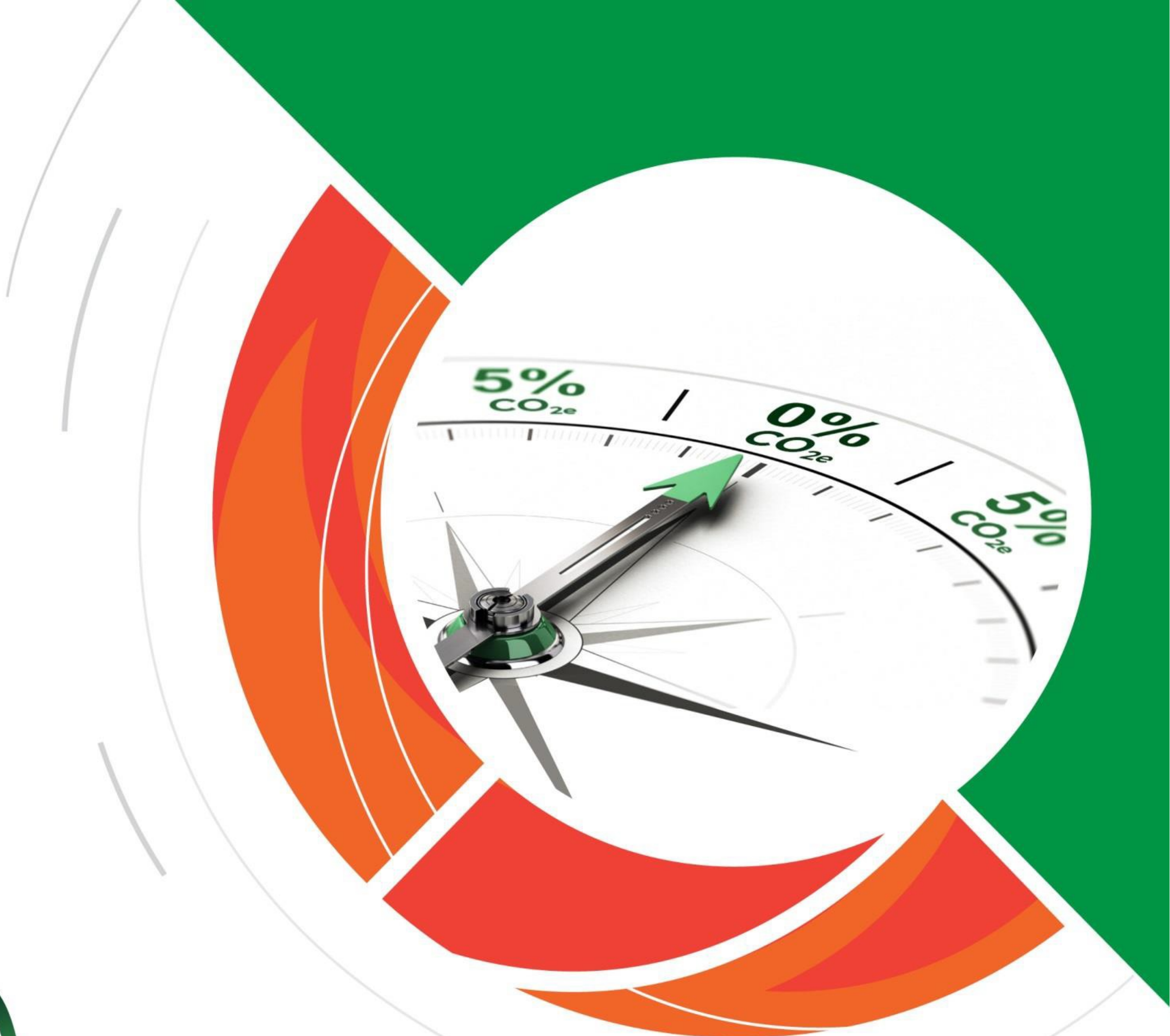

sanedi
South African National Energy
Development Institute

ROADMAP TOWARDS CLEANER FOSSIL FUELS IN SOUTH AFRICA PHASE 2

Coal Oil and Gas Decarbonisation Technology and Strategies

PROMETHIUM
CARBON

Executive Summary

Cleaner fossil fuels programme aims to reduce greenhouse gas emissions while still utilising fossil fuels as an energy source. South Africa relies heavily on fossil fuels, with coal accounting for 72% of the primary energy supply and 92% of primary energy for electricity production.

The burning of diesel and petrol in personal and commercial generators, as well as transportation, is another significant contributor to emissions. In South Africa, combustion of liquid fuels accounts for 10.8% of all emissions, with road transport being responsible for 91.2% of these emissions. Major industries like manufacturing and construction materials such as cement and steel are also responsible for a considerable amount of greenhouse gas emissions within the country.

Advances in technology, such as carbon capture and storage and energy efficiency improvements such as alternative fuels, can help reduce GHG emissions associated with fossil fuel use. South Africa's Cleaner Fossil Fuels Road Map aims to identify suitable technologies to improve energy efficiency and minimise the negative effects of energy production and use on climate change.

In Phase I of the Cleaner Fossil Fuels Roadmap, the aim was to assess the current energy supply and demand of the coal, oil, and gas value chains, and identify feasible technologies to manage GHG emissions and alternative feedstock options. The focus was to identify conversion technologies that could help to reduce the negative impacts on the environment cause by power generation processes.

Phase II of the Cleaner Fossil Fuels Roadmap narrows down the scope of technologies (based on certain techno-economic criteria) and offers a more in-depth examination and feasibility analysis of the technology options. Additionally, it also examines how well the technologies align with the country's climate change and Just Energy Transition requirements.

The Just Energy Transition (JET) is a concept and framework for transitioning South Africa's energy system towards a low-carbon, climate-resilient future while ensuring social and economic equity and broadly considers two components: 1) addressing the need for reliable energy supply that aligns with South Africa’s national climate change commitments and 2) supporting job creation, skills improvement, and economic development. This report serves as a technological assessment of cleaner fossil fuel technologies and their ability to support South Africa’s JET through an increase in the supply of energy to the national grid.

To provide a comprehensive evaluation, the assessment takes a holistic approach that considers the socio-economic drivers of these technologies, including their impact on employment and the necessary skills for their implementation. As such, the evaluation criteria included certain human capital assessment criteria, such as skill requirements for the technology. Without the necessary skills jobs cannot be created through the proposed technologies.

The Phase I technologies were further evaluated including infrastructure requirements, economic feasibility, technological readiness, and emissions reduction potential. It is important to note that Phase II of the Cleaner Fossil Fuels Roadmap is not a socio-economic assessment, therefore the assessment of the identified technologies for the feasibility analysis was based on a balance between the evaluation criteria.

As a result, 28 technologies were identified for the feasibility analysis, which have been outlined in the reference energy system (RES) in Figure 1. The RES offers a visualisation of the technologies considered and where they reside within the overall energy system.

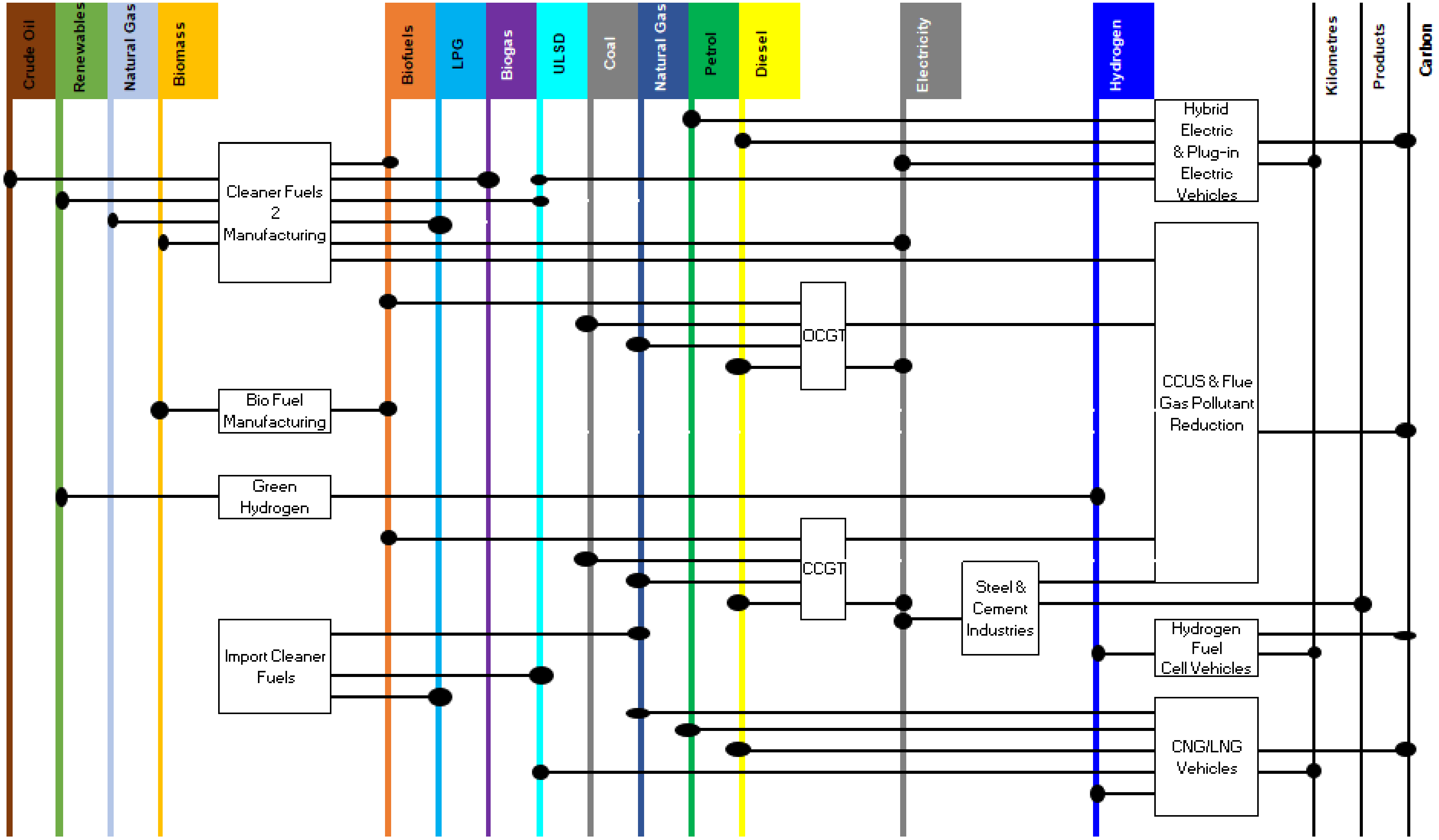

Figure 1: Reference energy system of the identified technologies for the Cleaner Fossil Fuels Roadmap Phase I

The identified technologies within the liquid fuels industry primarily focused on fuel switches for transportation. These switches included CNG/LNG vehicles, fuel cells, biofuel blending, green hydrogen manufacturing, hybrid electric vehicles and cleaner fuels. The technology implementation times vary within liquid fuel technologies with hybrid electric vehicles, plug in vehicles and ULSD fuel currently being available. Compared to the lead time of fuel cell vehicles and green hydrogen being 5 to 10 years.

For industry, cleaner fossil fuel technologies in the cement and steel industries were considered. Specific technologies such as clinker alternative materials, biochar and flue gas pollutant reduction technologies were considered. Again, lead time for technology implementation varies across the technologies and industries with clinker alternative materials for the cement industry reported as having an implementation period of less than 1 year, biochar implementation in the steel industry reported at less than 5 years and, flue gas pollutant reduction technology reported between 2-6 years.

Certain technologies overlap, especially in the case of Carbon Capture, Utilisation and Storage (CCUS) which is likely to play a critical role in decarbonising of technologies. Within coal fired stations equipped for CCUS, i.e. Medupi and Kusile, CCUS indicated a higher levelised cost per MWh as well as significant emissions reduction savings compared to non-CCUS coal power stations based on carbon prices in the long term. For diluted gas streams, the carbon capture systems have been estimated to reduce the net emissions per kWh by roughly 85-88%. CCUS could also play a significant role within the cement and steel industries, with estimated carbon capture potential estimated at 70% for concentrated gas streams.

Technologies presented in Phase I and further analysed here have been considered in term of complete value chains and in terms partial changes within a value chain. For complete value chains total levelized costs were considered. An example here is the production of electricity from building the power plant, the cost of the operation and maintenance and the cost of the fuel. Similarly full transport value chains consider the total cost of providing vehicle kilometres. In cases where partial value chain changes are suggested additional marginal costs are presented. Examples here include switching of fuels where only the additional cost for the fuel switch are presented. Retrofits are also only considered from an additional cost perspective.

The assumptions made for the calculation of the levelised and marginalised costs were largely based on the availability of information, specifically information applicable within the South African landscape such as the Power Generation Technology Data for Integrated Resource Plan of South Africa, 2017 (EPRI Report). International data sources such as the IEA levelised cost of electricity calculator for 2020 as well as the National Renewable Energy Laboratory, Transportation Annual Technology Baseline Data for 2020 were also used. When considering international cost data, a preference was afforded to information originating from developing countries.

There are also different risks associated with the various technologies including the proposed Carbon Border Adjustment Mechanism, the uncertainty of the carbon tax for coal power generation as well as certain socio-economic risks such as skills requirements, operational costs, job security, and maintenance.

Taking all the considered criteria into account identified technologies show potential to lower emissions in South Africa. These technologies were identified first by their emission reduction potential, as well as lead time for implementation to determine feasibility. Further in-depth research helped in identifying each technology’s cost implications, job opportunities, and the risks involved in their implementation.

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List of Acronyms

Acronym	Definition
AUSC	Advanced Ultra-Super Critical
CBAM	Carbon Border Adjustment Mechanism
CCGT	Closed Cycle as Turbines
CCS	Carbon Capture and Storage
CFB	Circulated Fluidised Bed
CNG	Compressed Natural Gas
CTL	Coal-to-liquid
DACC	Direct Air Carbon Capture
GHG emissions	Greenhouse gas emissions
GTL	Gas-to-liquid
IGCC	Integrated Gasification Combined Cycle Coal Power Plant
IPP	Independent power producer
JET	Just Energy Transition
LNG	Liquified Natural Gas
OCGT	Open Cycle Gas Turbines
RES	Reference Energy System
SC	Super Critical
UCG	Underground Coal Gasification
USC	Ultra-Super Critical

Introduction

Background information

Cleaner fossil fuels is a concept that implies using fossil fuels as an energy source, but with reduced GHG emissions. The goal is to utilise fossil fuels whilst minimising the negative effects of energy production and use on climate change. South Africa's energy and climate change issues are compounded by its heavy dependence on fossil fuels which make up approximately 90% of primary energy supply. Of this 90%, 72% originates from coal. In addition, 85% of electricity generation capacity is based on coal technologies and coal provides 92% of the primary energy used for electricity production.

Advances in technology have made it possible to use fossil fuels while lowering the number of emissions per unit of energy produced. The South African National Energy Development Institute (Sanedi) commissioned Phase I of the Cleaner Fossil Fuels Road Map, which aimed to identify suitable fossil fuel technologies for more feasible and efficient energy use, whilst addressing the Greenhouse Gas (GHG) emissions associated with these technologies.

The Cleaner Fossil Fuels Program aims to find technological solutions that decrease greenhouse gas emissions per unit of output from using fossil fuels, following the principles of reducing greenhouse gas emissions as outlined in Figure 2.

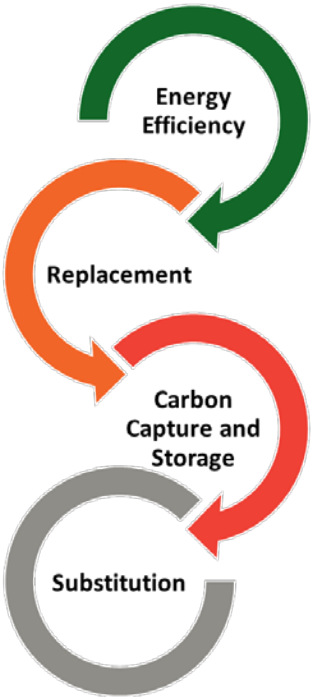

Figure 2: GHG reduction philosophy for Cleaner Fossil Fuels Program

Energy efficiency refers to the process that achieves improvements in operational outputs with the same amount of energy. Higher efficiencies require less energy input which in turn, results in less GHG emissions. Replacement of fossil fuel energy with non-fossil fuel energy, for example renewables and nuclear, eliminates carbon emissions, and Carbon Capture and Storage (CCS) includes the use of carbon capture technology to reduce and/or eliminate GHG emissions from fossil fuel use. Substitution includes feedstock co-firing or substitution of fossil fuel with less carbon intensive fuels or biomass.

As a result of South Africa's dependency on fossil fuels for the bulk of its energy supply, South Africa aims to leverage the concept of Cleaner Fossil Fuels in its journey to meet its Nationally Determined Contributions and decrease absolute GHG emissions.

Purpose and objectives

The purpose of the second phase of the Cleaner Fossil Fuels Roadmap is to use the findings from the first phase's report as a basis for further evaluating cleaner fossil fuels technologies in South Africa. This includes a more in-depth examination and feasibility analysis of technology options identified and how well they align with the country's climate change and just transition requirements. The Just Energy Transition is an initiative set out by Eskom which focusses on achieving a net zero emission status by 2050. This means that systems are put in place to reduce the country’s carbon emissions as well as increase sustainable jobs.

With the Just Energy Transition used as guidance, Phase II of the Cleaner Fossil Fuel Roadmap will help identify important aspects of each of the Phase I technologies to aid in the consideration of viable options for lowering emissions in South Africa. Narrowing the scope of the technologies based on certain qualifying criteria and showcase feasible techno-economic business cases for these technologies includes the availability, human capital, and infrastructure requirements and implementation time and cost.

Scope of work

Phase II of the Cleaner Fossil Fuels Roadmap report serves as a technological assessment of cleaner fossil fuel technologies within South Africa and aims to assess the technologies from Phase I of the Roadmap. The technological assessment included a review of the aforementioned technologies from the Phase I roadmap followed by a techno-economic feasibility study. The metrics used to assess the identified technologies included infrastructure requirements, economic feasibility, risks and emissions reduction potential. Some emphasis was placed on commercially available technologies.

Human capital requirements such as availability of skills and impact on jobs were also considered in the techno-economic analysis. However, this assessment is not a social assessment aimed at quantifying job creation and job losses associated with the implementation of certain technologies. Rather, these human capital requirements form part of the holistic approach to balancing technology development and socio-economic considerations.

Furthermore, the assessment mainly evaluated the impact these technologies would have on climate change and how feasible implementation would be. The optimisation of the applied technologies on their respective systems will not be included, nor would the design and construction details be assessed.

Methodology

The approach to this study was to critically review the Phase I report in the context of new information to identify which technologies should be considered in more detail. Using the review additional sources of information were identified with the aid a defined set of criteria. Finally, a feasibility analysis of the technologies was performed using acquired information from the literature and stakeholders to quantify the criteria. The detailed methodology is described below.

Review of the Phase I report

The approach for Phase I was to review the current energy supply and demand for the coal, oil and gas value chains within the overall energy sector, and to identify feasible technologies including alternative feedstock options, changes in conversion technology and technology to manage GHG emissions from power generation processes.

The assessment of the focal technologies from the Cleaner Fuels Roadmap Phase I for this review was based on the following criteria:

- **Infrastructure required:** whether major infrastructure developments were required compared to technologies that could be integrated within existing infrastructure more seamlessly.
- **Human capital requirements:** considering the skills required to implement the assessed technology, and whether those skills are available locally or not.
- **Economic feasibility:** the relative costs of development of the technology.
- **Emissions Reduction Potential:** the relative impact on GHG emissions reductions.
- **Technology readiness:** is assessed on how ready it is for implementation on the short term. However, we understand that such decisions must be taken together with Sanedi during project execution.

Figure 3: Assessment criteria from the Cleaner Fossil Fuels Roadmap Phase I

A key consideration is the balance between sufficient GHG emissions reductions, ease of implementation, human capital requirements, technology readiness and infrastructure requirements.

During this assessment the assumption is made that no new fossil fuel plants will be constructed, and these technologies will be implemented as additions or upgrades to existing plants as a motivation adopting a clean coal ideology. This means that opportunities where coal fuel sources can be exchanged for natural gas sources, expelled gasses can be cleaned or captured and stored, renewable energy generation or biofuels can be used will be assessed. The feasibility of these additions or upgrades will be outlined in this document and reasonable recommendations can be made on the choice of technologies to implement.

Stakeholder Consultations

The identification of focal technologies as well as areas for further analysis regarding those technologies will assist in the identification of industry stakeholders. Some of the stakeholders that we will be engaged with might include:

- **Eskom**: As their staff is working on implementing some of these technologies, they would be able to provide insight on the progress and provide additional information.
- **IPPs:** Specific focus will be on IPPs operating or planning to operate fossil fuel plants such as open cycle gas turbines.
- **Sasol:** As Sasol is one of the biggest fossil fuel consumers in South Africa and are focussing on shifting over to use some of the technology mentioned in the Phase I document, they might have performed feasibility studies themselves that might be beneficial for this project.
- **Industries** such as steel and metal, cement, chemical, etc. These industries also have some sections in their industrial processes that might benefit from implementing the technologies evaluated in this project.
- **Council for Geoscience:** Running pilot studies on the applications of carbon capture and storage can provide insight on the costs and logistics of the implementation of this type of technology.
- **Technology developers:** Consulting with entities that manufacture these technologies and research institutions focused on developing and evaluating these technologies.

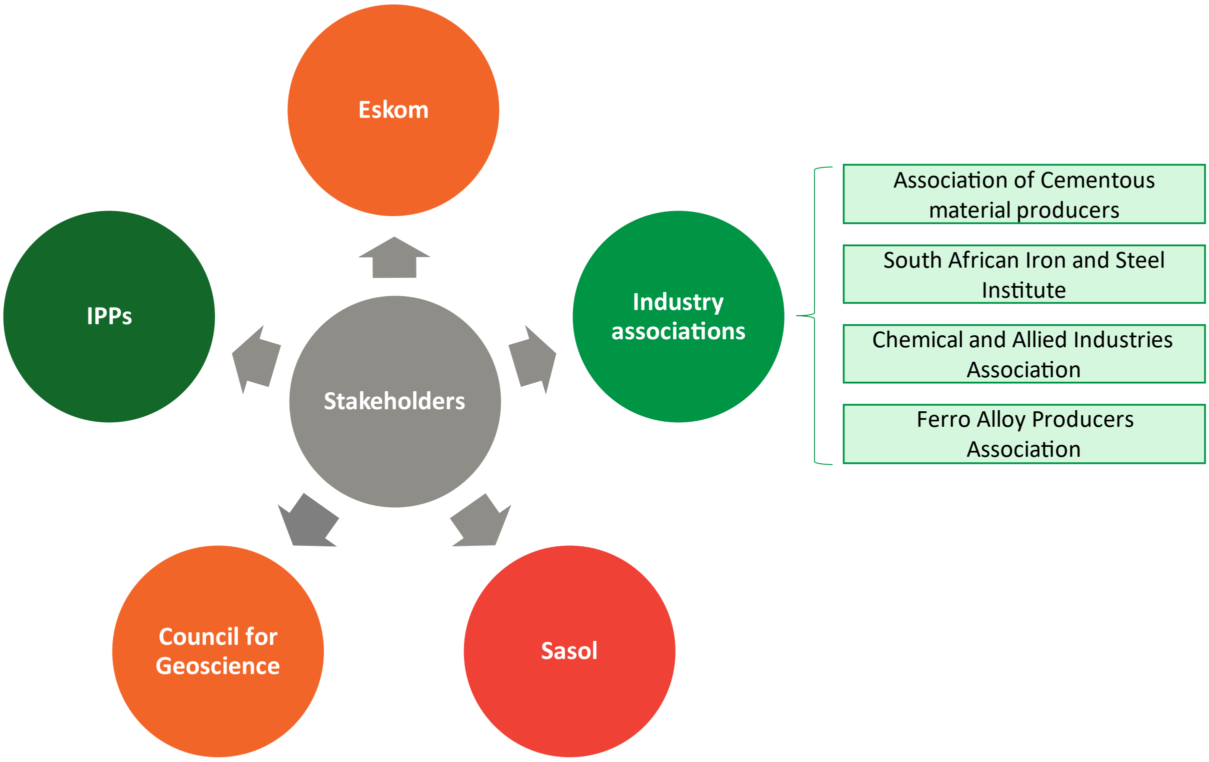

Figure 4: Potential stakeholders for Chapter 2

Feasibility analysis

A feasibility analysis will be undertaken for the focal technologies selected from the Phase I review, for immediate cost-effective integration into existing fossil fuel value chains. This approach will follow a techno-economic structure and will be based on the following criteria:

- High level **technical feasibility** assessment of each technology identified.
- Financial evaluation on the **economic feasibility** of each identified technology considering the capital and operational costs associated with the implementation of said technology. Where the economic value can either be revenue or cost savings. A discount rate of 8.2% will be used to calculate the levelised cost of a technology. This rate is based on the discount rate used in the current version of the IRP. This rate is a social discount rate while the private sector usually expects higher returns.
- **Technology readiness** for potential implementation in the short term.
- **Regulatory alignment** where we might consider the latest Integrated Resources Plan (IRP), the Liquid Fuels Roadmap, Hydrogen Society Roadmap, and the Biofuels Strategy and Blending of Fuels to name a few.
- **Risks** associated with the implementation of the focal technologies such as ***Lock-in of emission intensive technologies***, stranded asset risks and remaining economic life of sunset assets. It will also include an assessment of the impact of the South African Carbon Tax on any of the focal technologies.

