production (2019–2023)

Year	CO ₂ emission (Million metric ton CO ₂)	Source
2019	61,326	SASOL, 2024
2020	60,063	SASOL, 2024
2021	61,577	SASOL, 2024
2022	59,472	SASOL, 2024
2023	60,127	SASOL, 2024

Figure 3 represent the emission data in Coal to Liquid (CTL) from 2019 to 2023. CO₂ emissions from synthetic fuel production in South Africa ranged between 61,326 and 59,472 Million Metric ton CO₂ annually, with Sasol Secunda CTL plant being the primary contributor. The amount of CO₂ is gradually decreasing. Decarbonising this sector will require scaling up CCS, transitioning to green hydrogen, or shifting to other feedstocks, though the shift will cause significant technical and economic barriers. Focusing on the

acquired data, the plant-specific emissions data for Secunda is well-documented as per the Sasol’s annual reports and climate change reports. With the obtained data, the forecast of 2030 emission is found to be 56.66 Million Metric ton.

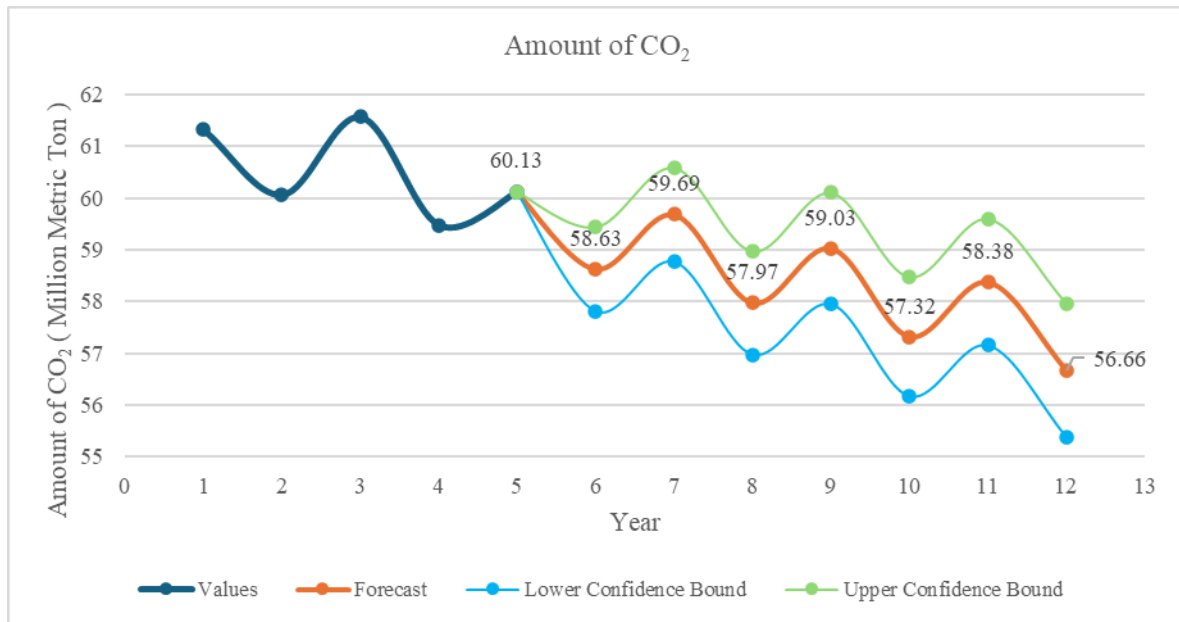


Figure 3: Graphical summary of CO₂ produced in the synthetic fuel industry in South Africa from 2019 to 2023 as cited in Table 2.

3.2. Mining Sector

South Africa’s mining sector is also a cornerstone of the South African economy like the energy production sector. The sector contributes to 6% of national greenhouse gas emission (Motaung, 2023). The extraction and processing of coal, gold, and Platinum Group Metals (PGMs) are particularly carbon intensive (Ndlovu & Adewuyi, 2025). The diesel-powered machinery, energy-intensive smelting, and coal exports further amplify emissions. For example, the production of PGMs, critical for global markets, involves high-energy processes that rely on coal-based electricity (Tokac, 2025). The mining sector largely utilises the emissions framework as defined by the Greenhouse Gas Protocol (GGP) (Benita, 2024). What has been uncovered during this study is that the mining sectors does not report more or rather is it is not intensively focused on CO₂ emissions like the energy generation sector. The mining sector classifies their emissions according to scopes. The scopes are defined in the following sub-sections in relation to the mining sector:

3.2.1. Scope 1: Direct Emissions

South Africa’s heavy reliance on coal, which accounts for approximately 70% of the country’s primary energy supply, contributes significantly to its status as the seventh-highest per capita emitter of greenhouse gases globally and over 40% of Africa’s total emissions (Onifade, 2024). In the mining sector, key sources of these emissions include fuel combustion from diesel-powered equipment such as trucks, excavators, and generators, fugitive emissions like methane released during coal mining or other mineral extraction processes, and on-site chemical reactions in processing plants (Hou, 2023). Addressing these emissions is critical to the Just Energy Transition, a focus area of the Presidential PhD Programme launched by the

South African Presidency to advance sustainable energy solutions (National Research Foundation, 2025).

