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INDUSTRIALISING THROUGH R&D AND INNOVATION

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ABBREVIATIONS

AfCFTA	African Continental Free Trade Area
AI	Artificial Intelligence
AsgiSA	Accelerated and Shared Growth Initiative for South Africa
CCS	Carbon Capture and Storage
CeSTII	Centre for Science Technology and Innovation Indicators
CO_2	Carbon Dioxide
CSIR	Council for Scientific and Industrial Research
DST	Department of Science and Technology
DSTI	Department of Science, Technology and Innovation
dti (the)	Department of Trade and Industry
dtic (the)	Department of Trade, Industry and Competition
EV	Electric Vehicle
FET	Further Education and Training
GDP	Gross Domestic Product
GERD	Gross Expenditure on Research and Development
HySA	Hydrogen South Africa
ICT	Information and Communications Technology
IDC	Industrial Development Corporation
IoT	Internet of Things
IP	Intellectual Property
IPR	Intellectual Property Rights
IPR-PFRD	Intellectual Property Rights from Publicly Financed Research and Development Act
GEAR	Growth, Employment and Redistribution
NACI	National Advisory Council on Innovation
NDP	National Development Plan
NGP	New Growth Path
NIPF	National Industrial Policy Framework
NIPMO	National Intellectual Property Management Office
NSI	National System of Innovation
NWU	North-West University
OECD	Organisation for Economic Co-operation and Development
PBMR	Pebble Bed Modular Reactor (SOC)
PCT	Patent Cooperation Treaty
PGMs	Platinum Group Metals

R&D	Research and Development
RDI	Research, Development, and Innovation
RDP	Reconstruction and Development Plan
RICs	Regional Innovation Centres
SACCCS	South African Centre for Carbon Capture and Storage
SEFA	Small Enterprise Finance Agency
SMMEs	Small, Micro and Medium Enterprises
TIA	Technology Innovation Agency
UCG	Underground Coal Gasification
UP	University of Pretoria
UTF	University Technology Fund
SANEDI	South African National Energy Initiative
S&T	Science and Technology
STI	Science, Technology and Innovation
STII	Science, Technology, Innovation, and Industrial
SU	Stellenbosch University
UCT	University of Cape Town
UWC	University of the Western Cape

1. EXECUTIVE SUMMARY

South Africa's journey in harnessing Research and Development (R&D) as a vehicle for economic transformation has been marked by both ambition and uneven outcomes. Since 1994, and more notably from the year 2000 onwards, the country has steadily increased its investment in R&D to drive innovation, stimulate industrial development, create employment, and ultimately enhance economic growth. However, the translation of this investment into tangible, sustained outcomes has proven elusive. This study delves into the science, technology, innovation, and industrial (STII) policy landscape to interrogate why these investments have not consistently delivered the intended results. Through a qualitative case study approach, the research examines several R&D-led programmes and projects, including Hydrogen South Africa (HySA), biotechnology, and the Joule electric vehicle (EV); Underground Coal Gasification (UCG), carbon capture and storage, and the Pebble Bed Modular Reactor (PBMR); University Technology Fund (UTF) and Innovus; broader technology development and innovation programmes; and the evolving digital economy. Each case offers a lens through which to explore the disconnect between policy ambition and performance, and provides critical insight into how innovation systems can either flourish or falter.

Findings suggest that South Africa is not short on policies along the STII landscape to translate ambitious R&D programmes into industrial development, employment and economic growth. The STII policy analysis highlights several aims, making prioritisation and coordination difficult in the context of limited resourcing. This finding challenges the notion that South Africa has great policies, suggesting that the measure of great policies must include ease of implementation. The case studies on launching new sectors reveal that the R&D stage is not sufficiently used to reduce the technology cost and resolve commercial viability, while on upgrading existing sectors it is failure to resolve integration challenges. The innovation strategy of innovation-active firms in South Africa prioritises improving existing products and services over creating new goods and services, making it difficult to drive extensive growth and create new employment opportunities. Underinvestment in the back end of the innovation process (technology commercialisation) limits translating university R&D outputs into upgrading existing sectors and creating new sectors.

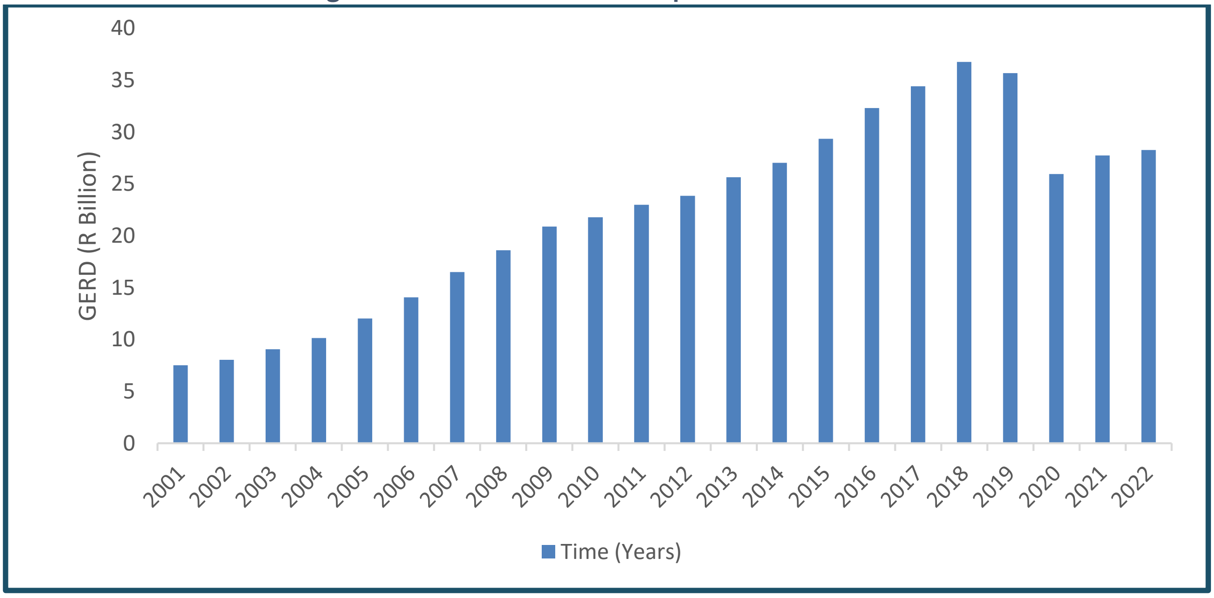
In conclusion, the study calls for practical policy interventions that focus not only on increasing R&D investment but in ensuring that the R&D step is used to reduce technology cost, resolve technology viability, and resolve integration and interoperability challenges within legacy sectors. Further, the study calls for practical policy interventions to incentivise active innovation and prioritise creating new goods and services as they support extensive growth and create employment opportunities.

2. INTRODUCTION

2.1 Setting the scene

South Africa has invested in R&D in the hope of increased innovation, industrial development, and subsequently economic growth. R&D investment has not yielded the expected increase in innovation and economic growth. Although there was a decline in 2017, South Africa's Gross Expenditure in Research and Development (GERD) presented in constant 2015 prices to adjust for inflation is on an upward trend between 2011 and 2022 (Figure 1).

Figure 1: South Africa's R&D expenditure since 2001



Source: CeSTII, 2022.

Overall, since 2001, South Africa has invested approximately R0.5 trillion in R&D. Since 1994, several policies on STII development have been put forward. Regardless of the policies, the expected causal relationship between R&D, innovation, and economic development has not been realised. As a percentage of gross domestic product (GDP), R&D intensity was 0.62% in 2024, which is below the 1% target set out in the 2002 National R&D Strategy.

Part of the reason for not scaling R&D to achieve the expected impact is the fragmentation that characterises the South African economy. Scholars like Gaglio, Kraemer-Mbula, and Lorenz (2022), alongside Andreoni, Mondliwa, Roberts, and Tregenna (2021), emphasise the necessity for South Africa to transcend fragmented initiatives. They advocate for a cohesive industrial policy that perceives R&D not merely as expenditures but as pivotal investments driving social equity and productivity.

This study seeks to understand what has caused and continues to cause South Africa's R&D efforts to not yield intended outcomes in innovation, industrial development, employment, and economic growth. The study employs a case study approach using some of the R&D-led projects in South Africa since 1994. The study recognises that South Africa does not lack policies to ensure R&D outcomes such as innovation, industrial development, employment, and economic growth. As such, the starting point is a policy analysis of the STII landscape under the Department of Science, Technology and Innovation (DSTI) and the Department of Trade, Industry and Competition (the dtic).

2.2 Policy analysis

The policies have intended aims, objectives, outcomes, and impact. Furthermore, the two departments and their agencies have several incentives to increase R&D, innovation, and industrial development. While these policies are highly intertwined, a meaningful evaluation will start at each policy and as a collective at the level of the National Systems of Innovation. This understanding will bring about clarity on what has worked and what has not worked along the STII policy landscape in South Africa.

2.2.1 Science, technology, and innovation policy

The main science, technology and innovation (STI) policies are the 1996 Science and Technology (S&T) policy and the 2019 STI policy. Table 1 shows STI policy aims/objectives, outcomes/targets, and impacts.

Table 1: STI policy aims/objectives, outcomes/targets and impacts

VARIABLES/POLICY	1996 S&T	2019 STI
Aims/objectives	Create the conditions that will support both creativity and innovativeness throughout our society. Transform the STI system to serve all South Africans. Counter STI policy fragmentation. Expand and transform human capabilities. Provide more support for research. Build the required STI institutions. Increase innovation to support economic growth and socio-economic development. To increase the financial resources for the system.	Foster a national system of innovation (NSI) in which creativity, learning and entrepreneurship can flourish. Expand research outputs and transform the research institutional landscape. Increase the financial resources for the system. Enhance policy coherence and programme coordination in the NSI. R&D-led industry development and encouraging high-technology exports. Support innovations with high social returns that are unlikely to gain traction because of market and other failures. GERD reaches 1.5% of GDP in the next decade.
Outcomes/targets	A greater than 6% per annum growth rate in the national investment in STI.	Developing a national innovation compact. Accelerated inclusive economic growth makes the economy more competitive and improves people's daily lives.
Impacts	Sustainable and inclusive development.	Sustainable and inclusive development.

Source: Adapted from DACST, 1996 and DSI, 2019.

The STI policy implementation approaches are the 2002 R&D strategy, the 2008 Ten-Year Innovation Plan, and the 2022 STI Decadal Plan (DST, 2002; DST, 2008; DST, 2022)[1]. Although the STI policy encompasses multiple objectives, its core intended outcomes are accelerated inclusive growth, a more competitive economy, and improved daily lives of South Africans. It is concerning that the STI policy entails several and wide-ranging aims, which can be challenging to realise fully because of resource constraints.

Transforming the NSI remains a challenge since the 1996 S&T policy. The 2020 Higher Education, Science, Technology, and Innovation Institutional Landscape report (DSI, 2020) recognises that the NSI in its current form has not been delivered since its adoption as a conceptual lens for innovation in 1996. This recognition is based on the framing of path dependency and lock-in. The NSI has been formed by past decisions and institutional practices that are difficult to change over time. It appears

[1] In September 2024 the Department of Science and Technology (DST) was renamed the Department of Science, Technology and Innovation (DSTI).

to have reached a plateau, where current strategies fail to generate new momentum. This implies the need for a deliberate pivot that might open new opportunities and higher performance.

Accelerated inclusive growth would require acceleration and decisiveness on the STI side. Equally, a competitive economy would require a competitive STI. On R&D investment, as already mentioned, South Africa has sustained an increasing R&D investment since 2000 and has since invested close to 0.5 trillion South Africa Rands. This is besides not reaching over 0.9% of GDP, thus well below the current target of 1.5% of GDP.

2.2.2 Industrial policy

The main industrial policies are the 2007 National Industrial Policy Framework (NIPF) and the 2019 Reimagined NIPF. Table 2 shows industrial policy aims/objectives, outcomes/targets, and impacts.

Table 2: Industrial policy aims/objectives, outcomes/targets, and impacts

VARIABLES/POLICY	2007 NIPF	2019 REIMAGINED NIPF
Aims/objectives	Set out government's approach to the industrial development of the South African economy. Facilitate diversification beyond our current reliance on traditional commodities and non-tradable services. Long-term intensification of South Africa's industrialisation process and movement towards a knowledge economy. Promotion of a more labour-absorbing industrialisation path, with a particular emphasis on tradable labour-absorbing goods and services and economic linkages that catalyse employment creation. Promotion of a broader-based industrialisation path characterised by increased participation of historically disadvantaged people and marginalised regions in the mainstream of the industrial economy. Contributing to industrial development on the African continent with a strong emphasis on building its productive capabilities. Providing greater clarity and certainty to the private sector and social partners with respect to investment decisions leading up to 2014 and beyond. Provide a reference point for substantial improvements in intra-governmental coordination.	Combine growth with transformation. Boost local production. Grow exports and expand African trade. Increase investment. Establish a more reliable and low-cost energy system while greening the economy overall. Grow employment. Enhancing the productive capabilities of the economy. Increase the economy's ability to produce more and more complex and high value-added products with greater efficiency. Produce more value using less resources. Transforming the racially skewed ownership, management and employment profile of the economy. Raise the economy's growth-to-employment potential to a much higher level.
Outcomes/targets	Growth and employment. Greater priority should be given to sectors that can generate the highest levels of employment and growth. Equally, focus on sectors that will move South Africa closer towards a	Industrialisation to replace imports and promoting exports in new industries. Grow investment in the private sector. Infrastructure through infrastructure fund.

	technologically sophisticated and knowledge-driven economy in the long term. GERD reaches 1% of GDP	Integration at the African continent. Inclusion (equity) through widening black entrepreneurs and worker share ownership. Inclusion (spatial) through launching a township economy programme and revising the Special Economic Zone approach. Innovation through digital economy, developing and diffusing new technologies. Expanding trade with Africa within the next five years, using the platform of the African Continental Free Trade Area (AfCFTA). Investment pledges of R2 trillion within a five-year period. R200 billion economic contribution and 160 000 jobs from black industrialists. 75% local procurement of non-designated products. Increased diffusion of locally developed technologies to accelerate the creation of successful products, processes and services or social and/or economic impact.
Impacts	Employment and economic growth	Sustainable economic growth and international competitiveness. Transformation and broader economic development.