Review of Cleaner Fossil Fuels Phase I

In this section the identified technologies in the Cleaner Fossil Fuels Roadmap Phase I report will be evaluated in terms of their emission reduction potential, infrastructure requirements, costs, human capital, lead time, and availability. Each technology will be assessed based on the before mentioned criteria to determine which are feasible in terms of implementation time and availability, these technologies will then be evaluated further to determine which can be successfully implemented. For the review, each technology will be categorised within the respective value chains to provide an overview of the impact each technology can have if implemented.

Coal and Gas Power Generation

The Phase I Report assessed 10 technologies across the Coal and Gas Generation value chains, looking at design and efficiency improvement technology.

The Coal Power Generation value chain follows the GHG Reduction philosophy outlined in Figure 2, and considered efficiency improvements, less carbon intensive feedstock, carbon removal through capture, transport and storage and finally, conversion of CO_2 to commodity products to achieve net-zero or negative carbon emissions.

Coal Power Generation

The Power Generation value chain indicates that the current base load power is provided by coal and nuclear plants, while peaking power is provided by diesel fired Open Cycle Gas Turbine (OCGT) plants. Most South Africa's coal plants are sub-critical designs averaging at 30.05% efficiency[1]. Additionally, high grade coal stocks are increasingly scarce to source, meaning most of the coal used is low grade coal.

Table 1: Identification of topics for further analysis and potential sources of information – Coal Power Generation

Technology	Topics for further analysis	Potential information sources
Steam Technology: Super Critical (SC)	This option has already been implemented by Medupi and Kusile Power Plants. Certain lessons regarding technology, costs and required infrastructure could be taken from these projects.	
	Infrastructure: The Phase I Report indicates that minor infrastructure is required. This is because South Africa has experience with SC at Medupi and Kusile Power Stations. However, it is important to note the decrease in efficiency when retrofitting the flue gas desulphurisation technology. **Human capital:** The phase I study does not consider the human resources required to implement this technology. The report notes the importance of coal plants in achieving a 'Just Transition'. **Costs:** The report indicates a high cost, requiring detailed justification and consideration. **Emissions Reduction:** The Phase I report rates as reasonable. **Availability:** The analysis in Phase I shows that this technology is commercially available.	**Infrastructure:** - Consultation with Eskom on infrastructure requirements - Integrated Energy Plan **Human capital:** - Review of literature in countries with SC plants. - Consultation with Eskom on human capital needs. **Costs:** - The phase I Report references costs per kW from 2017. It needs to be determined if these costs are still accurate. - Consultation with Eskom on costs **Emissions Reduction:** - The Phase I report indicates emissions reductions of between 0-80 gCO_2/kWh. - Department of Energy, Integrated Resource Plan. **Availability:** - Well established technology in South Africa
Steam Technology: Ultra Super Critical (USC)	**Infrastructure:** The Phase I Report indicates that minor infrastructure is required.	**Infrastructure:** - Review of literature in countries with USC plants.

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[1] Eskom, 2022 Annual Report, 2022_integrated_report.pdf (eskom.co.za)

Technology	Topics for further analysis	Potential information sources
	Human capital: The phase I study does not consider the human resources required to implement this technology. However, given the similarity of the technology to SC, it could also support South Africa's 'Just Transition'. **Costs:** The Phase I report indicates a 10% higher cost than SC plants, considering the cost of certain materials used in the construction. Initial capital and operational costs are higher with the addition of CCS. **Emissions Reduction:** The Phase I report rates as good. **Availability:** The technology is commercially available and is	- Engineering and Economic Evaluation of Ultra-Supercritical Pulverised Coal Power Plants: Phase I **Human capital:** - Review of literature in countries with USC plants. **Costs:** - The phase I Report lacks specific costs associated with the technology and its associated materials. It needs to be determined if these cost estimates are updated. - Review of literature in countries with USC plants. - Power Generation Technology Data for IRP of South Africa, 2017 **Emissions Reduction:** - A 10% reduction in CO_2 emissions (emissions between 740 and 800 g CO_2/kW) was reported. - Department of Energy, IRP Technology costs. **Availability:** - Not applicable. The technology is commercially available globally but still needs to be implemented in South Africa. - Consultation with Eskom on suitability in SA
Steam Technology: Advanced Ultra Super Critical (AUSC)	**Infrastructure:** The Phase I Report indicates that minor infrastructure is required. **Human capital:** The phase I study does not consider the human resources required to implement this technology. **Costs:** The costs are estimated to be higher than the USC technology, due to the use of certain materials. Initial capital and operational costs are higher with the addition of CCS. **Emissions Reduction:** The Phase I report rates as good. **Availability:** This technology is currently not commercially available and is still within the pilot programme phase.	**Infrastructure:** - Consultation with Eskom - Review literature for AUSC in countries with AUSC **Human capital:** - Consultation with Eskom - Review literature for AUSC in countries with AUSC **Costs:** - Consultation with Eskom - Power Generation Technology Data for IRP of South Africa, 2017 **Emissions Reduction:** - A decrease in emissions to between 670 and 740 gCO_2/kW was reported. - Department of Energy, IRP Technology costs. **Availability:** - Not applicable. The technology is in the demonstration phase.
Combustion Technology: Circulated Fluidised Bed (CFB)	**Infrastructure:** The Phase I Report indicates that minor infrastructure is required. The technology allows for flexibility of feedstock such as poorer quality coal and biomass. **Human capital:** The phase I study does not consider the human resources required to implement this technology. However, coal projects support South Africa's 'Just Transition'. **Costs:** Costs are estimated at 30% higher than pulverised coal SC plant with no FGD.	**Infrastructure:** - Consultation with Eskom - Review literature for IGCC in countries with IGCC - Engineering and Economic Evaluation of Ultra-Supercritical Pulverised Coal Power Plants: Phase I **Human capital:** - Consultation with Eskom - Review literature for IGCC in countries with IGCC **Costs:** - Power Generation Technology Data for IRP of South Africa, 2017 **Emissions Reduction:**

Technology	Topics for further analysis	Potential information sources
	Emissions Reduction: Emissions reductions are dependent on steam boiler design, SC or USC, but were rated as acceptable in the Phase I Report. However, emission of NO_x is low because combustion temperature is low. The technology is compatible with downstream flue gas removal. **Availability:** Commercially available technology. CFB are operating with USC in South Korea, with some SC units operating in China.	- Department of Energy, IRP Technology costs. **Availability:** - Not applicable. The technology is commercially available globally but still needs to be implemented in South Africa.
Combustion Technology: Integrated Gasification Combined Cycle Coal Power Plant (IGCC)	**Infrastructure:** The Phase I Report indicates that minor infrastructure is required. **Human capital:** The phase I study does not consider the human resources required to implement this technology. However, coal projects support South Africa's 'Just Transition'. **Costs:** The costs were estimated at R62,000 /kW with air separation units. This amounts to 68% higher than SC plants. **Emissions Reduction:** The Phase I report rates as good. **Availability:** The technology is in its demonstration phase, with a few international examples. However, it is noted that gasifier technology, similar to Sasol gasifiers, are complex to manage.	**Infrastructure:** - Review literature for IGCC in countries with IGCC - Consult with Sasol **Human capital:** - Review literature for IGCC in countries with IGCC - Consult with Sasol **Costs:** - The phase I Report references costs per kW from 2017. It needs to be determined if these costs are still accurate. - Power Generation Technology Data for IRP of South Africa, 2017 **Emissions Reduction:** - ER is estimated to be between 670 and 740 gCO_2/kW **Availability:** - Not applicable. The technology is commercially available globally but still needs to be implemented in South Africa.
Combustion Technology: Underground Coal Gasification	**Infrastructure:** The Phase I Report indicates that major infrastructure is required. **Human capital:** The phase I study does not consider the human resources required to implement this technology. **Costs:** The report does not quantify the potential costs of the technology. However, the report indicates there should be low plant costs in emerging markets. **Emissions Reduction:** Its reported that the ER for the project are good, however the report does not expressly stipulate the emissions reductions. **Availability:** The technology is in its demonstration phase, with extensive trials being undertaken in the U.S, Russia and Australia. Eskom operated Majuba power station using UGC.	**Infrastructure:** - Review of literature in countries with UCG - Consultation with Eskom - The Future of Underground Coal Gasification in South Africa, and The Future of Underground Coal Gasification in South Africa- Take Two **Human capital:** - Review of literature in countries with UCG - Consultation with Eskom - Consultation with South African Underground Coal Gasification Association **Costs:** - Review of literature in countries with UCG - Power Generation Technology Data for IRP of South Africa, 2017 - The Future of Underground Coal Gasification in South Africa, and The Future of Underground Coal Gasification in South Africa- Take Two **Emissions Reduction:** - Review of literature in countries with UCG - Consultation with Eskom - The Future of Underground Coal Gasification in South Africa, and The Future of Underground Coal Gasification in South Africa- Take Two **Availability:** - Not applicable. The technology is commercially available globally but still needs to be implemented in South Africa.

With the planned shutdown of baseload Eskom coal power stations over the next 20 years, additional generation capacity must be developed. A few of the technologies assessed above aim to make use of the existing infrastructure by improving the efficiency of the coal plants, for example SC, USC, AUSC. CFB technology is an example of substitution technology, where the fuel switch technology allows flexibility of feedstock to accommodate poorer quality coal and biomass. IGCC and UCG require major infrastructure development, as both require new power plants.

Some of the assessed technologies are commercially available, both locally and internationally, with all technologies (except UCG), implementable in the short term. Additional research into the topics identified above should be conducted, including engagement with stakeholders.

Gas Power Generation

The Power Generation value chain indicates that the current base load power is provided by coal and nuclear plants, while peaking power is provided by diesel fired Open Cycle Gas Turbine (OCGT) plants. This was considered in the Gas Power Generation value chain as energy efficiency technologies were considered for both OCGT and Combined Cycle Gas Turbines (CCGT).

The Phase I Report indicates that these technologies have significant efficiency gains and can be used to provide mid-merit to baseload power. However, this is on the assumption that there is a reliable source of natural gas, at sufficient scale. The LNG import infrastructure forms a key part of this value chain. LNG is discussed in section 0.

Table 2: Identification of information Topics for further analysis and potential sources – Gas Power Generation

Technology	Topics for further analysis	Potential information sources
Open Cycle Gas Turbines (OCGT): Diesel	**Infrastructure:** The Phase I Report indicates that major infrastructure is required. This is because the technology is dependent on gas infrastructure, which is lacking in South Africa **Human capital:** The phase I study does not consider the human resources required to implement this technology. **Costs:** Costs have not been included. **Emissions Reduction:** Diesel reductions would be less than coal fired power stations. **Availability:** The technology is commercially viable globally. Eskom own OCGT with diesel/kerosene fuel.	**Infrastructure:** - Review of literature - Consultation with Eskom **Human capital:** - Review of literature - Consultation with Eskom **Costs:** - Engagement with Eskom, who own OCGT which use diesel/kerosene fuel **Emissions Reduction:** - Reduction calculated at 0.25 kg CO_2/kWh **Availability:** - Not applicable. The technology is commercially available globally but still needs to be implemented in South Africa.
Open Cycle Gas Turbines (OCGT): Gas	**Infrastructure:** The Phase I Report indicates that major infrastructure is required. This is because the technology is dependent on gas infrastructure, which is lacking in South Africa **Human capital:** The phase I study does not consider the human resources required to implement this technology. **Costs:** The costs were rated as acceptable for business case development. Costs increase greatly with end-of-life boilers that need to be converted to pas firing plants.	**Infrastructure:** - Review of literature - Consultation with Eskom **Human capital:** - Review of literature - Consultation with Eskom **Costs:** - For a 732 MW plant, the costs were calculated at R9 000/kW. - The phase I Report references costs per kW from 2017. It needs to be determined if these costs are still accurate.

Technology	Topics for further analysis	Potential information sources
	Emissions Reduction: Reductions are reported as good. **Availability:** The technology is commercially viable globally. Eskom own OCGT with diesel/kerosene fuel.	**Emissions Reduction:** - Natural gas emissions were reported at 0.25 kg CO_2/kWh **Availability:** - Not applicable. The technology is commercially available globally but still needs to be implemented in South Africa.
Closed Cycle Gas Turbines (OCGT): Gas	**Infrastructure:** The Phase I Report indicates that major infrastructure is required. This is because the technology is dependent on gas infrastructure, which is lacking in South Africa. **Human capital:** The phase I study does not consider the human resources required to implement this technology. **Costs:** The costs were rated as acceptable for business case development. Costs increase greatly with end-of-life boilers that need to be converted to pas firing plants. **Emissions Reduction:** Reductions are reported as good. **Availability:** The technology is commercially viable globally. Eskom own OCGT with diesel/kerosene fuel.	**Infrastructure:** - Review of literature - Consultation with Eskom **Human capital:** - Review of literature - Consultation with Eskom **Costs:** - For a 732 MW plant, the costs were calculated at R10 000/kW. - The phase I Report references costs per kW from 2017. It needs to be determined if these costs are still accurate. **Emissions Reduction:** - Natural gas emissions were reported at 0.25 kg CO_2/kWh **Availability:** - Not applicable. The technology is commercially available globally but still needs to be implemented in South Africa.

Liquid Fuels

The Liquid Fuels value chain primarily focuses on liquid fossil fuels such as petrol and diesel. The technologies included in the assessment primarily focus on use of these fuels in the transport sector. The most impacted liquid fossil fuels by these technologies will therefore be petrol and diesel.

A summary of the information for each technology is provided in the Appendix. Based on this information, details for further research were identified in the table below. The topics for further analysis are identified for several different categories namely: infrastructure, human capital, costs, emission reductions and the availability of the technology.

Table 3: Identification of topics for further analysis and potential information sources – Liquid Fuels

Technology	Topics for further analysis	Potential information sources
CTL to GTL	This option has already been implemented by Sasol at the Secunda CTL plant. Further consultation with Sasol about whether they anticipate expanding or building further CTL plants is required. The potential impacts of this technology option are minimal when considering future options.	
CNG/LNG vehicle	**Infrastructure:** The phase I study indicates that significant infrastructure is required. Specific details of the infrastructure requirements are required. **Human capital:** human resources requirements to implement this technology should be considered in additional to the data from phase I study. **Costs:** The phase I study indicates that the costs associated with this option makes it suitable for business case development. Specific information about capital and operating costs should be included for more detailed analysis. **Emission Reduction:** The phase I study indicates that this technology could result in emission reductions up to 50%. More specific estimates of quantifiable emission reductions should be added. **Availability:** The analysis in Phase I shows that this technology is commercially available.	**Infrastructure:** - Review of literature. - Integrated Energy Plan 2016- Consultation with CNG Holdings **Human capital:** - Integrated Energy Plan 2016 - Review of literature- TIPS: "Petrol stations, workers and the just transition" - Consultation with CNG Holdings **Costs:** - Integrated Energy Plan 2016 - Review of literature. - NREL Annual Technology Baseline. Natural Gas - Consultation with CNG Holdings **Emission Reduction:** - Emission factors in the SA Methodological Guidelines. Switching a petrol vehicle to natural gas would result in 13.2tCO_2 reduction per TJ. This is roughly 20% reduction in emissions. **Availability:** - Available in South Africa through CNG Holdings. Details could be obtained through consultation and their website. - US DOE Alternative Fuels Data Center: "Natural Gas Vehicle Availability"
Fuel Cell Vehicle	**Infrastructure:** Phase I identified that extensive infrastructure will be required to implement fuel cell vehicles. Further details about this infrastructure will be required from further study. **Human capital:** human resources required to implement this technology should be considered in more detail. **Costs:** Phase I indicates that this technology would require consideration of options for a business case development. Specific information about the costs associated with vehicles and the fuelling costs require further research. **Emission Reduction:** Based on the Phase I analysis, this technology provides 100% emission reductions.	**Infrastructure:** - Hydrogen Society Roadmap. - Review of literature. - US DOE Annual Reports 2019. "Hydrogen Fuel R&D Subprogram Overview" **Human capital:** - Hydrogen Society Roadmap. - Review of literature. **Costs:** - Hydrogen Society Roadmap. - Review of literature. - US DOE Annual Report 2017. "V.E.5 Fuel Cell Vehicle Cost Analysis" - US DOE Annual Reports 2019. "Hydrogen Fuel R&D Subprogram Overview"

Technology	Topics for further analysis	Potential information sources
	Quantifiable values were not provided and should be included in the follow up research. **Availability:** In the Phase I analysis, this technology is still in the demonstration phase globally. Further information could be obtained on the progress of these demonstration projects as well as when commercial operation is expected.	- NREL Annual Technology Baseline. Fuel Cell (320-Mile) **Emission Reduction:** - Emission factors in the SA Methodological Guidelines. Fuel switch from diesel could yield 74.1tCO_2/TJ in reductions and 69.3tCO_2/TJ from petrol. **Availability:** - Consultation with Anglo American Platinum about the pilot at Mogalakwena Mine. - Review of literature.
Biofuel blending	**Infrastructure:** Major infrastructure will be required for this technology however more specific details are required in addition to the Phase I report information. **Human capital:** the human resources required to implement this technology needs to be considered in more detail. **Costs:** The Phase I analysis indicates that options should be considered for business case development. More specific quantifiable costs should be included. **Emission Reduction:** Phase I indicates that there could be more than a 50% reduction in emissions however a quantifiable estimate is required. **Availability:** The technology is widely used globally and is commercially ready for implementation.	**Infrastructure:** - Case studies in literature of countries that blend biofuel - US DOE Alternative Fuels Data Center: “Biodiesel” **Human capital:** - Case studies in literature of countries that blend biofuel **Costs:** - Case studies in literature of countries that blend biofuel - TIPS: “Petrol stations, workers and the just transition” - “Cost of Operations: ULSD vs. B20”. **Emission Reduction:** - Comparison of emission factors in the SA Methodological Guidelines. The default biodiesel emission factor from the IPCC results in emission reductions of 3.3tCO_2/TJ. **Availability:** - Not applicable. The technology is commercially available globally but still needs to be implemented in South Africa. - US DOE Alternative Fuels Data Center: “Biodiesel”
Power2X Fuels	**Infrastructure:** Major infrastructure will be required to manufacture other fuels from green hydrogen. Specific information about this infrastructure should be included in more detail. **Human capital:** the human resources required to implement this technology needs further consideration. **Costs:** The Phase I analysis indicates that this technology has a high cost requiring detail justification and consideration of options. No further quantifiable costs are provided apart from the current cost to produce green hydrogen of US\$5-8/kgH_2. A price of US\$2/kgH_2 is required to make the technology viable. **Emission Reduction:** The Phase I assessment of emission reductions indicates a rating of excellent as the technology is carbon free. A further comparison to provide quantifiable emission reductions is required. **Availability:** This technology is still in the Research and Development Phase. Further information about timelines for moving into the pilot phase is required.	**Infrastructure:** - Hydrogen Society Roadmap. - Review of literature. - Consultation with Sasol about conversion of H2. **Human capital:** - Hydrogen Society Roadmap. - Review of literature. - Consultation with Sasol about conversion of H2. **Costs:** - Hydrogen Society Roadmap. - Review of literature. - Consultation with Sasol about conversion of H2. **Emission Reduction:** - Emission reductions will depend on the fuel switch, but emission factors can be obtained from the SA Methodological Guidelines. A switch to SAF from Jet fuel could yield 71.5tCO_2/TJ in emission reductions. **Availability:** - Hydrogen Society Roadmap. - Review of literature. - Consultation with Sasol about conversion of H2.
Green hydrogen manufacture	**Infrastructure:** Major infrastructure is indicated by Phase I but no specific details are provided about what is required. **Human capital:** the human resources required to implement this technology requires further analysis. **Costs:** The Phase I analysis indicates that this technology has a high cost requiring detail justification and	**Infrastructure:** - Hydrogen Society Roadmap. - Review of literature. - US DOE Annual Reports 2019. “Hydrogen Fuel R&D Subprogram Overview” **Human capital:** - Hydrogen Society Roadmap. - Review of literature.