3.2.2. Scope 2: Indirect Emissions from Purchased Energy

Emissions classified as Scope 2 are emissions from the generation of purchased electricity, steam, heating, or cooling consumed by the mining company, basically, energy consumption. This refers to electricity consumed by mining operations, processing plants, and smelting facilities, which is primarily supplied by South Africa's coal-dependent power grid (ESKOM, 2025). According to the Minerals Council South Africa's Integrated Annual Review 2024, Scope 2 emissions are the largest contributor to the mining sector's carbon footprint, accounting for approximately 77% of combined Scope 1 and Scope 2 emissions.

3.2.3. Scope 3: Other Indirect Emissions

Emissions from activities within a company's value chain that are not directly owned or controlled, including both upstream and downstream processes, are classified as Scope 3 emissions according to the Greenhouse Gas Protocol (GHG Protocol, 2025). In the mining sector, these emissions include several significant sources, which can account for up to 95% of a company's total emissions profile (Sinai, 2024; Mining-technology, 2021). Upstream activities, for example, involve the emissions from the production of purchased goods like explosives, chemicals, or steel used in mining (ICMM, 2023). Downstream activities include emissions from the transportation and distribution of mined products, such as shipping coal or iron ore to export markets (ICMM, 2023). Additional sources of Scope 3 emissions in the mining sector are employee commuting and business travel, as well as the substantial downstream emissions from the use of the final mined products, such as coal burned in power plants or steel used in manufacturing (ICMM, 2023). For iron ore producers like BHP and Rio Tinto, most Scope 3 emissions come from overseas steel mills that use their metallurgical coal (Mining-technology, 2021).

The management of these indirect emissions is a significant challenge for the industry, which is why organisations like the International Council on Mining and Metals (ICMM) have developed guidance to help companies with accounting and reporting (ICMM, 2023). A Scope 1 and 2 emissions are reported by National Business Initiative. The report highlights the decarbonisation of South Africa's mining, petrochemicals and chemicals sector. This is a similar report done by Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (MMMSD). Anglo American also publicly reported on Scope 1 and 2 CO₂ emissions in the companies' climate change report 2023.

3.3. Manufacturing Sector Excluding CTL

South Africa's manufacturing sector, which includes steel production, cement manufacturing, and chemical processing, is a notable emitter of CO₂ (Climate Transparency, 2020). There are numerous manufacturing companies in South Africa. These industries require significant energy inputs, often sourced from coal-based electricity (Department of Mineral Resources and Energy, 2023). Their processes involve the release CO₂ as a by-product, such as cement clinker production (Madloul et al., 2012). The steel industry, led by companies like ArcelorMittal South Africa, relies on blast furnaces that burn coal-derived coke, resulting in high emissions (ArcelorMittal, 2024). Additionally, the chemical industry, including fertilizer and petrochemical production, contributes to emissions through energy use and chemical reactions inherent to production processes. Figure 4 compare CO₂ emissions of the South African steel industry with its competition.