Source: Adapted from the dti, 2007 and the dtic, 2019.

The implementation approaches are the 2007 Industrial Policy Action Plan, which issued annual interventions on 13 priority areas, and the 2019 sector-specific Master Plans; a total of eight Master Plans have been launched (the dti, 2007; the dtic, 2019). Like the STI policy, industrial policy is characterized by multiple and wide-ranging objectives. While a sector approach is necessary to drive focus, the numbers of sectors make prioritisation and resourcing difficult. Industrial policy seems to require other policies, such as trade and competition, to deliver on its mandate. The role of R&D and STI policies is clear in shaping towards the intended outcomes.

Considering different levers, balancing between employment and economic growth will always be a challenge. Intensive growth driven by technological intensity could erode employment in thriving sectors, while expansive growth offers employment opportunities by focusing STI away from existing sectors. This could imply STI underinvestment in existing sectors, resulting in them being less competitive over time. In this sense, the industrial policy outcome of employment and economic growth requires some decoupling between upgrading existing sectors to remain competitive while growing new sectors that are equally competitive.

Further, even within existing sectors, the ingredients to remain competitive are not similar. Some sectors might benefit from developing their own technologies, while others would benefit by licensing and integrating mature technologies, or a combination.

2.2.3 Science, technology, innovation, and industrial policy

STI policy adopts a broader approach, while industrial policy has a sectoral approach to development. Although there are some alignments, it does not appear to be part of policy formulation. As already mentioned, the number of sectors at the industrial policy level does not assist with any form of prioritisation. While employment growth is stated clearly on the industrial policy side, it is not the case on the STI policy side. This could be based on the understanding that STI intensity erodes employment, especially in existing sectors. Equally, if the lens is STI, then employment could be viewed as an uncontrolled consequence and not a variable to pursue.

Unlike industrial policy, STI development can be pursued outside of industrial activities up to a point of deployment. However, this thinking is underpinned by a linear model of innovation, which is one-directional and assumes no interaction with the market during development (Godin, 2006).

2.3 Theory of change

The policy analysis in Section 1.2 guided the framing of the theory of change. Because accelerated inclusive and employment growth has not happened in South Africa, it suggests that the pathway along the STII landscape has not been realised as envisaged. While South Africa has continued to invest in R&D, this is not reflected in the industrial performance (intensification and diversification), employment, and economic growth. Equally, several programmes have been implemented for the purpose of accelerating inclusive economic and employment growth. The output of the theory of change guides the development of practical interventions aimed at addressing the disconnect between research, innovation, and industrial application, with the goal of fostering innovation, industrial development, employment creation, and economic growth in South Africa. Along the STII landscape, several activities are taking place. Some are ongoing, such as R&D activities, while others are programmes with specific pre-defined timelines and targets.

These activities (efforts) have not resulted in the intended impact goal (effect). Within the South African STII policy landscape, the theory of change provides a framework that shapes the evaluation process and helps to define and position the research problem statement.

2.4 Research problem statement, objectives, and questions

South Africa has seen an increasing R&D investment since the year 2000, yet this has not resulted in increased innovation, industrial development, employment and economic growth. Based on the research problem statement, the research objectives are as follows:

i. To develop an understanding of the underlying factors that have caused and continue to influence South Africa's R&D efforts not yielding intended outcomes of increased innovation, industrial development, employment and economic growth.
ii. Based on objective (i), to develop practical policy interventions to significantly improve the translation of R&D investment into increased innovation, industrial development, employment and economic growth

Based on the research objectives, the following research questions guide the study:

i. How come South Africa's R&D investment has not resulted in sustained industrial performance?
ii. How could South Africa go about shaping the STII policy landscape bias towards extensive growth rather than intensive growth?
iii. What are the key drivers along the STII policy landscape to achieve both accelerated inclusive growth and employment?

3. LITERATURE SURVEY

The literature study reviews recent developments on the variables within research questions in South Africa. This further guides data gathering in each case study to answer the research questions.

3.1 Research and development

R&D is essential for technological progress in the economy (Ndlovu and Inglesi-Lotz, 2020). Using manufacturing R&D data between 1970-1993, South Africa's R&D is reactive, thus leading to a mixed R&D performance when compared to other emerging economies (Fedderke and Schirmer, 2006). Further, Fedderke and Schirmer (2006) found weak interactions among business, government, and research institutions, thus limiting the possibility of fully exploiting positive spillovers among them. At the time, 1993, there were few to no policies and interventions to directly stimulate R&D in industry in South Africa.

The 2002 National R&D Strategy was among the government's early interventions after the 1996 S&T policy. The strategy identified deficiencies as follows: R&D investment is low; increased exposure to security risk; declining scientific population; declining private sector R&D; lack of a policy framework on intellectual property (IP); and government fragmentation on S&T (Kaplan, 2004). Several strategies were proposed to help resolve these deficiencies. On innovation, new technology missions were launched along with biotechnology, information technology, technology for advanced manufacturing, technology for and from natural resource sectors, and technology for poverty reduction.

The Intellectual Property Rights from the Publicly Financed Research and Development Act No. 51 of 2008 (IPR-PFRD Act) was enacted to close the IP deficiency. Technology transfer between research institutions and industry largely remains low, possibly due to a mismatch in that industry prioritises knowledge for immediate decision-making, must-see knowledge as a valuable resource in the short term, and clarity on return on investment (Van Zyl, Amadi-Echendu and Bothma, 2007).

Ndlovu and Inglesi-Lotz (2020) argue that renewable energy R&D investments in South Africa have been historically too low to make a meaningful contribution in the energy sector and the economy. This is based on the data between 1996 and 2015. However, based on manufacturing R&D data between 2009 and 2014, the return on South Africa's R&D is higher than countries in the Organisation for Economic Co-operation and Development (OECD) (Steenkamp, et al., 2018).

The study by Steenkamp et al. (2018) did not include licensing activities such as importing established technologies as part of R&D. If this is high in South Africa compared to R&D spending, then the study omitted a key variable, thus resulting in an overestimate of R&D return in South Africa. If it had been included as part of R&D in their study, then a lower return on R&D could have been estimated. Part of this research involves understanding the contribution and size of R&D activities during technology import and localisation, as well as a comparison with local (in-house) R&D activities.

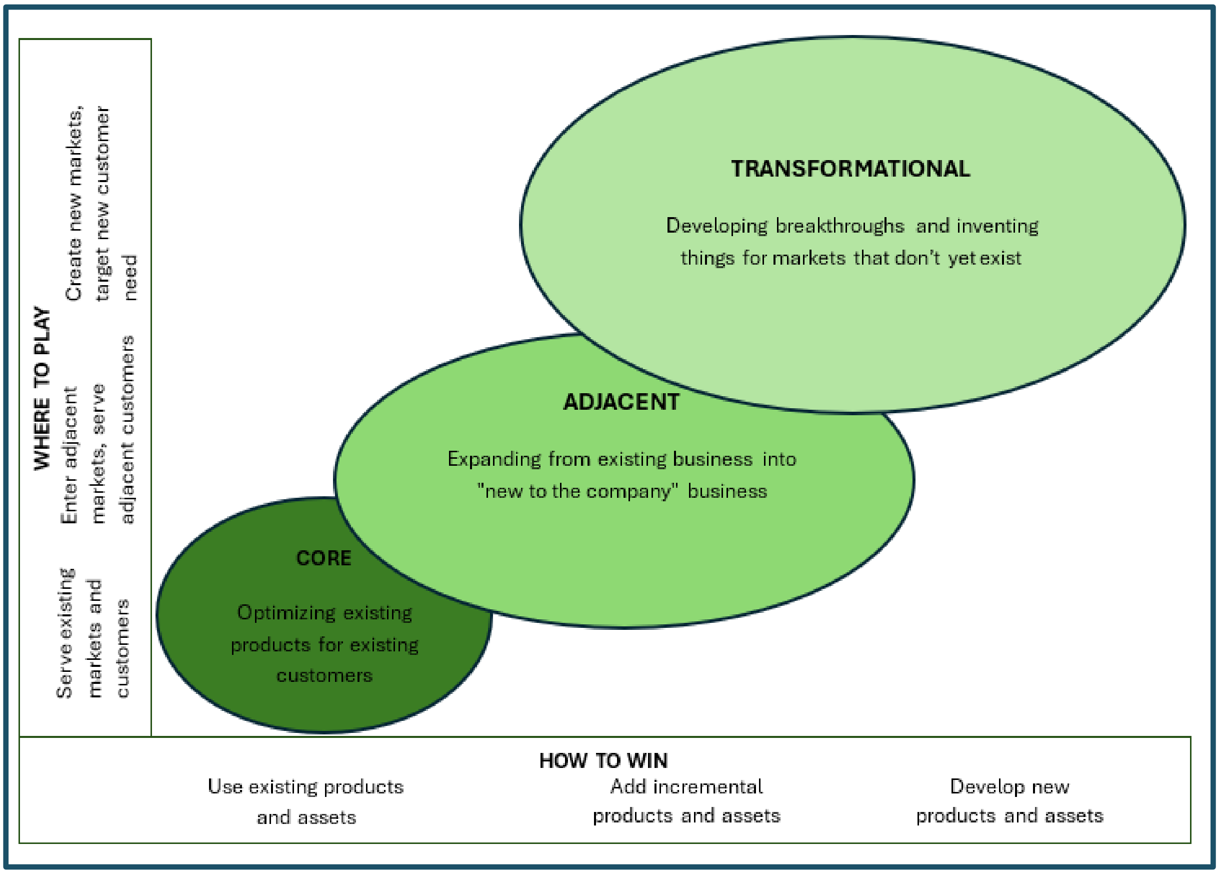
While manufacturing receives much attention in R&D studies, the services sector dominates the South African economy. As noted by Makgetla et al. (2022), the services sector accounts for approximately two-thirds of South Africa's GDP and employment. The two sectors, manufacturing and services, are highly intertwined; thus, manufacturing cannot succeed without adequate services (Makgetla et al., 2022). Among the few services R&D studies, firm-level R&D in information and communications technology (ICT) dominates in the services sub-sectors of banking, insurance, and retail (Kahn and Hounwanou, 2008). R&D is a proxy for innovation; firm-level innovation increases productivity, which in turn increases economic growth in the long term.

3.2 Science, technology, and innovation

According to the 2021/22 R&D survey, South Africa's R&D spans across two main research fields (HSRC, 2023). Division 1 is the natural sciences, technology, and engineering, while Division 2 is the social sciences and humanities. Based on R&D investment, Division 1 dominates at 78.2% while Division 2 is at 21.8%. R&D activities take place within the STII policy landscape. R&D types, also known as R&D patterns, include basic, applied, and experimental research. From this lens of R&D patterns, R&D has implications not only for innovation but for innovation types as well. Basic research focuses on theory development and empirical testing with no commercial interest in mind (Marire, 2022).

In contrast, applied research pursues knowledge to solve practical problems in society, and experimental research commercialises knowledge through developing technologies, processes, and products (Marire, 2022). Applied research emphasises immediate application, thus within the realm of core (incremental, efficiency, etc) innovation. Experimental research is the development side of the R&D process. Experimental research can either make significant improvements to existing technologies and/or create new technologies, in the form of hardware, software, or a combination. Experimental research is in the realm of adjacent (breakthrough, sustaining) and transformational (radical, disruptive) innovation. Figure 2 visualises the linkage between R&D patterns and innovation types.

Figure 2: The Innovation Ambition Matrix (a)

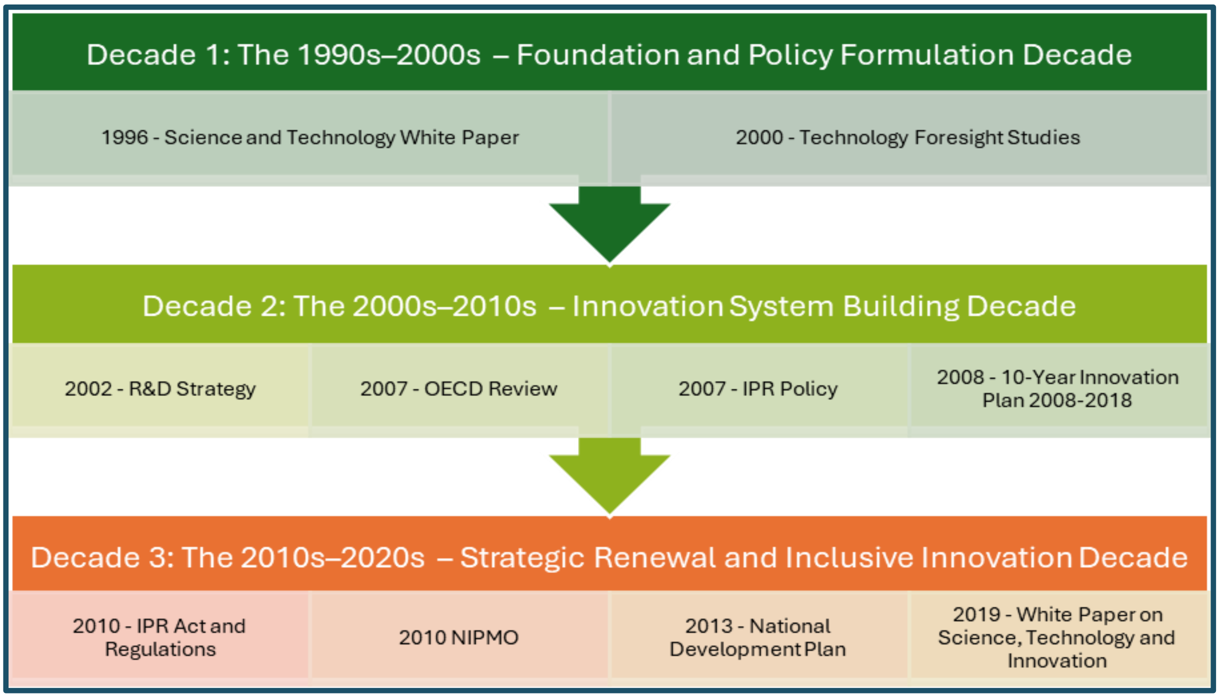


Source: Adapted from Nagji and Tuff, 2012. *Note:* (a) Circle sizes are illustrative only and reflect the 70-20-10 investment golden ratio across core, adjacent, and transformational innovation, rather than actual effort or investment levels. (Goffin and Mitchell, 2017).

