



**SARAO**  
South African Radio  
Astronomy Observatory

# An Impact Study of South Africa's hosting of the Hydrogen Epoch of Reionization Array (HERA)



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of the South African Radio Astronomy Observatory (SARAO)



## AUTHORS

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**Dr Bonita de Swardt**

Programme Manager: Strategic Partnerships for Human Capital Development, Human Capacity Development division of the South African Radio Astronomy Observatory (SARAO), Email: bonita@sarao.ac.za

**Monushia Zimri**

HERA intern based with the Human Capacity Development division of the South African Radio Astronomy Observatory (SARAO)

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# PREAMBLE

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Southern Africa has become a prime destination for the hosting of cutting-edge astronomy research infrastructure. In particular, Namibia and the Northern Cape province of South Africa offer a pristine environment for astronomical observations, unimpeded views of the southern sky as a result of the low population density in geographical areas, as well as an overall stable economic and geopolitical environment that has led to these regions attracting substantive international investment into astronomy infrastructure.

In the past three decades, the Southern African region has attracted international investment towards large-scale astronomy research infrastructure through the hosting of multi-messenger telescopes, such as the High Energy Stereoscopic System (HESS) in Namibia, the Southern African Large Telescope (SALT) in the Northern Cape province of South Africa, and the Square Kilometre Array (SKA) radio telescope, which is under construction in the Northern Cape. To add to this, there has been growing international interest in co-hosting of smaller astronomy telescopes, instruments and experiments on existing infrastructure sites to support broader research projects undertaken by the international astronomy community. The co-hosting of instruments on existing astronomy infrastructure sites is seen as a cost-effective option given that the fundamental infrastructure (e.g., roads, power, optical fibre and computational infrastructure), and local human resources for maintenance, operations and management of the infrastructure, are mostly in place.

In South Africa, the co-hosting of smaller astronomy telescopes, instruments and experiments on existing astronomy infrastructure sites has become an innovative mechanism for the country to attract direct foreign investment into research infrastructure, while building a technically skilled labour force that contributes to the maintenance and operations of the infrastructure. The co-hosting of astronomy instrumentation can therefore have additional economic and socio-economic impact on the communities closest to the infrastructure site through skills development and employment created for the construction, maintenance, and operations of the infrastructure. At the same time, the development of science research capacity who are trained in using the infrastructure is an additional outcome from co-hosting astronomy infrastructure, which can lead to more researchers involved with international collaborations and strengthen South Africa's research outputs in astronomy.

The Hydrogen Epoch of Reionization Array (HERA) is a radio astronomy experiment located on the site that hosts the MeerKAT and SKA telescopes, which is situated in the Astronomy Geographic Advantage<sup>1</sup> area in South Africa's Northern Cape province. HERA is an international collaboration

working towards building a telescope array with the ability to detect and characterize the power spectrum of the epoch of reionization. The construction of the network of 350 antennas forming part of HERA was completed in 2021, with the instrument currently undergoing commissioning and validation of its data. HERA is a co-hosted instrument on the MeerKAT / SKA site with local support for its construction, maintenance and operations provided by the South African Radio Astronomy Observatory (SARAO).

The HERA project was identified as an excellent case study to understand the economic and socio-economic benefits to South Africa in co-hosting international, smaller scale telescopes and instrumentation on existing astronomy infrastructure sites.

The HERA impact study was undertaken by SARAO's Human Capacity Development programme to gain insight into the benefits of co-hosted instrumentation by looking at the financial investment into the project through contributions towards infrastructure, equipment, running / operational costs, and human resources, including human capacity development in science and engineering. The financial contributions from various partnering institutions forming part of the HERA collaboration were assessed at a country-level to compare direct foreign investment into the project to the co-investment made by the hosting country through the provision of human resources. It was found that South Africa as hosting country has made significant investment into human resources needed for the construction, maintenance, operations, and management of HERA. This has provided employment opportunities for individuals from the local community closest to the telescope site. South Africa's continued investment into human capacity development in science and engineering has led to a growing number of researchers forming part of the international HERA collaboration and increased the country's footprint in contributing to ground-breaking astronomy research.

Overall, the HERA impact study provides clear evidence of the economic benefits of co-hosting astronomy instrumentation at the national and provincial level in South Africa that includes the direct benefits to the towns closest to the astronomy infrastructure site. This evidence-based report will assist long-standing questions on how communities closest to telescope infrastructure have benefitted from astronomy infrastructure development, even at a smaller scale through co-hosted instruments. It is the aim of this impact study to provide quantitative evidence of the economic and socio-economic benefits of co-hosting astronomy instrumentation, which can be used as a reference in showcasing how investment into co-hosted astronomy infrastructure can be used for economic development.

<sup>1</sup>More information on South Africa's Astronomy Geographic Advantage (AGA) Act of 2007 can be found at <https://www.sarao.ac.za/about/astronomy-geographic-advantage-act/>.

# ABBREVIATIONS

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AVN	African VLBI Network
CETA	Construction Education and Training Authority
DSI	Department of Science and Innovation
DFI	Direct Financial Investment
HartRAO	Hartebeesthoek Radio Astronomy Observatory
HCD	Human Capacity Development
HERA	Hydrogen Epoch of Reionization
HR	Human Resources
MeerKAT	MeerKAT Radio Telescope
NRF	National Research Foundation
PAPER	Precision Array for Probing the Epoch of Reionization
PFMA	Public Finance Management Act
SARAO	South African Radio Astronomy Observatory
SKA	Square Kilometre Array Telescope
UK	United Kingdom
US	United States
VLBI	Very Long Baseline Interferometry
R or ZAR	South African Rand



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# 1 Introduction



# 1. INTRODUCTION

## 1.1 Overview of the HERA Impact Study

The Hydrogen Epoch of Reionization Array (HERA) is a radio astronomy experiment located on the MeerKAT / SKA telescope site in the Northern Cape province of South Africa. HERA is funded through an international collaboration representative of organisations and institutions from Europe, South Africa, the United Kingdom (UK), and United States (US). To understand the economic and socio-economic impact of co-hosted astronomy instrumentation in South Africa, an impact study of HERA was undertaken by the South African Radio Astronomy Observatory (SARAO) who is responsible for the local management of the construction, maintenance and operations of the instrument.

The HERA impact study has been structured into three main areas of assessment which are described below:

- i. The first section of the HERA impact study report looks at the economic benefits of hosting HERA in South Africa. This involved quantifying the direct monetary investment made into the project (as reflected by SARAO's financial records in managing the project locally) through the financial contributions of various collaborating institutions and organisations. A detailed breakdown of the HERA expenditure shows costing towards the infrastructure, equipment, running / operational costs, as well as human capital costs by the provision of human resources for the construction, maintenance, operations and local management of the project. South Africa's financial contribution towards human capacity development (HCD) in developing the skilled scientists and engineers is additionally included in the expenditure breakdown. The final component of the economic impact assessment of HERA was to quantify the financial benefits of hosting HERA in the Northern Cape province, to further explore the benefits to the hosting province of the instrument.
- ii. The second part of the HERA impact study discussed in section 3 of the report involved a detailed assessment of South Africa's investment into HCD as part of the HERA collaboration in developing the skilled scientists and engineers in collaboration with researchers based at South African universities. In particular, the impact study explores how South Africa's hosting of this international instrument was used as a platform to build local scientific capacity for the country to fully participate in the HERA collaboration through its continued financial support for HCD in radio astronomy.
- iii. The final component of the HERA impact study was a socio-economic impact assessment of HERA which focused on local employment created through the hosting of the instrument in the Northern Cape province. A survey was conducted as part of the socio-economic impact assessment to gain insight into the demographics of workers employed locally to work on HERA, in addition to their skills development while working on HERA, their views and perceptions of HERA, as well as their living conditions / social environment to better understand the impact of the project on these individuals.

A summary of the main findings from the HERA impact study is provided in section 5 of the report.

## 1.2 Background to the HERA Project

HERA<sup>2</sup> is a staged experiment that will use the unique properties of the 21-cm transition line from neutral hydrogen to probe the Cosmic Dawn, from the birth of the first stars, galaxies and black holes through the full reionization of the primordial intergalactic medium (IGM) [1]. The epoch of reionization occurred roughly 150 million to 1 billion years after the Big Bang, with the neutral hydrogen permeating the Universe (following recombination) being warmed and reionized by the first luminous sources.