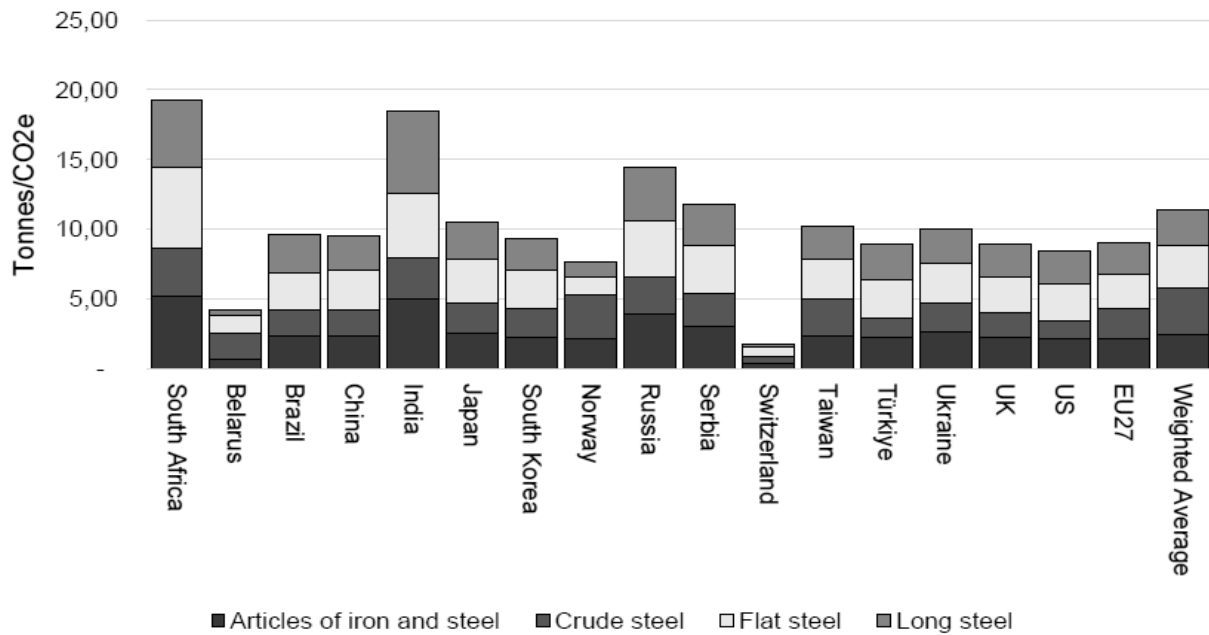


Figure 4: CO₂ emissions in the steel industry across the globe. Adopted from [Trade & Industrial Policy Strategies, 2022].

The graph displays CO₂ emissions in tonnes from various countries and the EU27, categorised into Articles of Iron and Steel, Crude Steel, Flat Steel, and Long Steel. South Africa and Japan show the highest total emissions, with South Africa peaking at around 20 tonnes, largely contributed by Articles of Iron and Steel. Japan also has significant emissions, with a balanced contribution across all categories. Brazil and China follow with notable emissions, particularly in Crude Steel and Articles of Iron and Steel. Most other countries, including the UK, US, and EU27 Weighted Average, exhibit lower and more evenly distributed emissions across categories, generally ranging between 5-10 tonnes. Norway stands out with the lowest emissions, around 2-3 tonnes. Norway has the lowest emissions because the country has a large supply of cheap and emission-free renewable electricity, which is essential for clean energy-intensive processes like hydrogen production for steelmaking (Bhaskar, 2022).

3.4. Transportation

The transport sector in South Africa is responsible for around 11% of the country's carbon dioxide emissions, with road transport contributing an overwhelming 90% of this total (Ntuli, 2024). South Africa's reliance on gasoline and diesel vehicles, coupled with an underdeveloped public transport system, contributes to this share. Although aviation and shipping currently contribute less, their emissions are increasing due to expanding trade and tourism activities (Zondi, 2025). Table 3 present the CO₂ emissions data of the transportation sector. The primary source for data up to 2022 is South Africa's 9th National Greenhouse Gas Inventory Report (2000–2022), published by the Department of Forestry, Fisheries and the Environment (DFFE) in February 2025. Data for 2019–2022 is extracted from Chapter 3 (Energy).

Table 3: CO₂ emissions in the transport industry.

Year	Transport Sector Emissions (Mt CO ₂ -eq)	Notes
2019	50.15	Slight decline amid economic slowdown and stable fuel prices.
2020	46.24	Drop due to COVID-19 lockdowns, reduced mobility, and fuel demand.
2021	48.83	Recovery in economic activities as travelling restrictions were relaxed.
2022	48.89	Stabilisation; increased travel, and freight volumes

Emissions are reported as CO₂ -equivalent (CO₂ -eq). 2019 had the highest emissions reported with a decline in 2020 due to the COVID-19 pandemic. 2021 and 2022 had a difference of 0,6 Mt CO₂-eq. The transportation sector is contributing to the CO₂ emissions massively. Almost second to energy sector due to the burning of fossil fuels, large freight etc (Ntuli, 2024 et al; Jaramillo et al, 2022). The data is reported in carbon dioxide equivalent (Mt CO₂-eq). Reporting greenhouse gases (GHGs) as carbon dioxide equivalent provides a single, standardized metric to compare the warming impact of different gases. This approach simplifies the complexities of climate science into an easily understandable and actionable number for policymakers, businesses, and the public (Anderson, 2025). Each greenhouse gas has a different Global Warming Potential (GWP), which is a measure of how much heat it traps in the atmosphere over a set period compared to carbon dioxide (Mathur, et al., 2022). The reference point which is CO₂ has a GWP of 1. To calculate a gas's CO₂-eq, its mass is multiplied by its GWP.

$$\text{CO}_2\text{-eq} = \text{Mass of gas} \times \text{GWP} \tag{1}$$

Another alternative for GWP is Global Temperature Potential (GTP). GTP is a measure of the temperature change at the end of that time relative to CO₂. Table 4 indicates the 100-year time horizon GWP of various gases relative to CO₂.

