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Integration of Socio-Economic Impact in the Development of the Square Kilometre Array of South Africa

The Square Kilometre Array (SKA) is one of the largest and most ambitious research infrastructure ever to be built. South Africa will be hosting one of its two main sites. The decision to host such an ambitious project for a middle-income country required careful consideration of the potential benefits and the associated risks for the socio-economic development of the country and the region more broadly. This working paper describes how the potential impact of SKA for South Africa was envisaged from the start of the project, how this was integrated in the project development, what policy initiatives and interventions were taken to maximize impact and the lessons learned, from South Africa's science policy perspective, during the early phases of the development of the SKA.

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Foreword

This working paper complements the recent policy report published by the OECD Global Science Forum on very large research infrastructures (VLRIs). It describes, as a case-study, how the scientific development of the Square Kilometre Array (SKA) radio telescope was integrated with thinking on the socio-economic development of South Africa and the region.

Astronomical research is very much a basic science endeavour. As such, its impacts, beyond the generation of new knowledge, are neither short-term nor predictable. Whilst it is generally accepted that societal progress over the long-term owes much to basic discovery science, VLRIs are becoming prohibitively expensive and challenging to build and maintain. What are the societal benefits of supporting these facilities and their operations is a question that science policy makers and research funding agencies are increasingly having to consider.

In emerging economies this question is critical and needs to be addressed in the context of pressing socio-economic challenges - poverty, unemployment, health burdens and inequality. South Africa’s decision to invest in the SKA required due attention to these realities, and careful consideration of the potential benefits and the associated risks for the socio-economic development of the country and the region more broadly.

The SKA is unique as it is the first international VLRI in which a middle-income country has played a leading role throughout the whole development and construction phase. As such, the SKA experience, whilst partially specific to the national context, has broader implications for RIs across the world. This is why the Expert Group overseeing the OECD Global Science Forum (GSF) project on VLRIs selected the SKA for an in-depth case study.

This working paper presents a series of lessons learned, from South Africa’s science policy perspective, during the early phases in the development of the SKA. It describes the important historical context, as well as the strategy and conditions required to generate broad impact, whilst responding to the expectations of many different stakeholders’, both nationally and internationally. The main author of this work, the late Dr Daniel Adams, (former Chief Director for Basic Sciences & Infrastructure at South Africa Department of Science and Technology), was uniquely placed to conduct this analysis, for which he carried out extensive consultation with South African stakeholders. This report is dedicated to Daniel who produced the initial draft, which was completed by Dr Adrian Tiplady, with support from Frédéric Sgard at the GSF secretariat.

It is hoped that this report will be informative and useful for science policy officials as well as research funders and VLRI managers in both emerging and developed economies. Comments from readers are welcomed. The Global Science Forum staff can be reached at gsforum@oecd.org.

The GSF is a Working Party of the OECD Committee for Scientific and Technological Policy (CSTP). Its main objective is to **support countries to improve their science policies and share in the benefits of international collaboration**. The GSF provides a venue for consultations and mutual learning among senior science policy officials of OECD member countries. It carries out analytical work on high-priority science policy issues.

The GSF's principal stakeholders are the government science policy officials who bring issues to the GSF for deliberation and analysis in an intergovernmental setting.

More information on the GSF mission and activities is provided at http://www.oecd.org/sti/inno/global-science-forum.htm.

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Executive Summary

Very large research infrastructures (VLRIs) play a critical role in frontier science but are also prohibitively expensive. Government and public research funders are therefore increasingly demanding regarding the socio-economic impact they may deliver beyond the production of knowledge. For a middle-income economy such as South Africa, this question is even more pertinent in the light of the many socio-economic challenges that the country has to face. For South Africa a major investment in a VLRI must be justified not only by the science but by the diversity of benefits that it is likely to bring to society as a whole.

This case study report describes how the potential benefits of hosting the Square Kilometre Array (SKA), the largest radio-telescope ever to be built, were integrated into the development life-cycle of the project. It analyses the initiatives/interventions by the South African Government and its funding agencies to maximize the SKA impact from local community up to international level. The report addresses the following questions:

How the potential impact of SKA for South Africa was envisaged from the start of the project and how this was integrated in the project development?

- What policy initiatives and interventions were taken by South Africa to maximize the SKA benefits at regional/national level and what impact assessment methodology and indicators were developed?
- What are the impacts measured to date and whether they match expectations
- What are the future impacts still expected at a broader scale and what are the required conditions for them to be realised?

The potential impacts of SKA for South Africa were envisaged from the start of the project. A decision-making framework was developed to ensure a high effective return on investment. This framework was built as a two-component value proposition model: how does South Africa benefit from the investment, and what benefit does the relevant research infrastructure derive from South Africa's investment? The return on investment resulting from the project framed in terms of value for local as well as national stakeholders. As assessing the actual benefit from VLRIs is notoriously challenging, a framework for assessing the economic and social impact of the SKA was developed in 2008 to address the effects of two clearly distinct activities: those related to the construction, operation and maintenance of the facility, and those related to the use of the facility for the purposes of scientific research.

Maximising the anticipated benefits was contingent to a number of actions that South Africa had to undertake. Different stakeholder expectations were inevitable, given the wide range of stakeholder groups involved in the SKA project. It was necessary to have a critical understanding of the value system adopted by each stakeholder group – and therefore, their expectations. South Africa's expectations could be largely met through top-down design of the SKA value proposition, and bottom-up interventions undertaken by South Africa to maximise potential indirect socio-economic benefit. The benefit framework, which was built around six strategic pillars (e.g. research enterprise, innovation, education, business development, community and cultural benefits, public good) recognised impact opportunities that would only be fully realised through strategic action, and thus informed key policy interventions to maximise opportunities for impact.

Based on the six-pillar benefit framework, an initial impact assessment of the SKA was conducted, including not only scientific and technical aspects, but including also an account of some of the societal benefits. The latter were important for ensuring successful and sustainable implementation of the project in South Africa and a earning a 'social license' to operate. While preliminary, this assessment suggests that the strategic interventions adopted to maximise potential benefit have been effective in delivering socio-economic impact.

Going beyond the beneficial impact generated during the development of the SKA are the potential long-term effects on a broad spectrum of beneficiaries and stakeholders. Those long-term effects can be summarised in four high-level focus areas:

- Enhancement of South Africa's reputation as a trusted partner and preferred destination for investment in science and technology;
- Accelerating the building of, and transition to a knowledge economy;
- Enhanced education and skills development; and
- Improved public good.

Initial evidence indicates that the SKA project has already generated impact in these four areas and that this is likely to get amplified as the project continues.

Finally, there are a number of lessons learned from the SKA in South Africa that are of value for all VLRI projects:

- *Ensure a Value Proposition and secure a 'Social License to Operate'*: Given that most VLRIs are funded, managed and operated by multiple stakeholders, and provide services to the international research communities at large, a clear understanding and formulation at the onset of the VLRIs' value proposition is a required condition for delivering the desired impact as well as for their sustainability. Ensuring legitimacy in public opinion is also a critical factor for the long-term success of research infrastructures. Securing a social license is dependent on the effective delivery of a multi-tiered value proposition that should be openly negotiated at the start of the research infrastructure project.
- *Impact presents itself as an opportunity, not a guarantee*: VLRIs have to recognise that broader impacts are opportunities at the outset, and that specific strategies and interventions must be agreed to and implemented early on to exploit inherent opportunities for impact. Wider impact will not necessarily be realised because of the establishment of a research infrastructures *ipso facto.*
- *Onboard multiple champions across the political spectrum*: VLRIs have both an international and national dimension, with decision-making structures in different countries distributed hierarchically and across different departments. Within each national system, multiple champions need to be established to provide resilience and ensure sustainable funding.

Introduction

Very large research infrastructures (VLRIs) in the field of astronomy are long-term scientific initiatives developed to produce frontier knowledge. As such, their impacts are neither short-term nor easily predictable. However, each new generation of VLRIs, in further pushing scientific and technology boundaries, is becoming more and more costly, with new investments routinely in the billions of euros for construction, and operation spanning decades. While scientific knowledge production is still very much at the core of their strategic objectives, there are also growing expectations that they should also deliver a range of societal and economic benefits, with an increasingly common question being: “What are the benefits for the society of supporting these investments and their operations?” (Florio, 2019[1]).

In a developing economy such as South Africa, this question is more relevant in the face of challenges of poverty, unemployment, health burdens and inequality. Public investment in large science facilities is often justified by the direct and indirect benefits that flow from having such facilities as well as by the science they perform. When South Africa decided to host the Square Kilometre Array (SKA) telescope, the country had to give careful consideration to its socio-economic realities and explicitly articulate the potential benefits as well as the associated risks.

This Case Study is not meant to be another report on the benefits or impact of the SKA per se but rather on how these aspects were integrated in the development life-cycle of the project. It focuses on the initiatives/interventions by South Africa to maximise the SKA impact from local community up to international level. This report unpacks and address the following questions:

- How the SKA potential impact for South Africa was envisaged from the start of the project and how this was integrated in the project development, as well as discussed, negotiated and agreed with the other SKA partners?
- What initiatives and interventions were taken from the South African side to maximise the SKA impact at regional/national level and, what impact assessment methodology or indicators may have been developed to monitor this impact?
- What are the impacts measured to date, do they match expectations?
- What future impacts are still expected and what are the conditions required for their occurrence?
- Any lessons learned from the SKA project regarding the generation of wide impact (and responses to stakeholders’ expectations) by future VLRI projects.

1 Background

1.1 South African Policy and Historical Context

South Africa's reputation as an attractive destination for astronomical observations was established in the early 20th century. Exceptional viewing conditions in parts of the country, as well as the support offered by the government at the time, led several leading observatories and institutions in the northern hemisphere to establish observing facilities near major South African cities (Cape Town, Johannesburg and Pretoria).

The deterioration of viewing conditions as a result of rapid urbanisation, however, led to the establishment of a new observing facility near the town of Sutherland in the Karoo region of South Africa. This led to the creation of the South African Astronomical Observatory (SAAO) in 1972, and the relocation of telescopes in Pretoria, Johannesburg and Cape Town to Sutherland. The optimal site, new instruments and a high calibre research community ensured that South Africa remained competitive in the field of astronomy throughout most of the 20th century.

By the late 1980s, it became increasingly clear that for South African astronomers and astrophysicists to continue conducting first-class research, the acquisition of a more powerful and sophisticated telescope would be necessary. This ultimately led to the development and construction of the largest single optical telescope in the Southern Hemisphere in 2005 - the Southern African Large Telescope (SALT) (Buckley, 2005[2]). In the meantime, the establishment of the Hartebeeshoek Radio Astronomy Observatory (HartRAO) in 1974 accelerated the development of radio astronomy in South Africa, supported by a number of local universities. By the time the early conceptualisation of the Square Kilometre Array (SKA) telescope began in the early 1990's, South Africa already had a strong multi-wavelength[1] community with a good research track-record.

The dawn of the new democratic dispensation in 1994 brought about significant policy shifts in the science, technology and innovation landscape. These policy shifts were articulated in the 1996 White Paper on Science and Technology, the 2002 National Research and Development Strategy and the 2008 Ten-Year Innovation Plan of the then Department of Science and Technology (now the Department of Science and Innovation). Two key policy formulations from these strategic plans were: (i) the identification of five scientific focus areas - *astronomy* and earth observation, indigenous knowledge, bioscience, paleontology, and the Antarctic, Islands and Oceans - as fields in which South Africa's geographical and knowledge advantages could be leveraged to great benefit; and (ii) using science, technology and innovation to transition from a resource-based economy to a knowledge-based economy[2].