Low frequency arrays such as HERA, can provide direct observations of the large-scale structure of the primordial IGM together with its evolution with time, via the 21-cm line of neutral hydrogen. By directly observing the large-scale structure of the primordial IGM as it is heated and reionized, HERA complements observations at other wavelengths, allowing for a better understanding of the astrophysics and fundamental cosmology of the early universe. The primary objective of HERA is to detect and measure the epoch of reionization.

HERA is a second generation instrument which combines efforts and lessons learned from other instruments such as the Murchison Widefield Array<sup>3</sup> (MWA) and the Donald C. Backer Precision Array for Probing the Epoch of Reionization<sup>4</sup> (PAPER). The latter instrument is considered as the phase I experiment of HERA and is also located on the site hosting the MeerKAT and SKA radio telescopes. The HERA experiment comprises of 350 parabolic dishes, each having a diameter of 14 metres. The phased construction of HERA on-site started in 2015 with the full complement of 350 dishes completed in 2021.

The design and construction of HERA is supported by an international collaboration consisting of the following partnering institutions:

- Arizona State University (Tempe, AZ USA),
- Brown University (Providence, RI USA),
- University of California Berkeley (Berkeley, CA USA),
- University of California Los Angeles (Los Angeles, CA USA),
- University of Cambridge (Cambridge, UK),
- Massachusetts Institute of Technology (Cambridge, MA USA),
- National Radio Astronomy Observatory (Charlottesville, VA USA),
- University of Pennsylvania (Philadelphia, PA USA),
- Scuola Normale Superiore di Pisa (Pisa, Italy),
- South African Radio Astronomy Observatory (Cape Town, South Africa),
- University of Washington (Seattle, WA USA).

Additional collaborators undertaking HERA research are based at Harvard University (Cambridge, MA USA), Rhodes University (Makhanda, South Africa), University of KwaZulu-Natal (Durban, South Africa), University of the Western Cape (Cape Town, South Africa), Imperial College London (London, UK) and California State Polytechnic University (Pomona, CA USA).

Funding for the construction of HERA was provided by US National Science Foundation<sup>5</sup>, the Gordon and Betty Moore Foundation<sup>6</sup>, as well as contributions from the University of Cambridge and South Africa's National Research Foundation<sup>7</sup> (NRF).

<sup>2</sup> The HERA website can be found at <https://reionization.org>.

<sup>3</sup> More information on the MWA can be found at <https://www.mwatelescope.org>.

<sup>4</sup> More information on PAPER can be found at <http://eor.berkeley.edu>.

<sup>5</sup> More information on the National Science Foundation can be found at <https://www.nsf.gov>.

<sup>6</sup> Information on the Gordon and Betty Moore Foundation at <https://www.moore.org>.

<sup>7</sup> See <https://www.nrf.ac.za>.

## 1.3 The HERA collaboration and South Africa's role

SARAO is a national facility of the NRF and is responsible for managing all radio astronomy initiatives in South Africa, including the MeerKAT radio telescope in the Northern Cape province, and the science and operational activities of the Hartebeesthoek Radio Astronomy Observatory (HartRAO) facility. SARAO also coordinates the African VLBI Network<sup>8</sup> (AVN) for the 8 SKA partner countries in Africa, as well as South Africa's contribution to the infrastructure and engineering planning for the SKA telescope.

As a national radio astronomy facility, SARAO is a key partner in the construction of HERA on the MeerKAT / SKA site, together with providing support for the maintenance and operations of the instrument. The roles of construction project management and project engineering were fulfilled by SARAO staff working at the Cape Town office of the organisation. The SARAO team worked closely with the HERA Project Manager based at University of California Berkeley during this phase of the project, who is responsible for the management and provides oversight on all deliverables feeding into the broader HERA collaboration.

SARAO appointed the human resources needed for construction of the instrument on-site with most individuals employed from the Northern Cape town of Carnarvon, which is the town closest to the MeerKAT / SKA site. Approximately half of these human resources have been retained to provide support for the maintenance and operations of HERA following the construction of the instrument in 2021.

The South African universities actively forming part of the HERA collaboration are Rhodes University, the University of KwaZulu-Natal and the University of the Western Cape. Researchers at these universities have supervised several postgraduate students (masters and doctoral) and hosted postdoctoral research fellows focusing on research related to HERA. Many of the postgraduate students and postdoctoral research fellowships were financially supported through SARAO's HCD programme. SARAO's HCD programme has therefore played a critical role in developing a research community focusing on topics related to the epoch of reionization and ensuring the inclusion of South African researchers in ground-breaking research that can be made with 21-cm instruments such as HERA.



<sup>8</sup> See <https://www.sarao.ac.za/science/avn/>.

## 2 Economic benefits of hosting HERA in South Africa



## 2. ECONOMIC BENEFITS OF HOSTING HERA IN SOUTH AFRICA

### 2.1 Measuring direct financial investment into HERA

The first component of the HERA impact study involved quantifying the direct monetary investment made into the project through financial contributions by various collaborating institutions<sup>9</sup>. The assessment was carried out using SARAO's financial records as provided for the South African management of the HERA project. This included monetary contributions that were paid directly to SARAO through various funding agreements with collaborating institutions. SARAO provided the necessary management support and purchasing experience needed to facilitate the spending for construction of the instrument.

SARAO's financial records allowed for the assessment of funds received from institutions outside of South Africa for the project, as well as the South African contribution to HERA. The international funding contributions are therefore seen as direct foreign investment into the South African economy through its hosting of the project. The funding contributions from collaborating institutions were categorised by country, with three countries providing direct investment into the project: the United States (US), South Africa and the United Kingdom (UK). The direct financial investment (DFI) into HERA by each of these countries is shown in Figure 1.

Figure 1 shows that the US has contributed 51% towards the total DFI for HERA, which corresponds to an investment of over R38 million (R 38, 060, 265). This represents the investment made by the US National Science Foundation, and Gordon and Betty Moore Foundation for the HERA project. South Africa as the hosting country has additionally contributed significantly to HERA with 44% (corresponding to an investment of over R32 million) contributed towards the total DFI of the project. This represents funding contributions by South Africa's NRF and the Department of Science and Innovation (DSI), with funding contributions managed by SARAO or by collaborating university partners in South Africa. The UK has contributed 5% (corresponding to over R3.5 million) towards the total DFI for HERA through funding from the University of Cambridge<sup>10</sup> and the UK Newton Fund.

The findings from the financial assessment of the impact study indicate that the total direct investment made towards the HERA project is well over R70 million (R 74, 090, 948), which was invested by the three countries over the period of 2013 to 2021. The annual expenditure towards HERA and associated HERA activities (this includes South Africa's contribution for HCD through the funding of postgraduate scholarships and postdoctoral fellowships on HERA related research topics) for the period 2013 to 2021 can be seen in Figure 2. This represents the annual direct investment towards HERA from all contributing countries. An increase in the DFI is observed from 2015, which marks the start of construction of the instrument in South Africa. The maximum annual DFI occurred in 2018 (R 23, 409, 564 i.e., 32% of the total DFI) at the peak of the construction efforts, with the annual DFI tapering off as the project neared completion over the period 2019 to 2021.