The Innovation Ambition Matrix illustrates the distribution and balance of core, adjacent, and transformational innovation activities as part of an innovation portfolio. From the lens of innovation investment, the golden ratio suggests a 70-20-10 split along core, adjacent and transformational innovation (Goffin and Mitchell, 2017). Depending on whether the technologies make business sense, they are deployed in the economy – manufacturing, services, or a combination. To arrive at whether technologies make business sense or not, one must have the technological capability of confronting, adapting, developing, and mastering new technologies (Cunningham, 2018). Technological capability positions firms to innovate across products, processes, and business models.

While South Africa has continued to stimulate innovation through investment and incentives, innovation activities are underwhelming (Cunningham, 2018). A review of the STI system between 1994 and 2010 found that state funding stalled with the introduction of new policies (Marais and Pienaar, 2010). This could imply that new policies were not adequately resourced, or the same resourcing was optimised for additional policies as well. The South African STI policy landscape has evolved since 1996 (Figure 3).

Figure 3: Evolution of South Africa's STI policy landscape (1996-2019)



Source: Adapted from OECD, 2021

What is evident in Figure 3 is that the STI policy responses since 1996 are progressive. The policy responses include new institutions such as the Technology Innovation Agency (TIA) and National Intellectual Property Management Office (NIPMO). Positioning STI for industrial development requires enhanced coordination of financial, human, natural and physical resources (Jegede and Ncube, 2021).

3.3 Industrial development

Industrial development is seen as the engine for developing and growing an economy (Rodrik, 2006). Industrial policy is at the heart of industrial development. Unlike government picking winners, one view is that industrial policy is a process between government and the private sector to jointly diagnose economic blockages and propose solutions (Rodrik, 2006). Whether it is creating new markets or supporting (upgrading) existing ones, successful industrial policy requires that the state works with market actors (Fine, 1997).

South Africa previously struggled with coherence and coordination in its industrial policy (Zalk, 2014). The industrial policy response to the coherence and coordination struggle was the establishment and adoption of sector Master Plans, which brought together government, labour and the private sector (Levin, 2021). Industrial policy works best when sector-specific, thus industrial development can be launched through localisation of established sectors, as was the case for South Africa's Motor Industry Development Programme (Barnes et al., 2004). This was followed by the Automotive Production and Development Programme in 2013 and the Automotive Master Plan for 2021-2035.

Several other sector Master Plans have been developed in sectors such as Plastics, Chemicals, Poultry, Steel, Furniture, Clothing, Textile, Footwear, and Leather. Levin (2021) identified several constraints for sector Master Plans in South Africa, and they include aggregate demand; imports; electricity; input or raw material costs and availability; rate of investment; technology upgrading; R&D and supply chains; labour-related factors and human capital; collaboration; and industrial finance.

While the constraints continue to exist, the sector Master Plans remain an excellent opportunity to deepen the linkages between R&D, STI, and industrial policy. Considering that the intended impact of South Africa's industrial policy is accelerated inclusive economic and employment growth, it is imperative to harmonise and align R&D and STI activities with industrial policy, or vice versa. The next subsection unpacks employment and economic growth in South Africa.

3.4 Employment and economic growth

The South African economy is biased towards degree holders; they contribute significantly to economic growth (Bhorat et al., 2016). Lower levels of education have been systematically excluded when looking at South Africa's labour market trajectory. Essentially, there is an oversupply of lower levels of education while an undersupply of degree holders. In part, the labour market trajectory could be attributed to the structure of the South African economy, which is characterised by massive levels of inequality, poverty, and unemployment. As an example, South Africa is the second-lowest country on income share of the middle and upper-middle class (50% of the population from the 40th percentile to the 90th percentile of income earners) at ~39% (Palma and Stiglitz, 2016).

The implication is that South Africa's middle and upper-middle class is among the poorest in the world, leaving them incapable of generating enough low-end service jobs (bottom 40%), which further exacerbates poverty, inequality, and unemployment in South Africa. Regardless, failure of the South African economy to absorb school leavers and further education and training (FET) graduates implies that South Africa is receiving a low return on investment (Bhorat et al., 2016). Weak economic growth has led to low levels of employment growth in South Africa, and not sufficient to reduce the persistent high unemployment rate (TIPS, 2024a). The mismatch of workers' skills and job requirements remains a challenge. Leshoro (2013) suggests a focus on creating new businesses as an approach to reducing unemployment.

Small, micro and medium enterprises (SMMEs) have not been able to close the gap, and their contribution to GDP and employment has dropped to 20% and 56%, respectively, in South Africa according to the latest TIPS Small Business Real Economy Bulletin (TIPS, 2024b). New SMMEs could contribute to upgrading existing sectors, creating new ones, or a combination. However, these SMMEs would require strong technological capabilities. A study of SMMEs found that they do not have knowledge in some of the critical factors influencing technology adoption (Afolayan and De la Harpe, 2015). Equally, they lack understanding of the roles that these critical factors contribute to the business and the process of technology adoption.

Looking at the textile and clothing sector, which has experienced significant decline due to Rand volatility and increased imports, SMMEs adopting emerging technologies could grow their networking capabilities, export orientation, and absorptive capacity (Tassin and Rambe, 2017). Encouraging SMMEs to use emerging technologies is imperative to growing their technological capability. While it is well understood that technology absorption drives firm growth and performance, technology usage was found to be a concern among African firms (Atiase et al., 2021). The study made use of human capital, financial capital, and electricity as predictor variables; and government quality and educational quality as control variables.

Technology absorption involves some level of R&D, even if it is light in intensity. Over time, firms that have succeeded in absorbing technologies are well-positioned to grow and intensify their R&D, thus further developing their technological capability. This appears to be a logical starting point for South Africa, by rapidly growing and enhancing the technological absorption capacity of local firms so that they can achieve accelerated inclusive economic and employment growth. Achieving the intended impact of accelerated inclusive economic and employment growth requires changes on the R&D side, especially the size and rate of R&D investment. Ensuring that firms are engaged in R&D activities, including technology absorption, to keep growing firm performance and remain competitive.

The evolution of the STII policy landscape has taken place within the macroeconomic policy landscape since 1994. The macroeconomic policies include the 1994 Reconstruction and Development Programme (RDP), the 1996 Growth, Employment and Redistribution (GEAR), the 2005 Accelerated and Shared Growth Initiative for South Africa (AsgiSA), the 2010 New Growth Path (NGP), and the 2012 National Development Plan (NDP). The next section presents the suggested case study methodology and case studies for the research.

4. CASE STUDY METHODOLOGY

4.1 Methodology motivation

A case study approach was used to understand what is working and what is not working in the STII policy landscape in South Africa. Firm and/or sector-level secondary data were used. In the pursuit of understanding how R&D and innovation catalyse industrialisation, particularly within emerging economies, a case study methodology offers a nuanced and in-depth perspective. This approach is especially pertinent when examining complex, real-world phenomena where contextual variables play a significant role.

Case studies are instrumental in theory building and hypothesis generation, particularly in areas where existing theories are inadequate or underdeveloped. Eisenhardt (1989) posits that case study research is valuable for developing new theoretical constructs and propositions, as it allows for the identification of patterns and relationships within complex data. In the context of industrial innovation, where rapid technological changes often outpace theoretical frameworks, case studies offer a means to generate grounded theories that reflect current realities. For example, Kalinowski et at. (2025) used case studies to explore Lean R&D practices in industry-academia collaborations. Their work resulted in the development of frameworks that enhance collaborative innovation efforts.

The case study methodology is particularly well-suited for exploring the multifaceted nature of industrialisation through R&D and innovation. Industrial innovation processes are inherently complex, involving a confluence of technological advancements, organisational dynamics, and socio-economic factors. Case studies enable researchers to delve deeply into these complexities by providing rich, contextual insights that other methodologies may overlook (Yin, 2009). This approach allows for a holistic examination of the phenomena, capturing the nuances and interdependencies that characterise industrial innovation ecosystems.

One of the primary strengths of the case study approach lies in its ability to investigate contemporary phenomena within their real-life contexts, especially when the boundaries between the phenomenon and context are not clear (Yin, 2014). In the realm of industrial R&D, where innovation processes are influenced by a myriad of internal and external factors, understanding the context is crucial. For instance, the adoption of new technologies in manufacturing is not solely a technical endeavour but also involves organisational change, workforce adaptation, and strategic alignment. Case studies facilitate an in-depth exploration of these dimensions, providing comprehensive insights into the implementation and impact of such innovations (Fekrisari and Kantola, 2024).

4.2 Case study description

Based on the analysis in the literature review, a series of case studies would contextualise the opportunities and challenges in the development and absorption of technology by different strata of businesses in South Africa. Secondary data has been used for each case study. The suggested case studies are described in the following five sub-sections.

4.2.1 Launching a new sector

This case study focuses on South Africa's efforts to create entirely new industries rooted in emerging technologies and strategic national priorities. Examples include the HySA programme, aimed at building a hydrogen economy based on the country's platinum reserves; biotechnology, supported through the National Biotechnology Strategy and innovation centres; and the development of the Joule EV, an ambitious attempt to enter the electric mobility market. These initiatives represent bold steps toward R&D and innovation-led growth. However, while they showcase the country's visionary policy orientation, many faced challenges related to funding, market uptake, and long-term sustainability.

4.2.2 Upgrade of existing sector

This case study explores how South Africa has tried to modernise traditional sectors such as energy through advanced technologies like UCG, carbon capture and storage (CCS), and the PBMR. These projects aimed to increase efficiency and environmental performance of existing sectors, particularly mining and energy. While technically ambitious, most of these initiatives have struggled with issues such as cost overruns, lack of public support, and limited implementation. Nonetheless, they reflect important attempts at industrial modernisation through R&D.

4.2.3 University spin-offs

This theme examines how universities are translating academic research into marketable innovations and start-ups. Examples include UTF, which provides venture capital for university-based innovations; the SMME Fund, targeting small and emerging businesses from academia; and Innovus at Stellenbosch University, a leading example of technology transfer and entrepreneurial development. These spin-offs highlight the importance of knowledge deployment and academia-industry linkages for technology and innovation-led start-ups.

4.2.4 Technology development and innovation

The case study cuts across sectors and focuses on domestic technological capabilities, including in-house R&D by firms, government-supported programmes, and innovation hubs. It includes successes and failures in mobilising local scientific knowledge for industrial application. It reflects the foundational need to invest in the full innovation pipeline from basic research to commercialisation while exposing structural constraints such as limited absorptive capacity in firms and misalignment between public and private R&D efforts.

4.2.5 Digital economy

The case study focuses on how South Africa is leveraging digital technologies to transform sectors and create new economic opportunities. Case studies like Takealot's township expansion and Tyme Bank's digital banking for the underbanked show how digital platforms can improve inclusion, convenience, and economic participation. The digital economy offers promising avenues for both extensive (new market creation) and intensive (efficiency gains) growth, although access disparities and digital skills gaps remain a challenge.

5. CASE STUDIES, DATA, AND ANALYSIS

5.1 Launching a new sector

5.1.1 Hydrogen South Africa

HySA was officially launched in 2008 as a long-term (15 years) research, development, and innovation (RDI) strategy on hydrogen and fuel cell technologies. The vision was to bring about wealth, jobs, and intellectual property rights (IPR) creation through the initiation of new high technology industries based on minerals found on South African soil, especially Platinum Group Metals (PGMs). South Africa has more than 75% of the world's known PGM reserves. HySA is structured into three distinct five-year phases:

i. Phase 1 (2008–2013): This initial phase focused on establishing foundational infrastructure and human capital. It saw the creation of three Centres of Competence: HySA Catalysis, HySA Infrastructure, and HySA Systems. These centres were instrumental in recruiting international experts, developing research facilities, and initiating the first wave of hydrogen and fuel cell technology research and development, laying the groundwork for subsequent advancements.
ii. Phase 2 (2013–2018): The second phase aimed at technology demonstration and validation. During this period, the programme emphasised showcasing the practical applications of hydrogen technologies in real-world settings. Efforts included pilot projects like powering rural schools with fuel cells and forming strategic partnerships with industry stakeholders to test and refine technologies. This phase was crucial in transitioning from theoretical research to tangible, demonstrable solutions.
iii. Phase 3 (2019–2024): The focus shifted to commercialisation and scaling up. The programme aimed to bring hydrogen technologies to market, reduce costs through mass manufacturing, and enhance the durability and reliability of these technologies. This phase also involved fostering public-private partnerships to facilitate the adoption of hydrogen solutions in various sectors, thereby contributing to economic growth and job creation.