These policy formulations became the drivers for the South African government's commitment to invest in astronomy as a basic science - not only for enabling excellence in science but also stimulating technology development and innovation as key enablers for economic development. They provided the strategic context in which South Africa decided to invest in the development of SALT, to prepare a successful bid to host the SKA project, and ultimately participate and invest in the international SKA program. Apart from the technical and scientific gains derived from hosting and developing large astronomy infrastructure, the investment in basic research infrastructure and its associated programmes were intended to help catalyse South Africa's transition towards a Knowledge-Based Economy.

1.2 Overview of the SKA Project

1.2.1 SKA Project

The SKA project[3] is a global effort to build the world's largest radio telescope array. At its fullest extent, it will include thousands of receivers distributed across Western Australia, and Africa (initially concentrated in South Africa), with its global headquarters located in the United Kingdom. The scale of the SKA represents a huge leap forward in engineering know-how and technology - a global collaborative effort to build a next-generation radio astronomy facility that will deliver a transformational scientific capability when operational. Deploying large numbers of radio telescopes, in two unique configurations, will enable astronomers to monitor the sky in unprecedented detail and survey the entire sky thousands of times faster than with any existing system. With a range of other large telescopes in the optical and infrared being built and launched into space over the coming decades, the SKA will perfectly augment, complement and contribute to scientific discovery.

1.2.2 SKA Governance

The SKA project is being implemented by the SKA Observatory[4] (SKAO), an inter-governmental treaty organisation formally established[5] in January 2021. There are three mechanisms through which a country, international organisation or institution may establish a formal relationship with the SKAO:

i. Membership – open to States and International Organisations;
ii. Associated Membership – open to States and International Organisations;
iii. Cooperating Party – open to any entity that may wish to cooperate with the SKAO.

Figure 1 shows the governance structure of the SKA Observatory. The SKAO Council consists of Member representatives, and may choose to admit Associated Members upon such terms as it determines. Similarly, the SKAO may choose to collaborate with Cooperating Parties through an appropriate agreement or arrangement. The SKAO has an office, appropriately staffed and led by the SKAO Director-General.

Importantly, the establishment of a formal relationship with the SKAO does not require a prescribed financial contribution. Financial contributions inform the 'share participation' of the respective parties in the SKA project, which are subsequently used to inform the following:

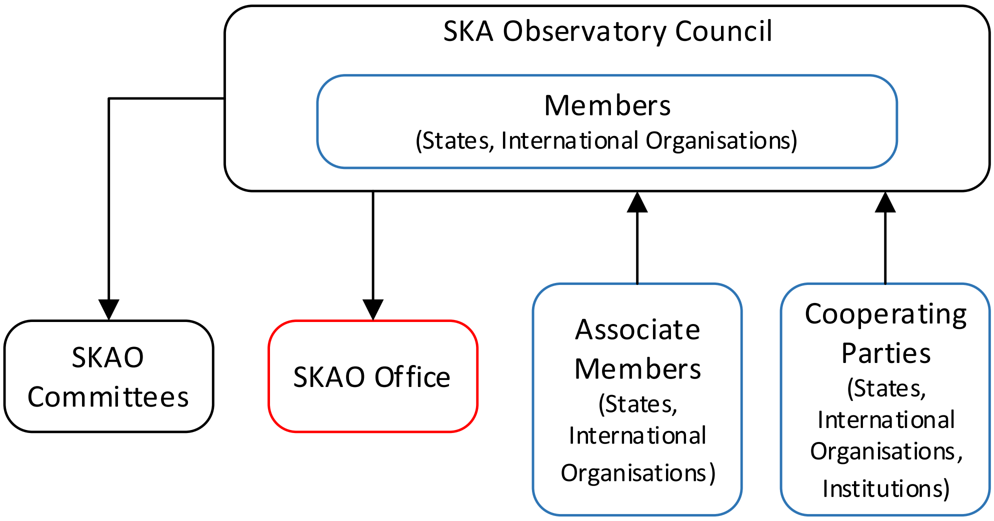
i. Participation in construction – whilst the model for participation in construction is always subject to Council decision, in the case of the first phase of the SKA a model of 'juste retour' is adopted. Participants are effectively 'guaranteed' a minimum level of work return – or industrial contracts to be awarded to industry in the respective Member or Associate Member states. Cooperating parties may be awarded similar rights by the Council;

ii. Participation in scientific operations – scientific operations is structured along the lines of a hybrid open-closed skies policy, with a minimum percentage being given to open skies observations – meaning that calls for scientific proposals will be issued to the entire astronomy community beyond the membership for a minimum amount of time. The majority of time is, however, restricted to the Members, Associated Members and Cooperating Parties (by decision of the Council). Members are given the right to participate in science observations at a level commensurate with the financial contribution. Two key points should be noted here:
    a. Strict adoption of the 'capacity to use' model means that participation in scientific observations is, *de facto*, reflective of the size of the scientific communities in each of the Member countries. There is, however, expected to be some deviation from this which is closely monitored;
    b. Given the nature of the SKA – with long science programs – international collaboration is required across large science teams to deliver the transformational science expected.

Thus, the metric used to measure 'scientific participation' is not simply guaranteed time but is a metric reflecting the FTE participation in science teams over time.

While financial contributions are negotiated and traditionally informed by a 'capacity to use' model, departure from this is not uncommon. This has effectively lowered the financial barriers to forming binding collaborations with the SKAO.

Figure 1: Governance structure of the SKA Observatory



South African representation[6] on the SKAO Council is through the South African Department of Science and Innovation, and the South African Radio Astronomy Observatory (SARAO)[7], which is a National Facility of the South African National Research Foundation (NRF)[8]. SARAO is responsible for implementing South Africa's strategic investments in radio astronomy, which includes constructing and operating the MeerKAT radio telescope in the Karoo, ongoing scientific programs at the HartRAO facility, coordination and delivery of astronomy research infrastructure and capacity across Africa (including the African Very Long Baseline Interferometry Network - AVN), as well as South Africa's contribution to the planning, construction and operation of the SKA telescope. Its funding, therefore is primarily from the national fiscus through the Department of Science and Innovation. Given the scope of its activities and depth of technical competence, SARAO actively collaborates scientifically and technically with a wide range of local and international partners and stakeholders, inside and outside of the radio astronomy sector. This does result in in-kind funding on joint projects.

1.3 South Africa's SKA Proposal

1.3.1 Bid Proposal

Following submission of an expression of interest to the then International SKA Steering Committee (ISSC) in 2003, SARAO[9] prepared and submitted a bid proposal in 2005, on behalf of South Africa and seven African Partner Countries[10], to host the SKA radio telescope. In 2006, the African bid (led by South Africa) was shortlisted along with Australia.

Following shortlisting of the two proposals, a range of scientific, technical and other studies related to operationalisation of the SKA project in Africa were undertaken in response to a more detailed request for information. In parallel, significant political effort was made to garner international support (some of which has had a lasting legacy, such as the establishment of the Africa-Europe Radio Astronomy Platform (AERAP) – a vehicle for investment and collaboration on radio astronomy)[11], whilst strategic investments were made on the premise that establishing a greenfield site with appropriate infrastructure (including scientific infrastructure) would create a conducive environment for deployment of astronomical facilities such as the SKA.

On 25th May 2012, the SKA Organisation (which had been created in November 2011 as a temporary structure to complete the site selection, to deliver the design of the SKA telescopes and to establish a solid governance structure) announced that the SKA project site was to be shared between Africa and Australia[12]. In order to accommodate a dual site solution, a split in receiver technologies (which directly map onto specific science cases) was adopted - the extensive mid-frequency dish array was allocated to SA, whilst the low-frequency aperture array was allocated to Australia.

1.3.2 Selection Criteria and Requirements

Selection of a site to host the SKA was informed by various weighted criteria, including scientific[13], technical[14], financial[15], and political[16] considerations that ensured an enabling environment for not only scientific observations, but for an inter-governmental organisation to construct and operate the SKA in the relevant host country for 50 years. Whilst the relevant bid proposals were assessed against these criteria by an independent panel of experts drawn from around the world, the ultimate decision to split the SKA across two sites was undertaken recognising the historical and current financial, scientific and political investments made by the respective telescope hosting countries.

Part of these investments in South Africa included the establishment of a greenfield site in the Karoo region of South Africa, as well as investments in the development of the South African designed and constructed MeerKAT radio telescope (launched in 2018) – a premier radio astronomy facility to be integrated with the SKA once built. This was a clear and deliberate strategy by South Africa, championed through various political leaders, to not only invest in South Africa's geographic advantage for astronomy, but to ensure the participation of the local scientific and engineering community within the SKA project – regardless of the site outcome.

1.4 Legacy of Strategic Interventions

In order to support the bid to host the SKA, being responsive to the anticipated hosting obligations and well-positioned to derive maximum benefit from participation in all phases (design, development, construction, implementation and operation) of the SKA life-cycle, South Africa undertook the following interventions prior to the SKA site bid outcome:

- Prepared a competent bid to host the SKA, which included the necessary measures to be put in place to enable the SKA Observatory to construct and operate in South Africa and protect its investment. This included protection of the site through unique legislation;
- Growing an astronomy research community, through a pipelined human capital development program, that could take advantage and participate in the scientific and technical programs of the SKA; and
- Investing in a greenfield site to create an enabling environment to host the SKA (from an infrastructure perspective), whilst developing a precursor SKA facility that provided a gateway to enable South African engineers to participate in the technology programme of the SKA and provide a platform for early SKA science (this was to become the Karoo Array Telescope, KAT-7, which ultimately became an engineering prototype for what was to become MeerKAT).

These initiatives were informed by a legacy of strategic interventions that stems from the country's historical investments in the development of large astronomy research infrastructure, exploiting its geographical location and addressing the skills deficit in science, technology and engineering.

Given the aforementioned considerations regarding broader societal benefit of investment in research infrastructure, South Africa's inherent goal to derive socio-economic benefit at various levels of the SKA development were realised through an appropriate codification of the value proposition for investment in research infrastructure, and the identification of further strategic interventions to maximise the opportunities for direct and indirect socio-economic benefit from investment in such research infrastructures.

1.4.1 Astronomy Geographic Advantage (AGA) Programme

In support of South Africa's bid to become a premier astronomy destination, the government initiated the Astronomy Geographic Advantage Programme, which aims not only to attract international astronomy projects to the region but also to build a significant astronomical and engineering platform in South Africa to support local and international astronomy projects. The programme committed significant funding and support for astronomy through large-scale research and development programmes (e.g. KAT-7[17]/MeerKAT[18]/SKA, SALT and HESS), legislation and protection; and human capital development. The AGA Programme was also intended to: (i) facilitate technology development and transfer; (ii) stimulate technological innovation - providing a benign research environment for the development of next-generation high-performance computing technologies, data storage systems, processing and utilisation of 'Big Data', artificial intelligence and even new systems of work and high-tech project management; and (iii) accelerate the transition to a knowledge-based economy.