Table 4: Examples of emission metric values from WGI. [Adopted from Pachauri & Meyer, 2014]

	Lifetime (yr)	GWP		GTP	
		Cumulative forcing over 20 years	Cumulative forcing over 100 years	Temperature change after 20 years	Temperature change after 100 years
CO ₂	none	1	1	1	1
CH ₄	12.4	84	28	67	4
N ₂ O	121.0	264	265	277	234
CF ₄	50 000.0	4880	6630	5270	8040
HFC-152a	1.5	506	506	174	19

While the GWP emphasises cumulative radiative forcing, or energy trapped in the atmosphere, over a given time horizon (Forster et al., 2007), the GTP instead focuses on the resulting equilibrium temperature increase at a specific future point. Though both metrics employ time horizons, GTP proves more sensitive to short-term effects for gases such as methane (CH₄) owing to its stress on peak temperature impacts, in contrast to GWP's

integration across the entire period (Forster et al., 2007; peter, et al., 2011). GWP serves as the standard for aggregating emissions in international agreements like the Paris Accord, GTP has been proposed for prioritising near-term temperature stabilisation, including limits to 1.5°C warming (Solomon et al., 2011; Shine, et al., 2005).

4. Pathways for Decarbonisation and Mitigation Strategies

To address its high CO₂ emissions, South Africa must pursue ambitious decarbonisation strategies while navigating economic and social constraints. Several pathways offer potential for reducing emissions without compromising development goals.

4.1 Transition to Renewable Energy

Energy transition is the global shift from fossil fuel-based energy systems to clean, renewable energy sources like solar and wind power (Sehlabo, 2025). Due to the amount of electricity being utilised in the various sectors, scaling up renewable energy sources is critical for decarbonising the energy sector. South Africa's abundant solar and wind resources present opportunities for large-scale renewable projects, as demonstrated by the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) (Eberhard & Naude, 2016).

Accelerating the retirement of aging coal plants and investing in grid modernisation can reduce reliance on fossil fuels. However, this transition requires significant financing, policy support, and retraining programs for workers in coal-dependent regions to ensure a just transition. Scaling up solar, wind, and hydroelectric power is critical. South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has added over 6,328 MW of renewable capacity since 2011 (Eberhard & Naude, 2016), but further investment is needed to replace coal plants. Replacing coal could also affect the economy because it is largely used in energy generation (Hanto, et al., 2022).

4.1.1. Wind Power to Electricity

Wind turbines convert the kinetic energy of moving air (wind) into mechanical energy and then into electrical energy through a series of aerodynamic and electromechanical processes. This involves capturing wind with blades, transferring rotation to a generator, and conditioning the output for grid integration (Desalegn, 2022; Chaudhuri, 2022). The process is efficient for large-scale renewable energy production. Figure 5 shows how wind is converted to energy.