HySA is divided into Catalysis, Systems and Infrastructure. Catalysis is hosted at the University of Cape Town (UCT) and Mintek, Systems at the University of the Western Cape (UWC), and Infrastructure at the North-West University (NWU) and the Council for Scientific and Industrial Research (CSIR). HySA was established to achieve a 25% share of the global Hydrogen and Fuel Cell market using novel PGM catalysts, components, and systems. Table 3: next shows some of HySA's innovation outputs since around 2010/11 when each centre was operational.

Table 3: HySA Innovation Outputs

	CATALYSIS	SYSTEMS	INFRASTRUCTURE
Master's	-	3	37
PhD	-	3	10
Papers	31	161	269
Patents	-	15	5
Trademarks	-	-	4

Source: University of Cape Town, University of the Western Cape, and Nelson Mandela University websites.

Based on Table 3, it appears that the focus has been largely on academia through publication and human resource capacity development through Master's and PhD qualifications. At the same time, the three centres of excellence have produced prototypes aligned with their focus areas with promising commercial applications.

It is estimated that South Africa has invested approximately R100 million per annum in HySA since 2008, implying that ~R1.7 billion has been invested since inception. Recently, 2022/23, HySA is located within the South African National Energy Initiative (SANEDI) under the DSTI Energy Secretariat. As noted in SANEDI's 2023/24 Annual Report, the purpose of HySA is to develop materials, components, and units in the early part of the fuel cell, stacks, as well as electrolyser catalysts and membrane electrode assemblies; and also to capitalise on abundant renewable resources in South Africa and deliver technologies for hydrogen production (linked to renewable energy), storage, and distribution.

The expected institutional outcomes of HySA under SANEDI are as follows:

- HySA Infrastructure as project partner responsible for the installation of the electrolyser for green hydrogen production at Masia Village.
- HySA Systems has signed six collaboration agreements with various entities (e.g. TF Design Pty Ltd – design, manufacturing and start-up of hardware related to hydrogen and fuel cell technologies).

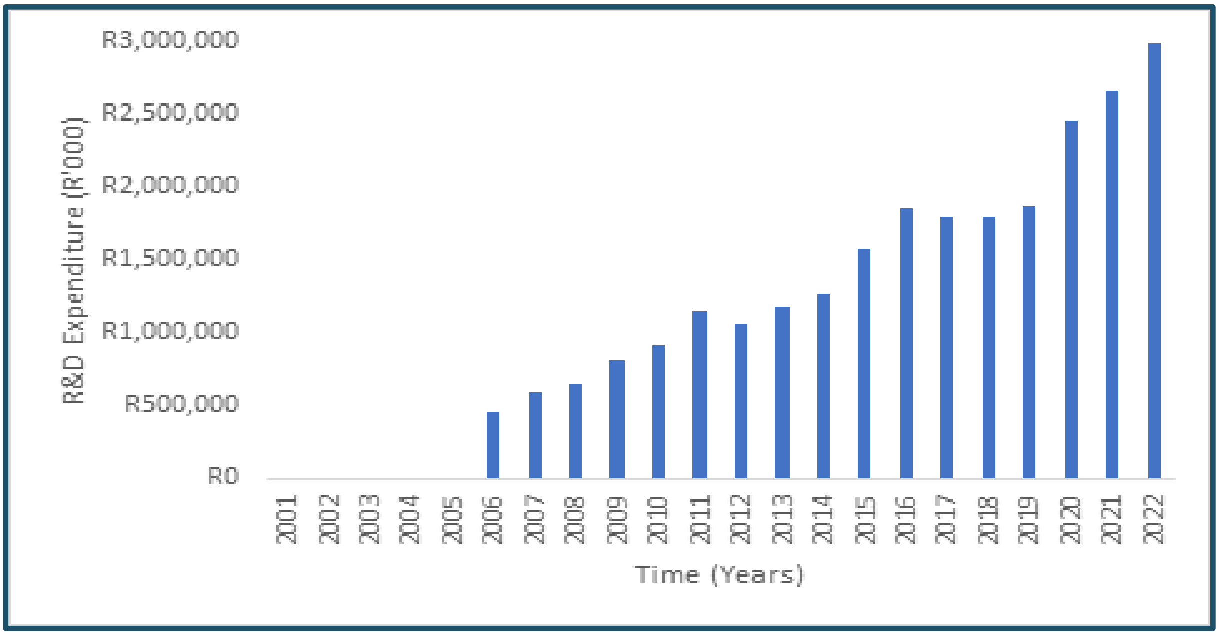
In 2023/34, the total expenditure on the DSTI Energy Secretariat was R10.4 million, of which 42% is personal expenditure. Between 2022/23-2023/24, SANEDI disbursed R421 million for Energy Secretariat research costs to third parties.

5.1.2 Biotechnology

Biotechnology can make important contributions to South Africa's priorities, such as human health, food security and environmental sustainability. South Africa's biotechnology strategy was developed in July 2001. The strategy focused on new institutional arrangements and actions for a government department. Key to the strategy is the creation of several regional innovation centres (RICs), which would hold the development of biotechnology platforms together, including bringing together industry and academia.

The main outcome of the RICs is economic growth and employment through innovation. Equally, it was envisioned that the RICs would stimulate the creation of IPs. At the onset, a R182 million budget was suggested for the RICs, R&D programmes, biotechnology advisory council, and venture capital funding. Biotechnology R&D investment has been on the rise since 2006 (Figure 4).

Figure 4: Biotechnology R&D investment



Source: CeSTII, 2022.

Based on this dataset, approximately R25 billion has been spent on biotechnology R&D since 2006. In 2013, the bioeconomy strategy succeeded the biotechnology strategy. On the outputs and outcomes side, data obtained from National Advisory Council on Innovation (NACI) STI indicators include publications, patents, contributions to GDP, and employment. Table 4 shows publications since 2013.

Table 4: South Africa number and world share of biotechnology and applied microbiology publications (articles and reviews only)

YEAR	NUMBER OF PUBLICATIONS	WORLD SHARE (%)
2013	187	0.64
2014	243	0.79
2015	183	0.59
2016	221	0.74
2017	235	0.73
2018	238	0.77
2019	283	0.88
2020	279	0.80
2021	265	0.76
2022	240	0.68
Base: 2013–2015	**204**	**0.67**

Source: NACI, 2024. STI Indicator report.

Table 5 shows biotechnology patent applicants and grants.

Table 5: South Africa biotechnology patent applications and patent grants at the European Patent Office

YEAR	APPLICATIONS	GRANTS
2013	2	4
2014	3	1
2015	0	6
2016	7	3
2017	7	3
2018	10	4
2019	3	7
2020	5	6

2021	2	2
2022	3	1
Base: 2013–2015	**2.67**	**3.67**

Source: NACI. 2024. STI Indicator report.

The biotechnology focuses on the technology, while the bioeconomy focuses on broader economic contribution of the bio sector.

5.1.3 Bioeconomy

The bioeconomy potentially offers significant economic value that is far beyond what is captured by biotechnology alone, and it is fundamental to strategies for inclusive industrial development, environmental sustainability, and job creation in South Africa.

Table 6 shows bioeconomy's contribution to GDP.

Table 6: Bioeconomy GDP output and share of total South African GDP

YEAR	BIOECONOMY GDP OUTPUT (R' MILLION AT CONSTANT 2025 PRICES)	BIOECONOMY'S SHARE OF TOTAL GDP (%)
2013	308 490	7.96
2014	319 083	8.11
2015	316 434	7.95
2016	311 091	7.75
2017	331 680	8.17
2018	355 945	8.14
2019	330 490	7.99
2020	326 816	8.31
2021	350 152	8.58
2022	349 733	8.41
BASE: 2013–2015	314 669	8.00

Source: NACI, 2024. STI Indicator report.

As noted in NACI's report, in 2022, the share of bioeconomy in total GDP (8.41%) was only marginally higher than at the onset of the strategy (8.0%). Table 7: shows the contribution to employment.

Table 7: Bioeconomy sector employment

	BIOECONOMY EMPLOYMENT	% TOTAL SA EMPLOYMENT
2013	1 605 942	10.7
2014	1 572 579	10.3
2015	1 821 920	11.6
2016	1 781 840	11.3
2017	1 750 643	10.9
2018	1 728 388	10.6
2019	1 718 497	10.6
2020	1 588 817	10.6
2021	1 545 589	10.7
2022	1671 333	10.9
Base: 2013 -15	1 666 814	10.9

Source: NACI, 2024. STI Indicator report.

As noted in NACI's report, the bioeconomy's share of total South African employment in 2022 is the same as it was at the onset of the strategy (10.9%). On employment and GDP, the contribution of both the biotechnology and bioeconomy strategies is minimal.

5.1.4 Joule electric vehicle

South Africa, through Optimal Energy, developed four EVs, Joule, prototypes in 2008. A total of R315 million was spent by 2012 on R&D and prototype development when Optimal Energy was shut down. Industrial Development Corporation (IDC) invested R300 million, and DSTI's Innovation Fund invested R15 million. The commercialisation of Joule was estimated at R9 billion. The main investor at the time, the government, did not proceed with the investment due to reasons such as the EV market not being viable at the time. Joule's growth was largely based on the export market at the time.

Joule was founded by two mechanical engineers who were previously actively involved in the Southern African Large Telescope. Joule prototypes were showcased around the world, yet it does not seem to have secured early customers and private investors. The innovation chasm, or technology valley of death, is cited by the founders as the cause for the failure. The requested R9 billion investments to Joule's large scale production facility is ~28 times the R315 million invested to produce 4 Joule prototypes.

5.2 Upgrading existing sector

5.2.1 Underground coal gasification

UCG is a gasification process applied to non-mined coal seams, using injection and production wells drilled from the surface, which enables the coal to be converted in situ into product gas. As noted by Zieleniewski and Brent (2008), UCG delivers gas suitable for synthesis, production of fuels and electricity, or for home usage. Between the year 2002 and 2007, Eskom developed and piloted Ergo Exergy's proprietary technology, Exergy UCG™ Technology, for Majuba Power Station. The output gas is core-fired in the coal burners; the pilot could co-fire a single burner at Majuba and contributed 6MW of electricity. On a successful pilot, the commercial plant would contribute 1.2GW of Majuba's 4.6GW capacity.

Unmined and unminable coal deposits, with such obstacles to mining as high fault frequency, volcanic intrusions and other complex depositional and tectonic features, are well suited for UCG. Majuba has unamenable coal deposits caused by multiple dolerite intrusions, which led to the closing of some of the mines. The prefeasibility in 2003 confirmed that the site is economically viable and suitable for Exergy UCG™ Technology, hence the decision to proceed with an industrial pilot to determine feasibility.

Exergy UCG™ Technology is designed in a way that reduces impact on the environment, such as air, soil, and water, and it is much more energy efficient than traditional gasification. Considering the declining coal reserves in South Africa, making traditional coal mining methods economically unviable, UCG is an alternative (Pershad et al., 2018). Eskom's use of Exergy UCG™ Technology falls under technology import and localisation.

According to Pershad et al. (2018), Eskom demonstrated the following with the 2007 Majuba pilot plant:

i. The technology provides cost-competitive fuel for future power generation. It derives this fuel from local, unused coal resources shielded from international market forces.

ii. It has been qualitatively proven that the technology works and is able to extract value from one of the most geologically complex coalfields in South Africa.

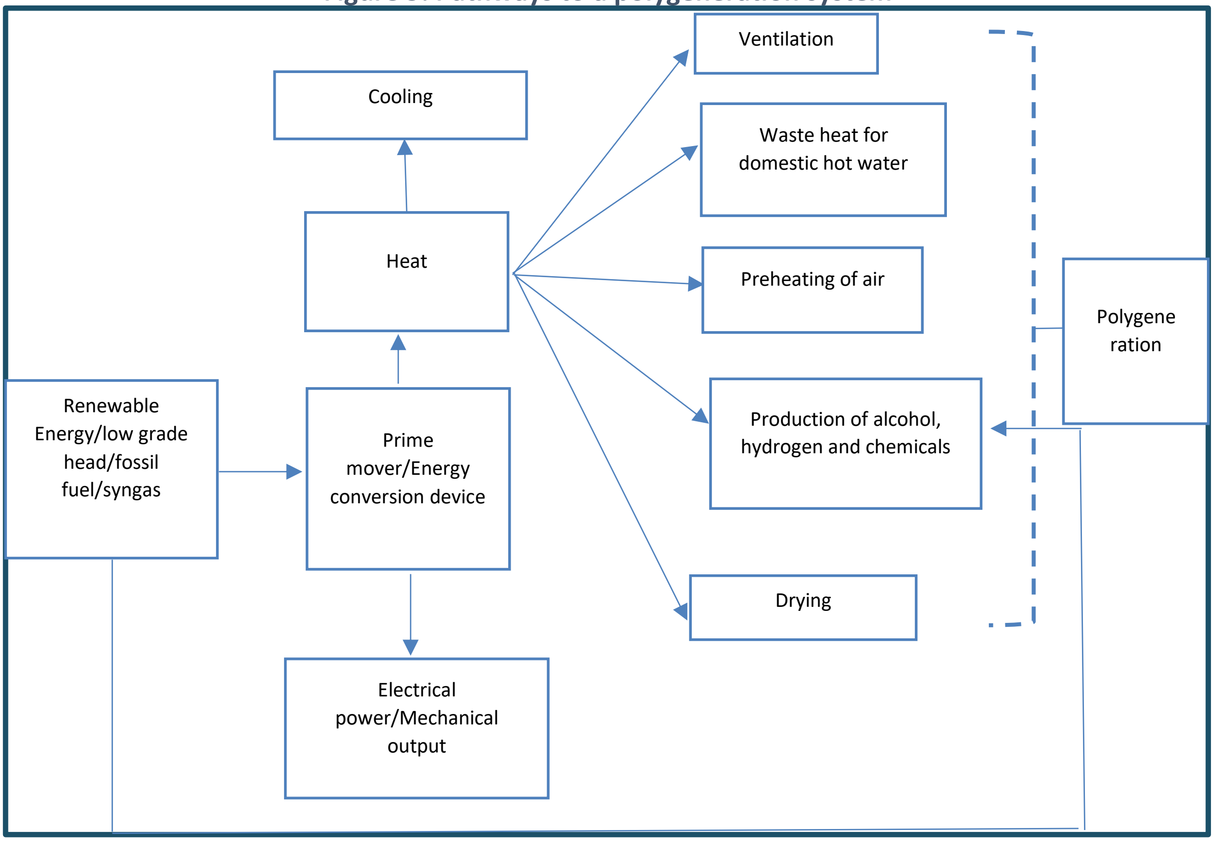
iii. There is a need to further quantify the performance of UCG™ technology, so that it can be optimised.

iv. The Eskom Board supports the technology, but due to Eskom's current financial constraints, a partner will be sought to further commercial development.

v. Eskom will, in parallel, shut down and rehabilitate the initial Majuba gasifier as part of the original research intent.