1.4.2 Establishment of a protected Astronomy Reserve

In order to protect regions exhibiting unique scientific qualities that support astronomical observations, particularly from next-generation astronomical facilities, Astronomy Advantage Areas have been declared and protected in the Karoo region of the Northern Cape Province through unique legislation (Astronomy Geographic Advantage Act, Act No. 21 of 2007)[19] that has been promulgated in South Africa. This legislation empowers the Minister responsible for science, technology, and innovation to protect areas[20] of astronomical advantage from all manner of radio and optical interference that may negatively impact astronomical observations. The area, colloquially referred to as a radio astronomy reserve, hosts the MeerKAT radio telescope and is the selected site for the SKA in South Africa. Importantly, given the historical investments made by South Africa into the site, and the unique protection that is afforded to it, the site also hosts a number of other international projects that have been attracted to it. This has catalysed unique scientific and technical partnerships between SARAO and international collaborators.

1.4.3 Supporting a Human Capital and Research Capacity Development Programme

At the cross-section of the technical and scientific requirement for each phase of the development life-cycle of large research infrastructure (such as the SKA) are people with the necessary skills. To ensure South Africa had a community to participate in the science and technology programs of the SKA, a range of robust human capital and research capacity development programmes were introduced. These programmes include an ambitious research chairs programme to attract prominent local and international researchers, a visitor's programme to facilitate mobility of researchers, and a dedicated SKA Human Capital Development Programme, which provided a pipeline of support that now stretches from school level through to post-doctoral fellowships, research chairs and university staff positions.

1.4.4 Development of MeerKAT

A major portion of South Africa's legacy investment was development and construction of the 64 dish MeerKAT as a technology and scientific precursor to the SKA. Such a strategy realised investment in a greenfield site suitable for hosting of the SKA, whilst ensuring technical and scientific participation of the South African community in the SKA project – regardless of the outcome of the bid.

The scientific and technical success of MeerKAT has been significant, establishing it as one of the premier radio astronomy facilities in the world[21] since it was commissioned in 2018. Its relevance as technical and scientific precursor to the SKA is clear - MeerKAT will eventually be fully integrated into the first phase of the SKA.

As demonstration of the SA government's commitment and support, the MeerKAT was declared one of 18 national Strategic Integrated Projects (SIPs) in 2012, reporting directly into the South African Presidential Infrastructure Coordinating Commission (PICC). The SIPs are recognised as key drivers towards delivery of the National Development Plan[22], which is intended to transform the economic landscape in the country, create a significant number of new jobs, strengthen the delivery of basic services and support the integration of African economies.

2 Decision Framework for Investment in Research Infrastructure

2.1 Value Propositions and the Social License to Operate

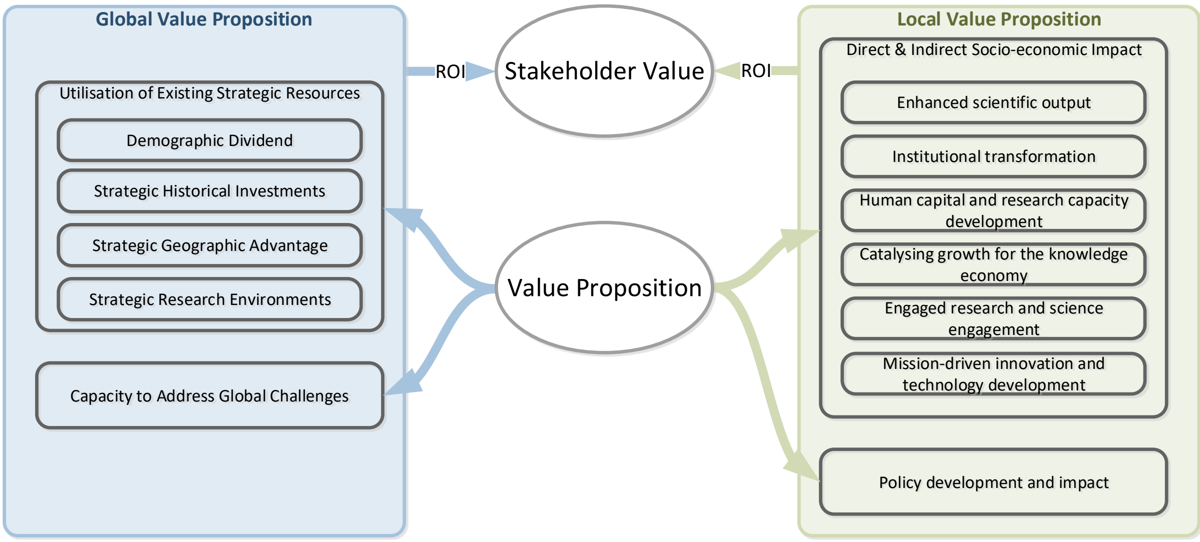
Due to competing national imperatives, resources for investment in large research infrastructures such as the MeerkAT/SKA are limited. It was therefore important for South Africa to utilise a decision-making framework that includes a high effective return on investment. Strategic investments made by South Africa over the past few decades in Big Science infrastructure has been informed by, and anchored on, a two-component value proposition model, described in Figure 2, which adopts an underlying principle of mutual benefit sharing (Adams and Tiplady, 2023[3]). That is – how does South Africa benefit from investment[23] in Big Science, and what benefit does the relevant research infrastructure derive from South Africa's investment? The return on investment resulting from delivery of the global and local value proposition ultimately creates value for South Africa's stakeholders, both internal and external.

Visible return on investment of public funds in research is a major consideration of governments today. Not only is innovation and the generation of economic and social benefit becoming increasingly reliant on the creation and exploitation of knowledge, but a globally connected society is also increasingly demanding of government to make the tangible impact arising from such investments visible to society. This demand can be expressed through the need for research infrastructures to retain a 'social license to operate' (by funders and decision-makers) to be seen as legitimate in the public world view.

The local value proposition (Adams and Tiplady, 2023[3]) speaks to the delivery of value that contributes to the broader direct and indirect socio-economic development objectives that characterise a developing economy such as South Africa. This complex set of objectives is informed by various national policy documents that ultimately provide policy intent towards the delivery of the National Development Plan (NDP 2030)[24] – a key long-range plan adopted in South Africa for socio-economic development. The global value proposition (Adams and Tiplady, 2023[3]) concerns the delivery of value to the global scientific enterprise, not only through the making available of research capacity to address global challenges, but also the utilisation of existing strategic resources and advantages that SA has at its disposal. This can range from historical investments, geographic advantage[25], strategic and unique research environments[26], and even taking advantage of the demographic dividend. Such a global value proposition ultimately supports the positioning of South Africa, from a science diplomacy perspective, as a key trusted and influential partner that positively contributes towards addressing global challenges and relevant global discourse – a preferred destination for scientific cooperation and investment.

The framing of such investments therefore becomes critical for their long-term success and sustainability. Ultimately, this is interrogated through a 'stakeholder value' framework, which assesses derived value from a return on investment (ROI) model based on the local, and global, value proposition – as described in Figure 2.

Figure 2: Two-component value proposition model, which informs South Africa's strategic investments in Big Science



Source: (Adams and Tiplady, 2023[3])

2.2 Defining Impact

The creation of large scientific facilities, such as the SKA, while driven by clear and compelling scientific needs, leads not only to scientific advances but also to a range of non-science benefits, outcomes, and impact for the funders and for wider society. At the time of development of the SKA bid proposal by South Africa, the government as primary funder and the NRF as implementing agency were fully aware of the significant public investment that would be required to host the SKA. Hence, they were compelled to give due consideration to the potential benefits and impact that could be derived as justification and accountability for the investment. This requirement was particularly important given the proposed site was located in an economically depressed rural area. As much as it was important (from a scientific and technical perspective) to have the SKA project located in the Karoo, good intentions regarding benefits were not enough. It was equally important to understand the impacts these interventions would be making and go beyond simple tracking and reporting of achievements.

There are a limited number of studies that assess actual benefit flows from large facilities, and those that are available show that measuring benefit flows is difficult. These difficulties include: quantifying benefits from research and non-economic benefits; and finding appropriate indicators/metrics for measuring the resulting impact of these benefits.

To help overcome these difficulties, a framework for assessing the economic and social impact of MeerKAT and the SKA was developed in 2008 by the Science Policy Research Unit at University of Sussex (unpublished). They proposed that the assessment of the impact of a large research infrastructure had to address the effects of two clearly distinct activities:

- those related to the construction, operation and maintenance of the facility – the “Build, Maintain and Operate” activities;
- those related to the use of the facility for the purposes of scientific research – the “Research Use.”

From the above sections and discussions, it could be deduced that the initial impact framework focused mainly on the long-term effects derived from the “Build, Maintain and Operate” activities and “Research Use” during the MeerKAT and SKA development and their effect on the return on the investments resulting from the delivery of the global and local value propositions. The latter speaks to the ‘stakeholder’ value or expectation which in turn drives the ‘social license to operate.’

3 Ex-ante evaluation of potential impacts from the SKA

3.1 Impact Model for Radio Astronomy and the SKA

The ex-ante analysis of the potential beneficial impacts of the development of the SKA is considered from the perspective of the SKAO, as well as from South Africa. From the SKAO perspective, the impact is two-fold, namely: (i) impact derived from Observatory directed (top-down) interventions; and (ii) aggregated or collective (cross-cutting) impact generated from the interventions by the members, collaborations and partnerships.

From an SKAO Member perspective (see Section 1.2.2), there are country specific impacts derived from interventions at national, regional and local levels. Projected high-level anticipated impacts to be derived during the development and implementation of the SKA are expected as follows[27]:

- *A better and more sustainable future*: Addressing global challenges by contributing to some of the United Nations' sustainable development goals to achieve a better and more sustainable future for all by 2030. Beyond its significant contribution to academic research, the SKAO will impact four core areas across the SDGs: the economy, society, sustainability and culture;
- *Building Cultural Diversity through science:* Being a multi-cultural, multi-national collaboration, the SKAO will be required to adhere to values of equality, diversity and inclusion in its leadership and at all levels through the Observatory, and embrace gender balance, nationality and representation of traditionally underrepresented groups;
- *A new frontier for science diplomacy:* SKAO will be championing science diplomacy by establishing new national communities in the field of astronomy, breaking down the traditional divide between developed and developing countries and encouraging government-level interaction and fostering international connections;
- *Capacity and skills development:* The development of the SKA project will generate knowledge, jobs, providing inspiration, increasing the skills base and developing industrial capacity in participating countries;
- *Leading big data challenges:* The Observatory will transport, process, store and distribute to the global community a deluge of data, making the SKA project one of the leading big data challenges and a research infrastructure that exemplifies the new challenges of data science;
- *Direct economic impact:* Direct economic benefit to member states in terms of contracts to industry, commerce and research institutes, informed by a model of *juste retour*;
- *Driving innovation:* Indirect returns through driving innovation and skills development in electronics, communications, computing and data science;
- *Adoption of Open science and open source practices*: These principles of open access are fundamental to maximizing the scientific impact and the impact in other areas of the Observatory, as well as contributing to the UN sustainable development goals; and
- *Ensuring a sustainable eco- and ecological system:* Sustainability is considered a foundational value of the observatory, underpinning all other activities. The observatory's aim is to build and operate a sustainable infrastructure over 50 years, and work to minimise negative environmental and other impacts over its entire lifetime. This includes conservation of resources, minimising waste

generation, maximising the use of renewable energy, and minimising the use of potable water during construction, among other measures.