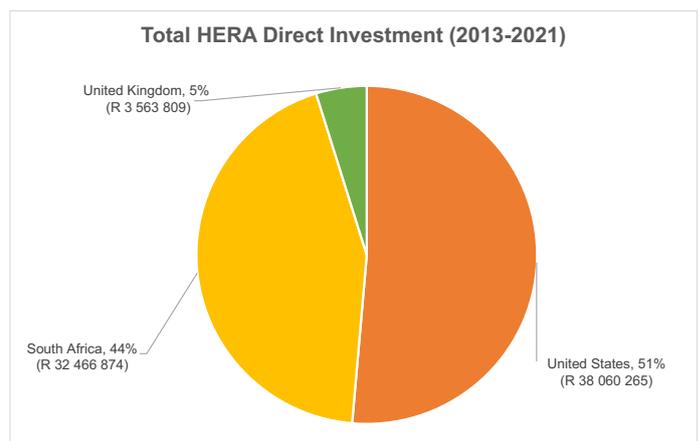
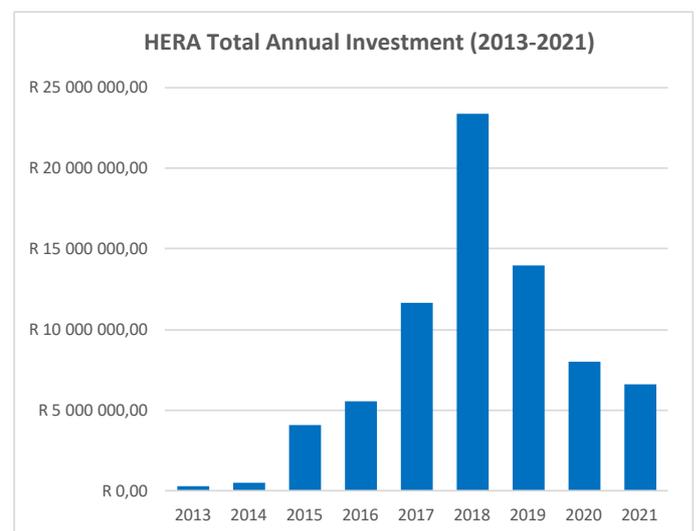


Figure 1: A country-level breakdown of the total direct investment into HERA for the period of 2013 to 2021.



Year	Cost (in ZAR)
2013	R 325,000
2014	R 505,000
2015	R 4,077,649
2016	R 5,545,859
2017	R 11,639,185
2018	R 23,409,564
2019	R 13,975,298
2020	R 7,989,035
2021	R 6,624,358
Total	R 74,090,948

Figure 2: Annual direct financial investment towards HERA over the period of 2013 to 2021.

<sup>9</sup> It should be noted that the financial assessment of the HERA impact study only includes direct monetary investment by collaborating institutions. Any in-kind contributions such as the provision of shared human resources partially working on HERA instrumentation, technology or science aspects, or direct provision of equipment, etc. through the collaborating institutions are not included in the financial assessment forming part of this report. It must however be acknowledged that these in-kind contributions from collaborating institutions are significant to the overall development and success of the project. But it remains a huge challenge to accurately quantify in-kind investment by collaborating institutions, which is beyond the scope undertaken by this study. The financial assessment of the HERA impact study should therefore be considered as a lower estimate to the total amount invested into the overall project.

<sup>10</sup> The total DFI for equipment or components provided by the University of Cambridge was obtained from commercial invoices used when importing the goods to South Africa. This represents a cost estimate for the equipment only and does not include labour costs for product development or in-house assembly as part of the university's in-kind contribution towards the HERA collaboration.

## 2. ECONOMIC BENEFITS OF HOSTING HERA IN SOUTH AFRICA

The annual direct investment contributed by the US, South Africa and the UK towards the HERA collaboration is shown in Figure 3. The annual investment made by South Africa to the HERA collaboration is to provide the necessary facilities, equipment, infrastructure and resources needed to host, physically build, maintain and operate the HERA telescope array. In addition to construction-related funding, South Africa also contributed to HCD by funding postgraduate scholarships and postdoctoral fellowships on HERA related research topics. Funding contributions by South Africa in 2013 and 2014 was only towards HCD. The contributions from the UK Newton Fund in 2015 and 2016 were mainly for equipment used for on-site skills development projects involving the local community in Carnarvon.

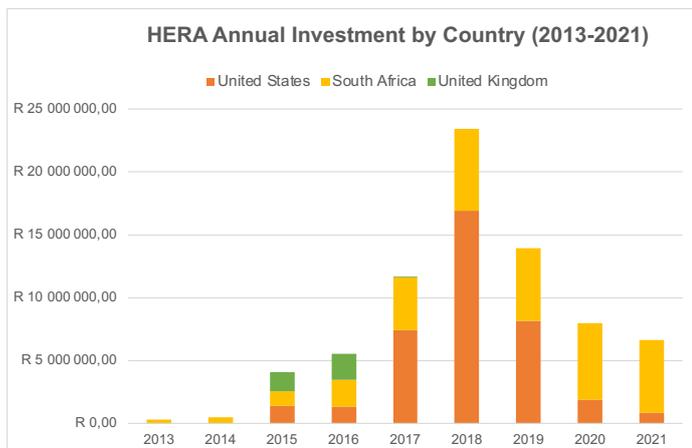


Figure 3: Annual direct financial investment by country towards the HERA project for the period of 2013 to 2021. The pre-construction funding contributions made by South Africa in 2013 and 2014 were towards human capacity development.

### 2.2 Breakdown of HERA Expenditure

A detailed financial assessment was performed using the project's financial records from SARAO. The expenditure was categorised into funding contributions for infrastructure development of the telescope array, equipment purchased for construction, and operational / running costs. The expenditure for human resources (HR) for the local management, construction and maintenance of HERA was obtained from SARAO's internal HR records<sup>11</sup>. The HCD expenditure includes postgraduate scholarships and postdoctoral research fellowships supported mostly by the SARAO HCD programme, but also includes financial support from other NRF postgraduate funding sources through the collaborators based at South African universities<sup>12</sup>.

A breakdown of the total HERA expenditure for the period of 2013 to 2021 is shown in Figure 4. It can be seen that the infrastructure costs were the largest expense accounting for 54% (R 40, 160, 370) of the project expenditure. A substantial investment of R 29, 111, 232 (corresponding to 39% of the total DFI) was made into funding of human capital through costs for staff and costs towards the development of science and engineering capacity, each making up 23% and 16% of the total DFI towards HERA, respectively. Expenditure towards equipment and operational costs have each contributed 3% and 4%, respectively, to the overall expenditure for HERA.

<sup>11</sup> Expenditure for HR includes salaries for staff working on-site in Carnarvon, as well as salaries for staff based at SARAO's Cape Town office.

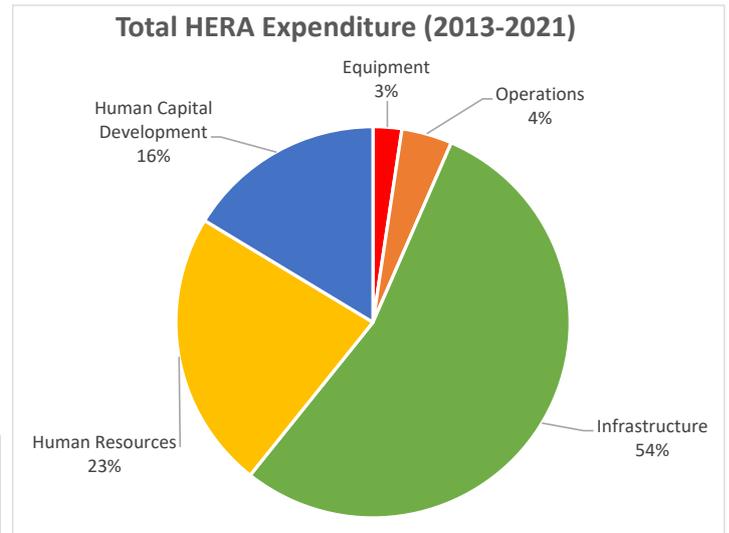


Figure 4: A breakdown of the total expenditure for HERA for the period of 2013 to 2021. The expenditure was categorised into funding contributions towards five areas: (i) infrastructure development, (ii) equipment purchased for construction, (iii) operational / running costs, (iv) human resources, and (v) science and engineering capacity development through financial support for postgraduate scholarships and postdoctoral research fellowships.

Figure 5 shows a breakdown of the annual expenditure towards HERA for the period of 2013 to 2021. Pre-construction expenditure in 2013 and 2014 was towards HCD through the funding of postgraduate scholarships and postdoctoral research fellowships. A constant level of investment into HCD has been maintained from 2015 to 2021 to fund research projects on HERA related topics. A peak in the expenditure is seen in 2018, which corresponds to the large spends in the infrastructure development mid-way through the construction of the telescope array. With construction of HERA coming to an end in 2021, most of the expenditure in this particular year was towards HR and HCD.