Beyond electricity generation, UCG can make other products, as shown in Figure 5.

Figure 5: Pathways to a polygeneration system



Source: Pershad et al., 2018.

To advocate for UCG, South African Underground Coal Gasification Association was established. To date, since 2002, it is estimated that Eskom has spent approximately R1 billion on the RDI of the Exergy UCG™ Technology and other related technologies.

5.2.2 Carbon capture and storage

Air pollution caused by burning coal is a health concern. Mpumalanga, a coal-intensive region where both Sasol and Eskom operate, is characterised among the worst air-polluted areas in the world, resulting in over 2200 deaths annually. The Council for Geoscience developed a R426 million CCS pilot in Leandra, with a grant funded by the World Bank Carbon Capture and Storage Trust Fund. The South African government provided financing equivalent of 65% of the amount.

The purpose of the pilot is to assess the feasibility of carbon dioxide (CO_2) in South Africa. While South Africa emits 500 million tonnes of CO_2 per annum, it has a theoretical geological storage capacity of 150 billion tonnes. CCS is a proven technology; it is downstream of the technology that requires further development at each location. Two demonstrations of CoalCO_2-X technology have been conducted at a cement plant in Limpopo and a power station in Gauteng. CoalCO_2-X technology captures carbon and converts it into fertilizer salt.

On R&D, the South African government established the South African Centre for Carbon Capture and Storage (SACCCS) within SANEDI in 2009. The CoalCO_2-X technology is under the DSTI Energy Secretariat, hosted within SANEDI. SANEDI has to date received approximately R421 million from DSTI. In partnership with SACCCS, the Council for Geoscience, and other international universities, the University of Pretoria (UP) has hosted the largest CCS research working group in South Africa since 2012.

The pilot still needs to be operated as part of the feasibility study with other funding, as the World Bank Carbon Capture and Storage Trust Fund was up to pilot installation.

5.2.3 Pebble Bed Modular Reactor

Pebble Bed Modular Reactor (SOC) (PBMR™) was established in 1999 in South Africa with the intention to develop and market small-scale, high-temperature reactors both locally and internationally. The PBMR is a helium-cooled, high-temperature reactor. Its ability to economically generate electricity and create high-value co-products such as hydrogen for the fuel of the future, desalinated water, and industrial or residential process heat, not only sets it apart from all previous nuclear reactors, but also from the next generation of energy sources.

The investors for PBMR included the South African government, IDC, Eskom, and Westinghouse from the United States. PBMR is a wholly owned subsidiary of Eskom. PBMR is a German technology from the 1950s that could not reach commercialisation due the anti-nuclear lobby in Europe following the fall of the Berlin Wall in the late 1980s. A feasibility study concluded in 2002 confirmed the viability of the technology in South Africa. The next phase was a prototype of a single module pilot demonstration at Koeberg Nuclear Power Station in Cape Town.

PBMR was established based on an annual sale of 30 units, with 20 on exports. To maintain scale economics, at least five units are required to be sold annually. Following the 2002 feasibility study, further investment was made in preparation for the pilot demonstration (Table 8:).

Table 8: Funding to PBMR in R'000 000

	2005/06	2006/07	2007/08	2008/09	2009/10	TO 2009/101/%
South African govt.	509	1056	2195	1009	1700	7595/81
Eskom	0	0	0	0	0	817/9
IDC	193	0	0	0	0	450/5
Exelon	0	0	0	0	0	102/1
Westinghouse	146	0	0	0	0	457/5
Total	848	1056	2195	1009	1700	9422/100

Source: Thomas, 2011.

As noted by Thomas (2011), PBMR's total investment by 2009/10 was R9,4 billion, with South Africa's government having invested R7.5 billion. The project required an additional R30 billion to commercialise the PBMR technology through a pilot (Thomas, 2011). The South African government continued to pour investment into the project had not confirmed any customers or new international investors. The challenge of securing customers and investors is like that of Joule EV. Unique to the PBMR is the very high cost of the pilot demonstration. The PBMR was finally discontinued due to high costs, technological challenges, and difficulties in obtaining investors (DMRE, 2017).

5.3 University spin-offs

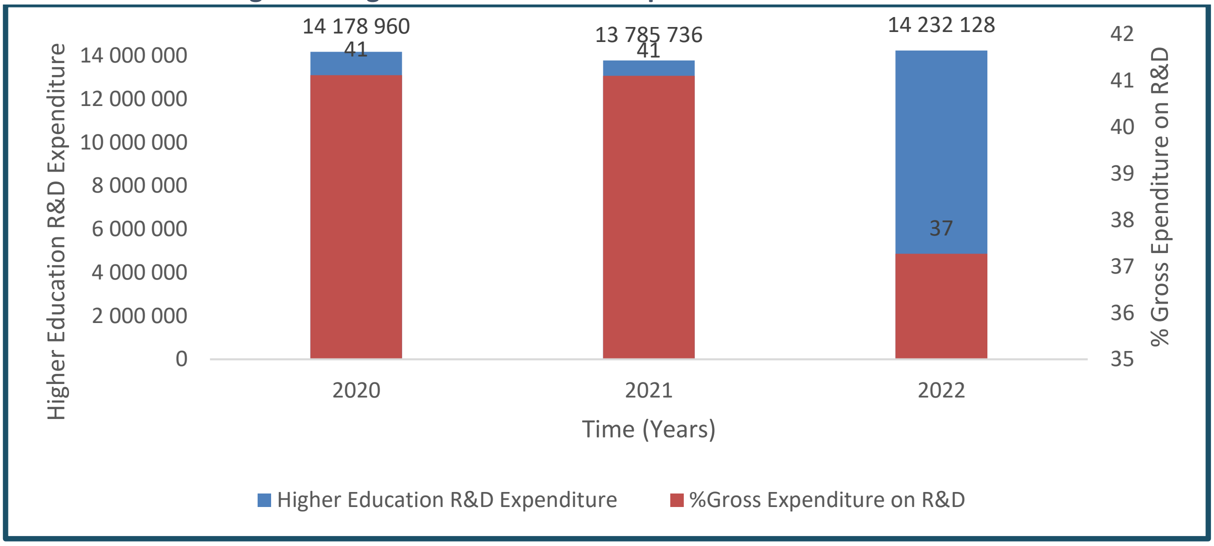
5.3.1 University Technology Fund

The University Technology Fund focuses on technologies emanating from South Africa universities. The fund supports the IPR-PFRD Act. Investors and founding partners include the SA SME Fund, UCT, Stellenbosch University (SU), Small Enterprise Finance Agency (SEFA), TIA, Tamela, and Stocks and Straus (also appointed a fund manager).

Since its establishment in 2020, the fund has invested in about 22 technologies across Seed, Series Seed, and Seed funding. The technologies are in biotechnology, health, artificial intelligence (AI), energy generation, and nanotechnology in space. The investment portfolio seems to be concentrated between UCT and SU, with a single investment at UP. Both SU and UCT invested R7.5 million in UTF I, of which the overall amount was R150 million, with SA SME Fund and Stocks and Straus contributing R125 million and R17.5 million, respectively.

UTF II was announced in January 2025 with R400 million investment. UP and the University of Witwatersrand (Wits) have joined as co-investors in UTF II. The focus of UTF II is on 15-20 companies having highly scalable technology IP across various sectors. Furthermore, UTF II caters to alumni of South African universities. While the UTF is progressive, it is worth noting that it focuses on the most practical projects and only scratches the surface as an investment to commercialise R&D in universities. Thus, it can be viewed as a pilot to universities R&D commercialisation. Between 2020 and 2022, South African universities spent R42 billion on R&D, on average, this funding accounts for 40% of GERD (Figure 6).

Figure 6: Higher education R&D expenditure and as % of GERD



Source: CeSTII, 2022.

Much more commercialisation investment is certainly needed to make an impact on R&D outputs emanating from South African universities.

5.3.2 Innovus

Innovus is an enabler for commercialising SU's IP through licensing or spin-out companies as part of SU's fourth revenue stream. The inventors and SU retain shareholding in spin-out companies. Although now governed by the IPR-PFRD Act of 2008, Innovus was established in 2002. Innovus is surrounded by other complementary SU enterprises to drive technology commercialisation. This includes sourcing funds and establishing a network to support the commercialisation strategy of either licensing or spin-out companies. The decision for spin-out or licensing is guided by parameters shown in Table 9.

Table 9: Technology commercialisation pathways

SPIN OUT	LICENSING
Offers a complete solution, e.g., software	Offers only part of a solution, e.g., mineral processing optimisation technique
Disruptive; changes paradigms	Offers an alternative to existing solutions
In an industry where spin-offs are an established commercialisation pathway, e.g., biotech, ITC	Technology not usually commercialised by a startup, e.g., chemical processes or single yeast
Scalable product range	Single product
Entrepreneurial team and a champion	Researcher, not interested in spinout

Source: Innovus,2023.

Between 2019 and 2023, Innovus's impact is as follows:

Table 10: Innovus's impact between 2019 and 2023

INDICATOR	VALUE (#)
Ideas developed	178
Provincial patents	33
Patent Cooperation Treaty (PCT) applications	49
Licenses	54
Current spin-out companies	33

Source: Innovus, 2023.

Since 1998, when the holding company US Enterprises was established, the impact on spin-out companies has been impressive. There has been quite a growth of spin-out companies since 2017. The South African National Survey of Intellectual Property and Technology Transfer is a survey to track overall activity in IP management and technology transfer at publicly funded research institutions in South Africa. Two surveys have been conducted, the baseline one from 2008-2014, and the second for 2014-2018. The third survey, 2019-2023, is currently underway. According to the survey, patents, spin-out information, and invention disclosure revealed a steady increase across publicly supported institutions.

The growth of spin-offs was particularly noted in the second survey (2014-2018), with Innovus playing a leading role. This shows that Innovus' performance is consistent with the larger national trend of increasing commercialisation capacity, demonstrating the survey's usefulness in evaluating the policy. After all, policy monitoring and evaluation is imperative in driving policy effectiveness.

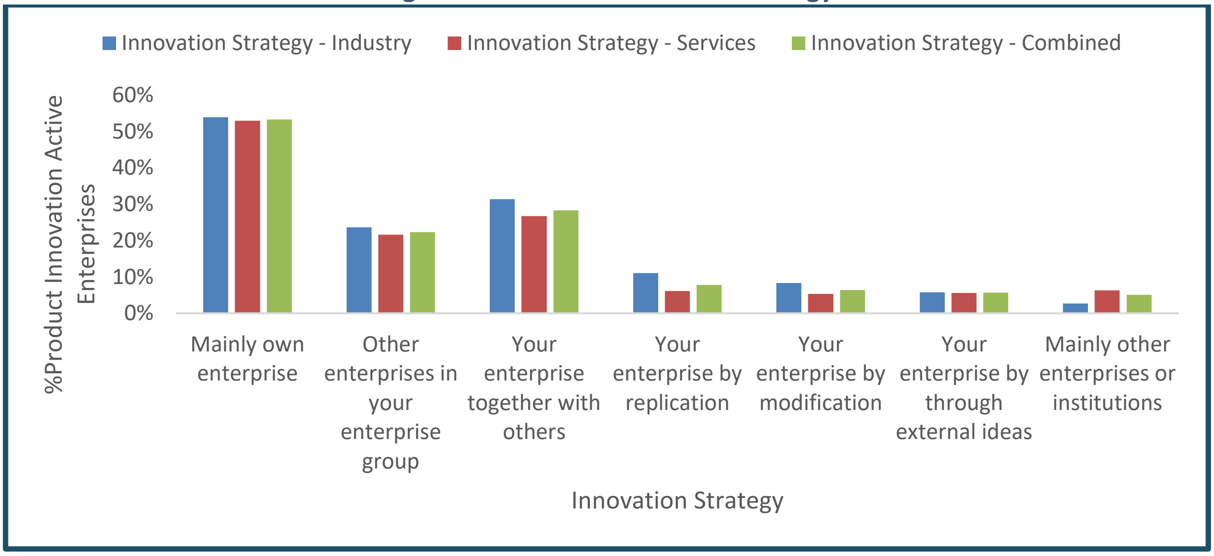
5.4 Technology development and innovation

The data in this section is focused on innovation-active firms in South Africa based on the innovation survey 2019-2021.

5.4.1 Innovation strategy and outcome

Product innovation strategies are a replication of how firms translate their R&D investment, expertise, and capabilities into marketable products. Among these strategies, product innovation is a key component as it directly influences customer demand, competitiveness, and market expansion. It's imperative for policymakers to understand these strategic orientations, as they indicate whether firms are driving industry diversification, opening new markets, or reinforcing existing ones. The innovation strategy depicted in Figure 7 demonstrates innovation choices made by innovation-active firms.