From a South African perspective, the 2008 NRF commissioned study[28] was the first attempt to formulate the anticipated direct and indirect benefits likely to accrue to the country from the design and construction of the MeerKAT Telescope, and future SKA. It made some projections of the likely benefits that will flow from the MeerKAT and the SKA based on a literature review of existing "big science" impact studies, and on several case studies chosen for their relevance to big science facilities. These projections were informed by the legacy of interventions discussed in Section 1. The anticipated benefits for South Africa are discussed in the following sections.

It should be noted that these anticipated benefits provided input into a business case for the SKA and radio astronomy investments. However, continuous assessment of potential benefits is necessary during the entire life-cycle of the project to ensure appropriate and timely responses to opportunities that may arise as a result of unintended outcomes, or changes in the external environment. This strategy of continuous horizon scanning is necessary to maximise opportunities for impact.

3.1.1 Anticipated benefits arising from South African Investment in Radio Astronomy

Informed by the impact framework discussed previously, the anticipated benefits were categorised in terms of (i) their derivation from the "Build, Maintain and Operation" and "Research use" activities; and (ii) their effects on economic development – mainly at regional level, and capacity creation and skills development.

Internal analysis of the socio-economic impacts derived from both the construction period and the operational phase were expected to have positive influences at various levels – from the rural towns closest to the SKA site, to the national and international context. Although the projected (in 2008) number of jobs created was deemed to be relatively small, it is significant for the rural and sparsely populated region where the telescope was to be constructed. An increase in tourism was identified as another economic benefit to the region. More recently, the Northern Cape Provincial Government, the province in which the Karoo region is located, has launched an Astro-Tourism Strategy that seeks to drive economic benefit from astronomy resources in the province. Table 1 summarises the anticipated impacts to be derived from the radio astronomy investments.

Table 1. Anticipated impacts as identified in 2008

Impact	Description
Technical	Impact derived from creating new instrumentation and methodologies; manufacturing new products and services; and developing new processes. The main beneficiaries will be local firms responsible for the manufacturing and development from in-house IP or licensed from international partners and the use of these new products, services and process in sectors outside astronomy.
Organizational	Application of new project management and other organisational tools can provide cost reductions and quality improvements in the participating companies; and such improvements may have an effect on future sales.
Commercial	The commercial impacts through the establishment of new firms will be highly dependent on the local innovation and entrepreneurial environment that will in turn depend on action taken to develop the knowledge economy and local industry support measures.
SA's reputation and international standing	Increased reputation of organisation (NRF/SARAO) among potential clients could translate into new contracts as "non MeerKAT/SKA-related" businesses learn of the new skills and knowledge acquired by firms working with MeerKAT and the SKA.

Individual knowledge and skills development	Skilled personnel (scientists, engineers, skilled operators) employed within SA in the construction and maintenance of the facilities will learn new skills, techniques, and knowledge. Application of these skills outside MeerKAT/SKA within SA will add to the impact of the programme. There is scope for these skills and knowledge to be transferred through personnel mobility (new employment elsewhere) or in the case of explicit knowledge, through their communication to third parties not engaged in MeerKAT and SKA;
Human Capital Development	The existing dedicated SKA/MeerKAT Human Capital Development Programme, would contribute to the training of new graduates (MSc, PhD) and Post-doctoral level personnel[29].
Skills shortages in South Africa	To address the anticipated skills needs[30] of MeerKAT and SKA the need arose for the establishment of a training programme, particularly for technicians and artisans needed to maintain and operate the facilities in the Northern Cape. In this regard an apprenticeship programme has already been developed. The MeerKAT programme also planned to increase the local ICT and SET skills base by investing in a Cyber Lab and appointment of science/maths teachers. The skills shortage in SA is made more acute by the historic and current problems of secondary and tertiary education, including widespread poor demographics of staff (largely ageing), very high drop-out and failure rates for students, poorly skilled (for business) graduates and low enrolment rates – especially for higher degrees.
Skills transfer to the non-R&D sector	The impact of scientists and engineers moving out of MeerKAT and the SKA project and into other sectors is likely to be high for the companies and individuals concerned. Overall, it was anticipated that the project will not draw skilled resources from other sectors of the economy. It will have a positive direct impact, although small when measured against the very large skills needs in SA.
Impact of "Research Use"	This impact derives from the technological effect on SA of the research activities that SA scientists may carry out in the observatory and that would not have been developed if the observatory had been constructed elsewhere. The key areas that will be impacted were identified as the development of (i) new concepts and theories and (ii) analytical techniques, skills and tacit Knowledge.
South Africa's Innovation and R&D Capacity	The 2008 NRF Study showed that MeerKAT and SKA could have positive impacts on most of the challenges identified in the 2007 OECD Report on Innovation Policy in SA. In this regard a necessary and required condition will be for the country to attract and retain young people into science, technology and engineering. This is where the development of the MeerKAT and SKA could make a significant contribution stimulating the education pipeline from science engagement programmes to excite and support learners to supporting human capital and research capacity development at tertiary institutions.
Impact on South Africa's Development Towards a knowledge economy	Of the 83 World Bank Knowledge Economy Measures, seven will be directly affected by the proposed programmes to build and operate MeerKAT and the SKA together with the associated HCD Programmes and the proposed infrastructure investment in broadband (including undersea) cable. Hence the building of the MeerKAT and SKA if carefully planned and managed will directly affect and impact the country's transition to a knowledge-based economy.
Cluster Development	The MeerKAT will involve research at the cutting edge of science and technology and would be a powerful attractor to draw in other research and high technology activities to the country and will promote a virtuous spiral leading to the growth of high technology businesses and creation of high technology startups. The size and concentration of effort of the SKA project will substantially enhance this effect through major skills and technical capacity building, particularly in the areas of data science, artificial Intelligence, systems architecture and software engineering. The MeerKAT and SKA development could be a catalyst for clustering these developments with industry, universities and national research facilities to derive significant beneficial impact for the country.

3.1.2 Factors maximising opportunities for impact

In order to maximise opportunities for impact, it was necessary to understand the processes through which impact may occur – more recently conceptualised as 'impact pathways' - including the diverse levels and distribution of local content in the construction and operation of the MeerKAT. It was realised that these opportunities would be contingent on:

- the existing South African technical and scientific capacity to support the construction and operation of the facility;
- the level to which SA scientists have the necessary expertise to access the facility and the benefit from its use;
- the construction and maintenance arrangements agreed to, and the extent to which they use and develop SA capacities (local content requirements);
- the types of institutional arrangements in place to develop and assist the transfer to other areas of the economy of knowledge, skills and other capacities gained through direct involvement with the facilities; and
- the arrangements for access to the facility by South African scientists and the development of local capacity to benefit from such access.

The 2008 NRF Report made some recommendations on a number of actions that can be taken to improve the likelihood of MeerKAT and the SKA providing a positive return, and which were subsequently executed.

3.2 Decision Making for Impact

The impact derived from the development and operation of the SKA project is driven by interventions with defined scope of influence, and decisions that are either bottom-up or top-down. An additional dimension is the level of the impact - that is, global, national, regional or local. A key question in this regard is: “Do opportunities for impact drive specific decisions within the SKA project, and is it a bottom-up or top-down approach?”

Negotiated positions in both the SKA Convention, and its various policy documents, codify some of the expectations that arise for a publicly (government) funded project in a top-down manner. For example, sustainability imperatives are global impact considerations that drive the SKA design in a top-down manner, as well as macro industrial and scientific return to funding partners delivered through the concept of *juste retour*[31]. The design of the SKA telescopes, the plans for their operation, and the observing programmes that will be conducted once they are operational, are all fundamentally driven by the scientific priorities of the global community of professional research astronomers.

However, local impact is critically important where research infrastructures are being established, to ensure a ‘social license to operate’. As a result, the project is strongly informed by a bottom-up approach, guided by on-the-ground conditions and stakeholder management activities being undertaken already by SARAO (the SKAO had the advantage of this 'vanguard' approach, where SARAO was already operating). This has resulted in contractual provisions that ensure effective local participation of small and medium business enterprises in construction activities, as well as relevant training and skills development initiatives. This bottom-up approach responded to the needs of the community, and how to achieve a ‘social license to operate’ to successfully establish and operate the SKA. However, these local communities are located within a national context with set priorities, and funding levers and hence the ‘license to operate’ is moderated in a top-down approach to ensure alignment with national priorities and to justify public spending.

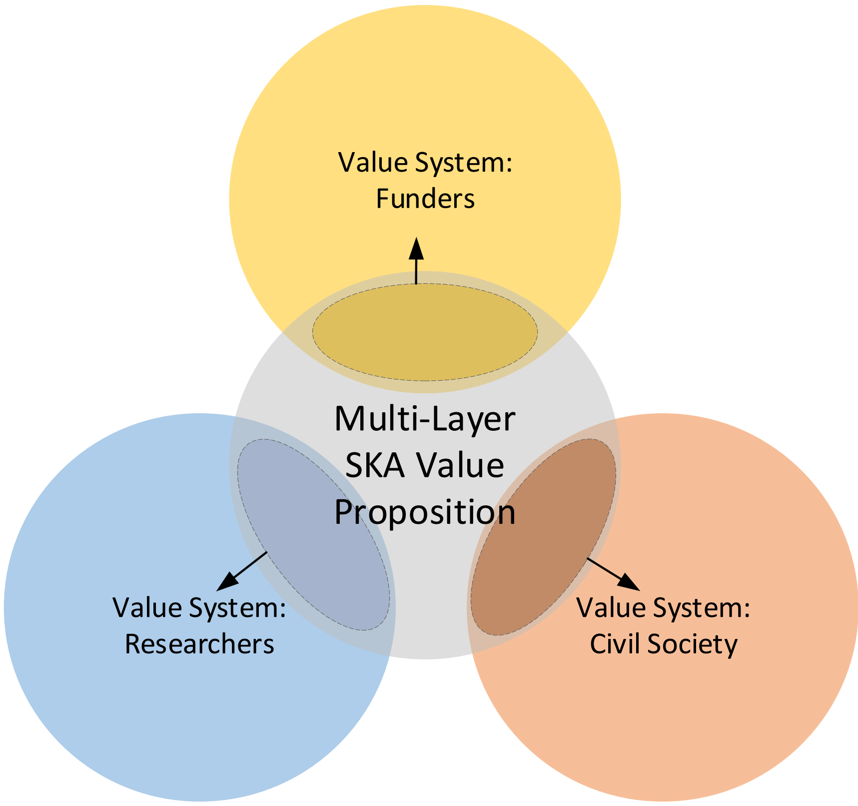
In response to the initial question, impact does drive specific decisions within the SKA project, regardless of whether a bottom-up or top-down approach is used.

3.3 Confronting Different Stakeholder Expectations

Different stakeholder expectations are to be expected, given the wide range of stakeholder groups involved in the SKA project. A good understanding of the value system adopted by each stakeholder group – and therefore, their expectations - is therefore necessary to properly assess potential alignment and overlap, which would inform the design of a multi-tiered value proposition that can be delivered in part, or in whole, to each stakeholder group. This conceptualisation is necessary to ensure a successful and sustainable delivery, and operation, of research infrastructures such as the SKA. The delivery of a multi-layered value proposition to all stakeholders is a critical success factor in deployment of such research infrastructures, which may come at a 'cost' premium.