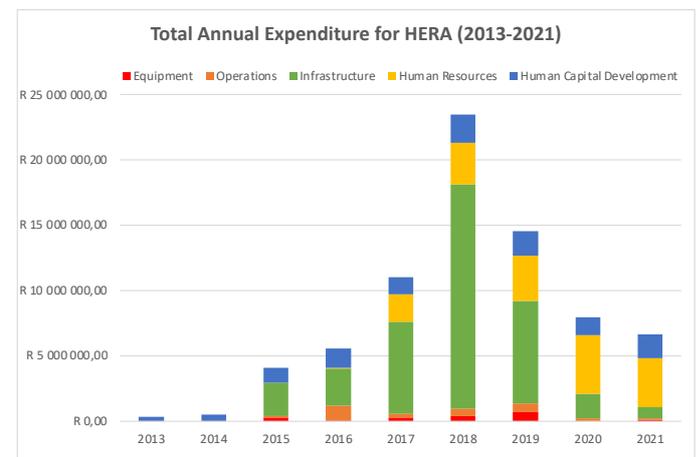


Figure 5: A breakdown of the annual expenditure towards HERA over the period of 2013 to 2021.

<sup>12</sup> For the HERA impact study, all scholarship amounts are based on SARAO's HCD programme level of support for the relevant academic year. This amount is considered a lower estimate as it only accounts for the scholarship award and not supplementary funds provided for travel and / or equipment that is typically associated with SARAO scholarships. Scholarship amounts also exclude any top-up funding from universities, which will increase the value of some scholarships.

## 2. ECONOMIC BENEFITS OF HOSTING HERA IN SOUTH AFRICA

### 2.3 Economic Benefits to the Northern Cape Province

One of the aims of the HERA impact study was to assess the economic benefits of hosting the HERA instrument at the provincial level in South Africa. In particular, the study will quantify the financial benefits of hosting HERA in the Northern Cape province, which is the hosting province of the instrument. The provincial financial assessment also looked at the economic impact of the construction of HERA on local towns in the Northern Cape province. This was done to assess how the town closest to the instrument, Carnarvon, benefitted from investment made into HERA.

The provincial and local financial assessments to quantify the economic benefits of hosting HERA were carried out by:

- i. Assessing the DFI into provinces in South Africa through the award of tenders<sup>13</sup> to suppliers during the construction period of HERA.
- ii. An assessment of the local expenditure made to suppliers located in various towns in the Northern Cape province.

SARAO's financial records on the HERA project allowed for both the provincial and local financial assessment with results presented below.

#### 2.3.1 Financial benefits of hosting HERA at the provincial level

SARAO, as a government funded research institution, requires a competitive bidding process through the issuing of a call for tender submissions for projects and financial amounts costing more than five hundred thousand rand<sup>14</sup>. SARAO's financial expenditure is governed by the guidelines and financial policies set out by National Treasury's Public Finance Management Act<sup>15</sup> (PFMA). A total of ten tenders was awarded by SARAO over the construction period of HERA from 2016 to 2019. Through the construction of HERA, over R25 million (R 25, 464, 016) in direct investment has been awarded to suppliers in South Africa through tenders.

The number of tenders awarded annually, and the corresponding total financial value of the tenders is shown in Table 1 for the period 2016 to 2019. On average, two tenders were awarded annually over this period apart from the year 2018 where a total of four tenders was awarded. The largest award value in tenders is observed for 2018 corresponding to an amount of over R14 million (R 14, 016, 039), which contributes to the peak in infrastructure expenditure seen in Figure 5.

Year	Tenders Awarded	Total Amount Awarded (in ZAR)
2016	2	R 1, 913, 251
2017	2	R 3, 934, 965
2018	4	R 14, 016, 039
2019	2	R 5, 599, 761

Table 1: Number of tenders awarded by SARAO and total financial value of tenders for the HERA Project (2016 - 2019).

<sup>13</sup> A tender is a competitive bidding process that is issued by a government or public entity to the general public. A tender is awarded to a person or company that must provide the goods or services in the manner agreed to and at the price offered as set out in a binding business contract.

Figure 6 shows the provinces that have benefitted from the award of tenders, which were issued to suppliers located within these provinces. The Northern Cape, Gauteng and Western Cape are the provinces that have directly benefitted from the tender awards made for the construction of HERA. Almost half of the total amount awarded for tenders (47%) was awarded to suppliers located in the Northern Cape province. This corresponds to a DFI of just under R12 million (R 11, 917, 469) into the Northern Cape. The Gauteng and the Western Cape provinces were awarded smaller tender amounts making up 34% and 19%, respectively, of the total amount awarded for tenders. Together, these tender amounts correspond to a direct investment of over R13 million (R 13, 546, 547) made to suppliers in these two provinces.

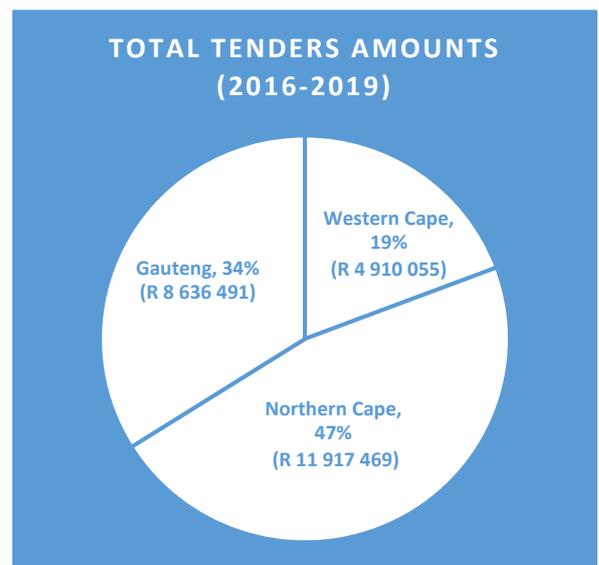
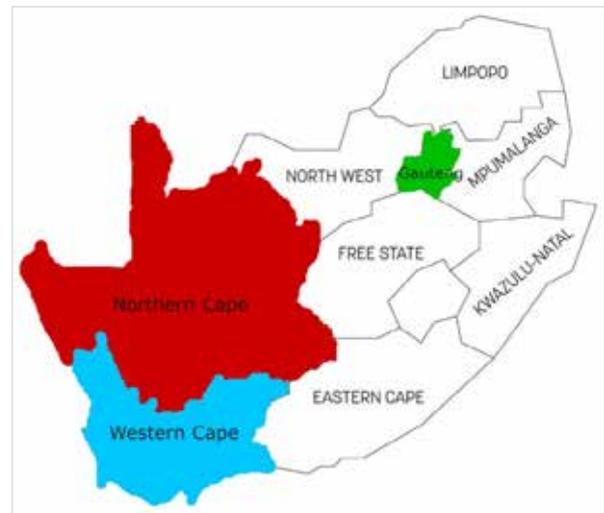


Figure 6: South African provinces that have benefitted from the award of financial tenders during the construction of HERA (top), which are the Gauteng, Northern Cape and Western Cape provinces. The total amount awarded through tenders to various provinces (bottom) over the period of 2016 to 2019.

<sup>14</sup> For the period over which the HERA impact study was undertaken, a value of five hundred thousand rand corresponded to the minimum amount for products or services for which a tender must be issued.

<sup>15</sup> <http://www.treasury.gov.za/legislation/pfma/act.pdf>.

## 2. ECONOMIC BENEFITS OF HOSTING HERA IN SOUTH AFRICA

### 2.3.2 Economic benefits to towns located in the Northern Cape Province

The SARAO financial records were used to carry out a detailed assessment of the total expenditure in the Northern Cape province, to quantify the DFI made into the local economy through expenditure to various suppliers located in towns in this province. The Northern Cape financial assessment included expenditure through the award of tenders described in section 2.3.1, and smaller expenditure amounts (i.e., amounts less than five hundred thousand rand) not requiring a tender process but still governed by the PFMA.