Technology	Topics for further analysis	Potential information sources
	consideration of options. Further quantifiable costs should be provided in addition to the current cost to produce green hydrogen of US$5-8/kg$H_2$. A price of US$2/kgH_2 is required to make the technology viable. **Emission Reduction:** The Phase I assessment of emission reductions indicates a rating of excellent as the technology is carbon free. A further comparison to provide quantifiable emission reductions is required. **Availability:** This technology is still in the Research and Development Phase. Further information about timelines for moving into the pilot phase is required.	**Costs:** - Hydrogen Society Roadmap. - Review of literature. - Consultation with Sasol about conversion of H2. - US DOE Annual Reports 2019. "Hydrogen Fuel R&D Subprogram Overview" **Emission Reduction:** - The largest reductions occur in fuel switching to green hydrogen. The emission reductions to produce green hydrogen is dependent on the source of electricity and country. Information to calculate the reductions could be taken from the Eskom annual report for the grid emission factor. - Consultation with Sasol as they are planning on green hydrogen in the future. **Availability:** - Hydrogen Society Roadmap. - Review of literature. - Consultation with Sasol as they are planning on green hydrogen in the future.
Use ultra-low sulphur diesel	**Infrastructure:** Minor infrastructure changes are required to switch vehicles to ultra-low sulphur diesel (ULSD). Some changes would be required to the supply chain, but specific details require additional information. **Human capital:** the human resources required to implement this technology requires further analysis. **Costs:** The Phase I analysis indicates that ULSD will be more expensive than the currently available 50ppm diesel. No quantifiable value is provided for the increased price or how much the infrastructure changes will cost. **Emission Reduction:** The Phase I analysis indicates that there are minimal reductions in GHG emissions as the sulphur content affects the SO_x emissions. An 80% reduction in SO_x is anticipated from the Phase I analysis. **Availability:** ULSD is commercially ready and available from international manufacturers already.	**Infrastructure:** - Review of literature - CHIETA: "Sector Skills Plan for the Chemical Sector" 2019 - "The Challenging Chemistry of Ultra-Low Sulphur Diesel" - Consultation with SAPIA **Human capital:** - Review of literature - CHIETA: "Sector Skills Plan for the Chemical Sector" 2019 - Consultation with SAPIA **Costs:** - Review of literature - Consultation with SAPIA **Emission Reduction:** - Minimal change in GHG emissions - Confirm 80% reduction of SO_x emissions through literature review **Availability:** - Consultation with SAPIA about what would be required for the switch
Cleaner Fuels 2 Manufacturing	**Infrastructure:** Minor enabling infrastructure is required but refineries will need upgrades to keep within the lower sulphur limits for petrol and diesel. Additional hydrogen plants may also be required to meet increased demand for desulphurisation. **Human capital:** The human resources required to implement this technology requires further analysis. **Costs:** The estimate provided in Phase I from SAPIA is US$2.5billion for all necessary refinery upgrades. **Emission Reductions:** Phase I indicates minimal GHG reductions from the lower sulphur limits. However, there could be an increase in emissions if further hydrogen plants are built. The SO_x emissions are reduced by 80% according to the Phase I analysis. **Availability:** The technology to produce low sulphur fuels is commercially ready and available globally.	**Infrastructure:** - Consultation with SAPIA - Literature review - CHIETA: "Sector Skills Plan for the Chemical Sector" 2019 - "The Challenging Chemistry of Ultra-Low Sulphur Diesel" - International Council of Clean Transportation. "An Introduction to Petroleum Refining and the Production of Ultra Low Sulphur Gasoline and Diesel Fuel" **Human capital:** - Consultation with SAPIA - Literature review - CHIETA: "Sector Skills Plan for the Chemical Sector" 2019 **Costs:** - Consultation with SAPIA - Literature review

Technology	Topics for further analysis	Potential information sources
		- "Cost of Operations: ULSD vs. B20". - International Council of Clean Transportation. "An Introduction to Petroleum Refining and the Production of Ultra Low Sulphur Gasoline and Diesel Fuel" **Emission Reduction:** - Minimal change in GHG emissions from lower sulphur limits - Confirm 80% reduction of SO_x emissions through literature review - Literature review for the possible increase emissions from additional hydrogen plants **Availability:** - Consultation with SAPIA about what would be required for the switch
Import clean fuels	**Infrastructure:** Additional infrastructure would be required. The NMPP and Transnet TM1 terminal would require upgrades for this approach. Details of these upgrades are not included as part of the Phase I analysis. **Human capital:** This option could result in job losses due to the closure of the SA refineries. However, there would be jobs associated with implementing the infrastructure changes. The human resources required for this requires further analysis. **Costs:** The infrastructure cost for upgrading refineries will be avoided however there are further costs associated with the additional infrastructure required to improve import capacity. These costs are not included as part of the Phase I report. **Emission Reduction:** This option would result in the refinery emissions being eliminated however these emissions are minimal in the context of the national inventory. Quantifiable estimates need to be included to enhance the information needed to make decisions. **Availability:** ULSD is available from international refineries. This technology option is commercially available.	**Infrastructure:** - Consultation with SAPIA **Human capital:** - Consultation with SAPIA **Costs:** - Consultation with SAPIA - International Council of Clean Transportation. "An Introduction to Petroleum Refining and the Production of Ultra Low Sulphur Gasoline and Diesel Fuel" **Emission Reduction:** - South Africa National GHG Inventory **Availability:** - Consultation with SAPIA

There are several different value chains represented in the liquid fuels industry in the table above. These include the current fossil fuels such as petrol and diesel, alternative fuels such as CNG or biofuels and finally the green hydrogen value chain. Some of the technology options are commercially available globally and can be implemented in the short term. These are predominantly within the fossil fuel and alternative fuel value chains with the green hydrogen technologies requiring a longer timeframe.

All of the technology options in the table above require further research to obtain specific costs related to their implementation and operation. Additional research into case studies around these technologies should be conducted. Several stakeholders were identified that could provide information including Sasol, Anglo American Platinum and SAPIA.

The emission reduction potential of the different technologies can be calculated using available literature and assumptions about the fuels displaced. The hydrogen linked technology options have the greatest potential for emission reductions as they are carbon free as opposed to a reduction in emissions from existing fossil fuels.

The green hydrogen manufacturing technology option will be split into two different categories when considered for further analysis. The first category is the local use market with small scale manufacturing plants. This category is much more likely to be commercially implemented in the next five years and can be used to synergise with the fuel cell vehicle technology option. The second option is the large-scale use and export markets. These types of plants are still in the R&D phase and will be implemented in a much longer timeframe. As such, the small-scale hydrogen manufacturing will be included in further analysis while the export, large scale manufacturing will be excluded.

The electric vehicle technology can also be split to better consider the option for further analysis. The hybrid electric vehicle technology is considered separately from the full electric vehicle technology. Full electric vehicles will be excluded from further analysis. This technology requires significant charging infrastructure and there is no emission savings unless powered by green energy. Furthermore, full electric vehicles are not directly related to making use of fossil fuels in a cleaner manner.

Hybrid vehicle technology will be included in further analysis. This technology is already commercially available in South Africa and is readily available. Additionally, the technology still makes use of fossil fuels and can be combined with ultra-low sulphur diesel to align with the cleaner fossil fuels development.

Industry

This section covers the application of cleaner fossil fuels technologies that focusses on the cement and steel industries. As the main source of carbon emissions in these industries are generated from burning fossil fuels and releasing the emissions into the atmosphere, Table 4: Identification of topics for further analysis and potential information sources – Industry mostly contains technologies associated with flue gas. Table 25 in the appendix contains a summary table for industry specific break downs and assessments of these technologies. Table 4 mainly focussed on identifying additional information needed for these technologies and where possible solutions may be found.

Table 4: Identification of topics for further analysis and potential information sources – Industry

Technology	Topics for further analysis	Potential information sources
Flue Gas Pollutant Reduction	**Infrastructure:** The infrastructure upgrades or additions required for implementation is little to none. Installation of technologies such as Selective Catalytic Reduction, wet or dry scrubbing with limestone, electrostatic precipitators, fabric filters, and activated carbon injection can achieve reduction in pollutants. **Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Costs:** Costs associated with this technology has been seen as acceptable for a business case development. However, specific costs involved should be included in addition to the information from the phase I. **Emission Reduction:** The phase I report states that only minor reduction in emissions are achieved from this technology. Further investigation into the emission reduction capability of the technology will provide more insight into its feasibility. **Availability:** The technology is commercially available and has low risk of execution.	**Infrastructure:** - Review of literature. - Review of projects where technology has been implemented presently. **Human capital:** - Review of literature. - Review of projects where technology has been implemented presently. **Costs:** - Review of literature. - Review of projects where technology has been implemented presently. **Emission Reduction:** - South African Methodological Guidelines emission factors for flue gasses - Review of projects where technology has been implemented presently to obtain emission reduction percentages. - Review of literature to obtain emission reduction percentages. **Availability:** - Review of literature - Consult with the technology suppliers in South Africa
Carbon Capture from Gas Streams	<u>For concentrated gas streams:</u> **Infrastructure:** The infrastructure upgrades or additions required for implementation is little to none. Chemical solvents such as mono ethanolamine can be used in absorber and stripper towers to capture CO_2. **Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Costs:** Costs associated with this technology has been seen as requiring consideration of options for business case development. The phase I report estimates the costs to be well below US$ 50 /tCO_2. **Emission Reduction:** The phase I report states that excellent reduction in emissions is achieved as this	<u>For concentrated gas streams:</u> **Infrastructure:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3[2] - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa[3] **Human capital:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Costs:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3

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[2] IEA, 2012. Carbon Capture and Storage: Legal and Regulatory Review. *IEA: International Energy Agency.*

[3] Glazewski, J., Glider, A. & Swanepoel, E. 2012. *Carbon Capture and Storage (CCS): Towards a regulatory and legal regime in South Africa.* Institute of Marine and Environmental Law (IMEL) and African Climate and Development Initiative (ACDI), University of Cape Town, Cape Town.

Technology	Topics for further analysis	Potential information sources
	technology is carbon free. However, further investigation into the emission reduction capability of the technology will provide more insight into its feasibility. **Availability:** The technology is commercially available and has low risk of execution. For diluted gas streams: **Infrastructure:** The phase I report states that significant infrastructure support is required for the implementation of the technology. Technologies including membranes, solvents, sorbents, and cryogenics can be adapted for most diluted industrial sources. **Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Costs:** Costs associated with this technology has been seen as requiring consideration of options for business case development. The phase I report estimates the costs for implementation to be between US\$ 50 – US\$ 100 /tCO$_2$. **Emission Reduction:** The phase I report states that excellent reduction in emissions is achieved as this technology is carbon free, but no quantifiable data was reported which requires further investigation. **Availability:** The technology is commercially available but has a medium risk of execution.	- Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Emission Reduction:** - Review of literature - South African Methodological Guidelines for emission factors and relate captured gas percentages found in literature with the reduction in emissions. - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Availability:** - Review of literature - Consult with the technology suppliers in South Africa For diluted gas streams: **Infrastructure:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Human capital:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Costs:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Emission Reduction:** - Review of literature - South African Methodological Guidelines for emission factors and relate captured gas percentages found in literature with the reduction in emissions. - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Availability:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa
Direct Air Carbon Capture	**Infrastructure:** The phase I report states that the infrastructure support required for the implementation of the technology would require significant additions and upgrades. This technology would require large fans to draw air in from the atmosphere into a collection, chemical solvents to remove the CO$_2$, and high temperatures to regenerate the chemical solvents.	**Infrastructure:** - Review of literature - IEA Direct Air Capture document and related regulations[4] **Human capital:** - Review of literature - IEA Direct Air Capture document

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[4] IEA. 2022. Direct Air Capture 2022. *IEA: International Energy Agency*.

Technology	Topics for further analysis	Potential information sources
	Human capital: Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Costs:** Costs associated with this technology has been seen as high and would require detailed justification and consideration as a viable option. The phase I report states that capture cost can be between US\$ 100 – US\$ 1000 per tonne. **Emission Reduction:** The phase I report states that excellent reduction in emissions is achieved as this technology is carbon free. However, further investigation into the emission reduction capability of the technology will provide a better understanding into its feasibility. **Availability:** The phase I document states that the technology is still a pilot program and would prove to be a high risk of execution. Phase I estimated that the implementation of this technology might be more 20 years away, but additional research into the timeline can provide more insight.	**Costs:** - Review of literature - IEA Direct Air Capture document **Emission Reduction:** - Review of literature - South African Methodological Guidelines for emission factors and relate captured gas percentages found in literature with the reduction in emissions. - IEA Direct Air Capture document **Availability:** - Review of literature - IEA Direct Air Capture document
Conversion to gas firing	**Infrastructure:** The phase I report states that major infrastructure adaptations would be required which would have extensive costs associated with it. **Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Costs:** Costs associated with this technology has been seen as acceptable for a business case development. However, the phase I report did not report on any specific costs involved. **Emission Reduction:** This technology would have good emission reduction capabilities with estimations of more than 50%. According to the phase I report, natural gas CO_2 emissions are 20% lower than sub-bituminous coal. For higher carbon content coal, the natural gas emissions are 36 to 40% lower. **Availability:** The technology is commercially available and has low risk of execution.	**Infrastructure:** - Review of literature - Consult with Limpsfield Engineering as they have implemented this technology at South African Breweries[5] o Consult with South African Breweries **Human capital:** - Review of literature - Consult with Limpsfield Engineering as they have implemented this technology at South African Breweries o Consult with South African Breweries **Costs:** - Review of literature - Consult with Limpsfield Engineering as they have implemented this technology at South African Breweries o Consult with South African Breweries; They stated that plants are more efficient and overall lower costs than coal firing, but conversion costs are not mentioned. **Emission Reduction:** - Review of literature - Consult with Limpsfield Engineering as they have implemented this technology at South African Breweries o Consult with South African Breweries **Availability:** - Review of literature - Consult with Limpsfield Engineering as they have implemented this technology at South African Breweries

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[5] Frost, H., Mavuso, Z. 2019. Combustion provider goes green to boost projects. *Creamer Media's Engineering News.* https://www.engineeringnews.co.za/article/combustion-provider-goes-green-to-boost-projects-2019-07-26.

Carbon Capture Storage Systems (CCS)

This section covers the application of carbon capture and storage technologies that focusses on the capture of CO_2 before it is released into the atmosphere. Currently there are no carbon capture and storage operations in South Africa, however, such technology is commercially available mainly in enhanced oil recovery purposes with a few in operations already. [6] Infrastructure that can facilitate CCS systems varies across countries and between individual refineries.[7] The CO_2 can be captured by a range of capture processes and technologies and is further discussed in the table below.

Topics for further analysis of these technologies and the possible sources of further information are identified in the table below. A summary table for CCS technologies and an assessment of these technologies is provided in Table 26 in the appendix.

Table 5: Identification of topics for further analysis and potential information – Carbon Capture Storage System (CCS)

Technology	Topics for further analysis	Potential information sources
Coal Power Plant with Carbon Capture and Storage	**Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Emission Reduction:** The phase I report states the emission reduction potential, however, the amount of GHG emissions that can be reduced should be further researched. **Availability:** The technology is commercially available and has low risk of execution.	**Human capital:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa. [8] **Emission Reduction:** - Review of literature - South African Methodological Guidelines for emission factors and relate captured gas percentages found in literature with the reduction in emissions [9][10] - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Availability:** - Review of literature - Consult with the technology suppliers in South Africa
Direct Air Carbon Capture (DACC)	**Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Emission Reduction:** The phase I report states the emission reduction potential, however, the amount of GHG emissions that can be reduced should be further researched.	**Human capital:** - Review of literature - IEA Direct Air Capture document **Emission Reduction:** - Review of literature - South African Methodological Guidelines for emission factors and relate captured gas percentages found in literature with the reduction in emissions [11] - IEA Direct Air Capture document

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[6] Adu, E., Zhang, Y. and Liu, D., 2019. Current situation of carbon dioxide capture, storage, and enhanced oil recovery in the oil and gas industry. The Canadian Journal of Chemical Engineering, 97(5), pp.1048-1076.

[7] Johansson, D., Rootzén, J., Berntsson, T. and Johnsson, F., 2012. Assessment of strategies for CO_2 abatement in the European petroleum refining industry. Energy, 42(1), pp.375-386.

[8] Yelebe, Z.R. and Samuel, R.J., 2015. Benefits and challenges of implementing carbon capture and sequestration technology in Nigeria. Int J Eng Sci, 4, pp.42-49.

[9] Odeh, N.A. and Cockerill, T.T., 2008. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. Energy Policy, 36(1), pp.367-380.

[10] Volkart, K., Bauer, C. and Boulet, C., 2013. Life cycle assessment of carbon capture and storage in power generation and industry in Europe. International Journal of Greenhouse Gas Control, 16, pp.91-106.

[11] Gambhir, A. and Tavoni, M., 2019. Direct air carbon capture and sequestration: how it works and how it could contribute to climate-change mitigation. One Earth, 1(4), pp.405-409.

Technology	Topics for further analysis	Potential information sources
	Availability: Technology is operating in very small scale and is prohibitively expensive and energy intensive. The phase I document states that the technology is still a pilot program and would prove to be a high risk of execution. Phase I estimated that the implementation of this technology might be more 20 years away, but additional research into the timeline can provide more insight.	**Availability:** - Not applicable. The technology is only operating in very small scale. - Review of literature - Consult with the technology suppliers in South Africa
Carbon Capture from Gas Streams	<u>Concentrated Gas Streams</u> **Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Emission Reduction:** The phase I report states the emission reduction potential, however, the amount of GHG emissions that can be reduced should be further researched. **Availability:** The technology is already proven and offered to many industries. <u>Carbon Capture from Dilute Streams</u> **Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Emission Reduction:** The phase I report states the emission reduction potential, however, the amount of GHG emissions that can be reduced should be further researched. **Availability:** The post-combustion capture has been demonstrated on full-scale power and industry plants but has a medium risk of execution	<u>Concentrated Gas Streams</u> **Emission Reduction:** - Review of literature - South African Methodological Guidelines for emission factors and relate captured gas percentages found in literature with the reduction in emissions. - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Availability:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa <u>Carbon Capture from Dilute Streams</u> **Human capital:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Emission Reduction:** - Review of literature - South African Methodological Guidelines for emission factors and relate captured gas percentages found in literature with the reduction in emissions. - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Availability:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa.
Carbon Storage	**Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Costs:** Costs associated with this technology has not been disclosed would require detailed justification and consideration as a viable option. **Emission Reduction:** The phase I report states the emission reduction potential, however, the amount	**Human capital:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Costs:**

Technology	Topics for further analysis	Potential information sources
	of GHG emissions that can be reduced should be further researched. **Availability:** The technology has a high execution risk with major infrastructure and costs required.	- Review of literature [12] - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 **Emission Reduction:** - Review of literature[13] - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Availability:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa
Carbon Dioxide (CO_2) Transport	**Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Availability:** The technology has a low execution risk and South Africa has experience in pipeline construction and transport.	**Human capital:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 - Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa **Availability:** - Review of literature - Carbon Capture and Storage – Legal and Regulatory Review Edition 3 Carbon Capture and Storage (CCS) – Towards a regulatory and legal regime in South Africa
Carbon Utilisation	**Infrastructure:** The phase I report states that major infrastructure adaptations would be required which would have extensive costs associated with it. **Human capital:** Human capital requirements is a possible area where further investigation and evaluation can be beneficial for further evaluating the technology. **Costs:** Costs associated with this technology has been seen as high and would require detailed justification and consideration as a viable option. **Emission Reduction:** The phase I report states that excellent reduction in emissions is achieved as this technology is carbon free, but no quantifiable data was reported which requires further investigation. **Availability:** The technology is still in research and development phases and would have high risks of execution. Phase I estimated that the implementation of this technology might be more 20 years away, but additional research into the timeline can provide more insight.	**Infrastructure:** - Review of literature - IEA's Legal and Regulatory Frameworks for CCUS[14] **Human capital:** - Review of literature - IEA's Legal and Regulatory Frameworks for CCUS **Costs:** - Review of literature - Consult with cement manufacturers that are considering implementing the technology. - Review case studies **Emission Reduction:** - Review of literature - If implemented correctly, emissions will only occur if leaks are present in the system. However, further resources must be consulted. **Availability:** - Review of literature IEA's Legal and Regulatory Frameworks for CCUS

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[12] Gislason, S.R. and Oelkers, E.H., 2014. Carbon storage in basalt. Science, 344(6182), pp.373-374

[13] Gislason, S.R. and Oelkers, E.H., 2014. Carbon storage in basalt. Science, 344(6182), pp.373-374.

[14] IEA, *Legal and Regulatory Frameworks for CCUS,* IEA: International Energy Agency. Retrieved from https://policycommons.net/artifacts/2618268/legal-and-regulatory-frameworks-for-ccus/3640847/.

Technology assessment conclusion

Based on the assessment of feasible technology options that will allow for the transition to cleaner fossil fuels in South Africa, it was identified that specific technologies are not a viable option based on particular reasons. Summary of such discussion is provided in the table below.

Table 6: Summary of technology assessment

Technology	Included/ excluded	Reason
Steam Technology: Super Critical (SC)	Included	IRP(2019) supports the investment into SC technology. SC Technology supports South Africa's 'Just Transition'.
Steam Technology: Ultra-Super Critical (USC)	Included	IRP(2019) supports the investment into USC technology. USC Technology supports South Africa's 'Just Transition'.
Steam Technology: Advanced Ultra Super Critical (AUSC)	Excluded	This technology is currently not commercially available and is still within the pilot programme phase.
Combustion Technology: Circulated Fluidised Bed (CFB)	Included	The technology allows for flexibility of feedstock such as poorer quality coal and biomass. Coal projects support South Africa's 'Just Transition' and is commercially available technology.
Combustion Technology: Integrated Gasification Combined Cycle Coal Power Plant (IGCC)	Excluded	This technology is currently not commercially available and is still within the pilot programme phase.
Combustion Technology: Underground Coal Gasification (UGC)	Excluded	Excluded by Eskom during Stakeholder engagement in Phase I Report.
Open Cycle Gas Turbines (OCGT): Diesel	Included	The technology is commercially viable globally as well as having costs that were rated as acceptable for business case development.
Open Cycle Gas Turbines (OCGT): Gas	Included	The technology is commercially viable globally as well as having costs that were rated as acceptable for business case development. However, this technology is dependent on major gas infrastructure.
Closed Cycle Gas Turbines (OCGT): Gas	Included	The technology is commercially viable globally as well as having costs that were rated as acceptable for business case development. However, this technology is dependent on major gas infrastructure.
CTL to GTL	Excluded	Already being implemented by Sasol at the Secunda CTL plant based on the minutes of the consultation in Phase I.
CNG/LNG vehicle	Include	The technology is already available in South Africa. Applicable to fleet applications. The Technology Readiness Level of this technology is TRL 9.
Fuel Cell Vehicle	Include	This technology has a Technology Readiness Level of 9 as it is commercially available in other countries.
Biofuel blending	Include	The technology to produce biofuel is already available and blending is practiced in other countries such as the US. This technology has a Technology Readiness Level of 9.
Power2X Fuels	Exclude	This technology is still in R&D phase and therefore falls below a Technology Readiness Level of 9
Green hydrogen manufacture – large scale, local and export market use	Exclude	This technology is still in R&D phase and therefore falls below a Technology Readiness Level of 9
Green hydrogen manufacture – small scale, local use	Include	This technology can be commercially applied in the next five years.
Full electric transition	Excluded	Excludes as electric vehicles are not directly related to cleaner fossil fuel use.
Hybrid electric vehicles	Include	This technology has a Technology Readiness Level of 9 and can be combined with the use of cleaner fuels like ultra-low sulphur diesel. These vehicles are commercially available in South Africa.
Use ultra-low sulphur diesel	Include	Existing vehicles can make use of the fuel. Transport infrastructure and sourcing is all that is required. This technology has a Technology Readiness Level of 9.
Cleaner Fuels 2 Manufacturing	Include	Technology option results in lower SOx with a potential for minimal GHG reductions from improvements in

		vehicle efficiency. This technology has a Technology Readiness Level of 9.
Import clean fuels	Include	Technology option results in lower SOx with a potential for minimal GHG reductions from improvements in vehicle efficiency. This technology has a Technology Readiness Level of 9.
Capture Technology: Flue Gas Pollutant Reduction	Included	In the stakeholder engagement of Phase I, Eskom said that alternatives to flue gas desulphurisation plants are being looked at for employment at Medupi as these plants can cost R40 billion. They are upgrading electrostatic precipitators for emissions standards compliance. Eskom also planned to implement low NO_x burners at old plant but due to limited funding the projects were stalled. This technology is commercially available, which gives it a Technology Readiness Level of 9, indicating it can be included into this study.
Capture Technology: Carbon Capture from Concentrated Gas Streams	Included	During stakeholder engagements in Phase I, investigations into this technology was being launched by Eskom and are targeted to be implemented at Kusile power station. This technology is commercially available, which gives it a Technology Readiness Level of 9, indicating it can be included into this study.
Capture Technology: Direct Air Carbon Capture	Excluded	The direct air capture of GHG would only be a viable option if the cost of the technology would be below US$200 per ton CO_2 captured according to Sasol.
Capture Technology: Carbon Capture from Diluted Streams	Included	During stakeholder engagements in Phase I, investigations into this technology was being launched by Eskom and are targeted to be implemented at Kusile power station. This technology is commercially available, which gives it a Technology Readiness Level of 9, indicating it can be included into this study.
Combustion Technology: Converting to Gas Firing	Excluded	Even though this technology has a Technology Readiness Level of 9, Eskom has excluded converting coal firing plants to gas firing during Phase I stakeholder engagements, as natural gas is currently not available, and the infrastructure required for making gas available could take several years. Sasol is scheduling the transition of the Secunda coal feedstock to gas feedstock; however, the switch will only happen over the next 10 years.
Combustion Technology: Green Hydrogen	Excluded	As per the stakeholder engagement in Phase I, Sasol stated that green hydrogen as a renewable energy source would only be viable if the cost of production would lower from the current US$7 to US$8 per kg, to US$2 per kg. As this technology is only in Research and Development stages, its Technology Readiness Level falls between 3 and 4 which is why it is excluded as a viable option.
Capture Technology: Carbon Utilisation	Excluded	No stakeholder mentioned the utilisation of carbon in any prospects. As this technology is only in Research and Development stages, its Technology Readiness Level falls between 3 and 4 which is why it is excluded as a viable option.
Capture Technology: Carbon Storage	Excluded	The carbon storage technology would only be a viable option if the cost and infrastructure required for the implementation of the technology is reduced.
Capture Technology: Carbon Dioxide (CO_2) Transport	Included	Technology option is viable in South Africa as South Africa has experience in pipeline construction and transport. Furthermore, such technology has a low risk for execution, and it is related to fossil fuels.