A practical realisation of this concept in respect of the SKA is described in Figure 3, where the value system of respective stakeholders is shown not to be coincident, thus necessitating a multi-layered value proposition that delivers sufficient value to each identified stakeholder group. Design of the segmented value proposition was indirectly a necessary pre-condition for the project to proceed. For example, whilst an open market may be the most cost-efficient environment in which to deliver such research infrastructure, funder expectations drove an acquisition model that adopts principles of *juste retour* – meaning that a proportion of financial commitments made by Members and cooperating parties are returned through construction contracts. Similarly, expectations of civil society – particularly those local communities immediately surrounding the SKA, who may be living in socio-economically depressed conditions – are almost entirely framed on direct economic benefit and opportunity.

Figure 3: Delivery of a multi-layer value proposition to different stakeholder value systems



Often, the value system of each of the stakeholders do not coincide, and in some cases the stakeholders are unaware of each other. Such a situation should be carefully managed through a centralised coordination that establishes a complete, system wide view of the stakeholder universe. For the most part, the SKA project was successful in such an approach, relying on cooperation of individuals that were able to represent and balance the expectations of different stakeholders.

As a result of the above approach, South Africa’s expectations could be largely met through top-down design of the SKA value proposition, and bottom-up interventions undertaken by South Africa to maximise potential indirect socio-economic benefit. For example, the top-down design of a *juste retour* model could be further exploited within South Africa through the development and adoption of local participation plans for civil infrastructure contracts that ensured the participation of sub-contractors from local communities. Similar examples could be cited across the project. This approach is not without risk, however, as it creates a highly complex stakeholder environment that could have an impact on programmatic, technical and scientific objectives.

4 Interventions to exploit Impact opportunities and deliver value

4.1 Benefit Framework

The initial scope of anticipated impacts of the SKA in South Africa led to the development of a more comprehensive benefit framework, which recognised impact opportunities that would only be fully exploited through strategic intervention. This framework was informed by different socio-economic studies conducted over the past 14 years – including those overseen by SARAO, as well as independent research undertaken within various local and international institutions.

The overall (national and international) impact of the development of MeerKAT and SKA is underpinned by the following strategic pillars of the benefit framework:

- Research Enterprise and Science Products
  - Enhanced impact of research community and outputs
- Innovation and Industrial spill over
  - Leveraged foreign direct investment
  - Intellectual property development
- Education and Skills Development
  - Science communication and awareness
  - Skills development across STEM fields
- Business and Enterprise Development
  - Lowered barriers of economic opportunity
- Community and Cultural Investment
  - Community development and cultural preservation
  - Delivery against Sustainable Development Goals (SDGs)
- Public Good
  - Enhanced international reputation and partnerships
  - Transferable skills to respond to public need

The first two pillars listed are ultimately benefits derived through delivery of SARAO's core mandate – the establishment and scientific exploitation of astronomy research infrastructure. The remaining pillars required specific interventions to maximise potential benefit. Successful deployment of this strategic framework – that is, utilising the framework to inform strategic interventions to maximise impact opportunities - ensures sustainable delivery against the 'stakeholder value' framework and support for the 'social license to operate', and forms the basis for discussion in the following sections.

4.2 Interventions to Exploit Impact Opportunity

The benefit framework introduced in Section 4.1 informed key interventions to maximise opportunities for impact. Sustainability of these interventions was not only a function of sufficient funding, but also required political, legal and community support (a 'social license to operate'). This section will give a brief summary of the interventions introduced, and the approach followed to develop an assessment framework.

4.2.1 Research Enterprise and Science Products

Strengthening of the research enterprise in South Africa has been envisaged to be on the back of a targeted and strategic education and skills development initiative (see Section 4.2.3), as well as the establishment of international partnerships catalysed through the establishment of a research infrastructure capable of delivering transformational science (MeerKAT). Establishment of international partnerships stimulates internationalisation, collaboration and resilience of South African research infrastructure. A number of interventions have been undertaken to strengthen these partnerships, many of which took advantage of the significant technical capacity established within SARAO to develop the Karoo site and MeerKAT:

- Establishment of long-term MeerKAT science programs driven by multiple, diverse scientific teams that include both the South African and international astronomy community[32]. The approach of an 'open skies'[33] policy informs more regular calls for proposals[34];
- Leveraging against the legacy investment in establishing the highly protected Karoo site to attract further international and local astronomy projects;
- Support and participation by SARAO in international SKA programs and activities, an example being participation in the SKA Pre-construction Engineering Phase (PEP) – a multi-year international design effort to deliver a detailed and costed design for the first phase of the SKA. Of the nine relevant work packages[35], SARAO led two, and provided technical leadership in five others.

South Africa's drive to strengthen international partnership found expression on the African continent, which was codified through a Memorandum of Understanding for Cooperation on Radio Astronomy, entered into with the SKA African Partner Countries. This strategic intent was delivered through a number of initiatives, such as:

- Contribution and participation in the HESS Gamma Ray Observatory (Namibia);
- The African VLBI Network (AVN) project, to establish radio astronomy research infrastructure and capacity across the African continent. This resulted in the establishment of the Ghana Radio Astronomy Observatory, as well as other ongoing initiatives in selected countries;
- Africa-wide human capital development initiatives, such as the Development in Africa through Radio Astronomy (DARA[36]) education and training programme, and the Big Data Africa Program[37]

4.2.2 Innovation and Industrial Spill-Over

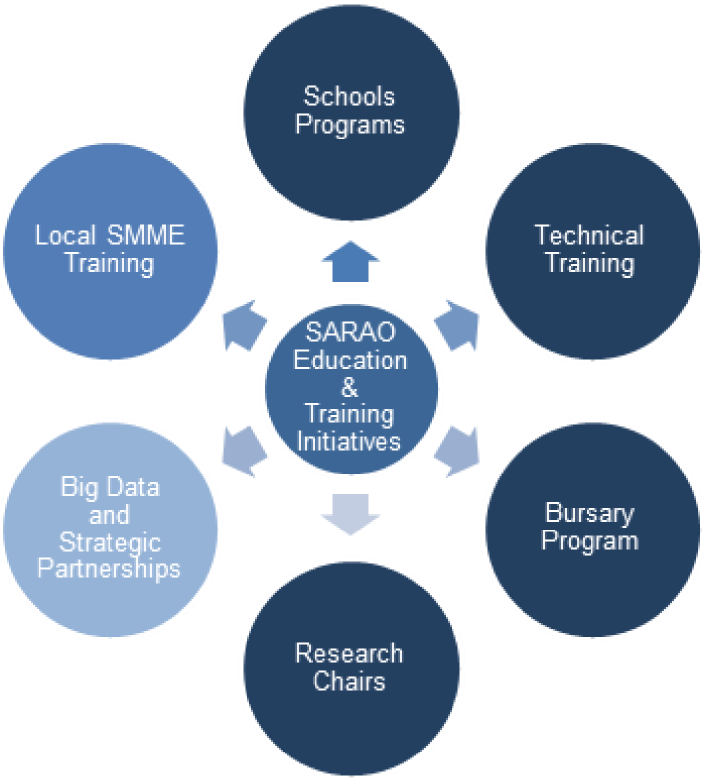
Innovate and industrial spill-over happened *de facto* through delivery of SARAO's mandate to establish and scientifically exploit next-generation radio astronomy infrastructure. However, to capture innovation products and intellectual property that may be taken to market, a commercialisation division was established within SARAO to promote an enabling environment for innovation, and capture and distil innovation products and intellectual property to market.

4.2.3 Education and Skills Development Initiatives

On the back of astronomy as a 'great attractor' of youth into science, technology, engineering and mathematics, SARAO implemented a number of interventions to build an education and skills development pipeline and develop highly relevant and transferable skills. Figure 4 describes the SARAO Education &

Skills Development Initiatives, directed into six focus areas: (i) Bursary Program; (ii) Research Chairs; (iii) Schools Programs; (iv) Local SMME[38] Training; (v) Technical Training; and (vi) Big Data and Strategic Partnerships.

Figure 4. Education and skills development interventions



Directed interventions were aimed at:

- Establishing a sustainable, resilient and vibrant research community in astronomy, data science and related technologies;
- Contributing to a STEM pipeline, and developing public awareness, by introducing comprehensive science engagement programmes;
- Training and supporting local SMME's to be able to take advantage of procurement opportunities presented by astronomy programmes;
- Developing capacity at an artisanal level within local communities to maximise local participation in the construction and operational phase of the SKA;
- Establishing strategic partnerships to support development of astronomy in South Africa, and on the African continent[39].

4.2.4 Business and Enterprise Development

In order to effectively lower the barriers to economic opportunity, an enabling environment for local business development was taken beyond SME training, including:

- Structuring procurement opportunities to promote local participation, with specific local participation goals; and

- Development of national high-tech industry through strategic engagement and support through Financial Assistance Programmes and home-grown cutting-edge technologies in a commercialisation pipeline;

4.2.5 Community and Cultural Investment

Through the MeerKAT and SKA program, SARAO launched various initiatives to deliver against specific Sustainable Development Goals in local communities, and establish itself as a 'corporate citizen'. These initiatives address such areas as:

- Cultural and heritage preservation through, for example, the MeerKAT Creative Community Initiative
- Gender balance and diversity through, for example, Women in Data Science Programs
- Community social development through, for example, grants to support social infrastructure such as soup kitchen, sports clubs and hospices.

4.2.6 Public Good

Maximising opportunities for public good required the establishment of an agile and responsive culture that could respond to national opportunities and threats. This required regular interfacing with key stakeholders beyond the immediate set of astronomy related stakeholders.

4.3 Quantitative and qualitative metrics for monitoring and evaluation

Quantitative and qualitative metrics used for monitoring and evaluation of impact from MeerKAT and SKA developments focused on:

- technical (mainly construction of service and research infrastructure);
- scientific aspects (knowledge products), including the development of the required capacities and capabilities; and
- local investment, which includes such metrics as job creation, youth employment, skills development and training, and expenditure with local suppliers and contractors.

However, without sophisticated analysis, such an approach does not capture the broader, nuanced socio-economic impact that occurs through unidentified impact pathways. The need existed for a broader socio-economic impact assessment, which is a systematic analysis to identify and evaluate the potential socio-economic and cultural impacts of a proposed development on the lives and circumstances of people, their families and their communities.

In view of the above, SARAO took the approach of conducting a series of scoping and baseline studies to collect and analyse data to define (or redefine) the outcomes and beneficial impacts of all the valued socio-economic components associated with the entire life-cycle for the development of the MeerKAT and SKA. The reports were also pivotal in the way that data is managed, and how general stakeholder engagements are managed to optimize positive impact.

A key activity that was undertaken in 2015 was the SKA Strategic Environmental Assessment study, which was a multi-disciplinary, holistic study to assess the environmental, social and economic impact of the SKA telescope in the Karoo. This led to outcomes and interventions specifically designed to minimise negative impacts across the environmental, social and economic spheres.