The Northern Cape financial assessment found that over R15 million (a total of R 15, 226, 295) was injected into the local economy in this province during the construction of HERA from 2015 to 2021. The towns that have benefitted from this investment are Carnarvon, Kimberley, and Calvinia. The location of the towns that have benefitted from this direct investment can be seen in Figure 7.

The total DFI into these towns is shown in Table 2. It can be seen that the town closest to the HERA instrument, Carnarvon, has benefitted significantly from this investment with a total expenditure of R 14, 574, 169 paid to suppliers in the town for goods / services over the construction period of the instrument.



Figure 7: A map of the Northern Cape province of South Africa showing the towns (circled in red) that have benefitted from direct financial investment during the construction period of HERA from 2015 to 2021.

Northern Cape Town	Total Direct Investment
Carnarvon	R 14, 574, 169
Kimberley	R 617, 280
Calvinia	R 34, 846

Table 2: Total direct investment into towns in the Northern Cape province resulting from the construction of HERA over the period 2015 to 2021.

### 2.3.3 Benefitting Economic Sectors in the Northern Cape

The total expenditure towards HERA for the Northern Cape province was grouped according to the relevant economic sector to ascertain which sectors in the province have benefitted most from investment into the project. The economic sectors presented in the *Northern Cape SKA Socio-economic Impact Assessment 2015* [2] were used for this purpose, which included nine sectors: agriculture, manufacturing, mining, utilities, construction, trade, transport, community, and business services.

The Northern Cape expenditure assessment for HERA found that three sectors, namely, the community, trade, and construction sectors have benefitted over the period 2015 to 2021. The benefitting economic sectors are shown in Figure 8 with majority of the expenditure directed towards the construction sector (99%), while minimal expenditure (less than 1%) has been made towards trade and the community sectors.

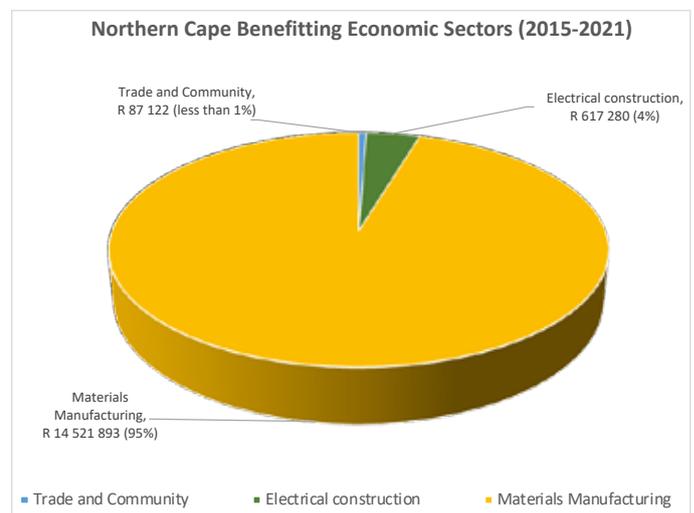


Figure 8: Northern Cape economic sectors that have benefitted from the construction of HERA over the period of 2015 to 2021.

The construction sector expenditure was further categorised into sub-sectors as defined by the Construction Education and Training Authority<sup>16</sup> (CETA). The two relevant sub-sectors identified were the materials manufacturing and electrical construction sub-sectors. The materials manufacturing sub-sector includes manufacturing of various wooden fixtures, tiles, sanitary ware, ceramic products, concrete and cement products, roof trusses, etc. Electrical construction deals with the assembling, installation and wiring of electrical systems in new homes and buildings. Most of the investment in the Northern Cape (outside of local employment) was towards the materials manufacturing sector with a total direct investment of R 14, 521, 893 made into the province during the construction of HERA. This was followed by an investment of R 617 280 into the electrical construction sector, which accounted for 4% of the expenditure.

It is clear from the economic sector assessment that the hosting of HERA in the Northern Cape has made a significant contribution to the construction sector in this province through the use of local contractors in supplying materials and services. This is a positive outcome and builds on the recommendations made by

<sup>16</sup> More information on the Construction Education and Training Authority (CETA), its mandate and sub-sectors covered through its skills development mandate can be found at <https://www.ceta.org.za/mandate-of-the-ceta/scope-of-coverage-of-the-construction-sector>.

## 2. ECONOMIC BENEFITS OF HOSTING HERA IN SOUTH AFRICA

the *Northern Cape SKA Socio-economic Impact Assessment 2015* [2] to use local contractors and sub-contractors in the Northern Cape province for the construction of radio astronomy infrastructure in the region, which will lead to business development, employment opportunities and skills development of individuals within the local communities. This investment will additionally build the construction sector in the province so that local companies and skills can be used for planned construction projects within the region, rather than outsourcing these projects to companies in other provinces.

### 2.3.4 Key findings on economic benefits of hosting HERA in the Northern Cape Province

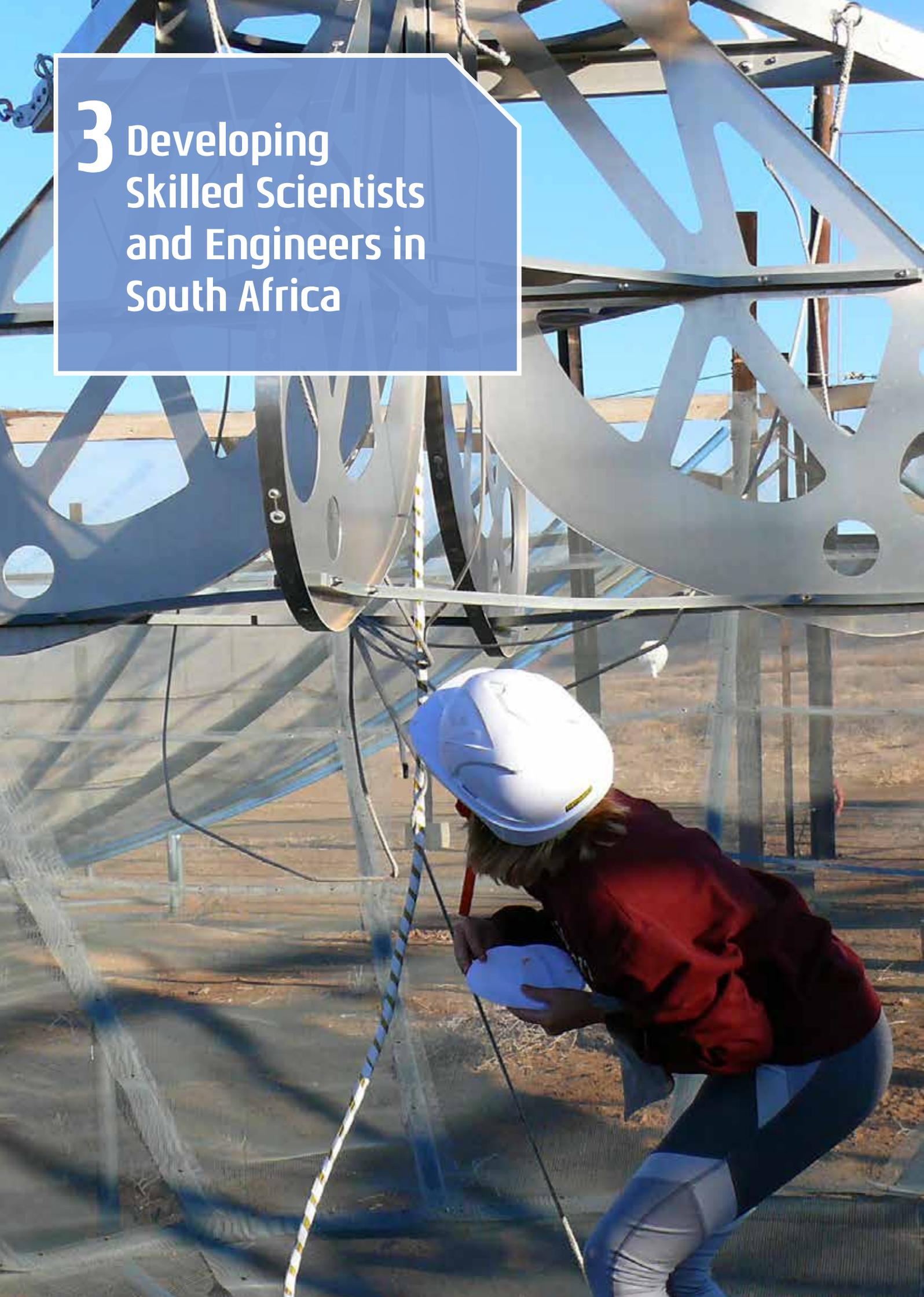
The financial assessment forming part of the HERA impact study has revealed the following insights into the economic benefits of hosting the telescope infrastructure in the Northern Cape province:

1. The Northern Cape province has benefitted the most out of all provinces in South Africa from direct investment made during the construction of HERA. Over R15 million (R15, 226, 295) in expenditure towards goods and services was made to suppliers based in this province during the construction of the instrument.
2. Local suppliers based in the closest town to the HERA instrument, Carnarvon, benefitted the most from the investment during the construction period when compared to other towns in the Northern Cape province. It was found that Carnarvon benefitted 95% (corresponding to R 14, 574, 169) in DFI through spends during the construction period, which were made to local suppliers.
3. Construction materials were predominantly sourced and fabricated from local suppliers in the Northern Cape province, which created an opportunity for local businesses in the province to directly benefit from financial opportunities brought by the construction of HERA.
4. Employment created locally during the construction of HERA provided further investment into the local economy by employing individuals mostly from Carnarvon. This created employment opportunities for the local community, which will be further discussed in section 4.
5. The purchase of equipment as part of funds provided by the UK Newton fund created training opportunities for the development of local artisans and technicians<sup>17</sup>. This allowed for individuals from the community to develop skills to access job opportunities beyond employment that can be created through the HERA project.



<sup>17</sup> SARAO has set up an artisan training centre in Klerefontein to offer practical training to local individuals undertaking an artisan qualification in areas of electrical, fitter and turner, and instrumentation and control. Funds from the UK Newton Fund was used to purchase some of the equipment used for training. Additionally, equipment was purchased for a Women Working for Water project that aims to train and employ women from local towns to assist with the removal of invasive alien vegetation from the MeerKAT / SKA site.

# 3 Developing Skilled Scientists and Engineers in South Africa



## 3. HERA'S CONTRIBUTION TO DEVELOPING SKILLED SCIENTISTS AND ENGINEERS IN SOUTH AFRICA

The financial assessment of the HERA project, presented in section 2, has revealed that approximately 16% of the total direct investment into the project was towards HCD through South Africa's continued investment into developing skilled scientists and engineering expertise in radio astronomy. This investment was used to support postgraduate scholarships and postdoctoral fellowships on research related to HERA.

This section provides an assessment of South Africa's investment in HCD as part of the HERA project in developing the skilled scientists and engineers in collaboration with researchers based at South African universities. In particular, the impact study will explore how South Africa's hosting of this international project was used as a platform to build local scientific capacity for the country to fully participate in the HERA collaboration through its continued financial support for HCD in radio astronomy.

### 3.1 South Africa's investment in Human Capacity Development in science & engineering

The first part of the assessment of support for HCD involved identifying postgraduate and postdoctoral research topics related to HERA that were funded by SARAO's HCD programme. This information was obtained using SARAO's HCD database which indicated the level of postgraduate study, or if a postdoctoral fellowship was undertaken. All information on SARAO supported students and postdoctoral fellows undertaking HERA research was verified by contacting the relevant university supervisor of the project. In addition, all South African researchers forming part of the HERA collaboration were contacted to provide information on students or postdoctoral fellows who have undertaken research on a HERA topic, which included individuals not funded by SARAO's HCD programme<sup>18</sup>.

Table 3 shows the number of awards made annually for postgraduate scholarships and postdoctoral research fellowships on research topics related to HERA. A total of 24 awards were made towards these HCD initiatives over the period of 2013 to 2021. 8 scholarships were awarded at both the masters and doctoral degree levels. Another 8 research fellowships were granted at the postdoctoral level. Since the start of construction of HERA in 2015, two to five awards have been made annually to fund masters, doctoral and / or postdoctoral research topics related to HERA<sup>19</sup>.

Year Awarded	Masters Degree Scholarships	Doctoral Degree Scholarships	Postdoctoral Research Fellowships	Total Number of Awards
2013	0	0	1	1
2014	2	0	0	2
2015	2	1	1	4
2016	0	1	1	2
2017	2	1	0	3
2018	0	2	3	5
2019	1	1	0	2
2020	0	0	0	0
2021	1	2	2	5

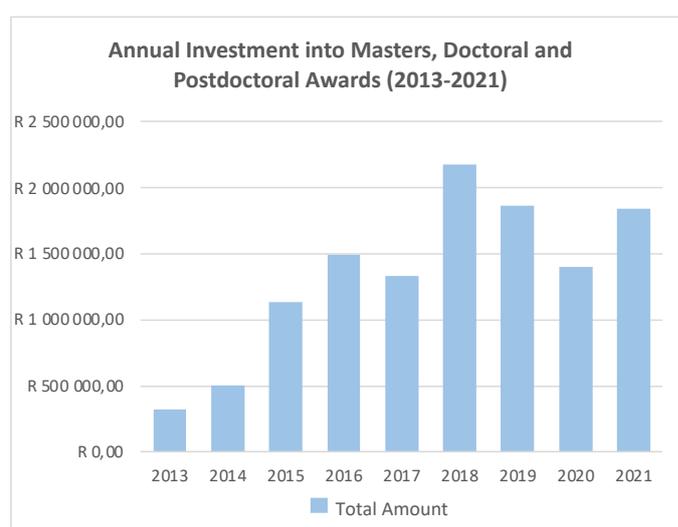
**Table 3: Annual number of postgraduate scholarships (masters and doctoral level of study) and postdoctoral fellowships awarded for research projects related to HERA over the period of 2013 to 2021.**

<sup>18</sup> Individuals not funded by SARAO's HCD programme received financial support either directly from the National Research Foundation, or from an award made by the relevant university at which they were registered. The latter funding for postgraduate studies or postdoctoral fellowships from the universities was usually associated with an award made by a Research Chair based at the university.

A financial estimate of South Africa's total investment into HCD in science and engineering related to HERA was obtained using the number of awards indicated in Table 3, together with SARAO's scholarship / research fellowship financial award levels for a specific year. The latter was used to benchmark all scholarships and postdoctoral fellowships awarded over the period of 2013 to 2021. The award amounts are, however, taken as lower estimates since it does not account for supplementary funding provided for travel and / or equipment that is typically associated with the full SARAO scholarship. Top-up funding for scholarship awards from universities has additionally not been taken into consideration in the financial estimate, which will lead to an increase in the value of some scholarships.

The HCD financial assessment found that South Africa invested over R12 million (R 12, 071, 142) in funding masters and doctoral scholarships, as well as postdoctoral fellowships focused on HERA research topics. 17% (corresponding to R 2, 004, 714) of the total investment into HCD was used to fund masters degrees, while 22% (corresponding to R 2, 685, 428) was used to fund students studying towards a doctoral degree. Most of the investment into HCD (61% corresponding to R 7, 381, 000) was used to support postdoctoral research fellowships.

The annual funding contribution towards masters and doctoral scholarships, and postdoctoral fellowships on research related to HERA is shown in Figure 9. Here it can be seen that South Africa maintained a continuous level of financial support for these HCD initiatives over the period of 2013 to 2021. An increased level of financial support for HCD is observed from 2015, which allowed for increased South African participation in HERA related research at the start of construction of the instrument. This early participation in research related to HERA has led to increased participation of South African researchers in the HERA collaboration.



**Figure 9: South Africa's annual funding contribution (2013 - 2021) towards masters and doctoral scholarships, and postdoctoral fellowships for research on HERA related topics.**

<sup>19</sup> This excludes the year 2020, where no new awards were made for postgraduate scholarships and postdoctoral research fellowships due to challenges faced by the COVID-19 pandemic in this particular year.