Feasibility Analysis

The review of the Phase I report identified technologies for further research and assessment. In the review, the areas for further research within each technology were identified with potential information resources.

In this chapter, a feasibility analysis of the identified technologies is presented. This analysis considers various parameters both quantitative and qualitative. The cost of implementation, emissions implications, implementation lead time are considered as quantitative parameters while human capital requirements and lock-in are discussed from a qualitative perspective. The levelised cost of electricity (LCOE) is used to assess cost competitiveness of power generation technologies. The LCOE is a useful metric that consolidates all direct technology costs, such as construction, fuel, carbon prices, operations and maintenance, into a single metric, and can be used across technologies with varying technical lifetimes.[15] As each technology is specific to each value chain, the metrics used to quantify the levelised cost accordingly would relate to that specific value chain. For the liquid fuels value chain, the metric used is R/km whereas the power generation and industry costs will be measured in R/kWh or R/MWh.

Electricity Generation

Coal Power Generation

South Africa's energy system is heavily dependent on coal as it constitutes about 90% of the country's electricity supply. The coal-fired power plants in the country are predominantly sub-critical, with only two supercritical plants, namely Medupi and Kusile. The decision to construct these two supercritical plants was made before the global shift away from coal as a primary energy source.

South Africa is also the largest producer of coal on the African continent, with both higher-grade coal and lower grade coal being exported.[16] Eskom uses over 90Mt of coal per annum with different coals grades being used across the different power stations. Generally, the coal used across the power stations are lower grade coal characterised by high ash content. [17]

A summary of the quantitative metrics is provided in the , the Medupi and Kusile power stations had estimated completion dates of under 6 years but, have taken more than a decade to complete.

The levelised costs presented in Table 7 vary between the marginal cost of implementing the technology and the total cost of generating electricity with that technology. The costs for CFB on SC and on USC represent the marginal cost of adding CFB technology onto SC or USC. Whereas the SC, USC and retrofitting with CCUS costs are levelised costs.

A levelised cost per MWh was used as the most appropriate metric for the capital and operating costs of the power plant and technologies assessed. The construction time for the Super Critical (SC) and Ultra-Super Critical (USC) power plants was estimated to be between three and a half to six years to complete. While the estimated lead time for implementing CFB technology onto these types of plants will be discussed with stakeholders, within South Africa the lead-time for these technologies are often extended due to project delays. For example, the Medupi and Kusile power stations had estimated completion dates of under 6 years but, have taken more than a decade to complete.

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[15] International Energy Agency, 2020, “Projected costs of generating electricity, 2020 edition”.

[16] Higher grade coal is classified as calorific values of 6000kcal/kg (or 23 MJ/kg), with medium and lower grade coal ranging from 5500 kcal (23 MJ/kg), 5000 kcal (21 MJ/kg) and 4500 kcal/kg (<20 MJ/kg).

[17] Ratshomo. K, Nembahe, R., 2015, “South African Coal Sector Report”.

Table 7: Coal power generation quantitative feasibility

Technology	Cost of technology	Potential emissions implications	Implementation lead time
SC	**Levelised cost-** R 1 505.21/MWh	Up to 180 kg CO_2/MWh reduction compared to sub-critical plants	3,5 – 6 years[18]
CFB- on SC	**Marginal Cost-** R21.02/ MWh	Emissions reduction of the technology fitted to	5-10 years
USC	**Levelised cost-** R812.88 MWh	Up to 300 kg CO_2/MWh reduction compared to sub-critical plants	3,5 – 6 years[18]
CFB- on USC	**Marginal cost-** R25.00/ MWh	Emissions reduction of the technology fitted to	5-10 years
Retrofitting: CCUS			
Retrofitting SC/USC with CCUS	**Levelised cost-** R3 158.64/MWh	31.43 kg CO_2/ MWh	5-10 years

As coal power technologies like SC and USC evolve, they require the use of higher-grade coal to operate effectively. This is an important metric to consider, not only in terms of the availability of coal but also the effect of coal prices on the fuel costs of the power plants. For example, the coal prices between these 3 different grades of coal varied from-

- Anthracite coal (30.1 MJ/kg) at **R3 342/t**
- 24.3 MJ/kg coal at **R3 038/t**, and
- 19 MJ/kg at **R2 370 t**[19]

The calculations in , the Medupi and Kusile power stations had estimated completion dates of under 6 years but, have taken more than a decade to complete.

Table 7 assumed coal prices for the corresponding technology, i.e., higher grade (30.1 MJ/kg) coal for USC and 19 MJ/kg coal for SC technology.

The retrofitting of combustion technology, specifically for sub-critical power stations with CCUS technology is an additional cross-cutting consideration. CCUS is further discussed in section 0. The levelised costs for retrofitting a coal power station with CCS was based on an IEA Study *The role and value of CCS in different national contexts*, published in 2019.[20]

The coal value chain has been central to South Africa's development and feeds into important downstream industries such as electricity generation and petrochemical production. Figures describing the number of jobs within the coal value chain vary depending on parts of the value chain included in the assessment. Employment figures vary from 800 000 direct jobs to 200 000 jobs within formal employment.[21,22]

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[18] Lee, HC. Lee, EB. Alleman, D. 2018. Schedule Modelling to Estimate Typical Construction Durations and Areas of Risk for 1000 MW Ultra-Critical Coal-Fired Power Plants, Energies.

[19] Coal prices for 28 February 2023.

[20] W. Pratama *et.al,* 2019, *"The role and value of CCS in different national contexts"*, Imperial College London for the Coal Industry Advisory Board.

[21] Decarbonising South Africa's Power System, National Business Initiative reports where figures were estimated at 0.4 million jobs in coal value chain (80k direct, 200-300k indirect and induced).

[22] M. Patel, N. Makgetla, 2021, *"The Coal Value Chain in South Africa"*, Trade and Industry Policy Strategies.

Despite the lack of concrete values, it is important to consider two aspects of the employment discussion, especially in the context of coal power generation. Firstly, certain jobs within the coal value chain should be preserved due to the remaining coal capacity needed for energy supply within South Africa. Secondly, additional consideration should be given to reskilling people in the coal value chain who could lose employment as coal power generation is phased out of the South African energy mix. Reskilling will enable workers to transition from jobs that are no longer sustainable in fossil fuel sectors to employment opportunities either in emerging clean energy sectors or, suitable alternative sectors.

South Africa faces constraints within the electricity supply network, particularly for ageing transmission and distribution infrastructure. These constraints result in reduced efficiency which in turn results in increased energy consumption and costs. It also hinders additional capacity being able to supply to the grid. Additionally, the location of energy projects face added restrictions due to the grid connection constraints. The transmission and distribution network in certain areas of the country is not well developed, which makes it difficult to connect new energy projects to the grid. This has led to delays in the connection of new energy projects.

Fuel Blending: Biofuels

Co-firing involves burning two or more different types of fuels simultaneously. This technique offers the advantage of using an existing plant to burn a new fuel, which may be less expensive or more environmentally sustainable. For instance, biomass is sometimes co-fired in existing coal plants instead of building new biomass plants. This involves utilising a secondary fuel, such as biomass, to substitute a percentage of the primary fuel, which is referred to as the co-firing rate.

Globally, a variety of feedstocks are used for cofiring and include bagasse, vegetable and agricultural waste, rice husks and wood waste.

Table 8: Coal power generation- fuel blending with biofuels quantitative feasibility

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
SC and USC - biofuel	Additional research is required	Emissions reductions should decrease with the percentage of fuel blending.	4 years [23]

It's important to note that there could be potential issues with using certain crops for co-firing, especially in South Africa. One of the primary concerns is the competition for land between food and energy crops, with there being a risk that energy crops may displace food crops and contributing to food insecurity. Additionally, certain crops are not suited for the South African environment due their significant impact on water resources. It's important to evaluate appropriate crops for cofiring in South Africa.

The quantitative analysis in Table 8 used wood chips or 'forest residue' as the appropriate fuel. The proximity of the biomass sources to the existing power plants is a strong determinant tin the feasibility of co-firing with biomass.

Fluidised bed combustion (FBC) boilers are well-suited for cofiring, and coal fired FBC units can be easily adapted for this purpose. Compared to PC boilers, FBC boilers can cofire higher ratios of biomass and handle biomass with a higher moisture content and larger particle size. While cofiring a higher ratio of biomass can lead to greater CO_2 emissions reduction, challenges related to biomass fuel availability, storage, and disposal must be addressed.[24]

Co-firing ratio can be implemented in stages over several years, for example as was implemented in the United Kingdom by the Drax Power Plant. The power plant tested cofiring in 2004 with a 3% co-firing ratio of locally

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[23] Electric Power Research Institute, 2017, "Power generation technology data for integrated resource plan of South Africa". The lead time for forestry residue, including wood chips, is reported to be 3.5 to 4 years.

[24] Zhang.X, Meloni.S, 2021, "Technology developments in the cofiring of biomass."

sourced wood. Thereafter, four 660 MW units were converted over a period of 10 years to be able to use 100% biomass on the generation of electricity.[25]

Additionally, the 2007 *Biofuels Industrial Strategy* indicates that biofuels are a key driver for socio economic development in South Africa, with the support for a local feedstock value chain being championed in the Strategy.[26]

Gas Power Generation

Combined cycle gas turbines recover heat from the turbine exhaust in a heat recovery steam generator (HRSG) to generate additional electricity, thereby increasing efficiency. CCGTs have a complex design and require longer periods of time to startup and shutdown. Hence, they are best suited for baseload to mid-merit electricity supply. Conversely, an open cycle gas turbine operates by compressing air from the atmosphere, which is then mixed with fuel and ignited in the combustion chamber. The high-pressure hot gases generated expand and pass through the turbine, producing power.

A summary of the quantitative metrics is provided in the table below. A levelised cost per MWh was used as the most appropriate metric for the capital and operating costs of the vehicle. The use of a CCGT has a levelised cost of R712.2/MWh.[27] . It is seen that CCGT technology can achieve approximately 392 - 462 kgCO_2/MWh [28] emission reductions. Currently, South Africa's future natural gas supply is uncertain however, the implementation lead time of this technology is approximately 3 years. [29]

Table 9: Gas power generation- OCGT and CCGT

Technology	Cost of technology	Potential emissions implications	Implementation lead time
New Gas Plants			
CCGT	**Levelised cost-** R993.08/MWh	392 - 462 kgCO_2/MWh	3 years
OCGT- Diesel	**Levelised cost-** R1 456.65/MWh	574 kgCO_2/MWh	2 years
OCGT- Biodiesel	**Additional Marginal cost compared to OCGT - Diesel-** R238.21/MWh	334 kgCO_2/MWh[30]	< 5 years
OCGT- Gas	**Levelised cost-** R1 687.37/MWh	413.28 kg CO_2/kWh	2 years

The roll out of combined cycle gas turbines roll will require employees for the construction and implementation of the technology. Therefore, it is estimated that the required human capital is 0.14 Jobs/MW during O&M and 1.30 Jobs-years/MW during construction and installation (C&I). Furthermore, supporting gas infrastructure is required and this will create additional jobs in the workshops that will be required for these retrofits.

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[25] Ibid.

[26] Department of Minerals and Energy, 2007, "Biofuels Industrial Strategy of the Republic of South Africa".

[27] Lyons, C. and Gross, C., 2015. Power Generation Technology Data for Integrated Resource Plan of South Africa.

[28] Sims, R.E., 2004. Renewable energy: a response to climate change. Solar energy, 76(1-3), pp.9-17.

[29] Lyons, C. and Gross, C., 2015. Power Generation Technology Data for Integrated Resource Plan of South Africa.

[30] The emissions reduction potential was calculated from the Methodical Guidelines for Quantifying Greenhouse Gas Emissions, which incorporates a percentage blending into the emissions factor for biodiesel.

CCGT's are expected to have a short time frame where design to installation take approximately 4 years. However, supporting gas infrastructure may take longer. The overall risk for execution for this technology is seen as medium since supporting gas infrastructure is required, which may take 4 to 6 years and there is a possibility of delays in infrastructure development to support the CCGT short lead times.

For fuel blending, renewable diesel, which is also known as hydrogenated vegetable oil (HVO), and biodiesel or fatty acid methyl ester (FAME), can both be blended with diesel fuel. Renewable diesel is compatible with existing diesel engines as it has the same chemical composition as fossil diesel. On the other hand, biodiesel has a different chemical composition to fossil diesel, which limits its blending. For example, Amazon web services have recently started transitioning to HVO to power back-up generators at its data centres in Europe. Furthermore in Europe, for example, biodiesel blends are limited to 7%.[31]

The emissions reductions associated with fuel switching will be proportionate to the percentage of biodiesel blended into the fuel.

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[31] International Energy Agency, 2021, "Renewables 2021: Biofuels". Biofuels – Renewables 2021 – Analysis - IEA

Liquid Fuels

The identified technologies within the liquid fuels industry primarily concentrate on fuel switches for transportation. These switches may involve the use of novel vehicles like hydrogen fuel cells or the utilisation of existing vehicles which can use biofuels or cleaner fossil fuels. The techno-economic feasibility of the identified technologies is presented in the subsequent sections.

CNG/LNG Vehicles

CNG/LNG vehicles make use of natural gas as their primary fuel. Compressed natural gas is primarily used for passenger transport and light commercial vehicles while liquified natural gas is used for heavier duty transport applications.

A summary of the quantitative metrics is provided in the table below. A levelised cost per kilometre travelled was used as the most appropriate metric for comparing vehicle overall costs. There are already several projects within South Africa that have implemented CNG vehicles for public transport thus a lead time of less than 5 years is expected. The use of a CNG vehicle has an overall levelised cost of R3.01/km. When compared to a similar diesel vehicle approximately 31.08gCO_2e could be saved for every km driven.

Table 10 CNG/LNG Vehicle quantitative feasibility

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
CNG/LNG vehicle	R3.01/km	234.56gCO_2e/km	<5 years

The roll out of more natural gas-powered vehicles could generate jobs in two distinct areas. The roll out will require additional filling stations specifically for gas vehicles thus increasing the human capital required to fill the vehicles. Furthermore, there will be a market for retrofitting existing vehicles to accept natural gas as a fuel. This will create additional jobs in the workshops that will be required for these retrofits.

Vehicles are generally expected to have an operational lifetime between 10 and 15 years. In the case of natural-gas vehicles, there are still carbon emissions from the combustion of gas in the engine. There is some carbon lock-in that may occur with CNG/LNG vehicles compared to electric or hydrogen fuel cell vehicles.

Fuel Cell Vehicles

Fuel cell vehicles are powered using a hydrogen fuel cell. Hydrogen fuel cells are suitable for all vehicle applications including light duty passenger transport to heavy duty industrial use. The source of hydrogen is an important consideration for fuel cell vehicles.

For this analysis, two methods of hydrogen production are considered, steam methane reforming and low temperature electrolysis. Steam methane reforming (SMR) is the predominant technology used to produce hydrogen from natural gas. Low temperature electrolysis uses renewable energy like wind and solar to produce hydrogen through electrolysis.

A summary of the quantitative metrics is provided in the table below. A levelised cost per kilometre travelled was used as the most appropriate metric for overall costs of owning and operating the vehicle. Both technologies have a similar overall levelised cost of R5.5/km. Only the fuel cell vehicle using hydrogen produced through electrolysis will have an emission saving of approximately 237.85 gCO_2e/km driven.

Table 11 Fuel cell vehicle quantitative feasibility

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
Fuel cell vehicle - SMR	R5.53/km	None. More emission intensive than the baseline diesel vehicle	5-10 years
Fuel cell vehicle – electrolysis	R5.52/km	27.78gCO_2e/kWh	5-10 years

By 2030[32], the fuel cell vehicle and hydrogen industry in South Africa has the potential to generate up to 1 million employment opportunities across various stages in the value chain. These roles primarily require skilled labour with a range of skill sets. The majority of these jobs will require some level of tertiary education.

Biofuel blending

Biofuel blending is practiced extensively in the US and Europe where biofuel is blended with either petrol or diesel to reduce the greenhouse gas emissions from the fuel. Bioethanol is generally used for blending with mineral petrol while other biofuels such as fatty acid methyl esters, are blended with mineral diesel. The amount of biofuel present in these blends depends on the specification standard and the combustion technology used.

A summary of the quantitative metrics is provided in the table below. A levelised cost per kWh produced was used as the most appropriate metric for price comparisons of fuel production. Bioethanol can be produced with an overall levelised cost of technology of R0.56/kWh fuel produced while biodiesel has an overall levelised cost of technology of R0.44/kWh fuel produced. This technology is widely practiced globally and can be implemented quickly should sufficient biofuel feedstock be available. The lead time for the implementation of this technology would be less than 5 years.

Table 12 Biofuel blending quantitative feasibility.

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
Bioethanol	R0.56/kWh	30% emission savings[33]	<5 years
Biodiesel	R0.44/kWh	50% emission savings[33]	<5 years

A bioethanol plant with production capacity of 158 000 m^3/year could generate approximately 8 500 jobs while a biodiesel plant with production capacity of 113 000 m^3/year could generate approximately 20 000 jobs[34].

Stakeholder consultation with Sasol provided additional insights into the current state of biofuel blending in South Africa. Although biofuel legislation exists in South Africa, no one currently produces it on a large scale due to the limited economic viability. The biggest cost factor in producing biofuels remains the collection and transport of feedstock due to contaminants such as water and air. The technology to produce biofuels is well established thus the largest barrier remains the supply chain. For example, sourcing biomass feedstock is difficult as the production cannot compete with food production for farmland.

Sasol has transferable skills from existing processes for biofuel production, and the farming industry is well-equipped with skills to produce the required biomass feedstock. Small-scale production is already in place in the

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[32] Bezdek, R. 2019. The hydrogen economy and jobs of the future. *Renew. Energy Environ. Sustain.* 4, 1

[33] Biofuels Pricing and Manufacturing Economics. [Available Online]: https://www.energy.gov.za/files/esources/renewables/biofuelspricingandmanufacturingeconomics.pdf.

[34] DMRE. Biofuels Pricing and Manufacturing Economics

country, while the major barrier to commercial-level production seems to be cost-effectiveness. Sasol is looking into gasification of biomass to produce fuels, with a timeline for implementation in 2026. This project will form part of its largest initiative to use green hydrogen.

Green Hydrogen manufacturing

Green hydrogen refers to hydrogen that is manufactured through electrolysis powered by renewable energy such as solar or wind. Hydrogen produced through this process does not emit any greenhouse gas emissions and can therefore be considered a clean fuel. Only small-scale applications of hydrogen such as vehicles are considered in this report. Large scale manufacturing for industry is expected to have a much longer lead time and require significantly more capital.

A summary of the quantitative metrics is provided in the table below. A levelised cost per kWh produced was used as the most appropriate metric for the capital and operating costs of the fuel production. Green hydrogen manufacturing has an approximate overall levelised cost of R2.70/kWh H_2 produced[35]. Hydrogen plants take several years to complete. It is anticipated that the lead time for implementation of green hydrogen could take between 5 and 10 years for small-scale plants.

Table 13 Green hydrogen manufacturing quantitative feasibility.

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
Green hydrogen	R2.70/kWh	Baseline dependent but a report by the South African DTIC estimates a reduction of 540 million tCO_2e by 2050	5-10 years

The DTIC in their proposed commercialisation strategy[36] envisages 650 000 jobs could be created through the green hydrogen economy. These jobs would be in various parts of the green hydrogen value chain and would primarily be skilled roles. South Africa already has experience in some of the required areas due to the operation of Fischer-Tropsch plants in other industries.

Discussions with Sasol yielded several insights into the current state of the industry around manufacturing green hydrogen. They are aiming for a production cost of $2/kg H_2 however the current cost to produce hydrogen is much higher. The largest cost factors are water purification, electrolyser manufacture and renewable energy. To reduce these costs, technology learning rates are important, and larger capacities are required to drive the costs down. Government and grant funding is a useful tool to make the larger capacities viable and is currently employed in the US and Europe. Green hydrogen requires 100% renewable energy and this requires large renewable energy plants as well as batteries which remain a significant portion of the overall cost. As a result of these factors, small scale green hydrogen manufacture, such as at a filling station, is likely to become more economically viable before large scale manufacture.

The technologies to produce green hydrogen exists however due to the significant costs, estimating the lead time for implementation becomes difficult. Small scale hydrogen could be implemented is likely to occur sooner, before 2030. Large scale hydrogen will only become economically viable post 2030 with the mining and long-haul sectors likely to transition first followed by other industries.

The skills required to implement green hydrogen are well developed in other industries and would only require minor reskilling. The skills required to manufacture the electrolyser for example, are similar to existing skills within the well-established automotive manufacturing industry. The hydrogen manufacturing skills are well represented in other industries in which Sasol operates and would be easily transferable.

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[35] DSI. South Africa Hydrogen Valley Final Report. South Africa Hydrogen Valley Final Report (dst.gov.za)

[36] DTIC. 2022. Proposed South Africa Green Hydrogen Commercialisation Strategy

Hybrid electric vehicles

Hybrid electric vehicles are primarily internal combustion vehicles that use petrol or diesel as a main fuel source but has an additional battery and electric motor used as a supplementary drive system. The battery of the system is charged through a couple of different means depending on the type of hybrid electric vehicle. These vehicles include normal hybrid electric, hybrid plug-in, and battery electric vehicles. Normal hybrid electric vehicles use what is known as regenerative braking, which means that when the brakes are applied to lose momentum, that energy is captured and stored in a battery. This charge is then used to accelerate the vehicle from a stationary or almost stationary condition up to where the internal combustion engine takes over again as the main driving source. For hybrid plug-in vehicles, they possess a charging port as well to aid in fast charging of the battery and regenerative braking as well[37].

The electric motors allow for reduced greenhouse gas emissions, increased fuel economy, and fuel cost savings. It is estimated that compared to internal combustion vehicles, hybrid electric vehicles can have reduced emissions of up to 0,05 $kgCO_2e/km$. A table that summarises the quantitative metrics is provided in Table 14. Using a levelised cost per kilometre estimation as a measurement of the capital and operational costs of the hybrid electrical and plug-in electrical vehicles as the most appropriate quantification. Levelised costs of between 2.56 – 3.10 R/km for hybrid electrical vehicles and between 2.57 – 4.00 R/km for plug-in electric vehicles have been found. As these vehicles are already available globally the full implementation time is estimated to be between 1 – 4 years for the vehicles alone. Although, the longest lead times for establishing hybrid electric vehicles are due to the extraction and mining of the raw materials. Considering the mining of raw materials, feasibility studies of full affordable implementation, and large-scale manufacturing operations, the technology might require 4 – 20 years to be ready for full execution into society[38].

Table 14: Hybrid electric vehicle manufacturing quantitative feasibility.

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
Hybrid electric vehicles	2,56 – 3,10 R/km	The IEA analysis indicated that a full lifecycle estimation in GHG emissions to be in the order of 50% compared to conventional internal combustion vehicles[38].	immediate
Plug-in electric vehicles	2,57 – 4,00 R/km		Immediate

The implementation of hybrid electric vehicle technology does have potential for job creation as a variety of skills would be required, ranging from technical expertise to business management. Therefor the human capital requirements can be provided as a qualitative rather than quantitative assessment. Some of the skills required includes technical knowledge such as knowledge of electric motors, batteries, control systems and electronics, designing, development and manufacturing knowledge to focus on key design concepts like structural design and aerodynamics whilst always still being manufacturable. Although, since the vehicle manufacturing industries are already in place, the initial job creation area specific to hybrid and full electric vehicles would largely be attributed to the manufacturing of the battery cells used to power these vehicles.