5 Impact status

Section 3 reflected on the potential benefits that could be derived from the development of MeerKAT and the SKA. This section gives an account of the true impacts measured to date (in relation to the anticipated benefits and impact formulated at the start of the project). The focus will not only be on the scientific and technical aspects but include an account of some of the societal benefits given their significance in ensuring successful and sustainable implementation and a ‘social license’ to operate.

5.1 Research Enterprise and Science Products

Development of the MeerKAT, and associated human capital development initiatives, had a material impact on the research enterprise in South Africa. High-impact scientific outputs delivered over a very short period (since the MeerKAT launch in 2018) have arguably established a global reputation of scientific and technical excellence for South Africa in the field of astronomy. Some key achievements to date include:

- Over the period 2007 to 2017, the mean normalised citation score (MNCS)[40] for astronomy and astrophysics has improved from 1.1 to 2.02 – meaning that the visibility of astronomy and astrophysics output from SA is twice the global average (Mouton et al., 2019[4]). There has also been a doubling in the relative field strength[41], and fourfold increase in the number of papers published. Anecdotally, this has improved even further in recent years since the launch of MeerKAT in 2018. In 2023, the MeerKAT Team were awarded the prestigious Royal Astronomical Society Group Achievement Award, for a series of spectacular scientific discoveries; and
- The size of the astronomy community has tripled over 15yrs, from 60 PhD astronomers to over 200, with a substantive increase in international collaboration.

The establishment of international partnerships is a necessary and required condition for the successful development of the MeerkAT and the SKA. The key benefits derived through these partnerships to date are:

- Improved Science Diplomacy – South Africa is increasingly becoming recognised as a destination for quality and competitive research and scientific outputs, world-class research infrastructure and an efficient science system – all of which position South Africa to actively engage on international matters through the platform of science diplomacy;
- Attraction of scarce skills from the international astronomy community, where four of the six Research Chairs in Astronomy were internationally recruited;
- Leveraged Foreign Direct Investments in local scientific infrastructure[42] and conferences, including the first IAU General Assembly to be hosted in Africa in 2024.

5.2 Innovation and Industrial Spill-over

Development of the MeerKAT, the pre-cursor facility to the SKA, by SARAO created an enabling environment for technology development and localisation, in partnership with South African industry. Key technology innovations developed by SARAO pursuant to the MeerKAT project include:

- Low cost and efficient super-computer data storage infrastructure, deployed at 30% the commercial cost and operated with an annual operational cost saving of R103 million, arising through non-commercial implementation of computing technologies. Such an innovation arose within SARAO to tackle the cost point and technical limitations of commercial data intensive compute platforms;

- General purpose computing platforms (Reconfigurable Open Architecture Computing Hardware – ROACH, and the SKA Reconfigurable Application Board - SKARAB), the primary building blocks for data processing developed by SARAO, in collaboration with international partners, and deployed on the MeerKAT telescope, and other telescopes worldwide;
- Passive Radar System (COMRAD) deployed to detect aircraft and airborne instruments without the use of an active radar[43]. This development by SARAO, in partnership with industry, arose due to the need to characterise and protect the MeerKAT and future SKA from airborne sources of radio frequency interference;
- High-speed Digitisers - a first design to sample and convert analogue signal to digital directly at the sensitive astronomy receiver without generating electromagnetic interference. This was designed and deployed for MeerKAT, to form part of the SKA in future; and
- 'Iron Hive', a low-cost, high-power efficiency, durable high performance computing platform, that takes advantage of immersive cooling technology. This was designed to confront the operational realities related to power and maintenance of super-computing infrastructure in the middle of remote, semi-arid regions.

A critical outcome of this work has been the development of work methodologies, skills and expertise that are being taken forward as best practice for the design and development of the SKA radio telescope. This includes the adoption of strong system engineering methods, which has realized substantial value to the MeerKAT project from both a cost containment[44], schedule and scientific performance perspective[45].

5.3 Education and Skills Development

The SARAO bursary program, designed on principles of pipelined support from school level through to post-doctoral fellowships and research chairs, has awarded over 1,500 grants for astronomy and related engineering disciplines since its inception in 2007, with 15% of those grants being awarded to students from African Partner Countries. Further programs have been implemented to support artisanal training, where 110 artisans have been trained in the Karoo date. Currently, six research chairs are supported to drive the development of local scientific capacity.

Strategic interventions at schools within the Karoo are informed by a focus on youth development and education, to enhance participation of the local community in various aspects of the project. To date, 20 schools surrounding the SKA site have active programs running that have been implemented by SARAO. Achievements include:

- School Bursary and Education Programs - Three full time maths and science educators are funded by SARAO in the local high school, whilst hundreds of school bursaries are awarded to learners wishing to access high school maths training;
- School Grants - SARAO established a Schools Grants programme, which awards grants to schools for investment in educational infrastructure such as classroom refurbishments, ICT infrastructure, and science laboratories.

SARAO have been able to leverage off strategic partnerships to support skills development initiatives across the African continent – for example, the Development of Africa through Radio Astronomy (DARA), and DARA BigData, undertaken in collaboration with the United Kingdom. The programs are designed to develop radio astronomy and data science skills and capacity on the African contingency. The most recent Data Science Intensive program, hosted by SARAO together with other partners, attracted over 2,000 applications from across the African continent – with only 20 places available.

5.4 Business Enterprise Development

The focus of SARAO economic development programme has been to lower the barriers to economic opportunity for local business on and around the SKA site. Some key outcomes include:

- Training in entrepreneurship and business development of over one hundred SMMEs in the Karoo, many of whom now regularly participate in radio astronomy procurement opportunities for construction and operational services;
- Graduation of nineteen (19) artists from the MeerKAT Creative Community Initiative (MCCI)[46];
- Establishment of a feedlot in collaboration with local agriculture cooperatives in order to mitigate the impact of reduced grazing capacity within the area and ongoing drought;
- Environmental projects in collaboration with other research institutions, such as the release of biological agents to assist with prosopis eradication[47]; and
- Promotion of Astro Tourism activities in the SKA area through training of astro-guides.

5.5 Community and Cultural Investment

Ongoing impact that results from community and cultural investments is reflected in the support the SKA project receives from local stakeholders, and in reports such as the Women in Data Science initiative[48]. Many impacts are delivered through a formal community development granting program, facilitated through SARAO, which includes support to soup kitchens and hospices, local sports clubs and provision of free Wi-Fi hotspots.

Investment in research infrastructure such as MeerKAT and the SKA represent critical investments as part of global efforts to address key sustainable development challenges, such as poverty-related communicable diseases, food security and climate change. South Africa's development of the MeerKAT and hosting of the SKA is an opportunity to invest in infrastructures as critical enablers and models for advancing sustainable development.

5.6 Public Good

The experience and skills acquired through development of the MeerKAT radio telescope were pivoted by SARAO to coordinate and lead the National Ventilator Project, a key COVID-19 intervention to successfully design and supply 20,000 locally conceptualised and built ventilators to the national health system within 8 months. This specific intervention received international attention as an exemplar of the public value of investment in basic research.

5.7 Overall assessment

It is perhaps difficult to assess the full scope of benefit and impact derived from radio astronomy investments in South Africa thus far. This relies on a range of economic and socio-economic models that may not accurately model the full socio-economic impact pathways. However, a recent unpublished independent socio-economic impact analysis of investments in radio astronomy to date, and the various interventions undertaken, reaches the following two conclusions:

"… *expenditure has had a significant positive impact on the South African economy, and is expected to continue once all construction is complete. These positive impacts have been critical in contributing to the developmental objectives of both the Northern Cape and South Africa."*

"… *the project has had a largely positive and significant impact on the national socio-economic conditions*

> *and scientific activity. Substantial contribution has been made towards education, skills development and employment opportunities in the country, as well as towards innovation, society and scientific activity.*"

It is perhaps fair to say, therefore, that the strategic interventions adopted to maximise potential benefit have been effective in delivering socio-economic impact.

6 Future opportunities

SKA is still very much an ongoing project. The main drivers for future opportunities and impact will be: (i) the construction and operation of MeerKAT Extension; (ii) construction and operation of SKA1 MID Telescope; and (iii) the future SARAO and its organisational strategy beyond construction of research infrastructure platforms.

6.1 MeerKAT Extension

The MeerKAT Extension (or MeerKAT+[49]) project will involve the construction of up to 16 additional dishes to bring to be added to the existing 64 MeerKAT dishes. The extension is jointly funded by Max-Planck-Gesellschaft (Germany), SARAO (South Africa) and INAF (Italy). The immediate and short-term benefits that will accrue to the local community will be derived through construction of additional infrastructure such as laying the foundations for the antennae, access roads, power, fibre, and water supply. However, the more sustainable and long-term benefits will accrue through the strengthening of international partnerships, and opportunities for new technology development. The project is an important step from an organisational sustainability perspective – ensuring continuity between the completion of the development of MeerKAT and its integration into the SKA1 MID telescope.

6.2 SKA1 MID Telescope

The direct benefits to be derived from SKA1 MID telescope are expected to be:

- Contracts to be awarded to South Africa over the next six years, pursuant to the principle of *juste retour* as well as other negotiated positions, which include: (i) construction contracts for civil infrastructure work packages (roads, fibre, electricity) and high-tech work packages undertaken by SARAO and local industry; and (ii) operations contracts with SARAO and other 3rd parties. These contracts will naturally realise job creation in both labour intensive and 'noble work' areas;
- Skills development through continued provision of bursaries and grants. A doubling of the bursary recipients (100 per year) in next 15 years to over 2800 in total is projected. Skills development will include the training of artisans, technicians, scientists, engineers and data professionals.

Scientific return on the investment expected to be reflected in the following impacts:

- Astronomy community will increase exponentially to more than triple[50] the current size. Achievement of this target will strongly depend on the availability of positions at universities, and research facilities and centres to appoint new staff and absorb PhDs and post-doctoral fellows;
- Scientific papers expected to also increase significantly and is projected to propel South Africa into the top 10 leading countries in this field (current ranking is 21), through meaningful participation in the science of the SKA;
- Continued commercialisation pipeline and technology development;
- Exposure of South African high-tech industry to international market opportunities;
- Community Development through continued NRF/SARAO community development projects and Karoo supplier development and training programmes for SMMEs.

6.3 Impact on SARAO and its organisational strategy

SARAO's long-term organisational strategy must be able to respond to the current changing external environment, driven by the evolution of the international SKA project. Over the next decade, SARAO will need to organisationally respond to three sequential phases that are largely dependent on the timelines of the SKA1_MID build program. These phases can be summarised below:

- SARAO Phase 1 - whilst operating, and scientifically exploiting MeerKAT, SARAO will be developing and executing the MeerKAT Extension project. It will also be participating in the continued design and development of the SKA1 MID telescope, whilst developing the SKA Regional Centre for scientific exploitation of the SKA telescope;
- SARAO Phase 2 - SARAO will continue to operate and use MeerKAT whilst participating in the construction of SKA1 MID telescope. Towards the end of the SKA1 MID build program, MeerKAT will be integrated into SKA1 MID, which will effectively transfer SARAO's major research infrastructure platform to the international SKA Observatory;
- SARAO Phase 3 – following completion of the SKA1 MID telescope, SARAO shall continue to operate the existing Hartebeesthoek site, along with designing and building an SKA Regional Centre (SRC). The SRC will be a major data-intensive research platform to enable the scientific exploitation of the SKA telescope by a local (and Africa-wide) user community, and will exist within an Open Science eco-system. In addition, SARAO shall operate and maintain the SKA1 MID telescope in partnership with the SKA Observatory through a joint partnership model. Recognising the potential strategic opportunities and given the current scope of technical expertise within SARAO, a vision to become a scientific and technology solutions provider to astronomy has been adopted.