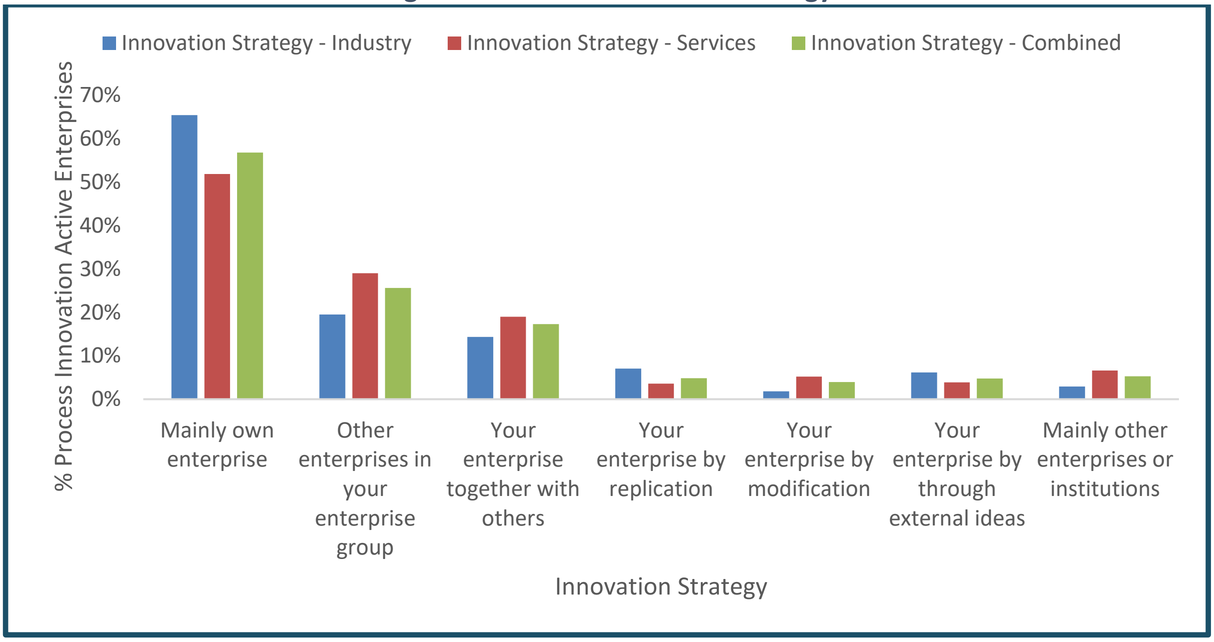
Figure 7: Product innovation strategy



Source: CeSTII 2019-2021 Innovation Survey.

Innovation active firms in South Africa largely develop product innovation while collaborating with external partners. This reflects the importance of internal capacity, as well as networks and knowledge spillover in driving innovation (OECD, 2018). The existence of incremental approaches such as replication and modification further indicates how firms adjust innovation to local contexts and resource constraints, a trend typical in emerging economies (World Bank, 2021). Overall, Figure 7 shows that while independence is vital, collaboration and external influences play an increasing role in shaping innovation outcomes. This is how firms approach product innovation. The pattern is similar for process innovation (Figure 8).

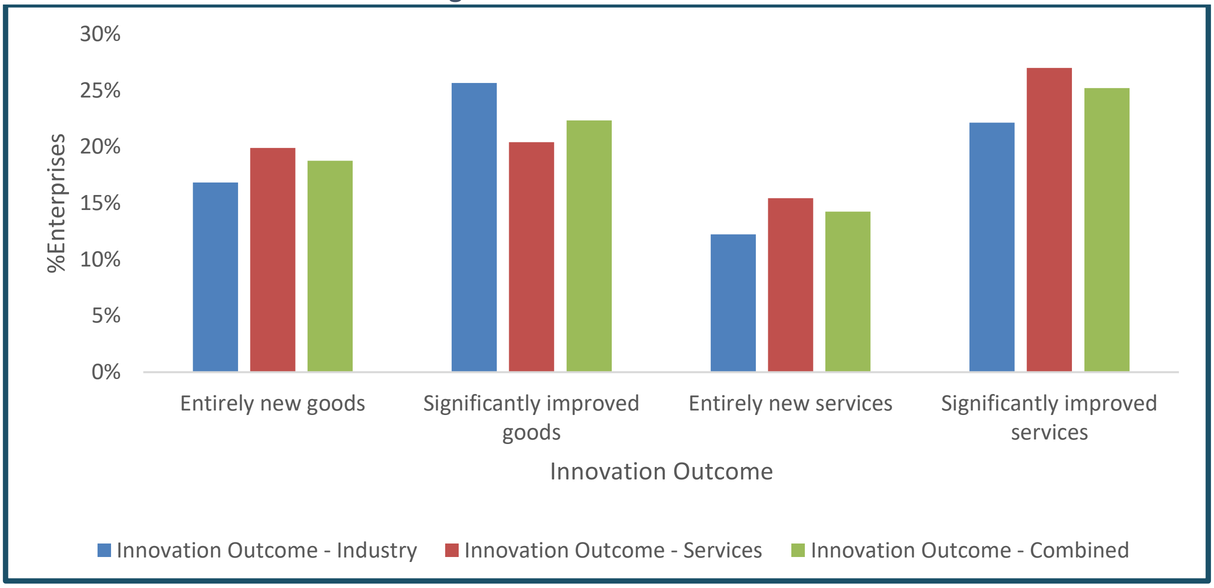
Figure 8: Process innovation strategy



Source: CeSTII 2019-2021 Innovation Survey.

The similar pattern on product and process innovation strategies, Figure 7 and Figure 8 respectively, suggests that firms decide on an innovation strategy, regardless of the type of innovation. Firms may use comparable innovation strategies, but their outcomes vary based on capabilities, market conditions, and sectoral context (OECD, 2018). Figure 9 demonstrates the innovation outcomes for South African innovation active firms.

Figure 9: Innovation outcome



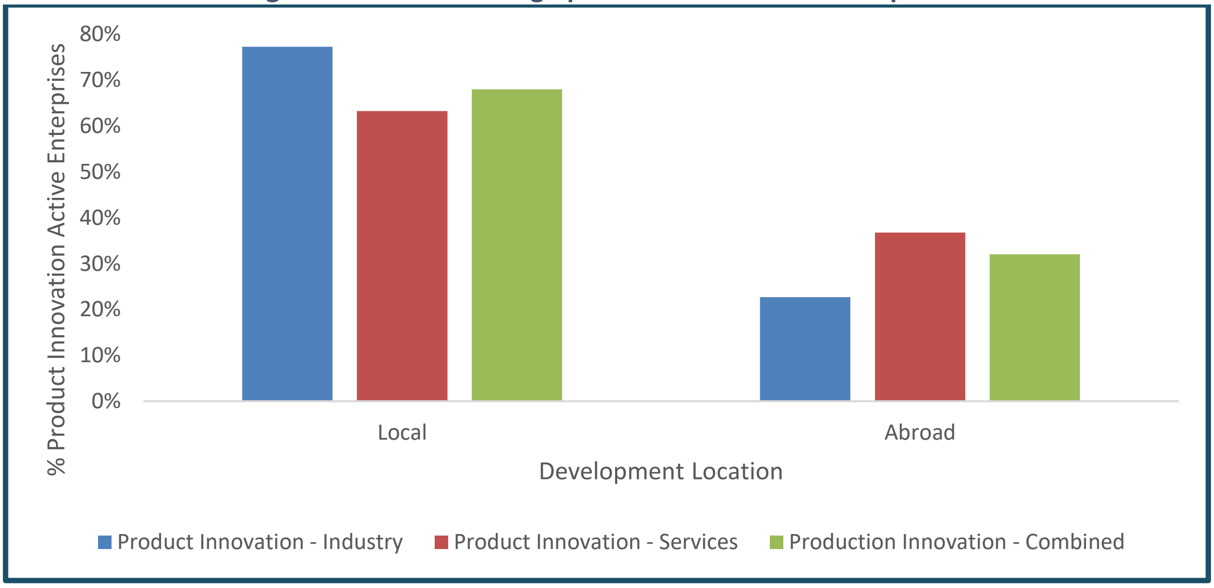
Source: CeSTII 2019-2021 Innovation Survey.

Figure 9 depicts the percentage of firms that reported launching completely new products or significantly enhanced goods and services. This offers a useful counterpoint to the earlier discussion of innovation strategies, as strategies reflect a firm's intent while innovation outcomes show adherence to strategy. Figure 9 shows that innovation outcome is biased towards improving existing goods and services when compared to entirely new goods and services. Through demand-side policy instruments such as public procurement for innovation, innovation active firm could consider shifting their strategies to creating new goods and services (Guerzoni and Raiteri, 2015).

5.4.2 Product innovation

Figure 10 shows product innovation development location.

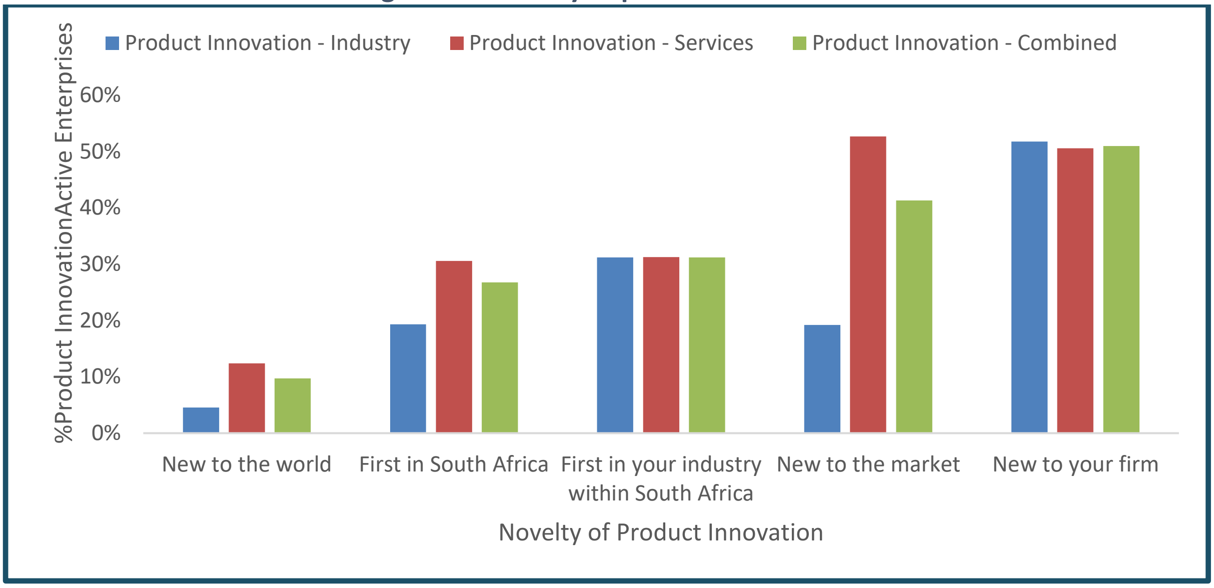
Figure 10: Local vs foreign product innovation development



Source: CeSTII 2019-2021 Innovation Survey.

Figure 10 shows that South African firms largely focus on in-house product innovation development while collaborating with international partners. It is crucial to strike a balance between local and international innovation to ensure sustainability, inclusivity, and responsiveness to South Africa's unique socioeconomic challenges. Figure 11 shows the novelty of product innovation.

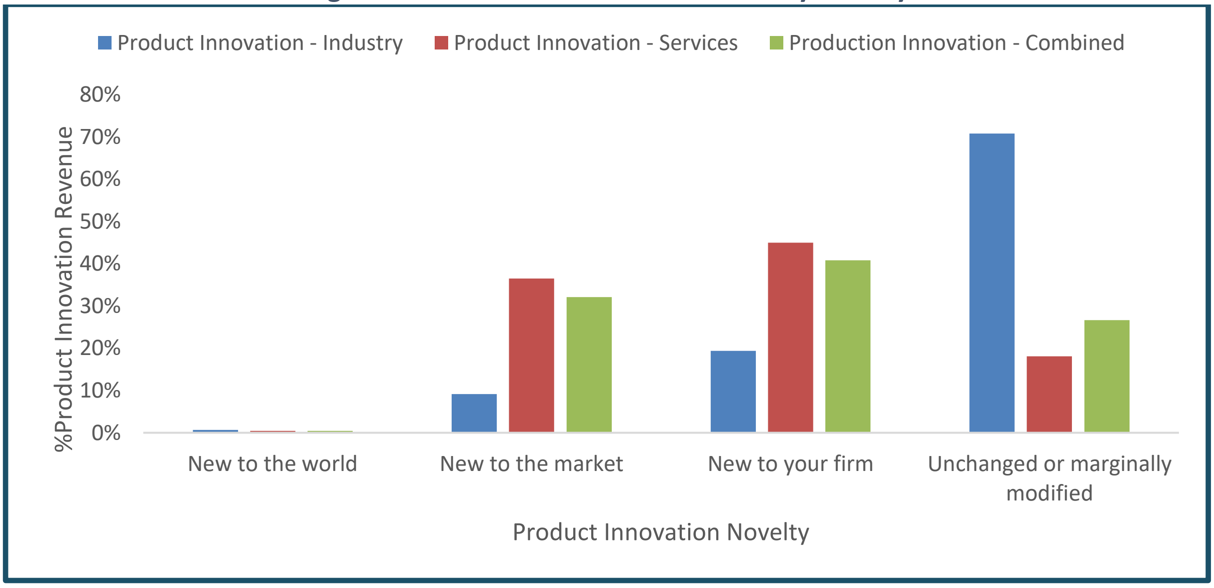
Figure 11: Novelty of product innovation



Source: CeSTII 2019-2021 Innovation Survey.