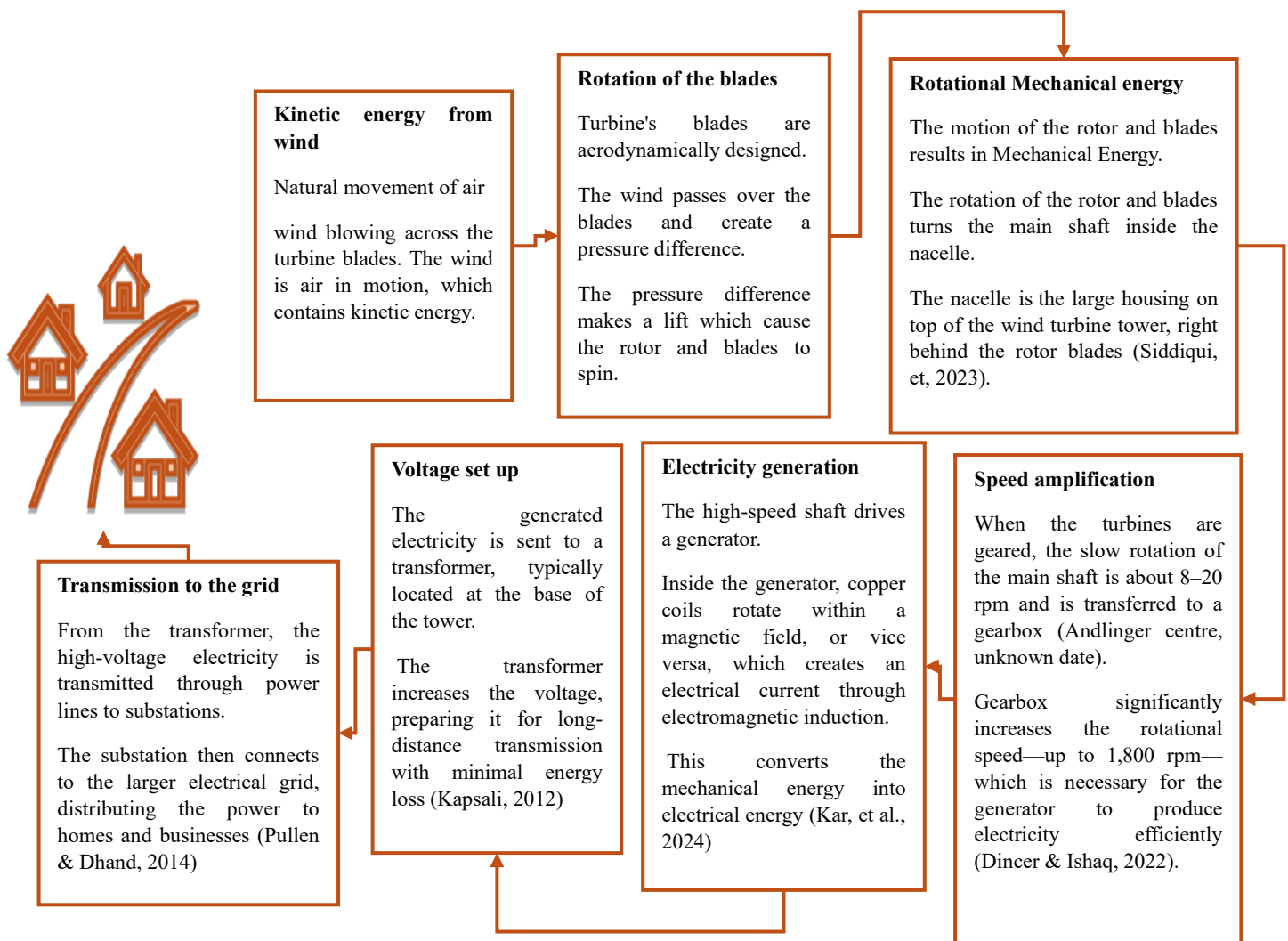


Figure 5: conversion of wind power to electricity.

4.1.2. Solar Energy to Electricity

Solar energy is the portion of the Sun's energy that reaches Earth's surface and can be harnessed for practical uses, such as exciting electrons in photovoltaic cells or fuelling natural processes like photosynthesis. This resource is free, clean, and abundant in most locations throughout the year, making it especially vital amid soaring fossil fuel prices and the atmospheric degradation caused by their combustion (Khatib, 2012). Solar energy generates electricity primarily through photovoltaic (PV) systems, which convert sunlight directly into electrical power using solar cells made from semiconductor materials like silicon (U.S. Energy Information Administration, 2024). Figure 6 shows the step-by-step process of converting solar energy to electricity.