### 3. HERA'S CONTRIBUTION TO DEVELOPING SKILLED SCIENTISTS AND ENGINEERS IN SOUTH AFRICA

Figure 10 gives the country / region-specific demographics for the recipients of scholarship and fellowship awards. Half of the recipients of awards were South African who were funded at the masters and doctoral level of study, with the exception of 1 South African who was awarded a postdoctoral research fellowship. There has been minimal participation from the SKA Africa partner countries with only 3 awards made to individuals from an SKA Africa partner country (i.e., 1 masters scholarship and 2 doctoral scholarships). A larger number of awards were made to international beneficiaries who are defined as individuals having nationalities from countries outside of the SKA Africa partnership, with most awards made at the postdoctoral level. The latter awards were used to grow research related to HERA at the South African universities in building a local skills base.

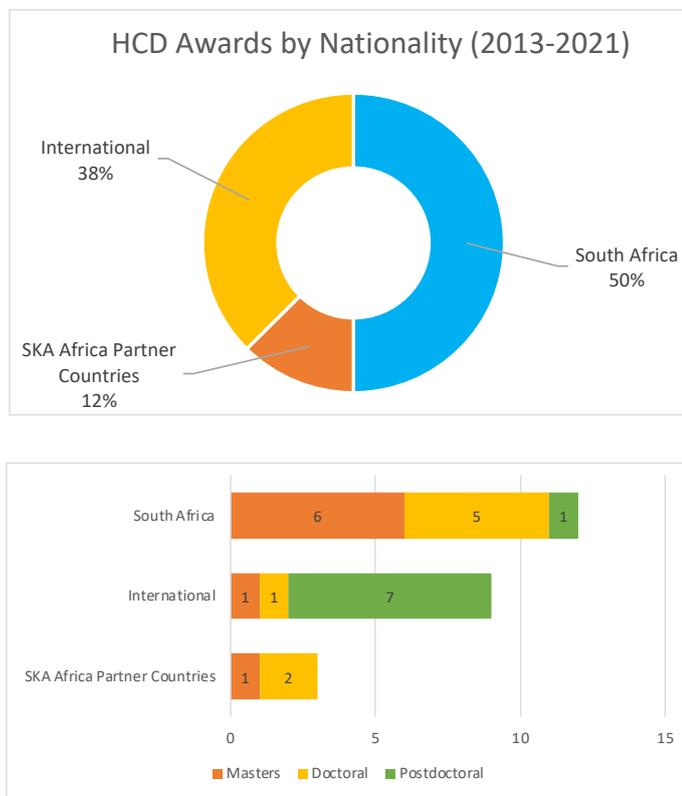


Figure 10: Country / region-specific demographics of the recipients of scholarship and fellowship awards undertaking HERA research topics (2013 - 2021).

The gender distribution of recipients of awards can be seen in Figure 11. Awards made to females have been very low with 3 awards (approximately 12.5% of the total number of awards) made at the masters, doctoral and postdoctoral level over the period of 2013 to 2021. The female participation in HERA research through the award of postgraduate scholarships and postdoctoral fellowships is significantly lower than the female participation observed for SARAO's broader HCD programme<sup>20</sup>. It is recognised that more needs to be done to make female students aware of this area of radio astronomy, and to encourage participation of young females students to take up masters and doctoral research opportunities through the South African HERA collaborators.

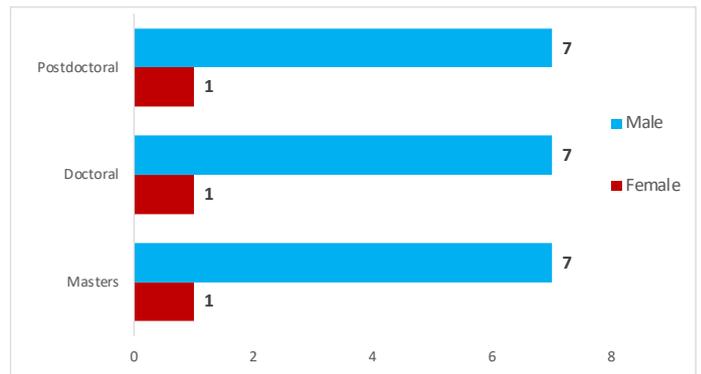


Figure 11: Gender distribution of recipients of masters and doctoral scholarships, and postdoctoral fellowship awards undertaking HERA research topics (2013 - 2021).

### 3.2 Participation of South African universities in HERA research

Figure 12 shows the South African universities where recipients of awards were registered for the specific postgraduate degree or postdoctoral research fellowship. More than half of the recipients of awards were registered at Rhodes University or the University of the Western Cape. A total of 3 masters degrees on HERA research was undertaken at each of these universities. A larger fraction of students was registered for a doctoral degree at Rhodes University, which supported 5 doctoral candidates over the period of 2013 to 2021. The University of the Western Cape had more postdoctoral researchers undertaking HERA research, with a total of 3 postdoctoral fellows registered at this institution. The same number of postdoctoral researchers were registered at the University of KwaZulu-Natal, together with 2 registrations at the doctoral level of study and 1 at the masters level of study. Fewer registrations are observed for Stellenbosch University and the University of Cape Town, with 1 masters degree student and 1 postdoctoral research fellow registered at each of these institutions, respectively.

It can be inferred that South African universities with researchers actively participating in the HERA collaboration have benefitted the most from the support towards postgraduate students and postdoctoral research fellows. In particular, the 3 universities who have benefitted most from this support are Rhodes University, the University of the Western Cape and the University of KwaZulu-Natal. These institutions are seen as leading the South African participation in HERA research conducted nationally.

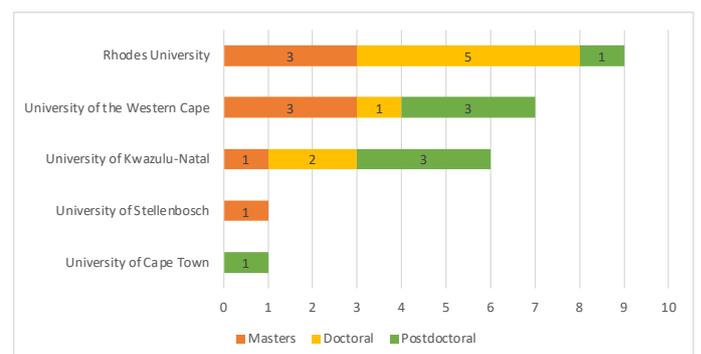


Figure 12: Registration of postgraduate students and postdoctoral fellows at the South African universities who have undertaken a HERA related research topic (2013 - 2021).

<sup>20</sup> Financial support for scholarships and postdoctoral fellowships offered through SARAO's HCD programme is predominantly awarded for research using the MeerKAT radio telescope, which is classified as a mid-frequency telescope array. Financial support is additionally provided for research topics using low-frequency telescope arrays with, for example, the HERA and the HIRAX experiments located in South Africa, allowing for the inclusion of research topics that encompass a broader area of the radio astronomy spectrum.

### 3. HERA'S CONTRIBUTION TO DEVELOPING SKILLED SCIENTISTS AND ENGINEERS IN SOUTH AFRICA

The research topics of the masters and doctoral degrees, and postdoctoral fellowships can be seen in Table 4. The academic year when the recipient of the award was registered and the university where the degree or fellowship was undertaken is additionally indicated in the table. Research conducted during the pre-construction of HERA focused mostly on the engineering / technical design of the instrument, and science related to data from the PAPER instrument. During the construction period of HERA, research topics were focused on data calibration aspects for 21-cm experiments together with simulations of the 21-cm signal detection. More recent topics include the exploration of using machine learning techniques in classifying the 21-cm signal detection that can be applied to data from HERA. Overall, the research topics funded over 2013 to 2021 were mostly directed towards science topics related to HERA rather than engineering topics.