Figure 11 shows product innovation new to the firm dominates, followed by new to the market, first in the industry in South Africa, first in South Africa and lastly new to the world. The low score on new to the world suggests low levels of original innovation among South African innovation active firms. This could be attributed to the shift to largely applied research when compared to basic and experimental research (Marire, 2022). Product innovation revenue further highlights this finding. Figure 12 shows product innovation revenue contribution by novelty.

Figure 12: Product innovation revenue by novelty



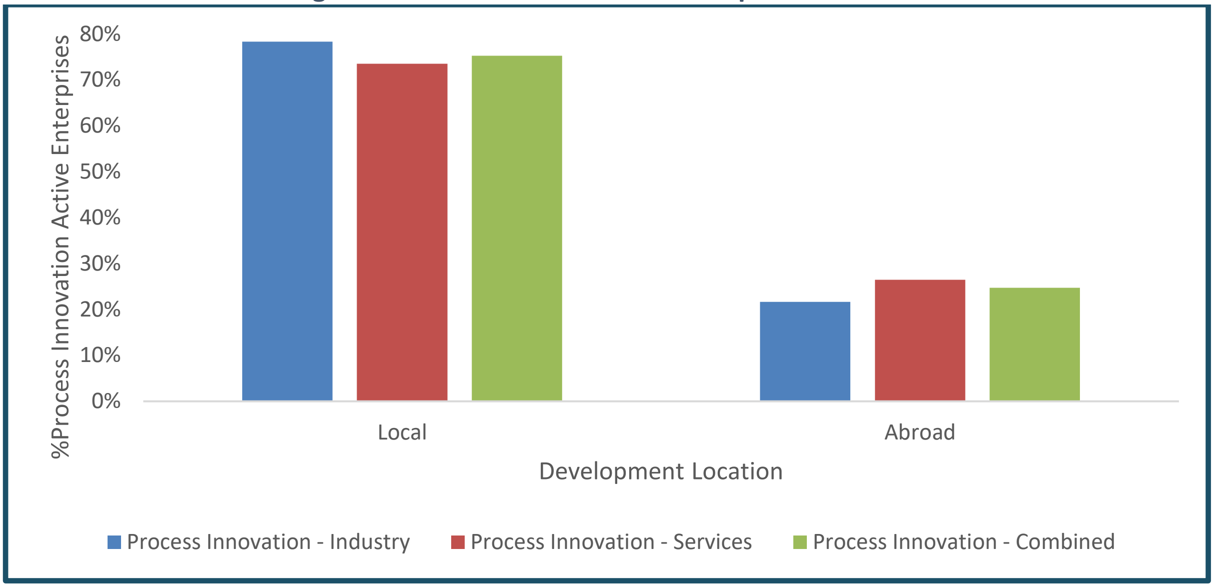
Source: CeSTII 2019-2021 Innovation Survey.

The total revenue based on product innovation in 2021 of the 21062 innovation active firms was R4426 billion, with product innovation new to the world making a significantly lower contribution. This is aligned with Goffin and Mitchell (2017)'s findings that the majority of revenue is generated from routine and incremental innovation.

5.4.3 Process innovation

Figure 13 shows the process innovation development location.

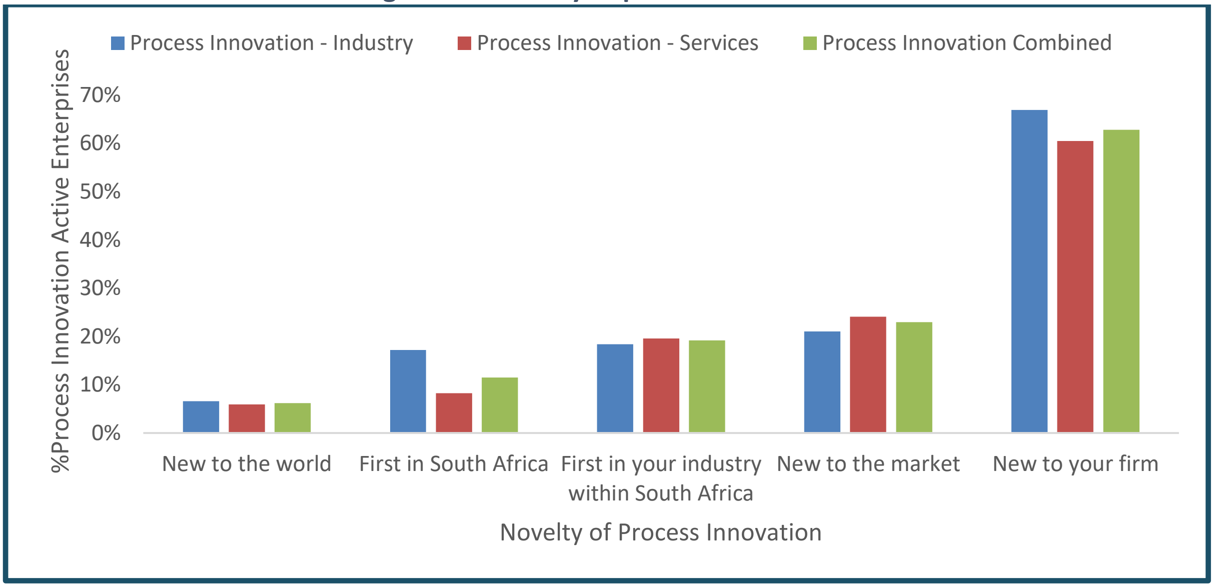
Figure 13: Process innovation development location



Source: CeSTII 2019-2021 Innovation Survey.

Figure 13 illustrates the distribution of process innovation created in South Africa compared to that acquired from abroad. Like product innovation, innovation-active firms in South Africa largely develop process innovation locally, highlighting stronger in-house innovation capabilities. Figure 14 shows the novelty of product innovation.

Figure 14: Novelty of process innovation



Source: CeSTII 2019-2021 Innovation Survey.

Novelty patterns for process innovation are like that of product innovation. New to the firm dominates, followed by new to the market, first in the industry in South Africa, first in South Africa and lastly new to the world. The low score on new to the world suggests low levels of original innovation among South African innovation active firms.

5.5 Digital economy

The 2024 NACI STI indicator report includes digitalisation among the high-tech sectors of biotechnology and nanotechnology. According to NACI, Digitalisation is the use of digital technologies to change a business model and is a process of moving to a digital business. AI drives digital transformation, encompassing innovations such as machine learning, 3D printing, the Internet of Things (IoT), data labelling platforms, and predictive analytics. Firms pursue digitalisation in response to growing consumer demands, to increase efficiencies, and to lower costs. Table 11 shows number of patents between 2011-2022 for digitalisation, nanotechnology and biotechnology.

Table 11: Patenting trends in select emerging technologies

YEAR	DIGITALISATION	NANOTECHNOLOGY	BIOTECHNOLOGY
2011	0	8	14
2012	1	7	8
2013	1	4	15
2014	1	5	20
2015	2	5	13
2016	3	4	14
2017	4	5	11
2018	5	3	12
2019	3	2	15
2020	3	8	10
2021	5	3	13
2022	4	6	13

Source: NACI, 2024. STI Indicator report.

According to NACI, biotechnology shows a higher level of inventiveness than the other two emerging technology fields. Digitalisation is still at its earliest stage of development, as seen from the lower level of patenting in this field on a yearly basis. UCT, with three patents, and SU, with two patents, are responsible for most of the patenting in the digitalisation sector. Table 12 shows a patent trend as a share of the world.

Table 12: South African patents in relevant emerging technology as a share of world total

YEAR	DIGITALISATION	NANOTECHNOLOGY	BIOTECHNOLOGY	ALL SECTORS
2011	0.03	0.02	0.03	0.03
2012	0.00	0.06	0.02	0.03
2013	0.03	0.06	0.01	0.03
2014	0.02	0.03	0.02	0.02
2015	0.02	0.04	0.03	0.02
2016	0.03	0.04	0.02	0.03
2017	0.03	0.03	0.02	0.03
2018	0.03	0.04	0.02	0.03
2019	0.05	0.02	0.02	0.05
2020	0.02	0.01	0.02	0.02
2021	0.02	0.05	0.01	0.02
2022	0.03	0.02	0.01	0.03

Source: NACI, 2024. STI Indicator report.

As a share of world total using patents as a lens, South Africa's contribution in digitalisation, nanotechnology and biotechnology is rather small. Patent is an innovation output and is used as a proxy for innovation performance. Table 13 shows publications on digitalisation, nanotechnology and biotechnology.

Table 13: Publications in the Emerging Focus Areas

YEAR	DIGITALISATION	NANOTECHNOLOGY	BIOTECHNOLOGY
2011	171	279	236
2012	192	343	144
2013	253	687	187
2014	247	778	234
2015	428	857	191
2016	470	1101	219
2017	572	1190	208
2018	809	1391	225
2019	921	1759	300
2020	981	2091	264
2021	1269	2166	279
2022	1518	2222	252

Source: NACI, 2024. STI Indicator report.

An increasing trend is observed for digitalisation and nanotechnology, while biotechnology does not display a trend. Publications are largely driven by universities from basic research while patents come out of experimental research. The findings could also suggest that biotechnology is less of an emerging field, rather focused on commercial activities – hence increasing the patent trend without a clear trend on publications. Table 14 shows the publications as a share of the world.

Table 14: Percentage share of publications for South Africa in the emerging technologies

YEAR	DIGITALISATION	NANOTECHNOLOGY	BIOTECHNOLOGY	ALL FIELDS
2011	0.34	0.20	0.85	0.56
2012	0.44	0.23	0.54	0.62
2013	0.52	0.42	0.65	0.62
2014	0.38	0.44	0.76	0.65
2015	0.52	0.45	0.63	0.68
2016	0.51	0.54	0.75	0.73
2017	0.56	0.54	0.74	0.74
2018	0.62	0.56	0.74	0.82
2019	0.60	0.67	0.91	0.84
2020	0.63	0.78	0.76	0.91
2021	0.66	0.77	0.81	0.94
2022	0.69	0.79	0.71	0.84

Source: NACI 2024 STI Indicator report.

Across the three emerging technologies, South Africa contributes less than 1%. As a share of the world, biotechnology's contribution is higher than digitalisation and nanotechnology. The linkage with manufacturing is considered next. Table 15 shows linkage to manufacturing.

Table 15: Trends of Manufacturing-related Emerging Technologies PCT Patents Contribution by Various Emerging Technologies

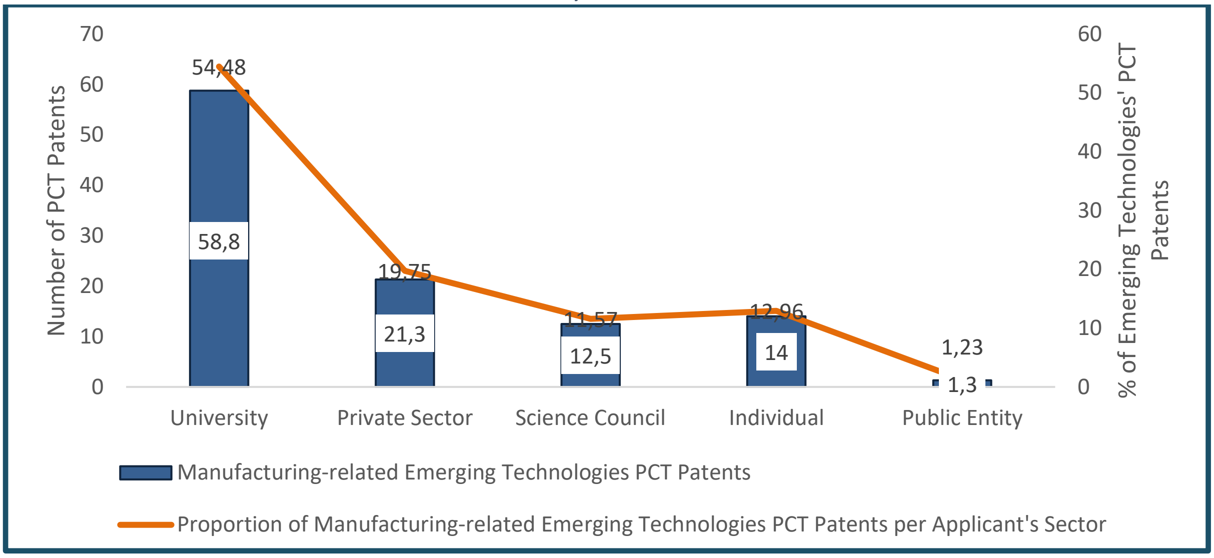
YEAR	BIOTECHNOLOGY	NANOTECHNOLOGY	INTERNET OF THINGS	ROBOTICS	AI AND MACHINE LEARNING
		%			
2013	55.56	33.33	0.00	11.11	0.00
2014	71.43	28.57	0.00	0.00	0.00
2015	82.35	17.65	0.00	0.00	0.00
2016	70.83	29.17	0.00	0.00	0.00
2017	60.00	40.00	0.00	0.00	0.00

2018	63.64	9.09	9.09	18.18	0.00
2019	53.85	7.69	23.08	7.69	7.69
2020	30.00	40.00	20.00	10.00	0.00
2021	70.00	30.00	0.00	0.00	0.00
2022	67.86	25.00	0.00	0.00	7.14
2013–2022	**63.89**	**24.07**	**8.70**	**4.63**	**1.85**

Source: NACI, 2024. STI Indicator report.

Biotechnology dominates manufacturing related patents, followed by nanotechnology and digitalisation. Figure 15 shows the sources of the PCT applications.