Marketing, charging infrastructure, and regulatory expertise are also important positions for full implementation to hybrid vehicle technology. However, another consideration factor for the implementation of these vehicles are the preferences of individuals, as distribution to private owners can be influenced by the style, appearance, and status of these vehicles while work ability has influence over the business markets. These are also key factors to consider for the successful incorporation of these vehicles into the public domain.

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[37] UMass Amherst. 2018. *Hybrid, Hybrid Plug-In, and Battery Electric Vehicles*. The Center for Agriculture, Food and the Environment: Clean Energy Extension.

[38] IEA. 2022. Global EV Outlook 2022 Securing supplies for an electric future.

Cleaner Fuels

Sulphur is a naturally substance in both petrol and diesel as a result of the crude oil used for their manufacturing. It is released as sulphur dioxide or sulphur particulates into the atmosphere when these fuels are burned. Owing to the presence of sulphur in the feedstock used to manufacture fuels, the emission of sulphur is directly linked to the amount of sulphur in the fuels, thus reducing the fuel's sulphur directly reduces the sulphur in the atmosphere. These emissions can prevent the use of major technologies for controlling pollution, which is why

reducing sulphur emissions can have a significant impact on reducing air pollution[39]. There are several methods already used to combat this including, replacing diesel fuels with Ultra-Low Sulphur Diesel (ULSD), manufacturing cleaner fuels like hydrogen, CNG/LNG, or reducing the dependence on higher pollutants like coal by importing cleaner fuels from other countries.

Most of these methods are already implemented such as replacing diesel with ULSD and importing cleaner fuels, however these are not readily available everywhere in South Africa yet. There have been analyses of the potential GHG emission reduction of these methods. Importing cleaner fuels such as CNG/LNG rather than using coal in operations such as power stations and in manufacturing sectors can reduce the GHG emissions by about 30%. A reduction in sulphur emissions has also been seen in using ULSD and in the manufacturing of cleaner fuels, where and 80% reduction in SO_x gasses is achieved from cleaner fuels 2 manufacturing programmes such as ULSD.

A quantitative metric summary is provided in Table 15 below. Here a levelised cost per kWh produced would be a good approximation to measure the capital and operating costs for producing cleaner fuels. However, engaging with stakeholders might provide more insight on what the operating costs associated with these technologies might be. Although most of these methods are already in use in South Africa, the infrastructure requirements are not necessarily fully in place yet. It is estimated that to manufacture cleaner fuels and to make ULSD readily available throughout South Africa it would require 2 – 6 years and an investment cost of R40 billion. And although South Africa is importing cleaner fuels like CNG/LNG from other countries, it would require 5 – 7 years and an investment of R15 to R25 billion to implement as a constant replacement for other fuels such as coal. This being said, stakeholders such as Sasol has already made investments into these technologies to fast track their implementation[40].

Table 15: Cleaner Fuels manufacturing and importing quantitative feasibility

Technology	Capital investment cost of technology	Potential emissions implications	Implementation lead time
ULSD	R40 billion	98% less $PM_{2.5}$ 99.5% less BC 96% less NO_x	Immediate
Cleaner fuels 2 manufacturing	R40 billion	80% SO_x reduction	2 – 6 years
Import clean fuels	R15 billion – R25 billion	30% GHG reduction	5 – 7 years

The production of fuels at refineries can generate approximately 484 478 jobs within the refinery itself and about 221 580 jobs in retail departments as stated by SAPIA in 2017[41]. The human capital required for operating a cleaner fuels manufacturing plant and importation hub is however uncertain, which can be a point to raise when collaborating with stakeholders on the topic to determine what the human capital might be.

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[39] Blumberg, K.O. Walsh, M.P. Pera, C., 2003. *Low-Sulfur Gasoline & Diesel: The Key to Lower Vehicle Emissions*. The International Council on Clean Transportation (ICCT).

[40] Creamer, T. 2022. *Sasol prepares to ramp up decarbonisation capex from 2025*.

[41] Rabbipal, S. 2017. *Petroleum and Liquid Fuels Industry Contribution to the Economy*, SAPIA.

Industry

This section delves into the utilisation of cleaner fossil fuel technologies in various industries, with a specific emphasis on the cement and steel sectors. The primary cause of carbon emissions in these industries arises from process emissions during the production of these materials, coupled with the burning of fossil fuels necessary for the requisite chemical reactions to occur. The following sections will present an analysis of the identified technologies' techno-economic feasibility.

Cement Industry

Cement is an important product for the construction industry around the world, and as a result, the cement production industry has a significant source of global CO_2 emissions, making up approximately 2.4% of the global CO_2 emission from industrial and energy sources. [42]

The production of clinker, a fundamental ingredient of cement, involves subjecting calcium carbonate to a sequence of intricate chemical reactions in a rotary kiln, which results in the release of carbon dioxide. According to a report done by the IEA, the direct CO_2 intensity of cement production increased about 1.5% per year during 2015-2021. In contrast, 3% annual declines to 2030 are necessary to get on track with the Net Zero Emissions by 2050 scenario. Hence, focus on two key areas is required – reduction of the clinker-to cement ratio and deploying innovative technologies such as carbon capture systems and clinker made from alternative materials.

Table 16: Cement industry technologies quantitative feasibility

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
Carbon Capture Systems	CCS is likely to play a critical role in decarbonising cement, as it would enable the capture of process emissions. The levelised cost of such technology is expressed in section 4.4 of the report.	The potential emissions implication of CCS is expressed in section 4.4 of the report	<5 years
Clinker Alternative Materials	Palm Oil Clinker (POCP)		
	The cost of POC itself can be considered as "zero" as it is usually disposed of as a waste material. However, when 50% of cement is replaced by POC, the cost of concrete is reduced by 41%.[43]	The use of POCP for cement replacement at about 40% in a cement-lime masonry mortar will reduce the carbon footprint by 32%. [44]	Short term : > 1 year
	Recycled cement		
	Just like the previously mentioned case, the cost of recycled cement can also be regarded as "zero" since it is produced by reusing cement materials. However, using recycled materials reduces the costs of lightweight cellular concrete (LCC) by 34-41%. [45]	Recycled cement from demolished inorganic building materials and/or waste concrete powder (WCP) The CO_2 reduction by usage of recycled cement ranged from 0.06 million tons to 0.72 million tons from the total annual CO_2 emissions from cement production.[46]	Short term : > 1 year

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[42] Gibbs, M.J., Soyka, P., Conneely, D. and Kruger, M., 2000. CO_2 emissions from cement production. Good practice guidance and uncertainty management in National Greenhouse gas inventories, pp.175-182.

[43] Kanadasan, J. and Abdul Razak, H., 2015. Utilization of palm oil clinker as cement replacement material. Materials, 8(12), pp.8817-8838.

[44] Jagaba, A.H., Kutty, S.R.M., Hayder, G., Baloo, L., Noor, A., Yaro, N.S.A., Saeed, A.A.H., Lawal, I.M., Birniwa, A.H. and Usman, A.K., 2021. A systematic literature review on waste-to-resource potential of palm oil clinker for sustainable engineering and environmental applications. Materials, 14(16), p.4456.

[45] Sonawane, T.R. and Pimplikar, S.S., 2013. Use of recycled aggregate concrete. IOSR Journal of Mechanical and Civil Engineering, 52(59).

[46] Oh, D.Y., Noguchi, T., Kitagaki, R. and Park, W.J., 2014. CO_2 emission reduction by reuse of building material waste in the Japanese cement industry. Renewable and Sustainable Energy Reviews, 38, pp.796-810.

The human capital required for operating and implementing CCS is uncertain, however it is known that the set of skills required for such technology is in line with engineering, geology, pipeline workers, construction workers and project and employee managers. The development of carbon capture and removal technologies presents valuable prospects for not only preserving but also increasing employment opportunities that align with climate objectives and the demands of local communities.[47] More information regarding CCS technology and the relevant human capital and skills required is expressed in section 0 and 0 of this report. While the exact numbers of skills required to implement recycled cement is unknown, it is seen that utilising recycled materials is considered more labour-intensive than using conventional construction materials. Such material provides additional jobs for architects, engineers and workers who are involved in the manufacturing and construction process of recycled cement, as well as the recycling operations and collection. [48]

The reduction of CO_2 emissions in the cement industry requires multiple measures and compliance with specific requirements. These measures typically involve a lengthy timeline and are incorporated into the cement production process. Implementing such measures comes with a cost, according to the IEA, Carbon Capture, Utilisation and Storage (CCUS) applications do not all have the same cost. Looking specifically at carbon capture, the cost can vary greatly by CO_2 source, from a range of USD 15-25/t CO_2 for industrial processes producing "pure" or highly concentrated CO_2 streams (such as ethanol production or natural gas processing) to USD 40-120/t CO_2 for processes with "dilute" gas streams, such as cement production and power generation.[49] Furthermore, manufacturing recycled concrete aggregate is estimated to cost an average of R200 per tonne.[50]

Steel Industry

Steel is a crucial element in modern society's construction and engineering materials. However, the industry must address environmental and economic pressures by reducing its carbon footprint. Presently, the steel industry is a major contributor to carbon dioxide emissions, producing about 1.3 billion tons of steel and releasing over two billion tons of CO_2. [51] According to a report done by IEA, over the past decade, total CO_2 emissions from the iron and steel sector have risen, largely as a result of increases in steel demand and required energy for production.

To achieve short-term reductions in CO_2 emissions, the focus should be on improving energy efficiency and increasing the collection of scrap for greater use in production. However, for more significant emissions reductions, adopting new technologies such as biochar, hydrogen usage, and CCUS will be necessary. [52]

Table 17: Steel industry technologies quantitative feasibility

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
Carbon Capture Systems	CCS is likely to play a critical role in decarbonising cement, as it would enable the capture of process emissions. The levelised cost of such technology is expressed in section 4.4 of the report.	The potential emissions implication of CCS is expressed in section 4.4 of the report	<5 years
Biochar	The total price of biochar has been calculated according to	It is seen that if 2% to 10% biochar is added to a coal blend, 1% to 5% of CO_2 emission reductions in	<5 years

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[47] Peridas, G. and Schmidt, B.M., 2021. The role of carbon capture and storage in the race to carbon neutrality. The Electricity Journal, 34(7), p.106996.

[48] Muhaisen, A. and Ahlbäck, J., 2012. Towards sustainable construction and green jobs in the Gaza Strip. ILO.

[49] https://www.iea.org/commentaries/is-carbon-capture-too-expensive

[50] Ohemeng, E.A. and Ekolu, S.O., 2020. Comparative analysis on costs and benefits of producing natural and recycled concrete aggregates: A South African case study. Case Studies in Construction Materials, 13, p.e00450.

[51] Kundak, M., Lazić, L. and Črnko, J., 2009. CO 2 EMISSIONS IN THE STEEL INDUSTRY. Metalurgija, 48(3).

[52] https://www.iea.org/reports/iron-and-steel

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
	three different prices of biomass: [53] 1. R1700/tonne biomass = R6400/tonne torrefied biochar. 2. R1100/tonne biomass = R4600/tonne torrefied biochar. 3. R220/tonne biomass = R2400/tonne torrefied biochar.	the steel industry is achieved, which is equivalent to 0.02-0.11 ton CO_2/ton crude steel. [54]	

Similar to above, the human capital required for operating and implementing CCS is uncertain, however it is known that the set of skills required for such technology is in line with engineering, geology, pipeline workers, construction workers and project and employee managers. As for the human skills required for the production and implementation of biochar, such skill levels vary from labourers to plant operators, and engineers who have higher level of skills. There is an opportunity for creating employment for unskilled, semi-skilled and skilled workers. The absolute number of employees per biochar production plant is unknown, however it is dependent on the size and production of the plant and the processes that are required to produce biochar.[55]

To reduce CO_2 emissions in the steel industry, a variety of measures must be taken, and specific requirements must be met. These measures usually require a significant amount of time and must be integrated into the steel production process. Until now, there has been a significant deficiency in the research regarding the assessment of the complete expenses associated with the production and regeneration of biochar. On a global scale, the average cost of biochar's was approximately R50 per kilogram, with prices ranging from as little as R1.66 per kilogram in the Philippines to as much R163 per kilogram in the UK. [56] For CCS technologies, as a mentioned above, the technology costs can vary greatly by CO_2 source, from a range of USD 15-25/t CO_2 for industrial processes producing "pure" or highly concentrated CO_2 streams (such as ethanol production or natural gas processing) to USD 40-120/t CO_2 for processes with "dilute" gas streams, such as cement production and power generation.

Flue gas pollutant reduction

Flue gas pollutant reduction technologies is relevant to the cement and steel industry as it applies to all industries using fossil fuel as energy and is subject to SA pollutant emissions regulations, i.e. Oil and Gas industry, Iron and Steel, Cement, and Petrochemicals.

The technology includes removal of pollutants from flue gases and are referred to collectively as flue gas desulphurisation (FGD). This includes removal of sulphur oxides (SOX), nitrous oxides (NOx), ash particulates (PM) and other toxic compounds such as mercury. Flue gas desulphurisation (FGD) is prominently done through wet or dry scrubbing with limestone. Although this technology is not particularly relevant to this study, it's worth

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[53] Marcos, M.; Bianco, L.; Cirilli, F.; Reichel, T.; Baracchini, G.; Echterhof, T.; Rekersdrees, T.; Mirabile, D.; Griessacher, T.; Sommerauer, H. Biochar for a Sustainable EAF Steel Production (GREENEAF2); Final Report; Publications Office: Luxembourg, 2019.

[54] Safarian, S., 2023. To what extent could biochar replace coal and coke in steel industries?. Fuel, 339, p.127401.

[55] Konz, J., Cohen, B. and van der Merwe, A.B., 2015. Assessment of the potential to produce biochar and its application to South African soils as a mitigation measure. Environmental Affairs Department: Republic of South Africa: Pretoria, South Africa.

[56] Ahmed, M.B., Zhou, J.L., Ngo, H.H. and Guo, W., 2016. Insight into biochar properties and its cost analysis. Biomass and Bioenergy, 84, pp.76-86.

mentioning that incorporating it through retrofitting can have an impact on the plant's thermal efficiency, which may ultimately reduce its overall efficiency.

Carbon Capture Storage Systems

This section covers the application of carbon capture and storage technologies and carbon dioxide transport technologies. It focusses on the capture and transport of CO_2 to prevent it from being released into the atmosphere. Infrastructure that can facilitate CCS systems varies across countries and between individual refineries.[57] The CO_2 can be captured by a range of capture processes and technologies such as carbon capture systems from diluted or concentrated gas streams. Furthermore, the captured CO_2 can be transported by use of numerous carbon dioxide transport infrastructures. The techno-economic feasibility of the identified technologies is presented in the subsequent sections.

Carbon Dioxide (CO_2) Transport

The process of carbon dioxide (CO_2) transport typically entails conveying CO_2 through pipelines as a gas, superficial liquid, or subcooled liquid. Additionally, other modes of transportation such as road or rail tankers, or ships can be utilised for CO_2 transport. This process is integral to the carbon capture storage systems explained below and is therefore commonly included in their operational process.

The following table summarises the quantitative metrics used to evaluate the capital and operating costs of transporting CO_2, with particular emphasis on the levelised cost per tonne per km and the chosen mode of transportation. Such breakdown is expressed according to a 20Mtpa project. This technology is widely practiced globally, and South Africa has extensive experience in pipeline construction and transport. The lead time for this technology is the measure of needed transportation time for departure from plant to arrival at customer location. Such time is dependent on the mode of transport in which the CO_2 is being transported. For example, road has a lead-time of 48 hours, whilst minimum and maximum intermodal rails have a lead-time of approximately 60 and 264 hours, respectively. [58]

Table 18: Carbon dioxide transport quantitative feasibility

Technology	Levelised cost of technology					Potential emissions implications	Implementation lead time
Carbon Dioxide Transport[59]	Distance (km)	0-180	181-500	501-750	751-1500	Such information is not relevant for such technology	Road: 48 hours
	Onshore pipe (MR/km)	R35.89	R34.83 – R96.22	R34.47 – R51.60	R34.08 - R68.08		
	Offshore pipe (MR/km):	R53.15	R46.64 – 128.85	R46.59 – R69.74	R52.45 – R104.88		Minimum intermodal rail: 60 hours
	Ship with liquefaction (MR/km):	R81.26	R34.42 – R95.09	R26.34 – R39.43	R16.97 – R33.90		Maximum intermodal rail: 216 hours

The development of carbon dioxide transport infrastructure has the potential to create a significant number of jobs, particularly during the construction and operational phases. For instance, the construction of a 1600km

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[57] Johansson, D., Rootzén, J., Berntsson, T. and Johnsson, F., 2012. Assessment of strategies for CO_2 abatement in the European petroleum refining industry. Energy, 42(1), pp.375-386.

[58] Boere, S., 2010. Carbon Regulated Supply Chains: Assessing and reducing carbon dioxide emissions in transport at Cargill Cocoa & Chocolate (Doctoral dissertation, Master Thesis).

[59] Koornneef, J., van Breevoort, P., Hamelinck, C., Hendriks, C., Hoogwijk, M., Koop, K., Koper, M., Dixon, T. and Camps, A., 2012. Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. International Journal of Greenhouse.

pipeline could generate around 1,990 jobs, requiring a workforce of 5,240 to 5,680 individuals. [60] Additionally, according to the Great Plains and Rhodium Group, the average number of project-related jobs related to CO_2 transport infrastructure is expected to reach 16,600 annually between 2021 and 2035.[61]

Carbon dioxide transport infrastructure usually has a long-term timeframe depending on distance and project scale, pipeline and associated equipment construction can take 4 years or more. A global range of CO_2 transport cost has an estimated default value of around R110/tonne. There is a low overall risk of execution for this technology due to the fact that South Africa has large amount of experience in pipeline construction and transport.

Carbon Capture from Concentrated Gas Streams

Carbon capture from concentrated gas streams removes carbon dioxide from gas streams using chemical solvents such as mono-ethanolamine (MEA) in an absorber tower. The gas removed is considered “concentrated” when it has a high concentration of carbon dioxide in the stream, and the stream has a high proportion of carbon dioxide relative to the other gases or impurities in the stream. After being removed, such gas is then routed to a stripping tower where the CO_2 is released from the solvent and is captured.

The table below presents a summary of the quantitative metrics. It is seen that globally using CCS reaches 2.8 gigatonnes per annum of CO_2 being sequestrated by 2050. Given the current state of development in South Africa, there are presently no active carbon capture and storage operations. Nonetheless, this technology is commercially available, primarily utilised for enhanced oil recovery purposes, with a limited number of ongoing operations.[62] The implementation lead time is approximately 5 years.

Table 19: Carbon capture from concentrated gas streams quantitative feasibility

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
Carbon Capture from Concentrated Gas Streams	R911.5/tCO2	Globally, it is seen that using CCS technology can sequestrated 2.8 gigatonnes/annum of CO_2 by 2050 [63]	<5 years

The implementation of CCS technology not only supports the creation of new jobs during the construction and operation of facilities but also generates employment opportunities in the associated supply chain. According to the IEA's Sustainable Development Scenario, over 2,000 facilities will be required by 2050, necessitating at least 100,000 employees. The supply of new materials, equipment, and professional services will also create additional jobs.[64]

Carbon capture technologies typically have a long timeframe and have an estimated cost well below US$ 50 per tonne of CO_2. Moreover, according to a report by the IEA, carbon captured from industrial processes producing “pure” or highly concentrated CO_2 streams can from a range of US$ 15-25/t CO_2.[65] There is a relatively low risk associated with their implementation, given that the technology is already proven and available to a broad range of industries.

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[60] Essandoh-Yeddu, J.K., 2010. Energy-economic analysis of power plant carbon dioxide capture and pipeline transport in Texas Gulf coast (Doctoral dissertation, University of Cape Coast).

[61] Suter, J., Ramsey, B., Warner, T., Vactor, R., Noack, C. and Nowak, J., 2022. Carbon Capture, Transport, & Storage Final Report. DOE Office of Policy.

[62] Adu, E., Zhang, Y. and Liu, D., 2019. Current situation of carbon dioxide capture, storage, and enhanced oil recovery in the oil and gas industry. The Canadian Journal of Chemical Engineering, 97(5), pp.1048-1076.

[63] Orr Jr, F.M., 2018. Carbon capture, utilization, and storage: an update. Spe Journal, 23(06), pp.2444-2455.

[64] Townsend, A.L.E.X., Raji, N.A.B.E.E.L.A. and Zapantis, A.L.E.X., 2020. The value of carbon capture and storage (CCS). Global CCS Institute: Docklands, Australia.

[65] https://www.iea.org/commentaries/is-carbon-capture-too-expensive

Carbon Capture from Diluted Gas Streams

Carbon capture from diluted gas streams removes carbon dioxide from flue gases. Similar to above, such stream is considered “diluted” when the gas stream has a low concentration of carbon dioxide and has a smaller proportion of carbon dioxide relative to the other gases or impurities in the stream. In post combustion capture, the CO_2 is removed after combustion of the fossil fuel. Thereafter, the CO_2 is liquefied or compressed and stored within an underground or ocean infrastructure.

A summary of the quantitative metrics is provided in the table below. Whilst such technology is less effective as carbon capture from concentrated gas streams, it is seen that a carbon capture from the plant flue gas can reduce the net emissions per kWh by roughly 85-88%.[66] The implementation lead time is approximately 5 years.

Table 20: Carbon capture from diluted gas streams quantitative feasibility

Technology	Levelised cost of technology	Potential emissions implications	Implementation lead time
Carbon Capture from Diluted Gas Streams (Plant Flue Gas)	R911.5-1823.0/tCO_2	Capture system that removes CO_2 from the plant flue gas winds up reducing the net emissions per kWh by typically 85 to 88 percent.	<5 years

The implementation of CCUS systems, much like carbon capture from concentrated gas streams, has the potential to create over 100,000 jobs by 2050[67]. These job opportunities will be available throughout the value chain, including construction, operation, and the supply chain. However, the Council of Geoscience in South Africa has identified a shortage of capacity and skills for constructing their CCUS facilities. Although it is too early to quantify the exact number of jobs the project will create, this will be possible once sequestration begins. To address the skills and capacity shortage, the Council of Geoscience is collaborating with external stakeholders.

Carbon capture from diluted gas streams technologies usually have a short timeframe of 10 years and have an estimate cost of between US$ 40 – US$ 120 /tCO_2.[68] There is a medium overall risk of execution for this technology due to the fact that carbon capture storage (CCS) technology will be an additional cost to any industry, and they will have to absorb these costs which may result in the increased costs of goods and/or services being passed on to the consumer. According to the Council of Geoscience, costs is currently the major inhibiting factor. Furthermore, there were several other unsuccessful initiatives to demonstrate the technology at large scale.

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[66] Rubin, E.S., Mantripragada, H., Marks, A., Versteeg, P. and Kitchin, J., 2012. The outlook for improved carbon capture technology. Progress in energy and combustion science, 38(5), pp.630-671.

[67] Townsend, A.L.E.X., Raji, N.A.B.E.E.L.A. and Zapantis, A.L.E.X., 2020. The value of carbon capture and storage (CCS). Global CCS Institute: Docklands, Australia.

[68] https://www.iea.org/commentaries/is-carbon-capture-too-expensive

Associated Risks

The implementation and operation of the technologies considered in the techno-economic analysis in the previous chapter may have certain associated risks. Risks associated with the implementation of carbon pricing and related regulations is relevant to this study and discussed further for each of the sectors considered. The predominant risk here is the uncertainty in the carbon price in the future and the impact on the export of products from South Africa as well as the local viability of technologies.

Two different carbon prices will be considered in this analysis, the international carbon price and the South African Carbon Tax. The international carbon price pathway from the IEA will be used while the projected carbon tax rate for South Africa will be sourced from the most recent budget announcement. The international carbon price is considered as this pricing could have implications for exporting South African products, an example of this is the EU CBAM. The local carbon tax is considered due to the potential implications for the viability of the technologies in South Africa. Both of these could incentivise lower carbon technologies relative to their alternatives.