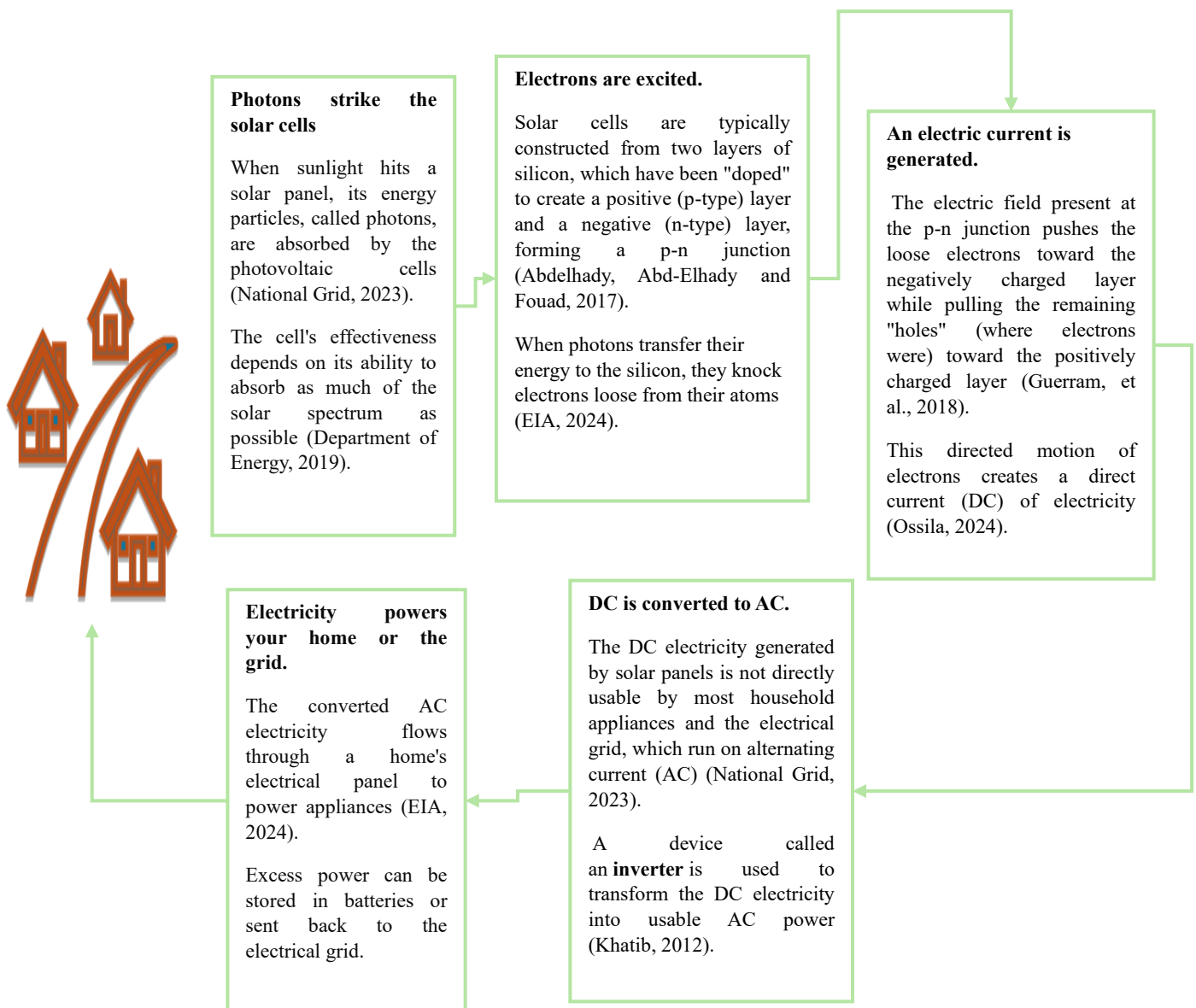


Figure 6: conversion of Solar energy to electricity.

4.1.3. Hydropower to Electricity

Hydropower can also be used as a substitute to fossil fuels energy. Hydropower is the conversion of the energy from flowing or falling water into electricity using a turbine and a generator, leveraging the continuous motion of the sun-powered water cycle (Kumar et al. 2011; Department of Energy 2024). Hydro power produces no greenhouse gas, making it environmentally friendly. The drawback is that the construction of dams can severely alter river ecosystems, block fish migration, and flood large areas of land, displace habitats and potentially affect biodiversity (Gasparatos et al. 2017; Anderson et al. 2015). Furthermore, building hydroelectric power plants requires significant capital investment in civil works, though operational costs are relatively low over the facility's long lifespan (Department of Energy 2024). The greatest disadvantage is its vulnerability to climate change. The amount of electricity generated can be negatively impacted by climate-related changes in weather patterns, particularly drought conditions that reduce water flow (Patel & Pakale 2015). Figure 7 shows how hydropower generates electricity.