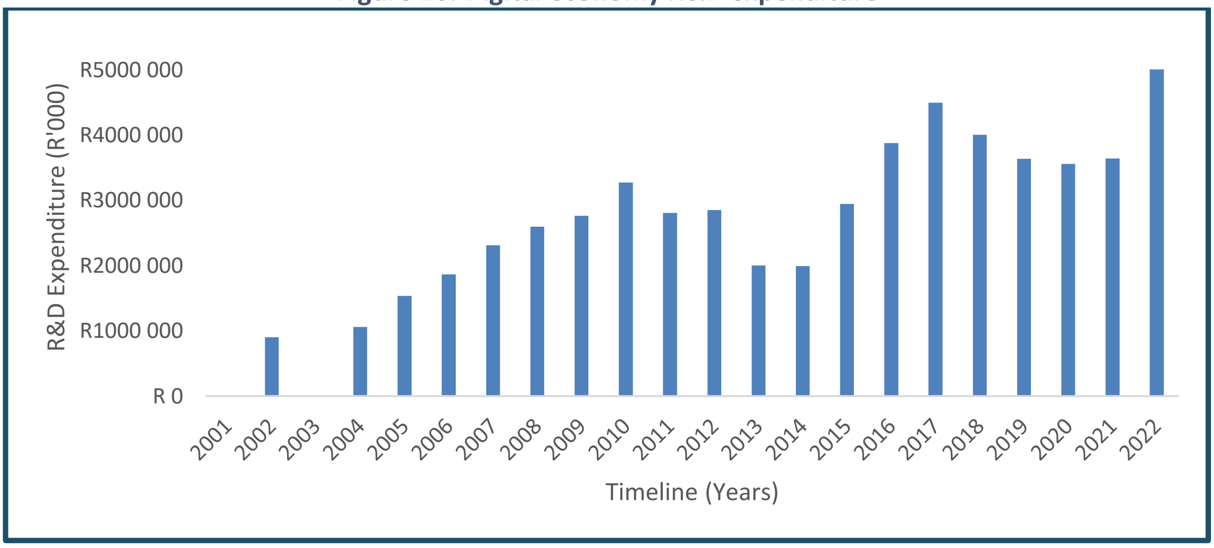
Figure 15: Manufacturing-related emerging technologies patents applications by applicant's sector, 2013-2022



Source: NACI 2024 STI Indicator report.

Universities dominate manufacturing-related emerging technologies patents. Besides the underdeveloped digital economy innovation outputs, South Africa heavily invested in R&D in information, computers, and communications technologies. Although only a proxy for the digital economy R&D expenditure, the total is R57 billion since 2001, aligned to the 2001 National R&D Strategy (Figure 16).

Figure 16: Digital economy R&D expenditure



Source: CeSTII, 2022.

At the same time, South Africa's digital economy is growing. The projections are for its contribution to GDP to be 15%-20% in 2025, an increase from the 8%-10% in 2020. The growth is largely driven by e-commerce's rapid growth since the COVID-19 pandemic. In 2023, sales from e-commerce hit a record R71 billion, a 29% increase from 2022. South Africa's digital economy has benefited from advanced digital infrastructure, a vibrant startup ecosystem, and a proactive government committed to fostering digital growth.

6. CASE STUDIES LESSONS AND DISCUSSION

The case study data has surfaced a few key themes to guide responding to research questions; each key theme is discussed next.

6.1 Fragmented institutional coordination and weak policy implementation

The HySA and PBMR case studies show that while South Africa has ambitious R&D programmes, their impact on industrial performance is often undermined by fragmented institutional mandates, policy incoherence, and a lack of long-term implementation strategies. For instance, PBMR's discontinuation, despite heavy investment, reflects structural failures in aligning R&D with market readiness and industrial uptake. This includes using R&D to reduce the cost of the technology, thus increasing its commercial viability. Similarly, while HySA presents high innovation potential, limited interdepartmental coordination is slowing its transition to full commercialisation.

This fragmentation helps explain why high R&D investments do not translate into sustained industrial performance. At the same time, commercial viability must be determined as early as possible to justify continued R&D investment, else the project must be stopped. To move towards extensive growth, a more cohesive STII architecture that bridges departments and ensures continuity beyond pilot phases is essential, as this prevents repetition and guarantees that R&D investments translate into sustainable, scalable outcomes rather than being lost in short-term efforts.

6.2 Limited technology absorptive capacity in the domestic industry

South Africa's domestic industrial base lacks the absorptive capacity needed to take up new innovations developed through R&D. The CCS and UCG case studies illustrate how the local ecosystem struggles to internalise and scale complex technologies without strong industry-academia integration and tailored support mechanisms. The inability of firms to absorb and adapt to new technologies reduces the effectiveness of technology import as an innovation strategy. Strengthening firm-level capabilities could foster broader technology diffusion and extensive industrial growth.

6.3 Missed opportunities in commercialisation and spin-offs

The Innovus and UTF case studies show promise in converting academic research into spin-offs. However, the national system of innovations still lacks a robust pipeline from invention to innovation to industry. Many university-based innovations are not scaled due to IP ownership conflicts, inadequate venture funding, or lack of commercialisation infrastructure and investment. Without efficient spin-off pathways, R&D remains locked in academic silos. Boosting tech transfer offices, incubators, and early-stage funding can serve as key drivers for inclusive industrial growth and employment.

There is certainly gross underinvestment in the downstream side of the innovation process, which is significantly constraining commercialization.

6.4 Uneven focus between legacy and emerging sectors

The Joule EV and Biotechnology case studies underscore the struggle to shift policy focus from legacy extractive industries to future-oriented sectors. R&D in legacy sectors like coal and mining receives disproportionate attention despite declining global competitiveness. Conversely, emerging sectors suffer from underinvestment and premature termination. At the same time, the capacity and capability to lead emerging sectors still lack in South Africa. The commercialisation cost for PBMR and Joule EV was disproportionately high, raising serious concerns about the understanding of the role of early-stage technology development and its linkage to commercial scale. The challenges faced by PBMR and Joule EV were not only limited to commercialisation costs but also early-stage technology issues, including the reactor design for PBMR and battery technology for the Joule EV.

While the STI policy landscape must continue to strategically pivot toward growth sectors such as green hydrogen, biotechnology, and the digital economy, it's worth noting that an emerging sector fundamentally differs from a legacy sector. As an example, the emerging sector must still search and secure a market; this has implications for the investment strategy and approach during early-stage development. Aligning incentives with emerging sectors can unlock inclusive employment pathways.

6.5 Strategic resource leveraging for global competitiveness

South Africa's abundant natural resources, particularly its vast reserves of PGMs, have been strategically utilised to position the country in the global hydrogen economy. The HySA case study exemplifies this approach by focusing on the development of hydrogen and fuel cell technologies. By capitalising on its PGM reserves, South Africa aims to become a key supplier of high-value-added products in the international fuel cell market. This initiative not only promotes technological innovation but also seeks to stimulate economic growth, job creation, and the development of specialised skills within the country.

6.6 Revitalising traditional industries through technological innovation

The modernisation of traditional industries through technological advancements is a key theme in South Africa's development strategy. The UCG and CCS case studies aim to enhance the efficiency and environmental sustainability of the coal and energy sectors. By integrating cutting-edge technologies, these initiatives seek to reduce carbon emissions and extend the viability of existing resources. Similarly, the PBMR case study represents an effort to innovate within the nuclear energy sector, aiming for safer and more efficient energy production. These endeavours highlight the country's commitment to transforming established industries through innovation.

6.7 Bridging academia and industry through university spin-offs

South African universities have become pivotal in translating academic research into commercial ventures, fostering innovation and entrepreneurship. The UTF and Innovus case studies exemplify efforts to bridge the gap between academia and industry. By providing funding, mentorship, and commercialisation support, these programmes enable researchers to develop market-ready products and services. This synergy not only accelerates technological advancement and start-ups but also contributes to economic development and job creation.

The progress of UTF and Innovus are aligned with the Intellectual Property Rights from Publicly Financed Research and Development Act No. 51 of 2008. This is a great example of moving from policy to impact. As already mentioned, more investment is needed in this area for wider and sustained impact. TIA is well positioned to scale this area of growth for South Africa. While the case study emphasises the sector's niche nature, fostering stronger linkages between innovation and mainstream industry remains a challenge. Innovations created within academic institutions and research centres must be effectively linked to well-established industries to scale, increase productivity, and boost competitiveness.

6.8 Advancing the digital economy through inclusive innovation

The digital economy in South Africa is expanding, with initiatives aimed at both upgrading existing sectors and creating new ones. Companies like Tyme Bank have leveraged digital platforms to provide accessible banking services, reaching underserved populations and promoting financial inclusion. Similarly, investments in AI infrastructure by global tech companies are enhancing the country's digital capabilities. These developments underscore the potential of digital innovation to drive economic growth, create jobs, and improve service delivery across various sectors.

The growth of the digital economy further elevates the role of services in industrial performance and overall economic growth.

7. CONCLUDING REMARKS

7.1 Research key findings

Based on South Africa's broader development goals, the following table draws practical lessons from five real-world case studies. These cases represent key moments of R&D investment—ranging from launching entirely new sectors to revitalizing old ones, from university spin-offs to the digital economy. Table 16 provides the research key findings and in relation to the three research questions.

Table 16: Case Study Lessons and Research Questions

CASE STUDY	RESEARCH QUESTION 1: WHY HAS SOUTH AFRICA'S R&D NOT RESULTED IN SUSTAINED INDUSTRIAL PERFORMANCE?	RESEARCH QUESTION 2: HOW COULD STII POLICY BE SHAPED TOWARDS EXTENSIVE GROWTH?	RESEARCH QUESTION 3: WHAT ARE THE STII DRIVERS FOR INCLUSIVE GROWTH AND EMPLOYMENT?
Launching a new sector (HySA, Biotechnology, Joule EV)	Failure to utilise the R&D step to de-risk technologies, reduce technology cost, and thus increase commercial viability.	Achieving extensive growth is more than a technology (technical) question; a broader appreciation of the technology commercialisation process is required.	Widening participation in technology development, having the patience to building capabilities for new sectors and strategically selecting labour-intensive technologies.
Upgrade of existing sector (UCG, CCS, PBMR)	Failure to utilise the R&D step to solve for commercial viability and successful integration into existing sectors for upgrades.	Technological upgrading requires additional support and R&D to resolver interoperability challenges with existing sectors.	A value chain approach is required for successful technological upgrading, thus supportive of other localisation ambitions.
University's spin-offs (UTF, SMME Fund, Innovus)	A combination of underinvestment in technology commercialisation and weak linkages with the private sector.	Nurturing university research outputs for technology commercialisation requires a long-term view with sustained investment along the entire innovation process.	A combination of increasing technology commercialisation investment and access to market, perhaps through public procurement for innovation.

Technology development and innovation	Firm-level innovation strategy is geared for improving goods and services rather than creating new goods and services.	The right incentives are required to encourage innovation active firms to pursue innovation to create new goods and services.	Public procurement for innovation on new goods and services is a good start encourage innovation active firms.
Digital economy (Upgrading existing sectors and creating new ones)	The digital economy is a transdisciplinary field, thus R&D programmes and investment must appreciate this reality.	Making choices to direct the digital economy largely towards extensive growth through investment and other incentives.	Public procurement for innovation on new digital goods and services is a good start to encourage digital firms.

7.2 Practical policy interventions

To position South Africa's R&D towards meaningful and sustained impact, the following practical policy inventions are suggested:

7.2.1 Incentives that reward real-world impact

Innovative initiatives such as fuel cells or biotechnology solutions do not always translate into jobs or industries. This is because policies often reward "outputs" like papers or patents, not outcomes like businesses and employment. Innovation policies and analyses in South Africa often concentrate on quantifiable outputs, such as patents and publications, rather than the practical outcomes they are intended to generate, including new businesses or employment opportunities. The 2005 NACI report, for example, highlights these outputs as primary measures of innovation, because it is often thought that producing papers and patents indicates technological capabilities (NACI, 2005).

Likewise, Kaplan (2014) contends that though these indicators provide helpful benchmarks, relying heavily on them may lead to a system where institutions and researchers prioritise quantifiable results over tangible economic and industrial impact. A shift is needed to significantly incentivise for outcomes and impact, thus the back end of the innovation process. This is not to reduce other incentives in the front end of the innovation process, rather to recognise that underinvestment in the back end is a constraint to innovation outcomes and impact.

7.2.2 Build strong innovation hubs – not just projects

One-off projects are no longer adequate to drive systemic effect and continued growth. A whole ecosystem approach is needed, where universities, small businesses, funders, and government all play together. An example would be an initiative similar to HySA, but with even more support systems for local entrepreneurs and young scientists. Perhaps the mission-oriented approach to innovation is required to cut across sectors.

The case studies mainly present sectoral R&D programmes and projects, with future programmes to be at a multi-sectoral level.

7.3 Managerial implications

Firm-level managers make decisive decisions about R&D, technology and innovation. Based on the case studies, the following managerial implications have surfaced:

- Innovation leaders need to align their projects with what the country needs now and tomorrow. It is not enough to be at the "cutting edge" while being socially and economically irrelevant.

- As seen in the university spin-off ecosystem, innovation thrives in environments where knowledge, finance, and application intersect. Managers should build networks beyond their sectors, including research councils, development finance institutions, and NGOs.
- The case studies under upgrading existing sectors highlights the challenges of integrating new technologies into legacy sectors, such as energy, to enhance competitiveness. For legacy sectors to thrive, managerial know-how in continuously handling and integrating technologies is imperative.

7.4 Further research

The research has surfaced insights on understanding R&D in South Africa and its relation to innovation, industrial development, employment and economic growth. While the surface insights are progressive, further research is suggested as follows:

- South Africa needs empirical work on how R&D activities link to local value chains. For example, do spin-offs in biotechnology lead to local manufacturing jobs or outsourced production? Research should examine spillover pathways from innovation to industry.
- Much of the STII literature focuses on macro-level indicators. More qualitative, community-based research is needed to assess how digital and STI innovations are perceived, accessed, and utilised by marginalised communities, informal workers, and SMMEs.
- There is a knowledge gap around how STII policies are implemented within institutions.

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