The IEA models several different pathways with differing carbon prices[69]. In their Announced Policies Scenario, emerging market economies with a net zero pledge can expect a carbon price of R547/tCO_2[70] (\$30/tCO_2) by 2030 increasing to R2 917/tCO_2 (\$160/tCO_2) by 2050. These prices increase when looking at the Net Zero Emissions by 2050 Scenario with prices of R1 641/tCO_2 (\$90/tCO_2) by 2030 and R3 646/tCO_2 (\$200/tCO_2) by 2050.

A study conducted by SANEDI assessing the business case for CCS implementation considered a different trajectory for the carbon price. This study has a low and high scenario for carbon prices, with the low scenario estimating \$23/tCO_2e by 2030 and \$40/tCO_2e by 2050. The high scenario estimates \$147/tCO_2e by 2030 and \$350/tCO_2e by 2050.

Another set of carbon price pathways was developed by the Network for Greening the Financial System (NGFS)[71]. These scenarios include current policies as well as a net zero trajectory and result in a range of carbon prices. By 2030, these prices range from \$10/tCO_2 to \$275/tCO_2, by 2050 the range of prices increases and ranges from \$10/tCO_2 to \$700/tCO_2. The full trajectories are indicated in Figure 5 below.

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[69] IEA. “World Energy Outlook”. 2022

[70] Exchange rate of R18.23/USD (Average rate at 21 Feb 2023)

[71] NGFS. Climate Scenarios for Central Banks and Supervisors. 2022

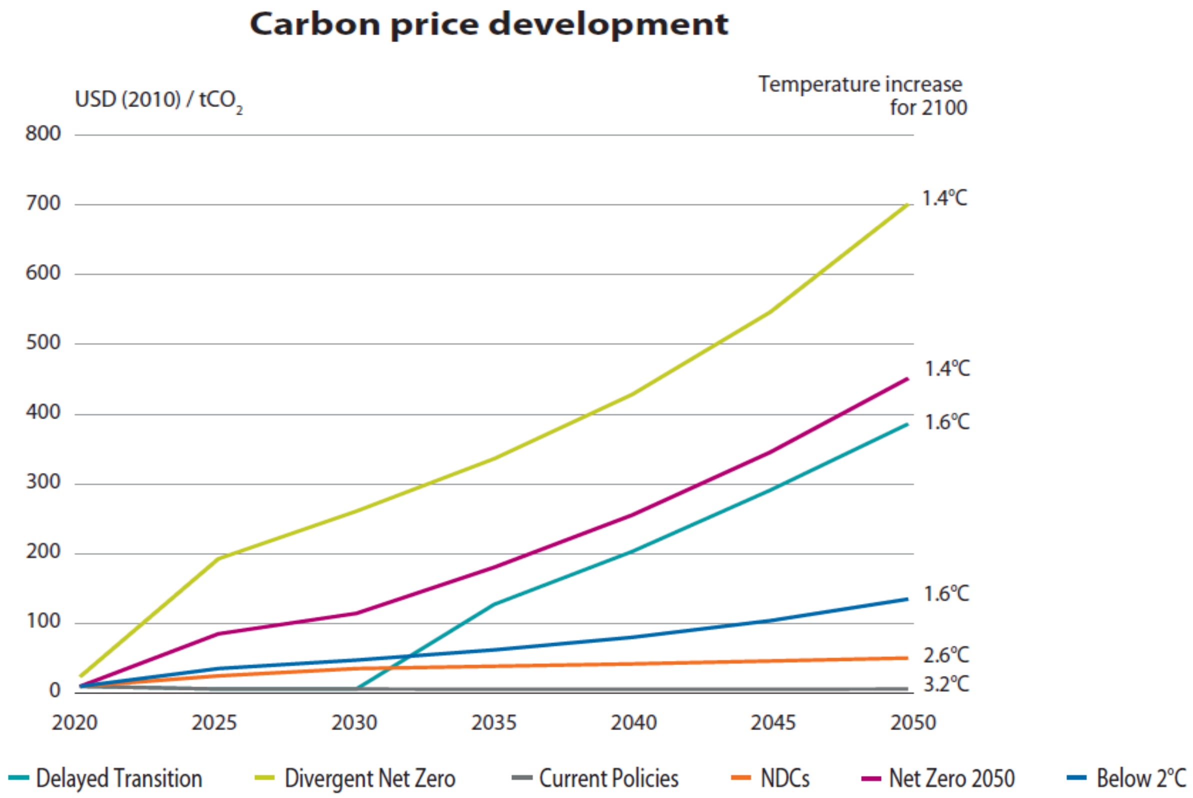

Figure 5 NGFS Carbon price scenarios

The projected values in the South African carbon tax system are aligned to expected international prices with the tax rate increasing from R144/tCO_2e in 2022 to R462/tCO_2e in 2030. This trend is expected to continue post 2030 with the South African tax rate following the international carbon price.

As highlighted by the above carbon price projections, there is significant uncertainty in the prices that could be expected. Particularly after 2030 where the divergence in the various pathways becomes greater. This divergence represents the greatest risk in terms of carbon pricing as it may directly impact the local viability of technologies as well as the exports from South Africa into the global market.

The EU is in the process of implementing regulations for a Carbon Border Adjustment Mechanism (CBAM) and will likely being a transition phase in October 2023[72]. Under this system, a price is applied to carbon emissions from products that enter the EU and are produced elsewhere. This serves to encourage cleaner industrial production in non-EU countries. The system aims to address the concept of carbon leakage where companies move production from the EU to countries with less stringent climate policies thus resulting in higher emissions for products that are used within the EU.

The CBAM will primarily focus on emission intensive industries such as cement, steel and hydrogen but will be expanded as it is phased in to cover 50% of emissions within the EU ETS. There is significant uncertainty in the price that will be applied in the CBAM as well as uncertainty as to what emissions will be covered by the system, i.e. whether it will only cover direct emissions or include indirect emissions as well.

Several technologies discussed in the analysis may not be directly impacted by the CBAM but will indirectly impact on companies exporting to the EU. Reductions in emissions through electricity generation or liquid fuel technologies will affect reduce the CBAM effects on these companies.

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[72] European Commission, Taxation and Customs Union. Carbon Border Adjustment Mechanism.

Additionally, carbon lock-in may also be a risk associated with certain technology options. Carbon lock-in is defined as the continued use of greenhouse gas emitting technologies while delaying the transition to carbon free options. This concept is relevant as several technologies considered in this assessment make use of fossil fuels and could cause carbon lock-in.

There may be additional risks that are harder to quantify particularly from a social aspect. These risks include risks such as social acceptability for example. The impact of the different technologies on jobs with that sector is another potential social risk that is difficult to quantify without a detailed jobs analysis.

Electricity Generation

The risk of carbon lock-in is relevant to installed coal generation capacity, i.e. the emissions from the Medupi and Kusile power plants.[73] Despite no new coal power plants planned for future builds, the emissions from the operation of Medupi and Kusile may result in lock-in for their operation lifetime unless CCS is implemented. The retrofit of CCS at these two plants will reduce the carbon lock-in risk by reducing the carbon emissions from the plants. Medupi and Kusile were designed to be CCS ready and as such this retrofit is feasible from a technical aspect. There is limited risk of carbon lock-in from the remainder of the existing coal plants in the country as most of these are scheduled for decommissioning before 2040.

Furthermore, the decommissioning of power plants could have an impact on those directly employed in the coal value chain. There is a risk related to the jobs within the coal value chain as these skills may not be directly transferable without some reskilling[74]. However, as discussed in section 0, the number of affected people is unknown given the role coal will continue to play within electricity generation in South Africa with the operation of Medupi and Kusile. It’s important that skills within the utility are developed and utilised in the long term at Medupi and Kusile.

The implementation of gas power generation has similar carbon lock-in risks to that of new build coal plants. These plants will likely emit greenhouse gases throughout their operational life resulting in carbon lock-in. The current IRP allows for additional gas generation to be added to the energy mix and when considered with the current gas capacity undergoing the necessary regulatory processes, the risk of carbon lock-in resulting from gas is high. The carbon lock-in risk reduces when CCS is implemented at these plants.

Additionally, there is a risk regarding the South African carbon tax. There is regulatory uncertainty as to whether Eskom will continue to be allowed to offset their carbon tax against the renewable energy premium post 2026. Both coal and gas power generation plants will be subject to carbon tax on the resulting emissions. A coal plant could have a potential carbon tax of about R370/MWh by 2030 while an open cycle gas turbine could pay approximately R300/MWh assuming an emission factor of 0.8tCO_2e/MWh for a coal plant and 0.65tCO_2e/MWh for gas. If the carbon tax aligns with the international projected carbon price, these values could increase by 2050 to R2 900/MWh and R2 400/MWh respectively. The risk from these prices reduces significantly when CCS is installed at these plants.

There is also a risk of high natural gas prices which will inevitably impact the execution of open cycle gas turbines. Natural gas prices are more susceptible to international markets and price fluctuations compared to coal.

Liquid Fuels

The liquid fuels sector is predominantly driven by vehicle fleets and technologies. Under the current carbon tax design in South Africa, these are only taxed if they make use of petrol or diesel derivatives as the carbon tax forms about 9c/litre of the fuel levy. This rate could increase with the projected international prices thus raising the cost

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[73] *Op cit.* IRP 2019.

[74] NBI. It all hinges on Renewables. 2021

to operate vehicles using these fuels. There is substantial risk and uncertainty for these technologies as these prices are uncertain.

The associated infrastructure to produce the various liquid fuels will also be subject to the carbon tax due to the emissions from the refining process. This adds a further risk to these technologies and the continued operation of the supporting infrastructure required.

Alternatively, when importing fuels rather than manufacturing them there are also associated risks. Not only would the construction of the required infrastructure to import fuels have tax payments and process emissions related to implementation, but it can also lead to economic implications. For example, upgrading existing power plants to support imported natural gas can require shutting down key power stations to upgrade them, which might not have a desirable outcome on power generation. This might also mean that if the primary source of natural gas is from imports, a monopolised economy might develop that can raise the price of electricity generated from it.

Evaluating the risks within the transport sector, fuel cell vehicles and green hydrogen production will have limited exposure to the carbon tax as they are zero emission technologies. The implementation of these technologies will generally reduce the exposure to carbon pricing structures like the carbon tax. However, any production infrastructure that does have emissions above the threshold may be subject to the carbon prices thus representing a risk to these technologies.

There is an additional risk with certain technologies resulting in carbon lock-in. Carbon lock-in occurs when certain technologies are implemented that generate emissions throughout their operational life. The investment in these technologies causes lock in for their lifetime. For example, the average vehicle has an operational lifetime of 10-15 years. The combustion of fuel in the vehicle results in emissions throughout its lifetime. Carbon lock-in may occur due to the natural gas vehicle, biofuel blending, hybrid electric and cleaner fuels technology options assessed in this report. Certain of these technologies will have less carbon lock in such as the hybrid electric and natural gas vehicles.

Although hybrid and plug-in electric vehicles do have lower operational emissions compared to that of regular internal combustion vehicles as these vehicles combust less fuel resulting in less carbon tax being paid. However, these vehicles do have larger production emissions associated with them as they require normal manufacturing processes similar to internal combustion vehicles as well as manufacturing processes for the batteries.

Some of the risks identified can be mitigated by switching to lower carbon emitting technologies thus resulting in fewer emissions that can be taxed. Supporting infrastructure for the identified technologies could ensure that the most energy efficient equipment is used as well as other mitigation options like renewable energy or CCS.

Industry

The most significant GHG emitting industries are the cement and steel with discussions surrounding flue gas pollutant reduction technologies. The main challenges facing these industries relate to government policies, regulations, and carbon pricing. In light of the Paris Agreement and the urgent need to lower emissions and encourage more sustainable industries, the cement and steel sectors are prime candidates for regulatory action.

The cement and steel industry are major contributors to the construction sector, with cement being the second-most consumed material after water. Due to the increasing demand, GHG reduction measures and policy actions are critical to reduce emissions from the cement, concrete and steel industries. General policy actions to reduce emissions from these industries include carbon pricing, public procurement to spur demand, financial support for R&D, and command-and-control measures. To encourage use of new lower-carbon materials or technologies, proposed mechanism are financial incentives.[75] Hence, utilising environmentally sustainable cement/steel materials or production processes that incorporate technologies such as CCUS systems or biochar can mitigate the risk of carbon pricing and regulatory actions. Nonetheless, any production infrastructure that surpasses the emissions threshold could be subjected to carbon pricing, thereby posing a risk to these industries.

Technologies that reduce flue gas pollutants will be less affected by the carbon tax as they are considered low-emission solutions. The implementation of such technologies typically reduces the exposure to carbon pricing frameworks, including the carbon tax. Nevertheless, production infrastructures that exceed the emissions threshold may still face the risk of being subject to carbon pricing, posing a potential challenge to these technologies.

The adoption of certain technologies in the cement and steel industry may result in carbon lock-in where emissions are generated throughout the operational life of the technology. This could pose a significant risk as companies may be locked into using high-emitting technologies for the duration of the technology's life cycle, whereby the transition to low carbon alternative input materials, fuels, processing units, heat generators, etc., can be delayed by decades.

Lastly, when looking at the cement industry and the implementation of palm oil clinker, the social risks related to deforestation for palm oil plantations needs to be discussed. With the increase in the world population and the demand for renewable energy, specifically in efforts to reduce greenhouse gas (GHG) emissions, a greater need for oilseeds has been created. This has led to the expansion of oilseed farming, particularly in tropical countries that produce oil palm.[76] The expansion of palm oil plantation is under intense public scrutiny as it causes tropical deforestation and biodiversity loss in these tropical countries. Therefore, if the utilisation and integration of palm oil clinker as an alternative is being considered, it is crucial to analyse and discuss the potential social and reputational challenges that may arise from it.

The risk identified can potentially be mitigated by switching to lower carbon emitting production technologies therefore resulting in fewer emissions that can be taxed. Supporting infrastructure for the identified technologies could ensure that the most energy efficient equipment is used as well as other mitigation options like CCS. Furthermore, to mitigate the social risk associated with the production of palm oil clinker, the use of other clinker alternative materials should be investigated. For instance, substitutes such as calcined clay, pozzolans, fly ash and slag.

Carbon Capture Storage Systems

The implementation of carbon capture storage systems, particularly for CO_2 capture from power plants and industries with high point source emissions, presents several challenges and concerns related to the storage of large amounts of CO_2 underground. These challenges include potential liabilities and risks, which must be addressed to ensure widespread public acceptance of these systems. [77]

The risks associated with the storage is often considered more important than those associated with the capture. Although attempts have been made to address the issue, concerns about the possibility of leaks are frequently raised in conversations about the underground storage of significant amounts of CO_2. This presents a significant danger. Leakage rates are believed to range from 0.00001% to 1% of the CO_2 that is stored. However, with careful injection design and management it should be possible to ensure long-term safe storage.[78] CO_2 leakage is greatly

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[75] Busch, P., Kendall, A., Murphy, C.W. and Miller, S.A., 2022. Literature review on policies to mitigate GHG emissions for cement and concrete. Resources, Conservation and Recycling, 182, p.106278.

[76] Naidu, L. and Moorthy, R., 2021. A review of key sustainability issues in Malaysian palm oil industry. Sustainability, 13(19), p.10839.

[77] Mohammad, M., Isaifan, R.J., Weldu, Y.W., Rahman, M.A. and Al-Ghamdi, S.G., 2020. Progress on carbon dioxide capture, storage and utilisation. International Journal of Global Warming, 20(2), pp.124-144.

[78] Blunt, M., 2010. Carbon dioxide storage. Grantham Institute Briefing Paper, 4.

dependant on the permeability of the geological structure and its faults. [79] By use of pressure diffusion, dissolution, precipitation and capillary trapping the risk of leakage can be reduced. Whilst it is evident that there are risks associated with carbon capture storage systems, the various risks and uncertainties associated with its deployment have not yet been addressed clearly.

There are also risks associated with the transport of CO_2, where because of it being denser than air, it can collect underground with a risk of asphyxia[80] at high concentrations. This can be mitigated with appropriate design and monitoring and careful siting. [81]

Although the possibility of CO_2 leakage is a significant concern associated with this technology, the use of natural and engineered barriers in the storage systems ensures the long-term permanence of the captured CO_2. Therefore, it can be argued that the system will effectively trap CO_2 for an extended period, and the risk of non-permanence is negligible.

Additionally, these technologies are expected to have a minimal impact from the carbon tax as they are recognised as low-emission solutions. By incorporating such technologies, industries and power plants can generally reduce their exposure to carbon pricing frameworks, including the carbon tax. Nonetheless, any production infrastructure that exceeds the emissions threshold may be subject to carbon pricing, thereby posing a risk to these technologies.

Possible mitigations against the risks identified above could be ensuring proper infrastructure, development and management of CCS systems to prevent leakage from occurring. The permeability of the geological structure and its faults must be investigated, and the use of pressure diffusion, dissolution, precipitation and capillary trapping can help reduce such risk. Additionally, to reduce the risk of carbon tax, the switch to lower carbon emitting production technologies will result in fewer emissions that can be taxed.

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[79] Mohammad, M., Isaifan, R.J., Weldu, Y.W., Rahman, M.A. and Al-Ghamdi, S.G., 2020. Progress on carbon dioxide capture, storage and utilisation. International Journal of Global Warming, 20(2), pp.124-144.

[80] Asphyxia occurs when there is a lack of oxygen available underground or in the storage system.

[81] Blunt, M., 2010. Carbon dioxide storage. Grantham Institute Briefing Paper, 4.

Conclusion

The assessment of feasible technology options that will allow for the transition to cleaner fossil fuels in South Africa consisted of analysing the qualitative and quantitative metrics of the viable technology options listed in Table 6. The assessment provided a more extensive analysis based on the technologies' emission reduction potential, cost implications, implementation lead-time, required human capital and risks associated with each technology. These metrics can be used by Sanedi to identify which technologies are most feasible when conducting further research or investment in the transitioning to lower GHG emission energy use in South Africa.

As the technologies listed in Table 6 have been identified as possible alternatives for their already implemented equivalents, they have emission reduction potential. This was the initial identification criteria used to eliminate some of the technologies along with the availability of the technology before conducting in-depth research on each of the remaining technologies. The research then focussed more on the cost implications each technology will have, and how long it would take to be operational. These criteria were then used as a sorting mechanism for the technologies identified which are listed in Table 21.

Table 21: Feasible Technology Options Summary

Technology	Lead Time	Cost Implications
Hybrid Electric Vehicles	Immediate	R3,10/km
Plug-in Electric Vehicles	Immediate	R4,00/km
Ultra-Low Sulphur Diesel	Immediate	-
Biodiesel	< 5 Years	R0,44/kWh
Bioethanol (Petrol Biofuel Blend)	< 5 Years	R0,56/kWh
Carbon Capture of Concentrated & Diluted Gas Streams	< 5 Years	-
CNG/LNG Vehicles	< 5 Years	R3,01/km
OCGT – Biodiesel	< 5 Years	R238.21/MWh
OCGT – Diesel	2 Years	R1 456.65/MWh
OCGT – Gas	2 Years	R1 687.37/MWh
Cleaner Fuels 2 Manufacturing	2 – 6 Years	-
Flue Gas Pollutant Reduction (Plant Retrofit)	2,6 Years	R471.55/MWh
CCGT	3 Years	R993.08/MWh
Super Critical	3,5 – 6 Years	R1 505.21/MWh
Ultra-Super Critical	3,5 – 6 Years	R812.88/MWh
Import Clean Fuels	5 – 7 Years	-
Fuel Cell Vehicles	5 – 10 Years	R5,53/km
Green Hydrogen Manufacturing	5-10 Years	R2,70/kWh

As seen in Table 21 some of the technologies have already been implemented into the public sector, however this does not necessarily mean that they would have the biggest impact on climate change nor on the economy. For example, hybrid electric vehicles are already available and does have a positive effect on emission reductions, but as only a few vehicle models are currently available, individual consideration criteria like status, over all look and branding can negatively impact the marketing of such vehicles, decreasing its emission reduction potential and increasing its cost implications. For this reason, risk assessment was another key evaluation point to consider each technology on, in order to give insight into the feasibility of each technology.

One of the major risks involved in implementing new technologies into various sectors would be job security. Implementing new manufacturing or operational processes would create job opportunities but it is also important to consider whether these opportunities would require specifically highly skilled career paths or would it open a broad range of career paths. Another consideration is whether old positions would be able to transition into the new positions or if they would then have to be phased out to make way for new positions.

Appendix A. Technology Summary from Phase I

Table 22: Technology summary from Phase I: Coal Power Value Chain

Technology	Description	Cost	Regulation	Timeframe	Emission reduction potential	Infrastructure required (information provided)	Does the tech meet the criteria?
Steam Technology: Super Critical (SC)	Supercritical boilers are once through steam generators that don't require a steam drum to separate water and steam.	\$\$\$ R37 000/kW		Short Term	**Acceptable** CO_2 Emissions between 800 -880 gCO_2/kWh compared to >880 gCO_2/kWh	Minor	**Yes** - The technology relates to fossil fuels. - Commercially operational - Proved technology, both locally and internationally
Steam Technology: Ultra Super Critical (USC)	Ultra-Supercritical boilers are once through steam generators that don't require a steam drum to separate water and steam	\$\$\$ 10% higher than SC		Short Term	**Good** CO_2 emissions 740 – 800 gCO_2/kWh	Minor	**Yes** - The technology relates to fossil fuels. - Commercially operational - Proven technology internationally
Steam Technology: Advanced Ultra Super Critical (AUSC)	AUSC plants are designed to operate in the range of 700 to 760 °C and 35 to 36 MPa. The plants are envisaged to be the highest efficiency coal plants	\$\$\$ Higher than USC		Short Term	**Good** CO_2 emissions 670 - 740 gCO_2/kWh	Minor	**No** - The technology relates to fossil fuels. - Not commercially proven. - Only pilot plants and programmes.
Combustion Technology: Circulated Fluidised Bed (CFB)	In CFB plants, coal and limestone are fed into a bed of hot particles suspended in turbulent motion (fluidised) by combustion air, blown in through a series of distribution nozzles.	\$\$ 30% higher than pulverised coal SC plant with no FGD		Short term	Acceptable	Minor	**Yes** - The technology relates to fossil fuels. - Commercially operational - Proven technology internationally - Compatible with SC or USC plants - Handles flexibility in feedstock and poorer quality coal.
Combustion Technology: Integrated	Coal is partially oxidised in air or oxygen at high pressure to produce a	\$\$\$		Short term	Good CO_2 emissions 670 to 740 gCO_2kWh	Minor	**No** - The technology relates to fossil fuels.