7 Lessons learned

7.1 Generation of Broad-Impact during SKA Development

Section 4.1 described the key strategic pillars of the impact framework used to articulate the generation of broad impact derived from development of MeerKAT and SKA, namely

- Research enterprise and science products;
- Innovation and industrial spill-over
- Education and Skills Development;
- Business Enterprise Development
- Community and Cultural Benefit
- Public Good

Looking more broadly to the beneficial impact generated across all these pillars during the development of MeerKAT and the SKA, a critical question to ask is: 'What are the long-term effects of the generation of these impacts on the full spectrum spectrum of beneficiaries and stakeholders (society as a whole)?'

Based on the detailed account in Section 5 of the benefits realised across the different pillars, the long-term effects can be summarized into four high-level focus areas:

- Enhancement of South Africa's reputation as a trusted partner and preferred destination for investment in science and technology;
- Accelerating the building of, and transition to, a knowledge economy;
- Enhanced education and skills development; and
- Improved public good.

7.1.1 Enhancement of SA's reputation as a preferred research destination and trusted partner

The global value proposition delivers value to the global community in two parts (Adams and Tiplady, 2023[3]) : the provision of research capacity, expressed through enhanced internationalisation of science in South Africa, to address global scientific challenges; and the provision of unique and strategic research resources that enhance global scientific output, making South Africa a preferred destination for scientific investment and collaboration, and enhancing South Africa's international scientific standing and visibility. A strong reputation for being a viable destination for investment in science and technology infrastructure enables South Africa to not only attract further investment, but also provides an enabling environment for South Africa's efforts and participation in science diplomacy.

The drivers for the longevity and sustainability of an enhanced reputation are:

- the development and promulgation of globally unique legislation for the establishment and protection of areas suitable for the operation of astronomy facilities;
- utilising the country's geographic advantage for the establishment of next-generation and globally competitive radio astronomy facilities at a world-class site;
- ensured growth of a diverse, sustainable and transformed globally respected technical and scientific research capacity, and derive socio-economic benefit from investment in research infrastructure; and

- harnessing collective knowledge through mutual benefit sharing, which assists in meeting global challenges faced by society and enhance global science capacity.

7.1.2 Accelerating the establishment of a Knowledge Economy

The development of a knowledge economy enables greater participation in the fastest growing sectors of global trade, typified by knowledge intensive products and services. Whilst investment in science, technology, engineering and mathematics (STEM) research is seen as key to catalyse the development of a knowledge economy, it is important for South Africa to utilise a decision-making framework that ensures a high effective return on investment. Included in this framework was therefore the decision to participate in global research infrastructure.

The wide beneficial impacts derived for development of the MeerKAT and SKA to date provided the necessary and required building blocks for transitioning to a knowledge economy, namely:

- Competitive and world-class infrastructure (both knowledge and physical) as key enablers for knowledge generation and exploitation;
- Transferable skills, capacities and capabilities;
- Creation of a demanding environment (stringent, highly specified requirements for research infrastructure development) for local industry to push the innovation envelop;
- Lowering of the barriers to economic opportunity; business and enterprise development;
- Mission-driven innovation to develop knowledge products and services through engage on global research infrastructure; and
- Policy-enabled and targeted support for a conducive innovation culture.

Anecdotal evidence exists that suggests that the development of MeerKAT and SKA served as a catalyst for accelerating the building of a knowledge economy in South Africa. The long-term and ongoing impact of this role will require sustainable maintenance and support of the above building blocks.

7.1.3 Enhanced education and skills development

From the onset, central to the development and implementation of the MeerKAT and SKA was the requirement for the necessary scientific and technical skills. However, despite the existing baseline in this regard, the scope and size of the SKA required a much broader and larger skills base. The short-term beneficial impacts resulting from the development of the MeerKAT and SKA were the introduction of targeted programmes and projects aimed at education and skills development from school to tertiary level as well as artisanry, vocational and community training.

The effects of the broadened impact generated during the development of the MeerKAT and SKA are:

- Development of a sustained STEM-related education and skills development[51] pipeline from school to tertiary education level;
- Institutionalised funding and support systems and programmes;
- Availability of a pool of domain specific expertise and transferable skills that were able to respond to national opportunities and threats, such as COVID19;
- Awareness of the reciprocal interaction between human capital development, and access to research infrastructure.

Research infrastructures have the ability to attract and retain a critical mass of highly skilled individuals, whilst providing a benign, enabling environment for mission-driven innovation and international research collaboration. A key benefit of such a critical mass is the development of transferable skills, which not only expresses itself through the strengthening and contribution towards the broader scientific knowledge, but can bring about technological innovation and the production of products and processes that arise as a consequence of the research activity itself, or development of the research infrastructure.

The biggest threat to the long-term maintenance of an enhanced education and skills development system driven by the needs and requirements of the MeerKAT and SKA will be the absorptive capacity of the science system and industry to absorb the available skills and expertise.

7.1.4 Improved public good

Improved public good resulting from the generation of impact during development of the MeerKAT and SKA stems from the recognition of a need for a 'social license to operate' as a critical driver in ensuring the adoption of an 'engaged research' agenda, where broader public participation, engagement and understanding is a necessary condition to ensure broader societal support and, in many cases, enhanced research impact[52].

Ensuring *informed public opinion* is critical for a successful science system in South Africa. Firstly, it ensures successful implementation, or adoption, of scientific results. Ranging from public policy development to the adoption of preventative public health measures such as during the COVID-19 pandemic, ongoing science engagement has been a cornerstone of successful adoption. Secondly, ensuring *legitimacy in public opinion* is critical for ensuring ongoing sustainable investment in research infrastructure. This 'social license to operate' manifests itself through public discourse, and ultimately at the ballot box.

During the development of MeerKAT and preparation for implementation of the SKA, the project through various interventions and investments in local communities provides a mechanism for community development and supporting sustainability of local culture and heritage. Hence, strengthened its role as a corporate citizen and obtaining a 'social license to operate'. This is further strengthened through the project having established itself as a credible actor and trusted partner within the 'South African national system of innovation' and research enterprise, with the capability of delivering innovative socio-economic returns to the broader public.

The primary effect from the generation of wide impact during development of MeerKAT and SKA has been the creation of an enabling environment to contribute towards achievement of the UN Sustainable Development Goals[53].

7.2 Response to Stakeholder Expectations

The delivery of wider impact must take into account the value system of the stakeholder group to which that impact is being "delivered". For example, the manner and type of impact within local communities surrounding the SKA – located in a semi-arid region that is economically depressed – is quite different from that experienced at a national scale. This requires a multi-tiered value proposition that is delivered and managed through a multi-tiered stakeholder management framework that engages with, and delivers, a tailored value proposition to different stakeholder groups.

For example, the initial proposition of a major research infrastructure platform in the Karoo – whilst clearly important against a variety of national and international stakeholder needs – could have been perceived by the local community, on the outset, to have little value given that their needs were far more immediate: bread on the table. As a consequence, it was necessary to develop and create a value proposition that would appeal to the local stakeholder group – local employment, access to economic opportunity, investment in education and health infrastructure. This was coupled with a key strategy to manage the 'expectation gap' – the gap that exists between stakeholder expectations, and value proposition delivery. This was managed on both sides (management of expectation, and delivery of a viable and sustainable value proposition) to reduce the 'expectation gap' to a minimum. Significant increase in the 'expectation gap' would result in social discontent and loss of a 'social license to operate'.

Similarly, delivery against national, political expectations must acknowledge the decision-making framework of government agencies. This is often informed by political timescales, constrained by the periodicity of the election cycle. Therefore, major and high-profile research infrastructures – which often require political champions – must ensure adequate returns on shorter timescales. Visible progress for the public is important.

A word of caution, however. Whilst broader national stakeholder expectations are being delivered, the existing socio-economic conditions within rural communities are confronted with a highly resourced and skilled project delivery program for research infrastructure. A non-negligible risk exists that rural communities perceive such projects as a possible vehicle for government service delivery, including expectations for research infrastructure projects to intervene on key functions that fall within the mandate and responsibility of local government. This expectation needs careful management, to ensure that research infrastructure does not become a victim of its own success.

7.3 Opportunities for Collaboration

The SKA project provides a unique model for inter-governmental and inter-organisational collaboration on science infrastructure, enabled through establishment of the SKA Observatory (SKAO) as an inter-governmental treaty organisation (see Section 1.2.2).

The delivery of science from the SKA is intended to be through a collaborative network of SKA Regional Centres established in the various Member countries. Collaboration at a local level is facilitated through local structures, and dependent on the relevant strategies adopted. The 'capacity to use' model provides an excellent opportunity to collaborative networks to grow and increase the user-base, this will be an important vehicle to build capacity in the African Partner Countries.

A range of instruments are therefore available to enable collaboration by other organisation as and research infrastructures with the SKAO across a variety of areas, including scientific, technical, or even at a governance level where experience in establishing the SKAO can be shared more broadly. Whilst collaboration is fostered on an informal basis with a range of organisations and communities, the most basic level of formal collaboration is through a Cooperating Party agreement. In making arrangements for such an agreement, the SKAO Council may agree to whatever rights it wishes to provide to the party in questions. Criteria for Membership and Associate Membership are more restrictive, given the associated diplomatic privileges and immunities that arise.

7.4 Lessons for Future Very Large Research Infrastructures (VLRI)

This SKA case study provides some valuable lessons that could be extrapolated for future VLRI projects:

- *Ensure a Value Proposition and secure a 'Social License to Operate'*: Given that most VLRIs are funded, managed and operated by multiple stakeholders, and provide services to the international research communities at large, a clear understanding and formulation at the onset of the RI's value proposition is a required and necessary condition for delivery on its mandate and sustainability. The value proposition is not only necessary for decision-making by prospective partners and collaborators, but also influences the strategic approaches and interventions for managing the expectations of local communities (where the RIs are located) to see visible 'value' being returned to society. This value should be made visible to relevant stakeholders at all times.

- Ensuring legitimacy in public opinion is critical for ensuring ongoing sustainable investment in research infrastructure. This ‘social license to operate’ manifests itself through public discourse, and ultimately at the ballot box. It is a critical success factor for the long-term success of establishment and operation of research infrastructure in the modern world[54]. Securing such a license is dependent on the effective delivery of the multi-tiered value proposition, interrogated at the onset of the research infrastructure.
- *Impact presents itself as an opportunity, not a guarantee*: VLRIs have to recognise that broader impacts are opportunities at the outset, and that specific strategies and interventions must be agreed to and implemented early on to exploit inherent opportunities for impact – wider impact is not realised from the establishment of research infrastructures *ipso facto.*
- *Onboard multiple champions across the political spectrum*: VLRIs have both an international and national dimension, with decision-making structures for member states distributed hierarchically and across different departments. Across the national system, multiple champions should be established to provide resilience to funding streams.