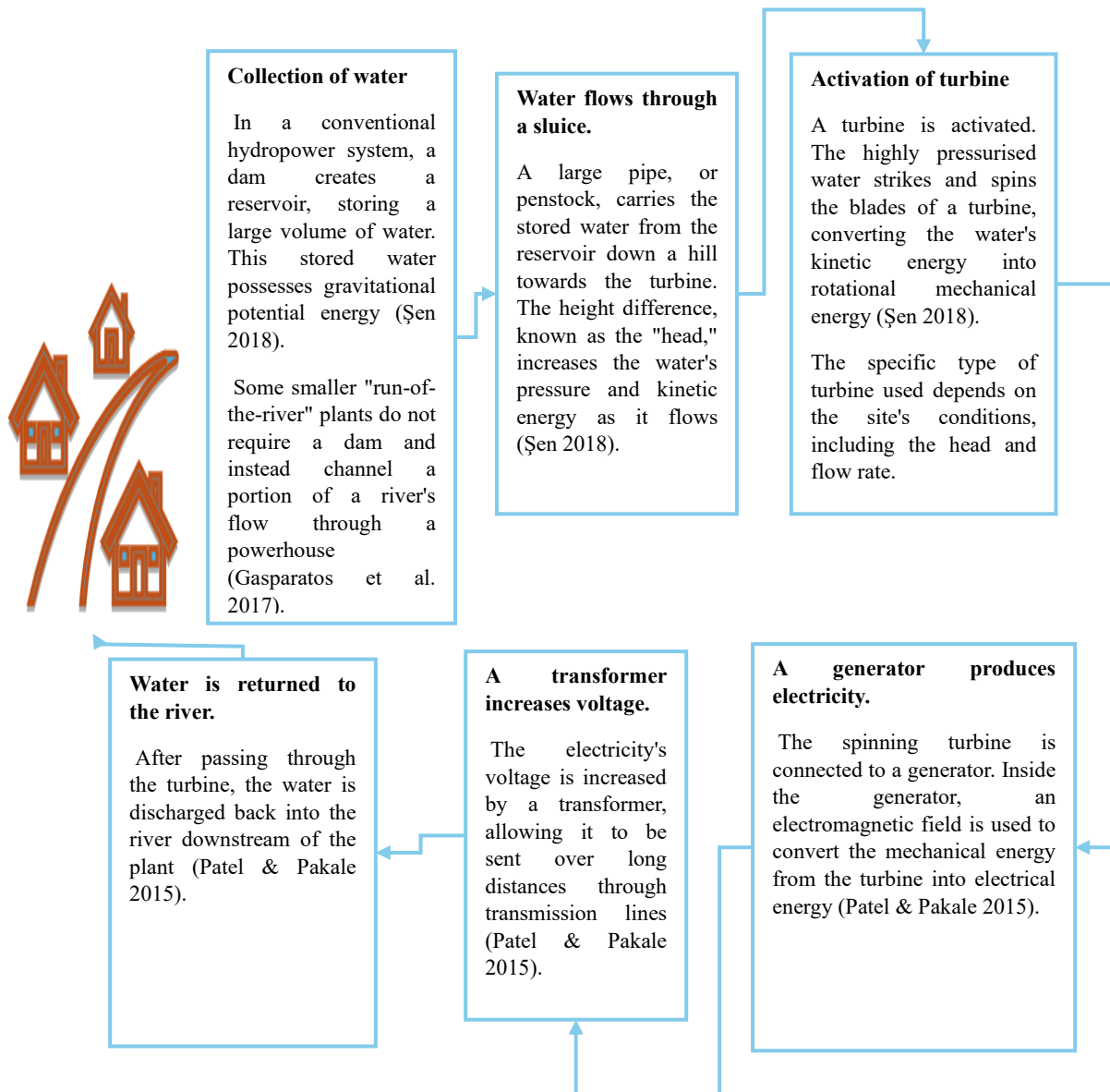


Figure 7: Conversion of hydro power to electricity

4.2 Energy Efficiency and Industrial Upgrades

Improving energy efficiency across key industrial sectors remains one of the most immediate and scalable strategies for curbing global greenhouse gas emissions, especially as total energy-related CO₂ emissions reached a record 37.8 gigatons in 2024, despite modest efficiency gains of just 1%. This approach not only aligns with broader net-zero goals but also delivers co-benefits like cost savings over time and enhanced resource security. Building on the points raised, let's delve deeper into sector-specific opportunities, emerging technologies, real-world examples, and persistent challenges, drawing from recent developments as of 2025.

4.2.1 Energy Sector: Retrofitting and CCS as Core Levers

The energy sector, particularly power generation, accounts for a significant share of emissions, but upgrades to existing infrastructure offer substantial potential. Retrofitting coal

and gas-fired power plants with energy-efficient turbines, advanced controls, and heat recovery systems can reduce fuel consumption without full replacement. The most efficient method is the integration CCS. The retrofitting of CCS will allow the capturing of CO₂ from flue gases for underground sequestration or reuse. With the amount of Carbon dioxide that is emitted in the South African sectors, the scaling up of CCS is required including how to overcome storage site limitations.

4.2.2 Mining Sector: Renewables and Efficiency to Slash Footprints

Mining operations are often located in the remote areas and are energy-intensive based on the finding of this study. Enhancing efficiency through electrified haul trucks, automated drilling, and on-site renewable microgrids can cut emissions in select operations. Transition to renewable energy such as solar and wind energy can reduce the carbon footprints. The mining sector contributes to carbon GHG through the usage of electricity. Employing these transitions can reduce the fossil fuel-based electricity.

4.2.3 Manufacturing Sectors: Targeted Tech for High-Impact Cuts

The manufacturing sector, which includes heavy industries such as steel and cement production, is particularly challenging to decarbonise due to its high CO₂ emission intensity. In steel production, transitioning from traditional blast furnaces to Electric Arc Furnaces (EAFs) represents a major advancement. EAFs, which utilize recycled scrap metal, produce approximately 75% less CO₂ per ton of steel, around 0.4 tons compared to 1.8 tons from blast furnaces, and consume about 70% less energy. (Green Steel World Editorial Team, 2022). For cement, which relies on energy-hungry kilns, adopting efficient technologies like vertical roller mills and alternative fuels (e.g., biomass) can indeed reduce emissions by up to 20%, as noted, by optimising grinding processes and cutting clinker use (National Cleaner Production Centre South Africa, 2024). Complementary measures include clinker substitutes like calcined clay, which alone slash CO₂ by 40% in plants operational since 2024 (Hasanbeigi et al., 2024). Retrofitting the CCS is fundamental as well, targeting process emissions from limestone calcination.

4.2.4 Transportation Industry: Efficiency Meets Electrification

Transportation, the second-largest emitter after energy, can see reductions of CO₂ through efficiency upgrades like aerodynamic designs for trucks, lightweight materials, and predictive logistics software that optimises routes and loads. In South Africa, the utilisation of rail transport is essential where rail can incorporate solar energy to the system.

4.3 Policy and International Cooperation

Strong policy frameworks, such as carbon pricing or emissions caps, can incentivise industries to adopt cleaner practices. South Africa's Climate Change Bill and its commitments under the Paris Agreement indicate meaningful progress; however, implementation remains slow. Local companies need to be part of forums which will provide information on international partnerships that deals with climate change financing. Policies which talk to the employment of green technologies needs to be finalised and presented to relevant parties. Awareness campaigns on Just Energy Transition Partnership (JETP) are not implemented to its full potential. Strengthening South Africa's Carbon Tax Act (2019) and enforcing stricter emission standards could incentivise decarbonisation.