Technology	Description	Cost	Regulation	Timeframe	Emission reduction potential	Infrastructure required (information provided)	Does the tech meet the criteria?
Gasification Combined Cycle Coal Power Plant (IGCC)	syngas, which after treatment is burnt to generate electricity.	68% more than SC plant- R62,000/kW					- Not commercially proven. - Complex to manage- Sasol Secunda gasifiers complex.
Combustion Technology: Underground Coal Gasification	UCG involves burning (reacting) coal in situ/in-seam, using a mixture of air or oxygen, possibly with some steam, to produce a syngas,	$$		Medium Term	Good	Major	**No** - The technology relates to fossil fuels. - Not commercially proven. - Uncertainties and unknown timeline

Table 23: Technology summary from Phase I : Gas Power Value Chain

Technology	Description	Cost	Regulation	Timeframe	Emission reduction potential	Infrastructure required (information provided)	Does the tech meet the criteria?
Open Cycle Gas Turbines (OCGT): Diesel	Open cycle generates electricity from gas turbine combustion	$ (needs further details)		Short Term	**Good** Less than coal fired power stations	Major	**Yes** - The technology relates to fossil fuels. - Commercially operational - Mature technology **but requires gas infrastructure**
Open Cycle Gas Turbines (OCGT): Gas	Open cycle generates electricity from gas turbine combustion	$ 132 MW plant- R9,000 /kW		Short Term	**Good** CO_2 emissions are 28% less diesel, 50% < coal fired	Major	**Yes** -The technology relates to fossil fuels. -Commercially operational -Mature technology **but requires gas infrastructure**

Technology	Description	Cost	Regulation	Timeframe	Emission reduction potential	Infrastructure required (information provided)	Does the tech meet the criteria?
Closed Cycle Gas Turbines (OCGT): Gas	Closed Cycle Gas Turbines use combined cycle recovers heat from the turbine exhaust in a heat recovery steam generator	$ 132 MW plant- R10,000 /kW		Short Term	**Good** CO_2 emissions are 28% less diesel, 50% < coal fired	Major	**Yes** -The technology relates to fossil fuels. -Commercially operational Mature technology **but requires gas infrastructure**

Table 24: Technology summary from Phase I : Liquid Fuels

Technology	Description	Cost	Regulation	Timeframe	Emission reduction potential	Infrastructure required	Does the tech meet the criteria?
CTL to GTL	Switch feedstock for CTL plant to GTL						Yes - The technology relates to fossil fuels. - Commercial operation. - Sasol has already implemented this feedstock switch at its CTL plant.
CNG/LNG vehicle	Convert diesel vehicle to CNG	$		Short term	Acceptable	Significant	Yes - Fuel switch between fossil fuels . - Commercially ready.
Fuel Cell Vehicle	H2 fuel cell vehicles	$$		Medium Term	Excellent	Major	Yes - Fuel switch from fossil fuel to hydrogen. - Pilot demonstration phase
Biofuel blending	Blend biofuel with petrol and diesel	$$	Regulation in place	Medium Term	Good	Major	Yes - Fuel blending with fossil fuels. - Commercially Ready
Power2X Fuels	Green H2 to make other fuels such as SAF	US$5-8/kgH2 $$$		Long Term	Excellent	Major	Yes - Fuel switch from various fossil fuels to hydrogen derived fuels. - Research and Development phase
Green hydrogen manufacture	Green H2 production	US$5-8/kgH2 $$$		Long term	Excellent	Major	Yes - Value chain for fuel switch from various fossil fuels to hydrogen. - Research and Development phase
Hybrid electric and full electric transition	Shift towards hybrid or full electric vehicles	$$		Medium term	Excellent	Significant	No - Full electric vehicles are not directly fossil fuel related.
Use ultra-low sulphur diesel	Change fuel in trucks to 10ppm sulphur diesel (ULSD 10ppm)	$$		Short Term	Low	Minor	Yes - Fossil fuel related - Commercially ready
Cleaner Fuels 2 Manufacturing	Lower sulphur specification for petrol and diesel to 10ppm	$$$		Short Term	Low	Minor	Yes - Fossil fuel related - Commercially ready
Import clean fuels	Import clean fuels and shut down refineries in SA	$$		Short Term	Low	Major	Yes - Fossil fuel related - Commercially ready

Table 25: Technology summary from Phase I : Industry

Technology	Description	Cost	Regulation	Timeframe	Emission reduction potential	Infrastructure required (information provided)	Does the tech meet the criteria?
Flue Gas Pollutant Reduction	Removal of pollutants SOx, NOx, fly ash, mercury, from flu gases, using various chemical processes. For NOx – Staged air and fuel mixing combustion. Also post combustion Selective Catalytic Reduction (SCR). For SOx – Flue Gas Desulphurisation (FGD) through wet or dry scrubbing with limestone. Particulates – Electrostatic precipitators and fabric filter. Mercury – Fabric filters and injection of activated carbon.	$	Regulations are in place	Short Term Less than 10 years	Low Minor or no reduction in GHG	Minor Little to no supporting infrastructure required	**Yes** - Commercially Available technology; - Low risk of execution; - Is related to Fossil fuels
Carbon Capture from Concentrated Gas Streams	CO_2 is removed from gas streams using chemical solvents such as mono-ethanolamine (MEA) in an absorber tower, then routed to a stripping tower where the CO_2 is captured. The lean solvent is recycled to the absorber tower. If the CO_2 has a high concentration in the feed stream, the process is more efficient and plant size is minimised because other inert gases like nitrogen does not take up space and energy.	$$ Cost estimated to be well below US$ 50 /tCO_2	Is Regulated by the International Energy Agency (IEA) and CDM	Short Term Less than 10 years	Excellent Carbon free emission	Minor Little to no supporting infrastructure required	**Yes** - Commercially Available technology; - Low risk of execution; - Is related to Fossil fuels
Direct Air Carbon Capture	Large fans draw in air from the atmosphere and via two technology	$$$		Long Term	Excellent Carbon free emission	Significant	**No** - Pilot programs operational;

	approaches, removes CO_2 from the atmosphere. Liquid DAC systems pass air through chemical solutions (e.g., hydroxide solution) which removes the CO_2. The system regenerates the solvent and releases the CO_2 by applying high-temperature heat while returning the rest of the air to the environment. Solid DAC technology uses solid sorbent filters that chemically bind with CO_2. When heated and placed under a vacuum, they release the concentrated CO_2, which is then captured for storage or use.	Capture cost, from US$ 100 to US$ 1 000 / ton		Greater than 20 years		Project requires supporting infrastructure for execution	- High risk of execution;
Carbon Capture from Dilute Streams	Technologies (membranes, solvents, sorbents, and cryogenic) developed for coal and natural gas based systems can be adapted for most dilute industrial sources. In post combustion capture, the CO_2 is removed after combustion of the fossil fuel. CO_2 is captured from flue gases.	$$ Cost estimated to be well between US$ 50 – US$ 100 /tCO_2	Is Regulated by the International Energy Agency (IEA) and CDM	Short Term Less than 10 years	Excellent Carbon free emission	Significant Project requires supporting infrastructure for execution	**Yes** - Commercially available; - Medium risk of execution; - Is related to fossil fuels
Conversion to gas firing	Coal feed kilns can be converted into natural gas firing, or gas is co-fired with coal. Gas burner technology is mature. The lower carbon intensity of gas provides a lower carbon footprint.	$		Short Term Less than 10 years	Good >50% reduction in GHG emissions (Natural gas CO_2 emissions are 20% lower than sub-bituminous coal. For higher carbon content coal, the	Major Extensive high cost infrastructure required for execution	**Yes** - Commercially available; - Medium risk of execution; - Is related to fossil fuels

					natural gas emissions are 36 to 40% lower)		
Green Hydrogen	Green hydrogen is produced via water electrolysis using renewable energy sources such as solar or wind. If the hydrogen is combined with natural gas or pulverised coal it can reduce CO_2 emissions.	$$$	ISO standards are in place but no official South African Regulations as of yet – The South African Hydrogen Society Roadmap establishes a national framework for hydrogen policies and actions	Long Term Greater than 20 years	Excellent Carbon free emission	Major Extensive high cost infrastructure required for execution	**No** - In Research & Development phase; - High risk of execution; - Is not related to fossil fuels (Renewable energy)
Carbon Utilisation	Technology involves the capture of CO_2 by processes described and subsequently processed via chemical and/or commodities and products. This will help to offset the cost of carbon capture. Can be used in concrete curing. Mineralised the injected CO_2.	$$$		Long Term Greater than 20 years	Excellent Carbon free emission	Major Extensive high cost infrastructure required for execution	**No** - In Research & Development phase; - High risk of execution; - Is not related to fossil fuels (Renewable energy)

Table 26: Technology summary from Phase I : Carbon Capture Storage Systems

Technology	Description	Cost	Regulation	Timeframe	Emission reduction potential	Infrastructure required (information provided)	Does the tech meet the criteria?
Coal Power Plant with Carbon Capture and Storage	CO_2 is captured via amine chemical processes, either post, pre combustion or through oxyfuels.	$$ SC plant with CCS is 2.3x cost of SC pant without CCS – R86,000/kW (2017). Excludes CO_2 pipeline transport and storage site.	Currently legislative guidance for CCS technology is lacking. However, as indicated in both the World Bank Report (2010), as well as in an international survey undertaken by Baker & McKenzie for the period November 2010 to June 2011, there have been several recent amendments	Medium Term - capture technology can be included in the design and construction as per other coal plants. However, the transportation and storage engineering and construction may add a few years to this	**Excellent** CO_2 capture rate 85 to 95%	The site requires suitable geology to ensure CO_2 is securely trapped underground. However, there are limited coal power plants with CCS, because of high cost involved. Major enabling infrastructure is required.	**Yes** - technology is well understood and explored -low risk for execution - is related to fossil fuels.

			and/or refinements to existing South African legislation and regulations that are relevant to CCS technology. These changes are on-going and include: [82] 1. Changes to relevant South African National Standards for the transport of hazardous / dangerous substances (CO_2 falls under the definition of "class 2 dangerous goods" in terms of South African National Standard (SANS 10228:2006 4th Edition). 2. During June 2010, the Department of Environmental Affairs published a new suite of environmental impact assessment (EIA) regulations and listed activities (GN R543, 544, 545, 546 and 547 of 18 June 2012, as amended). These were published with an aim of streamlining the authorisation application process and the activities required to be authorised prior to commencement. 3. In July 2011 the Department of Environmental Affairs published a number of	timeline due to uncertainty inherent in this design.			
Direct Air Carbon Capture (DACC)	Removal of CO_2 from the air by use of large fans that draw in air from the atmosphere and via two technology approaches – Liquid DAC and Solid DAC systems.	$$$ Capture cost, from US$ 100 / ton to US$ 1 000 / ton		Long Term - depending on the rate of deployment, which can accelerate through supportive policies and market development, costs for DAC could fall to competitive levels over the next 10 to 15 years.	Excellent	There is a significant enabling infrastructure required. Liquid solvent systems require 900 degrees C to release captured CO_2, whereas solid sorbent systems require 80 degrees C to 120 degrees C.	**No** - Technology is operating in very small scale - is prohibitively expensive and energy intensive. - has a high risk for execution
Carbon Capture from Concentrated Gas Streams	Carbon dioxide is removed from gas streams using chemical solvents such as mono ethanolamine (MEA) in an absorber tower, then routed to a stripping tower where the CO_2 is released from the solvent and the CO_2 is captured. The lean solvent is recycled to the absorber tower.	$$ The cost of carbon capture from concentrated sources is much lower than from diluted sources. The cost is estimated to be well below US$ 50 per ton CO_2.		Short Term - design and construction will be 2 to 3 years.	Excellent	Minor to insignificant enabling infrastructure is required. Carbon dioxide is removed from concentrated gas streams using chemical solvents such as mono-ethanolamine (MEA) in an absorber tower, then routed to a stripping tower where the CO_2 is released from the solvent and the CO_2 is captured. The CO_2 is transported to a geological storage site and is pumped underground.	**Yes** – Technology is already proven and offered to many industries - Related to fossil fuels - has a low risk for execution.
Carbon Capture from Dilute Streams	Carbon capture of CO_2 that has been removed from dilute flue gas stream sources and stored	$$ The cost of carbon capture from dilute CO_2 sources is		Short term - capture technology can be included in the design and construction or	Excellent	Significant enabling infrastructure is required. Carbon dioxide is removed from diluted flue gas streams using	**Yes** – The post-combustion capture has been demonstrated on full-

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[82] Glazewski, J., Gilder, A. and Swanepoel, E., 2012. Carbon Capture and Storage (CCS): Towards a regulatory and legal regime in South Africa. *Institute of Marine and Environmental Law (IMEL) and African Climate and Development Initiative (ACDI), University of Cape Town: Cape Town, South Africa*.

	in underground or ocean structures.	higher than from concentrated streams and range US$50 to above US$ 100 per ton CO_2 captured.	draft waste regulations and norms and standards for comment. These include but are not limited to the Draft Waste Classification and Management Regulations (GN 435 of 1 July 2011) and the Draft National Norms and Standards for the storage of Waste (GN 436 of 1 July 2011). 4. Proposed amendments to the National Environmental Management: Integrated Coastal Management Act. 5. Integrated Resource Plan 2010 – provides for electricity planning up to 2030.	retrofitted. However, the transportation and storage engineering and construction may add a few years to this timeline due to uncertainty inherent in this design.		chemical solvents in an absorption column, then routed to a regeneration column where the CO_2 is released from the solvent. The CO_2 is then compressed or liquified and sequestrated into an ocean or underground structure.	scale power and industry plants. - it is related to fossil fuels. – has an excellent emission reduction potential. However, it is important to note that the technology has a medium risk for execution and demonstration of the technology at large scale is lacking.
Carbon Storage	Carbon Storage is geo-sequestration that involves injecting CO_2, generally in supercritical form to depths greater than about 800 meters. The high pressure keeps the injected CO_2 supercritical.	Additional information required with regards to costs associated with carbon storage technology.		Long Term - the CGS pilot project aims to start injections in 2 years' time where after monitoring of at least 2 years will be required to determine the viability of continuing with commercialisation at the pilot site. The timeline and cost for CCS can only be determined based on the results of the pilot project.	Excellent	Major enabling infrastructure is required. The suitability of any particular site depends on many factors, including proximity to CO_2 sources and other reservoir-specific qualities such as volume, porosity, permeability, and potential for leakage.	**No** - there is a high execution risk - major infrastructure and costs required.
Carbon Dioxide (CO_2) Transport	Carbon Dioxide Transport is the transport of CO_2 through pipelines in the form of a gas, a supercritical fluid or in the subcooled liquid state..	Costs for pipeline construction vary, depending upon length and capacity, servitude costs, whether the pipeline is onshore or offshore, the terrain it should cover and injecting and delivery infrastructure.		Long Term - depending on distance and project scale, pipeline and associated equipment construction can take 4 years or more.	Such information is not relevant to this technology.	Major enabling infrastructure is required. Pipeline infrastructure would be required to gather and transport CO_2 to large reservoirs not co-located to the major CO_2 sources . Such infrastructure will add considerable cost to CCs projects.	**Yes** – South Africa has experience in pipeline construction and transport. -The technology is related to fossil fuel. -there is low risk for execution. However, such technology is not

							commercially viable without financial intervention or incentive.

Appendix B. Technology Summary for Phase II

Table 27: Quantitative feasibility of viable technologies

Technology	Cost implications[83]	Potential emissions implications	Implementation lead time
New Coal Power Plants			
SC	R 1 505.21/MWh (levelized cost)	Up to 180 kg CO_2/MWh reduction compared to sub-critical plants	3,5 – 6 years[84]
USC	R812.88/MWh (levelized cost)	Up to 300 kg CO_2/MWh reduction compared to sub-critical plants	3,5 – 6 years[18]
CFB- on SC	R21.02/ MWh (additional marginal cost)	Emissions reduction of the technology fitted to	5-10 years
CFB- on USC	R25.00/ MWh (additional marginal cost)	Emissions reduction of the technology fitted to	5-10 years
Retrofitting coal power plants			
Retrofitting SC/USC with CCUS	R3 158.64/MWh (additional marginal cost)		
New Gas Plants (OCGT)			
CCGT	R993.08/MWh (levelized cost)	107-126 gC/kWh	3 years
OCGT- Diesel	R1 456.65/MWh (levelized cost)		2 years
OCGT- Gas	R1 687.37 /MWh (levelized cost)	0.25 kg CO_2/kWh	2 years
Fuel blending			
OCGT- Biodiesel	R238.21/MWh (additional marginal cost)		< 5 years
Liquid Fuels			
CNG/LNG vehicle	R3.01/km (levelized cost)	66.5gCO_2e saved/kWh of fuel used	<5 years
Fuel cell vehicle - SMR	R5.53/km (levelized cost)	None. More emission intensive than the baseline diesel vehicle	5-10 years
Fuel cell vehicle – electrolysis	R5.52/km (levelized cost)	255.9gCO_2e saved/kWh of fuel used	5-10 years
Bioethanol	R0.56/kWh (additional marginal cost on diesel engine)	30% emission savings	<5 years

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[83] The cost implications for these technologies consolidates the direct costs of the technology. For example, the levelised cost of energy in the case of power generation or the cost per kilometre driven for a new vehicle type.

[84] Lee, HC. Lee, EB. Alleman, D. 2018. Schedule Modelling to Estimate Typical Construction Durations and Areas of Risk for 1000 MW Ultra-Critical Coal-Fired Power Plants, Energies.

Biodiesel	R0.44/kWh (additional marginal cost on diesel engine)	50% emission savings	<5 years
Green hydrogen	R0.56/kWh (additional marginal cost on diesel engine)	Baseline dependent but a report by the South African DTIC estimates a reduction of 540 million tCO_2e by 2050	5-10 years
Hybrid electric vehicles	2,56 – 3,10 R/km	The IEA analysis indicated that a full lifecycle estimation in GHG emissions to be in the order of 50% compared to conventional internal combustion vehicles[38].	Immediate
Plug-in electric vehicles	2,57 – 4,00 R/km		
ULSD	R40 billion	98% less $PM_{2.5}$ 99.5% less BC 96% less NO_x	Immediate
Cleaner fuels 2 manufacturing	R40 billion	80% SO_x reduction	2 – 6 years
Import clean fuels	R15 billion – R25 billion	30% GHG reduction	5 – 7 years
Capture Technology: Industry			
Cement Industry			
Carbon Capture Systems	CCS is likely to play a critical role in decarbonising cement, as it would enable the capture of process emissions. The levelised cost of such technology is expressed in section 4.4 of the report.	The potential emissions implication of CCS is expressed in section 4.4 of the report	<5 years
Clinker Alternative Materials	Palm Oil Clinker (POCP)		
	The cost of POC itself can be considered as "zero" as it is usually disposed of as a waste material. However, when 50% of cement is replaced by POC, the cost of concrete is reduced by 41%.[85]	The use of POCP for cement replacement at about 40% in a cement-lime masonry mortar will reduce the carbon footprint by 32%. [86]	Short term : > 1 year
	Recycled cement		
	Just like the previously mentioned case, the cost of recycled cement can also be regarded as "zero" since it is	Recycled cement from demolished inorganic building materials and/or waste concrete powder (WCP)	Short term : > 1 year

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[85] Kanadasan, J. and Abdul Razak, H., 2015. Utilization of palm oil clinker as cement replacement material. Materials, 8(12), pp.8817-8838.

[86] Jagaba, A.H., Kutty, S.R.M., Hayder, G., Baloo, L., Noor, A., Yaro, N.S.A., Saeed, A.A.H., Lawal, I.M., Birniwa, A.H. and Usman, A.K., 2021. A systematic literature review on waste-to-resource potential of palm oil clinker for sustainable engineering and environmental applications. Materials, 14(16), p.4456.

	produced by reusing cement materials. However, using recycled materials reduces the costs of lightweight cellular concrete (LCC) by 34-41%. [87]	The CO_2 reduction by usage of recycled cement ranged from 0.06 million tons to 0.72 million tons from the total annual CO_2 emissions from cement production.[88]	
Steel Industry			
Carbon Capture Systems	CCS is likely to play a critical role in decarbonising cement, as it would enable the capture of process emissions. The levelised cost of such technology is expressed in section 4.4 of the report.	The potential emissions implication of CCS is expressed in section 4.4 of the report	<5 years
Biochar	The total price of biochar has been calculated according to three different prices of biomass: [89] 1. R1700/tonne biomass = R6400/tonne torrefied biochar. 2. R1100/tonne biomass = R4600/tonne torrefied biochar. 3. R220/tonne biomass = R2400/tonne torrefied biochar.	It is seen that if 2% to 10% biochar is added to a coal blend, 1% to 5% of CO_2 emission reductions in the steel industry is achieved, which is equivalent to 0.02-0.11 ton CO_2/ton crude steel. [90]	<5 years
Flue Gas Pollutant			
Flue gas pollutant reduction (Plant Retrofit)[91]	Wet Scrubber > 400MW = 471.55 (ZAR/MWh) Dry Scrubber > 200MW = 439.87 (ZAR/MWh)	FGD will achieve minimum GHG reductions and will impact existing plants thermal performance.	2.6 years
Carbon Capture Storage Systems			

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[87] Sonawane, T.R. and Pimplikar, S.S., 2013. Use of recycled aggregate concrete. IOSR Journal of Mechanical and Civil Engineering, 52(59).

[88] Oh, D.Y., Noguchi, T., Kitagaki, R. and Park, W.J., 2014. CO_2 emission reduction by reuse of building material waste in the Japanese cement industry. Renewable and Sustainable Energy Reviews, 38, pp.796-810.

[89] Marcos, M.; Bianco, L.; Cirilli, F.; Reichel, T.; Baracchini, G.; Echterhof, T.; Rekersdrees, T.; Mirabile, D.; Griessacher, T.; Sommerauer, H. Biochar for a Sustainable EAF Steel Production (GREENEAF2); Final Report; Publications Office: Luxembourg, 2019.

[90] Safarian, S., 2023. To what extent could biochar replace coal and coke in steel industries?. Fuel, 339, p.127401.

[91] United States Environmental Protection Agency. Air Pollution Control Technology Fact Sheet. [Available Online]: E:\9010 PRT\9010-241\New Fact Sheets\New English\fs FDG final.wpd (epa.gov).

Carbon Capture from Concentrated Gas Streams				CCUS to contribute to reduction in GHG emissions at a scale of approximately 1 $GtCO_2/yr$[92]			<5 years
Carbon Capture from Diluted Gas Streams				Capture system that removes CO_2 from the plant flue gas winds up reducing the net emissions per kWh by typically 85 to 88 percent.			<5 years
Carbon Dioxide (CO_2) Transport	Distance (km)	0-180	181-500	501-750	751-1500	Such information is not relevant for such technology	Road: 48 hours
	Onshore pipe (MR/km)	R35.89	R34.83 – R96.22	R34.47 – R51.60	R34.08 – R68.08		Minimum intermodal rail: 60 hours
	Offshore pipe (MR/km):	R53.15	R46.64 – 128.85	R46.59 – R69.74	R52.45 – R104.88		Maximum intermodal rail: 216 hours
	Ship with liquefaction (MR/km):	R81.26	R34.42 – R95.09	R26.34 – R39.43	R16.97 – R33.90		

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[92] Orr Jr, F.M., 2018. Carbon capture, utilization, and storage: an update. Spe Journal, 23(06), pp.2444-2455.

Appendix C. Data Assumptions – Electricity Generation

C.1: Coal Power Generation

The evaluation of Coal Power Generation in South Africa utilized the following assumptions and methodology:

Scenario Selection: Although South Africa has committed to not building any new coal power stations, sufficient and updated information for the refurbishment of coal power stations, specifically applicable in the South African landscape, could neither be obtained from the identified stakeholders nor from publicly available resources. For example, the costs associated with upgrading power stations to super critical or ultra super critical power stations with the additional of CFB were not publicly available to the.

The data sources used include the Power Generation Technology Data from the Integrated Resource Plan of South Africa, 2017(EPRI report) as well as the IEA levelised cost of electricity calculator data sheet for 2020.[93] For international datasets such as the IEA levelised cost of electricity calculator data sheet, data from developing countries were prioritised and where such data were not available, data from developed countries were used.

Furthermore, the IEA levelised cost of electricity calculator data sheet for 2020 includes the costs for the entire life cycle of the power plant, starting at construction costs, capital costs, operation and maintenance costs as well as fuel costs and carbon costs. For these calculations, fuel costs were calculated separately, considering South African fuel prices. Carbon prices were not included.

Assumptions, and sources:

Levelised cost of energy: new SC coal power station: 70.55 $/MWh. Source: IEA levelised cost of electricity calculator for 2020, the levelised cost ($/ MWh) for a 722 MW USC power plant in Australia was used as input for the calculation.

Levelised cost of energy: new USC coal power station: 37.71 $/MWh. Source: IEA levelised cost of electricity calculator for 2020, the levelised cost ($/ MWh) for a 400 MW USC power plant in the India was used as input for the calculation.

Marginal cost of CFB on SC power plants: Source: Power Generation Technology Data for Integrated Resource Plan of South Africa (EPRI report), 2017, and adjusted for inflation.

Marginal cost of CFB on USC power plants: Source: Power Generation Technology Data for Integrated Resource Plan of South Africa, 2017(EPRI report), and adjusted for inflation.