8 Conclusion

South Africa has been able to realise beneficial socio-economic impact from investment in research infrastructure, such as the SKA. This realisation has hinged on a multi-pronged approach that included:

- Design and delivery of a multi-layered SKA value proposition that delivers against key stakeholder groups, including but not limited to the research community, funding agencies and the ordinary public (particularly those communities in the vicinity of the SKA facility);
- Pursuant to the above, the multi-layered value proposition facilitated the establishment of cross-sectoral buy-in at government and civil society level, resulting in increased institutional and funding resilience;
- Definition of a benefit framework to guide the design and execution of strategic interventions to maximise opportunities for socio-economic impact, some of which lead to the establishment of a ‘social license to operate’ within the Karoo.

These three elements should be considered as critical success factors in ensuring the sustainable establishment and operation of future research infrastructure.

References

Adams, D. and A. Tiplady (2023), *Big Science in South Africa: A catalyst for human capital development and mission-driven innovation*, IOP, https://doi.org/ISBN 9780750336291. [3]

Buckley, D. (2005), *Africa's giant eye : building the Southern African Large Telescope*, Observatory, South Africa :SALT Foundation (ISBN)062034783X. [2]

Florio, M. (2019), *Investing in Science*, The MIT Press, https://doi.org/10.7551/mitpress/11850.001.0001. [1]

Mouton, J. et al. (2019), *A scientometric assessment of physics in South Africa*, https://www0.sun.ac.za/scistip/wp-content/uploads/2022/06/2019_Final_Report_Statistics_in_South_Africa_March_2019v.pdf. [4]

Endnotes

[1] Enabled through access to optical, radio and gamma-ray astronomy facilities.

[2] Ten Year Innovation Plan for Science and Technology, 2008, Available online: https://www.gov.za/sites/default/files/gcis_document/201409/ten-year-plan-science-and-technology.pdf

[3] A full technical and scientific description of the SKA radio telescope can be found at www.skao.int.

[4] The SKA Observatory succeeded the SKA Organisation, which was established as a not-for-profit company in 2011 to prepare for the construction of the SKA telescope.

[5] At the time of writing, the SKAO Members are Australia, China, Italy, The Netherlands, Portugal, South Africa, Switzerland and the United Kingdom with several other countries aspiring to membership or engagement with SKAO in the future.

[6] The SKA Observatory Convention provides for two Council representatives per Member, one of which is the voting representative. Whilst each Member is free to choose its representatives, there is a legacy to include representatives from both government and the science community.

[7] In 2017, SKA South Africa, then a Business Unit of the NRF, merged with the Hartebeeshoek Radio Astronomy Observatory to form the South African Radio Astronomy Observatory (SARAO), a National Facility of the NRF. SARAO (SKA South Africa+HARTRAO) has since become the primary implementing agent for South Africa's strategic investments in radio astronomy, and has executed strategic projects and programs to established globally competitive research infrastructure platforms at a world-class site; ensure the growth of a diverse, sustainable and transformed globally respected technical and scientific research capacity; and derive collateral socio-economic benefits for the local communities from investment in research infrastructure.

[8] The National Research Foundation (NRF) is a statutory body responsible for enabling and funding research in South Africa. It does this through provision of grants and bursaries, as well as establishing and operating national research infrastructure platforms. Further information can be found at www.nrf.ac.za

[9] SARAO shall be used throughout this discussion paper. However, it should be noted that prior to 2017, SARAO was SKA South Africa, a Business Unit of the NRF.

[10] Namibia, Botswana, Mozambique, Madagascar, Mauritius, Kenya and Ghana. In 2011, Zambia officially joined the group of African Partner Countries. The involvement of these African Partner Countries was necessary in order to comply with the scientific requirements of the SKA – a configuration covering 3,000km in extent.

[11] Formal declarations of support were obtained from Heads of State and Governments of the African Union, which adopted a Declaration at their 2010 General Assembly giving unequivocal support to the SKA in Africa. A further Written Declaration by the European Parliament was received in 2011, giving support for the development of radio astronomy infrastructure and capacity in Africa.

[12] Determination of the final site was the subject of extensive deliberation by a panel of independent experts, based on an agreed decision-making framework.

[13] Including: current and future radio frequency quietness, configuration design, troposphere and ionosphere, environmental and climatic considerations

[14] Including: infrastructure design and access to bulk infrastructure

[15] Including: cost of deployment and operation

[16] Including: political, social and other factors that may influence the construction and operation of the SKA by an international organisation in the relevant hosting country over a 50-year period. Government support was a clear consideration, and the host country should exhibit the characteristics of a stable, mature and transparent socio-economic and financial environment

[17] Karoo Array Telescope (KAT-7) is a seven-dish array, established by SARAO as an engineering prototype for the larger MeerKAT radio telescope. Further information can be found at https://www.sarao.ac.za/science/kat-7/

[18] The MeerKAT radio telescope is a 64-dish array designed, constructed and operated by SARAO. Whilst it is a precursor to the SKA, and will be integrated with it, it is on its own right one of the premier radio astronomy facilities in the world.

[19] Available on: https://www.gov.za/documents/astronomy-geographic-advantage-act

[20] Implementation of the Act enabled the (i) declaration of a core area, in which all detrimental activities are prohibited; (ii) declaration of a central astronomy area, surrounding the core area, in which all activities must adhere to environmental thresholds (eg radio interference, light pollution); (iii) declaration of a co-ordination area, surrounding the central astronomy area in which there is co-ordination of activities

[21] The demand for use of MeerKAT by the international community is measureable, with Open Time calls for scientific proposals receiving applications for three to four times the amount of observing time available.

[22] National Development Plan 2030, Available at: https://www.nationalplanningcommission.org.za/National_Development_Plan

[23] In the context of this position paper, investment is executed through a variety of different forms from both financial investment to technological and research collaboration, to the hosting of research infrastructure platforms in South Africa.

[24] *Our Future – Make it Work: National Development Plan 2030* [Online], Available: https://www.gov.za/sites/default/files/gcis_document/201409/ndp-2030-our-future-make-it-workr.pdf [accessed 12th May 2021]

[25] Namely access to the southern oceans and southern skies, unique biodiversity, and the country's rich paleontological heritage.

[26] In some cases, the 'misfortunes' plaguing the country, such as HIV/AIDS and Tuberculosis, offer unique opportunities for collaboration from which foreign institutions could derive significant benefit from

[27] Unpacked in more detail at: https://issuu.com/ska_telescope/docs/ska_prospectus

[28] The South African Square Kilometre Array (SKA) Project: A Study of the Tangible and Intangible Benefits to South Africa from the Design and Construction of the MeerKAT Telescope and its Possible Extension. Prepared for National Research Foundation by Quotec Ltd, March 2008 (unpublished).

[29] At the time of the SKA bid, the total number of research astronomers in South was only 58 in 2005. Emigration and retirement of skilled workers coupled to the slow rate of replacement was creating a shortage of experienced professionals to pass on their skills to new graduates in the workplace. The initiative taken by the MeerKAT project team to retain and import experienced astronomers was a useful example of how this can be tackled, including in the university sector. The South African national initiative for new research chairs would play a major role in growing the research capacity in astronomy/Astro-physics with already 3 chairs awarded in 2008 in these areas.

[30] Having a long-term stable employer requiring high-level skills in the Northern Cape will add a strong incentive to local school leavers and diploma holders to train further with MeerKAT, including in apprenticeship schemes. SKA is a long term and large-scale project which would place sufficient demand on the local infrastructure to warrant new training programmes, especially for electronic/electrical specialists and mechanical/refrigeration technicians.

[31] The convention, and procurement approach, effectively enables countries to participate in construction and operation of the SKA telescope at a level that is proportional to their level of financial contribution.

[32] Whilst is may be easy to suggest that international collaboration within the science community happens *de facto*, the conceptualization and design principles of access and usage of research infrastructure can have a marked effect on international scientific collaboration

[33] An 'open skies' policy provides free access and utilisation of astronomy observatories to the global astronomy community, outside of any formal partnership or collaboration responsible for funding the construction and operation of the facility. Access is primarily determined through a competitive process based on double blind, independent review of scientific proposals. Such a policy can typically be hybridised to deliver against specific strategic outcomes.

[34] Regular calls for scientific proposals to the international community are launched. To date these calls are usually heavily over-subscribed, reflective of the importance of the MeerKAT to global radio astronomy

[35] There were 11 work packages in total, but two work packages were specific to Australian infrastructure deployment and receivers

[36] This programme (https://www.dara-project.org/) is co-funded by South Africa and UK's Newton Fund, and involves intensive training of students across Africa in radio astronomy techniques

[37] This program involves the rollout of high-performance computing and training programs in African Partner Countries (https://www.darabigdata.com/)

[38] Small, medium and micro business enterprise

[39] Initiatives such as the Development in Africa with Radio Astronomy (DARA), and DARA Big Data, projects - jointly funded by the UK and SA – have been very successful in training the first generation of radio astronomers and data scientists in SKA African Partner Countries.

[40] The mean normalised citation score (mncs) is an indicator of visibility and impact based on citations. This indicator is normalised to account for differences in the citation behaviour of different scientific fields as well as different publication years. A higher MNCS indicates more visibility and impact with an MNCS between 0.8 and 1.2 generally considered average.

[41] The relative field strength (RFS) measures what proportion of a country or organisation's total scientific output is in a specific field and compares that to what proportion of the world's total scientific output is in that same field. An RFS equal to 1 indicates that the country or organisation is just as strong or active in that field as the whole world is, while a higher value indicates more strength or activity.

[42] Including: MeerLICHT telescope in partnership with The Netherlands and United Kingdom; HERA telescope, in partnerships with the USA and United Kingdom; the C-BASS telescope, in partnership with the USA and United Kingdom; and MeerKAT Extension, in partnership with Germany and Italy.

[43] See: www.sarao.ac.za/news/the-south-african-radio-astronomy-observatory-sarao-has-invested-in-a-system-to-track-aircraft-and-other-airborne-instruments-with-passive-radar/

[44] A previous 10 year financial analysis, which included the full build program of MeerKAT, indicated a total budget deviation of no more than 2%

[45] The MeerKAT radio telescope, following its commissioning in 2018, is widely regarded as on of the premier radio astronomy facilities of its type in the world.

[46] The aim of MCCI is threefold: 1) source craft makers from disadvantaged backgrounds; 2) provide them with creative skills training, as well as basic business and marketing skills; and 3) Introduce them to the first steps in how to run sustainable businesses in arts and craft.

[47] SARAO is working with authorities to ensure alien species are eradicated.

[48] https://www.sarao.ac.za/wp-content/uploads/2021/03/Women-in-Data-Science-Report-FINAL-min.pdf

[49] https://www.meerkatplus.tel/

[50] This is only possible if there are positions available at universities.

[51] The broadening of this impact beyond astronomy is facilitated through the SARAO human capital development program, which recognizes the need to support astronomy and related scientific and engineering disciplines. As a collateral benefit, this promotes higher rates of multi-disciplinary research.

[52] An excellent example is in the dealing of matters of public health, where an informed society is more likely to adopt good public health measures to combat communicable disease.

[53] https://sdgs.un.org/goals

[54] This is mirrored in the corporate world, where long term organisational sustainability was becoming increasingly dependent on the shift away from the traditional ‘shareholder’ model, where the primary objective is to make profit for its shareholders, to a ‘stakeholder’ model, where the primary objective is to create value for its stakeholders.