4.4 Green Hydrogen and Alternative Fuels

Green hydrogen, produced through electrolysis powered by renewable energy sources such as solar and wind, represents a versatile and zero-emission energy carrier that can significantly contribute to decarbonising hard to reduce sectors, including heavy industry like steel production and chemical manufacturing such as for ammonia synthesis and methanol production (IRENA, 2023). Unlike grey hydrogen derived from fossil fuels, green hydrogen avoids carbon emissions at the point of production, making it a cornerstone for achieving net-zero goals in energy-intensive applications where electrification alone is insufficient (Chege, 2021). South Africa's strategic position as a global green hydrogen exporter is strengthened by its abundant renewable energy resources. The energy resources are solar radiation and its strong wind potential along the coastline and its established port infrastructure, such as the ports of Richards Bay and Ngqura, which facilitate efficient maritime export of hydrogen derivatives like ammonia (Macingwane and Schönborn, 2024).

The country's Hydrogen South Africa (HySA) program and the Revised Green Hydrogen Commercialisation Strategy outline ambitious targets, including capturing a 4% share of the global green hydrogen market by 2050 and scaling production to 3.5–4 GW of electrolyser capacity by 2030. This can potentially generate up to 1.2 million tons of green ammonia annually through projects like the Coega Green Ammonia initiative (IRENA, 2023). This export-oriented approach not only leverages South Africa's competitive advantages in low-cost renewable energy, but it positions the country as one of the world's lowest cost producers (Prieska Power reserve, 2023). but also promises substantial economic benefits, including the creation of over 300,000 jobs in green industries and an estimated GDP boost of up to 5% by mid-century, while domestically reducing reliance on coal and curbing emissions in line with the country's Nationally Determined Contributions under the Paris Agreement (IRENA, 2023).

The transition away from traditional coal-to-liquid (CTL) fuels, which currently provide roughly one-third of South Africa's liquid fuel supply through facilities such as Sasol's Secunda refinery, is a critical step toward reducing the country's carbon intensity (Crompton et al., 2024). Biofuels that are derived from feedstocks like sugarcane or algae, could replace gasoline and diesel blends by 2030 through advancing the research. Initiatives like Sasol's exploration of biomass integration and government incentives under the Biofuels Industrial Strategy could accelerate this shift, fostering rural development through agricultural feedstocks and aligning with broader just energy transition goals by repurposing coal-dependent skills toward sustainable fuel production (Crompton, et al., 2024). Overall, these alternatives have the potential to significantly reduce emissions from South Africa's transport sector, which is a major contributor to the country's total CO₂ output.

5. Conclusion

This study has systematically analysed the carbon intensive nature of South Africa's key industrial sectors namely energy production, mining, manufacturing, and transportation. It has revealed their unequal contribution to the nation's CO₂ emissions profile. As Africa's most emitter, South Africa accounts for approximately 33% of continental greenhouse gas outputs, positioning it within the global top 15 polluters. Empirical data highlights the energy sector's dominance in GHG emissions. The sector is responsible for 45% of total emissions through ESKOM's coal-fired operations, which released 151.11–153.47 Million Metric tonnes of CO₂ annually from 2019 to 2023. In mining, Scope 2 emissions from coal-derived electricity comprise 77% of the sector's footprint, while manufacturing sector generates process-embedded CO₂. The transportation sector is largely road-dependent, and it yields 11% or 48–50 million tonnes CO₂-equivalent per year.

The proposed decarbonisation pathways, encompassing renewable energy transitions, efficiency enhancements, policy reforms, and alternative fuels, provide a strong framework for reconciling environmental laws with socio-economic laws. Expanding the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) to harness solar resources. Sectoral upgrades such as CCS retrofits in energy infrastructure, electrified fleets in mining, electric arc furnaces in steel production and rail modal shifts in transportation hold potential reductions of CO₂.

Future studies should focus on long-term tracking of indirect Scope 3 emissions across mining supply chains, along with economic analyses of the Just Energy Transition Partnership's (JETP) impacts, while involving stakeholder input to improve measures for a fair energy shift. Policymakers should speed up PhD-led innovations via the Presidential Programme, by building cross-disciplinary teams to test small-scale hybrid renewable-synthetic fuel projects. In the end, South Africa's path to a low-carbon industrial future depends on combined efforts in technology, policy, and partnerships. By integrating these approaches, a fair energy transition can move the country beyond its reliance on fossil fuels, creating a model of sustainable growth that reduces serious climate risks and strengthens its leadership in Africa's environmental efforts. Coupled with more pilot's projects, sustainability of these integrations will be guaranteed.

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