Adjusted costs: The levelised costs that were obtained from the IEA and the EPRI report were adjusted for inflation as follows:

Levelised cost of energy: new SC coal power station: 70.55 $/MWh, which was a cost calculated for 2020, multiplied by the US CPI for 2023 divided by 2020, and converted to South African Rands using the US dollar exchange rate on 21 February 2023.

The fuel price for coal was obtained from the Coal Price Agency[94]at 162.12 USD/t and converted to ZAR/MWh. This was done adjusting the price of coal from USD/t to ZAR/t, after which using a coal calorific value of 21MJ/kg, the fuel price was converted to ZAR/GJ. GJ was converted to MWh using the constant 3.6. An efficiency of a super critical plant was assumed at 35%. The fuel price per MWh was added to the adjusted Levelised cost of energy (ZAR/MWh).

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[93] The IEA levelised cost of electricity calculator is available for download at: Levelised Cost of Electricity Calculator – Data Tools - IEA

[94] Date accessed: 15 February 2023 Coal price in South Africa $146, steam coal, anthracite 15.09.2023 (coal-price.com)

Levelised cost of energy: new USC coal power station: 37.71 $/MWh, which was a cost calculated for 2020, multiplied by the US CPI for 2023 divided by 2020 value, and converted to South African Rands using the US dollar exchange rate on 21 February 2023.

The fuel price for coal was obtained from the Coal Price Agency[95], 162.12 USD/t, and converted to ZAR/MWh. This was done adjusting the price of coal from USD/t to ZAR/t, after which using a coal calorific value of 21MJ/kg, the fuel price was converted to ZAR/GJ. GJ was converted to MWh using the constant 3.6. An efficiency of an ultra super critical plant was assumed at 40%. The fuel price per MWh was added to the adjusted Levelised cost of energy (ZAR/MWh).

Marginal cost of CFB on SC power plants: Costs were adjusted for inflation from 2017 to 2023, using the US CPI values for 2017 and 2023.

CCUS onto Coal power

The levelised cost of energy was used (ZAR/MWh), as obtained from the 2017 EPRI report. The data assumed the retrofitting of one 750 MW unit with CCUS. The cost of this refurbishment was adjusted from its 2017 estimation, with inflation using the US CPI index.

C.2: Gas Power Generation

Scenario Selection: Four scenarios were selected for this technology assessment, the building of new OCGT power stations that use diesel in one scenario and natural gas in another scenario. The fuel replacement of diesel with biodiesel in the OCGT power station was calculated as the third scenario whereas the technology assessment for a new CCGT power station was selected as the fourth scenario.

Sufficient and updated information for the construction of new gas power stations, specifically applicable in the South African landscape, could neither be obtained from the identified stakeholders nor from publicly available resources.

The data sources used include the Power Generation Technology Data for Integrated Resource Plan of South Africa, 2017(EPRI report) as well as the IEA levelised cost of electricity calculator data sheet for 2020 and the NRAL[96] data set.[97] For international datasets such as the IEA levelised cost of electricity calculator data sheet, data from developing countries were prioritised and where such data were not available, data from developed countries were used.

Furthermore, the IEA levelised cost of electricity calculator data sheet for 2020 includes the costs for the entire life cycle of the power plant. These costs include construction costs, capital costs, operation and maintenance costs as well as fuel costs. For these calculations, fuel costs were calculated separately, considering South African fuel prices. Carbon prices were not included.

Assumptions, and sources:

Levelised cost of energy: open cycle gas turbine with an internal combustion engine using diesel as a fuel source were obtained from the IEA levelised cost of electricity calculator for 2020. The levelised cost ($/ MWh) for a 980 MW OCGT power plant in the Brazil was used as input for the calculation.

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[95] Date accessed: 15 February 2023 Coal price in South Africa $146, steam coal, anthracite 15.09.2023 (coal-price.com)

[96] National Renewable Energy Laboratory. Transportation Annual Technology Baseline (ATB) Data. 2020. [Available Online]: https://atb-archive.nrel.gov/transportation/2020/files/2020_ATB_Data_VehFuels_Download.xlsx

[97] The IEA levelised cost of electricity calculator is available for download at: Levelised Cost of Electricity Calculator – Data Tools - IEA

Levelised cost of energy: open cycle gas turbine using natural gas as a fuel source came from the IEA levelised cost of electricity calculator for 2020. The levelised cost ($/ MWh) for a 980 MW OCGT power plant in the Brazil was used as input for the calculation.

Levelised cost of energy: combined cycle gas turbine using natural gas as a fuel source were source from the IEA levelised cost of electricity calculator for 2020. The levelised cost ($/ MWh) for a 980 MW CCGT power plant in the Brazil was used as input for the calculation.

Marginal cost of fuel switch from diesel to biodiesel in an OCGT power plant: Source: NRAL data set.

Adjusted costs: The levelised costs that were obtained from the IEA and the NRAL data set were adjusted for inflation as follows:

Levelised cost of energy: open cycle gas turbine with an internal combustion engine using diesel as a fuel source- 68.89 USD/MWh (including construction costs, decommissioning costs, total capital costs and operations and maintenance costs). This cost was calculated for 2020 and adjusted to 2023 costs by multiplying by the US CPI for 2023 divided by 2020, and converted to South African Rands using the US dollar exchange rate on 21 February 2023.

The fuel price for diesel was obtained, 1.28 USD/L, and converted to ZAR/MWh. The fuel price per MWh was added to the adjusted Levelised cost of energy (ZAR/MWh).

Levelised cost of energy: open cycle gas turbine using natural gas as a fuel source- 68.89 USD/MWh (including construction costs, decommissioning costs, total capital costs and operations and maintenance costs). This cost was calculated for 2020 and adjusted to 2023 costs by multiplying by the US CPI for 2023 divided by 2020, and converted to South African Rands using the US dollar exchange rate on 21 February 2023

The fuel price for natural gas was obtained, ZAR/L, and converted to ZAR/MWh. The fuel price per MWh was added to the adjusted Levelised cost of energy (ZAR/MWh).

Levelised cost of energy: combined cycle gas turbine using natural gas as a fuel source- 46.97 USD/MWh (including construction costs, decommissioning costs, total capital costs and operations and maintenance costs). This cost was calculated for 2020 and adjusted to 2023 costs by multiplying by the US CPI for 2023 divided by 2020, and converted to South African Rands using the US dollar exchange rate on 21 February 2023

The fuel price for natural gas was obtained, ZAR/L, and converted to ZAR/MWh. The fuel price per MWh was added to the adjusted Levelised cost of energy (ZAR/MWh).

Marginal cost of fuel switch from diesel to biodiesel in an OCGT power plant: Source: NRAL data set.

Appendix D. Data Assumptions – Liquid Fuels

D.1: CNG/LNG Vehicles

In the pursuit of assessing the economic viability of Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) vehicles within the South African context, we employed a comprehensive methodology based on the following assumptions and data sources:

Scenario Selection: We adopted the Advanced Technology Baseline (ATB) Mid scenario from NREL transport scenarios[98], which incorporates the assumption of certain technology breakthroughs.

Calculation steps, Assumptions, and sources:

Vehicle Lifetime: We assumed a vehicle lifetime of 15 years, consistent with industry standards, and a total mileage of 178 000 miles (286 402 km) over the vehicle's life. The mileage schedule was derived from the National Highway Traffic Safety Administration (NHTSA) guidelines (2006) and is provided in the NREL[98] Document - 'Column Description' Sheet, cell C51.

Capital Cost: The capital cost of CNG/LNG Vehicles was determined using the ATB Mid 2020 data provided by the NREL, amounting to $31 180 (2017 USD). This value was converted to South African Rand (ZAR) using the following formula:

Capital Cost (ZAR) = ATB Mid 2020 Capital Cost (USD) × (US CPI[99] Jan-23 / US CPI[99] Jan-17) × Exchange Rate (USD/ZAR, Feb-23)

NPV Capital Expenditure (Capex): We calculated the Net Present Value (NPV) of the capital expenditure using the calculated ZAR capital cost and an 8.2% discount rate[100].

Fuel Price: To estimate the fuel price, we converted the Utility-factor-weighted fuel price ($2.22/gallon equivalent [gge]) from NREL to 2017$/kWh, factoring in the conversion rates:

Fuel Price (2017$/kWh) = ($2.22/gge) ÷ (0.112194 mmBtu/gallon)[101] ÷ (293.0832 kWh/mmBtu)[102]

This value was subsequently converted to 2023 ZAR/kWh using the appropriate inflation-adjusted rates.

Driving Distance: We determined the annual driving distance by dividing the total mileage over 15 years (178,000 miles) by 15, resulting in 11 867 miles/year (19 094 km/year).

Total Fuel Consumption: Total fuel consumption was calculated by dividing the annual driving distance by the fuel economy (23.2 miles/gge) provided by NREL and then converting the result into kilowatt-hours (kWh) based on energy conversion factors.

NPV Operating Expenditure (Opex): The NPV Opex was calculated using the Excel NPV formula, considering the operating costs for all 15 years and the 8.2% discount rate.

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[98] National Renewable Energy Laboratory. Transportation Annual Technology Baseline (ATB) Data. 2020. [Available Online]: https://atb-archive.nrel.gov/transportation/2020/files/2020_ATB_Data_VehFuels_Download.xlsx.

[99] US Bureau of Labour Statistics. [Available Online]: https://www.bls.gov/regions/mid-atlantic/data/consumerpriceindexhistorical_us_table.htm.

[100] Department of Mineral Resources and Energy. Integrated Recourse Plan. 2019. [Available Online]: IRP-2019.pdf (energy.gov.za).

[101] National Renewable Energy Laboratory. Transportation Annual Technology Baseline (ATB) Data. 2020. [Available Online]: Definitions | Transportation | 2020 | ATB | NREL.

[102] National Renewable Energy Laboratory. Transportation Annual Technology Baseline (ATB) Data. 2020. [Available Online]: Million BTU to Kilowatt-Hours Conversion (MMBTU to kWh) (inchcalculator.com).

LCOE Calculation: The LCOE was calculated by dividing the NPV Capex value by the sum of the driving distance over the 15-year period, added to the NPV Opex value divided by the same driving distance sum. This calculation results in an LCOE of 3.01 ZAR/km.

In the evaluation of emissions associated with CNG and LNG vehicles, we utilized the following assumptions and methodology:

Emissions per Kilometre: The emissions per kilometre were calculated using emissions data provided by the NREL, which specified emissions as 78 100 gCO2e/mmBtu. We divided this value by the conversion factor from mmBtu to kilowatt-hours (kWh), which is 293 kWh/mmBtu.

Emissions per Kilometre (gCO2e/kWh) = Emissions per mmBtu (gCO2e/mmBtu) ÷ Conversion Factor (kWh/mmBtu)

This calculation resulted in an emissions value of 266.48 gCO2e/kWh.

Emissions per Kilometre (gCO2e/km): The total emissions per year were determined by multiplying the calculated emissions per kilowatt-hour by the total fuel consumption per year, which amounted to 16 819 kWh/year. To arrive at emissions per kilometre, the total annual emissions were divided by the annual driving distance, accounting for the miles to kilometre conversion factor.

Emissions per Kilometre (gCO2e/km) = Total Annual Emissions (gCO2e/year) ÷ (Annual Driving Distance (km) ÷ Miles to Kilometre Conversion Factor)

This calculation yielded an emissions value of 234.56 gCO2e/km.

D.2: Fuel Cell Vehicles

In the assessment of the economic viability and emissions profile of Steam Methane Reforming Fuel Cell Vehicles within the South African context. The following assumptions and methodology were adopted:

Scenario Selection: Our analysis aligns with the Advanced Technology Baseline (ATB) Mid scenario, which accounts for potential technology advancements.

Vehicle Lifetime: A vehicle lifespan of 15 years was assumed, consistent with industry norms, accompanied by a total mileage of 178 000 miles (286 402 km).

Capital Cost: The capital cost for Steam Methane Reforming Fuel Cell Vehicles was sourced from the ATB Mid 2020 data provided by NREL, amounting to $53 140 (2017 USD). To adapt this value to the South African context, we employed the following conversion formula:

Capital Cost (ZAR) = ATB Mid 2020 Capital Cost (USD) × (US CPI Jan-23 / US CPI Jan-17) × Exchange Rate (USD/ZAR, Feb-23)

NPV Capital Expenditure (Capex): The Net Present Value (NPV) of the capital expenditure was calculated using the calculated ZAR capital cost and an 8.2% discount rate.

Fuel Price: To estimate the fuel price, we converted the Utility-factor-weighted fuel price ($12.07/gallon equivalent) from NREL to 2017$/kWh, factoring in the conversion rates:

Fuel Price (2017$/kWh) = ($12.07/gge) ÷ (0.112194 mmBtu/gallon [gge]) ÷ (293.0832 kWh/mmBtu)

This value was subsequently converted to 2023 ZAR/kWh using the appropriate inflation-adjusted rates.

Driving Distance: The annual driving distance was determined by dividing the total mileage over 15 years (178 000 miles) by 15, resulting in 11 867 miles/year (19 094 km/year).

Total Fuel Consumption: Total fuel consumption was calculated by dividing the calculated annual driving distance by the fuel economy (56.7 miles/gge) provided by NREL and then converting the result into kilowatt-hours (kWh) based on energy conversion factors.

NPV Operating Expenditure (Opex): The NPV Opex was calculated using the Excel NPV formula, considering the operating costs for all 15 years and the 8.2% discount rate.

LCOE Calculation: The Levelized Cost of Energy (LCOE) was calculated by dividing the NPV Capex value by the sum of the driving distance over the 15-year period, added to the NPV Opex value divided by the same driving distance sum. This calculation results in an LCOE of 5.53 ZAR/km.

The estimation of emissions for Steam Methane Reforming Fuel Cell Vehicles was carried out with the following assumptions and methodology:

Emissions per Kilowatt-Hour (gCO2e/kWh): The emissions per kilowatt-hour were calculated using emissions data provided by NREL, specifying emissions as 120 000 gCO2e per million British Thermal Units (mmBtu). This value was divided by the conversion factor from mmBtu to kilowatt-hours (kWh), which is 293.0832 kWh/mmBtu.

Emissions per Kilowatt-Hour (gCO2e/kWh) = Emissions per mmBtu (gCO2e/mmBtu) ÷ Conversion Factor (kWh/mmBtu)

This calculation resulted in an emissions value of 409.44 gCO2e/kWh. The emissions comparison was conducted against a conventional diesel baseline, derived from the NREL ATB, with a value of 97 600 gCO2e/mmBtu. This value was converted to 333.01 gCO2e/kWh, which shows that the emissions would be higher than the average diesel vehicle emissions.

In our evaluation of the economic feasibility and emissions impact of Electrolysis Fuel Cell Vehicles within the South African context, we adopted the following assumptions and methodology:

Scenario Selection: Our analysis adheres to the Advanced Technology Baseline (ATB) Mid scenario, which incorporates the presumption of technology advancements.

Vehicle Lifetime: We assumed a vehicle lifespan of 15 years, in line with industry standards, along with an undiscounted total mileage of 178 000 miles, which was determined based on the mileage schedule developed by NREL.

Capital Cost: The capital cost for Electrolysis Fuel Cell Vehicles was acquired from the ATB Mid 2020 data provided by NREL, amounting to $53 140 (2017 USD). To adjust this value to the South African context, we employed the following conversion formula:

Capital Cost (ZAR) = ATB Mid 2020 Capital Cost (USD) × (US CPI Jan-23 / US CPI Jan-17) × Exchange Rate (USD/ZAR, Feb-23)

NPV Capital Expenditure (Capex): The Net Present Value (NPV) of the capital expenditure was calculated using the calculated ZAR capital cost and an 8.2% discount rate.

Fuel Price: To estimate the fuel price, we converted the Utility-factor-weighted fuel price ($12.05/gallon equivalent) from NREL to 2017$/kWh, considering the following conversion rates:

Fuel Price (2017$/kWh) = ($12.05/gge) ÷ (0.112194 mmBtu/gallon) ÷ (293.0832 kWh/mmBtu)

This value was subsequently converted to 2023 ZAR/kWh using the appropriate inflation-adjusted rates.

Driving Distance: The annual driving distance was calculated by dividing the total mileage over 15 years (178,000 miles) by 15, resulting in 11 867 miles/year (19 094 km/year).

Total Fuel Consumption: Total fuel consumption was computed by dividing the calculated annual driving distance by the fuel economy (56.7 miles/gge) provided by NREL and then converting the result into kilowatt-hours (kWh) using energy conversion factors.

NPV Operating Expenditure (Opex): The NPV Opex was determined using the Excel NPV formula, considering the operating costs for all 15 years and the 8.2% discount rate.

LCOE Calculation: The Levelized Cost of Energy (LCOE) was calculated by dividing the NPV Capex value by the sum of the driving distance over the 15-year period, added to the NPV Opex value divided by the same driving distance sum. This calculation results in an LCOE of 5.52 ZAR/km.

Emissions Estimation for Electrolysis Fuel Cell Vehicles as emissions per Kilowatt-Hour (gCO2e/kWh): The emissions per kilowatt-hour were computed using emissions data provided by NREL, specifying emissions as 120 000 gCO2e per million British Thermal Units (mmBtu). This value was divided by the conversion factor from mmBtu to kilowatt-hours (kWh), which is 293.0832 kWh/mmBtu.

Emissions per Kilowatt-Hour (gCO2e/kWh) = Emissions per mmBtu (gCO2e/mmBtu) ÷ Conversion Factor (kWh/mmBtu)

This calculation resulted in an emissions value of 77.11 gCO2e/kWh.

D.3: Biofuel Blending

The Levelized Cost of Electricity (LCOE) calculation for biofuels blending followed these steps:

The capital cost value was obtained from the article titled[103] "Biofuels Pricing and Manufacturing Economics." Subsequently, the manufacturing cost[103], initially denominated in cents per litre (c/l), was adjusted to Rands per litre (R/l) through division by 100. The operational cost was determined by multiplying the R/l manufacturing cost by the plant's capacity[103], which was first converted from cubic meters (m^3) to litres, dividing by the conversion factor of 1000.

The manufacturing cost, expressed in Rands per litre (R/l), was further refined by dividing it by the Net Calorific Values[104], measured in Mega Joules per litre (MJ/l). Following this adjustment, the manufacturing cost was divided by the MJ to kWh conversion factor[105] of 0.2777778 kWh/MJ to yield the manufacturing cost in Rands per kilowatt-hour (R/kWh).

The computation of the energy output entailed multiplying the plant's capacity by 1000 to convert it into litres. Subsequently, this value was multiplied by the manufacturing cost in R/kWh, representing the cost per unit of energy per year. To assess the Net Present Value of Capital Expenditure (NPV Capex), the Excel formula was used, incorporating the capital costs and the discount rate as inputs. Similarly, the Net Present Value of Operational Expenditure (NPV Opex) was determined using the Excel formula, using the summation of operational costs across all years and the discount rate as input parameters.

Ultimately, the LCOE was computed by dividing both the NPV Capex and NPV Opex values by the summation of the annual energy values, and these two results were summed to express the LCOE in Rands per kilowatt-hour (R/kWh).

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[103] Biofuels Pricing and Manufacturing Economics. [Available Online]: https://www.energy.gov.za/files/esources/renewables/biofuelspricingandmanufacturingeconomics.pdf.

[104] EngineeringToolbox.com. [Available Online]: Fuels - Higher and Lower Calorific Values (engineeringtoolbox.com).

[105] [Available Online]: Megajoules to Kilowatt-Hours Conversion (MJ to kWh) (inchcalculator.com)

D.4: Green Hydrogen Manufacturing

The calculation of the Levelized Cost of Electricity (LCOE) for green hydrogen began with obtaining the Levelized Cost of Hydrogen[106] (LCOH). The LCOH value was obtained in 2021 U.S. dollars per kilogram of hydrogen (2021\$/kgH2). The LCOH value was converted from 2021\$/kgH2 to South African Rand per kilogram of hydrogen (ZAR/kgH2) by multiplying it with the U.S. Consumer Price Index[107] (CPI) for January 2023 and then dividing by the U.S. CPI[107] for January 2021 and multiplying with the USD/ZAR exchange rate of February 2023. Subsequently, the adjusted LCOH value in ZAR/kgH2 was further refined by dividing it by the net calorific value[104] of hydrogen, resulting in the LCOE expressed in South African Rand per kilowatt-hour (ZAR/kWh) 2.70 ZAR/kWh.

D.5: Hybrid Electric Vehicles

The LCOE calculations for Hybrid Electric vehicles within the South African context, had the following steps and assumptions:

Scenario Selection: We did calculations based on the 20 mile electric range vehicles and the 50 mile electric range vehicles.[108]

Vehicle Lifetime: We assumed a vehicle lifetime of 15 years, consistent with industry standards, and a total mileage of 178 000 miles over the vehicle's life. The mileage schedule was derived from the National Highway Traffic Safety Administration (NHTSA) guidelines (2006) and is provided in the NREL[98] Document - 'Column Description' Sheet, cell C51.

Capital Cost: The capital cost was determined using the data provided by the NREL (2017 USD) and was converted to South African Rand (ZAR) using the following formula:

Capital Cost (ZAR) = ATB Capital Cost (USD) × (US CPI[109] Jan-23 / US CPI[99] Jan-17) × Exchange Rate (USD/ZAR, Feb-23)

NPV Capital Expenditure (Capex): We calculated the Net Present Value (NPV) of the capital expenditure using the calculated ZAR capital cost and an 8.2% discount rate[110].

Fuel Price: To estimate the fuel price, we converted the Utility-factor-weighted fuel price (2017\$/gallon equivalent) from NREL to 2017\$/kWh, factoring in the conversion rates:

Fuel Price (2017\$/kWh) = (2017\$/gge) ÷ (0.112194 mmBtu/gallon)[111] ÷ (293.0832 kWh/mmBtu)[112]

This value was subsequently converted to 2023 ZAR/kWh using the appropriate inflation-adjusted rates.

Driving Distance: We determined the annual driving distance by dividing the total mileage over 15 years (178 000 miles) by 15, resulting in 11 867 miles/year (19 094 km/year).

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[106] DSI. South Africa Hydrogen Vally. 2021. [Available Online]: South Africa Hydrogen Valley Final Report (dst.gov.za).
[107] US Bureau of Labour Statistics. [Available Online]: Consumer Price Index Historical Tables for U.S. City Average : Mid–Atlantic Information Office : U.S. Bureau of Labor Statistics (bls.gov).
[108] National Renewable Energy Laboratory. Transportation Annual Technology Baseline (ATB) Data. 2020. [Available Online]: https://atb-archive.nrel.gov/transportation/2020/files/2020_ATB_Data_VehFuels_Download.xlsx.
[109] US Bureau of Labour Statistics. [Available Online]: https://www.bls.gov/regions/mid-atlantic/data/consumerpriceindexhistorical_us_table.htm.
[110] Department of Mineral Resources and Energy. Integrated Recourse Plan. 2019. [Available Online]: IRP-2019.pdf (energy.gov.za).
[111] National Renewable Energy Laboratory. Transportation Annual Technology Baseline (ATB) Data. 2020. [Available Online]: Definitions | Transportation | 2020 | ATB | NREL.
[112] National Renewable Energy Laboratory. Transportation Annual Technology Baseline (ATB) Data. 2020. [Available Online]: Million BTU to Kilowatt-Hours Conversion (MMBTU to kWh) (inchcalculator.com).

Total Fuel Consumption: Total fuel consumption was calculated by dividing the annual driving distance by the fuel economy (miles/gge) provided by NREL and then converting the result into kilowatt-hours (kWh) based on energy conversion factors.

NPV Operating Expenditure (Opex): The NPV Opex was calculated using the Excel NPV formula, considering the operating costs for all 15 years and the 8.2% discount rate.

LCOE Calculation: The LCOE was calculated by dividing the NPV Capex value by the sum of the driving distance over the 15-year period, added to the NPV Opex value divided by the same driving distance sum. This calculation results in an LCOE of 2.56 – 3.10 ZAR/km.

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