Masters	Doctoral	Postdoctoral
Investigation and Characterization of the HERA Dish and Feed using Electromagnetic Simulations (2014, Stellenbosch University)	Observing cosmic reionization with PAPER: polarized foreground simulations and all sky images (2015, Rhodes University)	Observing the Epoch of Reionization with HERA (2013, Rhodes University)
Calibration and wide field imaging with PAPER: a catalogue of compact sources (2014, Rhodes University)	Unveiling the Epoch of Reionization with HERA (2016, Rhodes University)	Hardware development and calibration for the HIRAX and HERA Arrays (2015, University of KwaZulu-Natal)
Calibration techniques for 21-cm experiments with application to HERA: quasi-redundant calibration analysis (2015, University of KwaZulu-Natal)	Correlation calibration (2017, University of KwaZulu-Natal)	Revealing the childhood of the Universe with low frequency radio telescopes (2016, University of the Western Cape)
Detecting Galaxies in the Epoch of Reionization (2015, University of the Western Cape)	Covariance Calibration (2018, University of KwaZulu-Natal)	21-cm simulations and model fitting for HERA and the future SKA1-LOW (2018, University of the Western Cape)
Reconstruction of the Ionization history from 21-cm maps with deep learning (2017, University of the Western Cape)	Studying the Epoch of Reionization with HERA (2018, Rhodes University)	Data analysis for HERA (2018, University of KwaZulu-Natal)
A 150 MHz all sky survey with the Precision Array to Probe the Epoch of Reionization (2017, Rhodes University)	Chasing the cosmic dawn with HERA (2019, Rhodes University)	Simulations of the 21-cm signal from the Epoch of Reionization (2018, University of the Western Cape)
Observations of cosmic reionization with the Hydrogen Epoch of Reionization Array: simulations of closure phase spectra (2019, Rhodes University)	Observing cosmic reionization with HERA (2021, Rhodes University)	Machine learning for HERA (2021, University of KwaZulu-Natal)
Classifying non-redundancy in the HERA array (2021, University of the Western Cape)	Simulating and Analysing Systematics in the Hydrogen Epoch of Reionization Array (2021, University of the Western Cape)	Solving Non-redundancies in the HERA Experiment (2021, University of Cape Town)

Table 4: HERA research topics undertaken by recipients of scholarship awards and postdoctoral fellowships. The year of registration for the degree / research fellowship and associated South African university are indicated for each research topic.

A total of 7 masters degrees and 1 doctoral degree has been awarded on HERA research topics over the period of 2013 to 2021. The HERA project has therefore contributed to developing the local skills base of scientists with more than half of the students supported being South African. This together with the 8 postdoctoral fellowship awards for early career researchers has contributed to growing South Africa's participation in the collaboration.

South Africa's growing participation in the HERA collaboration can additionally be seen through research publications produced by the HERA collaboration. Table 5 shows HERA research papers that have been published over the period of 2016 to 2021 having an author / co-author affiliated with a South African university. 12 research papers have been published in this period with an author / co-author affiliated with a South African university. Most of the research publications had an author / co-author affiliated with Rhodes University, which had an affiliation on 11 HERA research publications. This was followed by the University of the Western Cape having an author / co-author affiliation on 2 HERA research papers. Both the University of KwaZulu-Natal and the University of Stellenbosch had an author / co-author affiliation on 1 HERA research publication.

Year	University	Research Paper Publication
2021	Rhodes University	Understanding the HERA Phase I receiver system with simulations and its impact on the detectability of the Epoch of Reionization delay power spectrum
2020	Rhodes University	Redundant-baseline calibration of the hydrogen epoch of reionization array
	University of KwaZulu-Natal	
	University of the Western Cape	
	Rhodes University	Detection of cosmic structures using the bispectrum phase. II. First results from application to cosmic reionization using the Hydrogen Epoch of Reionization Array
	Rhodes University	Measuring HERA's Primary Beam in Situ: Methodology and First Results
	Rhodes University	Imaging and Modeling Data from the Hydrogen Epoch of Reionization Array
	Rhodes University	Absolute Calibration Strategies for the Hydrogen Epoch of Reionization Array and Their Impact on the 21-cm Power Spectrum
	University of the Western Cape	Foreground modelling via Gaussian process regression: an application to HERA data
	Rhodes University	Mitigating Internal Instrument Coupling for 21-cm Cosmology. II. A Method Demonstration with the Hydrogen Epoch of Reionization Array
2019	Rhodes University	Optimizing sparse RFI prediction using deep learning
	Rhodes University	The HERA-19 Commissioning Array: Direction-dependent Effects
2017	Rhodes University	Hydrogen Epoch of Reionization Array (HERA)
2016	University of Stellenbosch	The Hydrogen Epoch of Reionization Array Dish. II. Characterization of Spectral Structure with Electromagnetic Simulations and Its Science Implications

Table 5: HERA research publications having an author / co-author affiliated with a South African university (2016 - 2021).

## 3. HERA'S CONTRIBUTION TO DEVELOPING SKILLED SCIENTISTS AND ENGINEERS IN SOUTH AFRICA

### 3.3 Human Capacity Development through the international HERA Collaboration

This section takes a broader look at HCD through the international HERA collaboration, to gain insight into how the project is contributing to the development of scientists (and engineers) at institutions forming part of the international collaboration. A similar HCD assessment as described in section 3.1 was carried out but excluding the financial component of the study. The HERA international collaborators were requested to provide information on postgraduate students and postdoctoral research fellows, registered at their respective institutions, who have undertaken a research project related to HERA. This information was provided by each of the international HERA collaborators in February 2022 through a collated database<sup>21</sup>. The collated database represents the most updated HCD information on postgraduate students and postdoctoral research fellows forming part of the HERA collaboration (outside of South Africa) to date, which is presented in this section.

HCD information was received from 7 international institutions (outside of South Africa) forming part of the HERA collaboration. These included institutions in Canada (McGill University), Italy (Scuola Normale Superiore), the UK (University of Cambridge, Queen Mary University of London) and the US (Arizona State University, Brown University, University of California Los Angeles). A country-level breakdown of the number of postgraduate students and postdoctoral fellows who have undertaken research on a HERA related topic is shown in Figure 13.

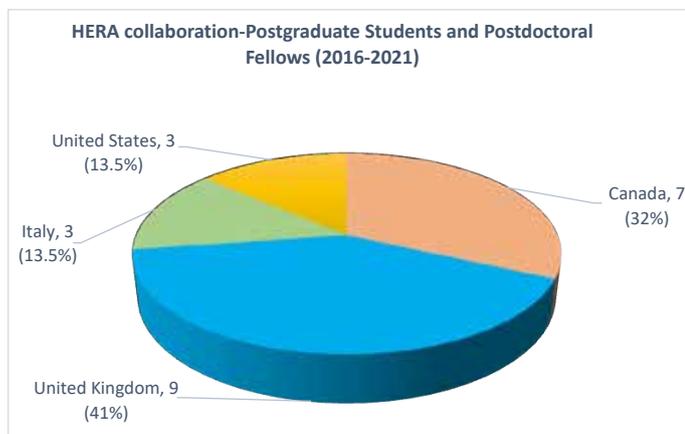


Figure 13: A country-level breakdown of the postgraduate students and postdoctoral fellows undertaking HERA research at international institutions forming part of the HERA collaboration (2016 - 2021).

The majority of postgraduate students and postdoctoral fellows (corresponding to 9 out of 22) represented in the international HCD assessment have undertaken research at a UK institution. This is followed by 7 postgraduate students and postdoctoral fellows at McGill University in Canada. Both Italy and US institutions have a total of 3 postgraduate students and postdoctoral fellows affiliated with institutions in these countries.

An institutional breakdown of the number of postgraduate students and postdoctoral fellows who undertook research on

a HERA related topic is shown in Figure 14. It can be seen that McGill University has the most postgraduate students and postdoctoral fellows who have conducted HERA related research out of all collaborating institutions (7 out of 22), which is followed by Queen Mary University of London (5 out of 22) and the University of Cambridge (4 out of 22). Scuola Normale Superiore has a total of 3 postgraduate students and postdoctoral fellows who have carried out research related to HERA, whereas the US institutions, Arizona State University, Brown University, University of California Los Angeles have each a single research student or postdoctoral fellow affiliation. Furthermore, it can be seen that McGill University and Queen Mary University of London have the largest number of postdoctoral fellows who have undertaken HERA research with each having hosted 4 and 3 postdoctoral fellows, respectively. The University of Cambridge has had the largest number of doctoral students undertaking research on a HERA topic, with 4 students affiliated with this institution.

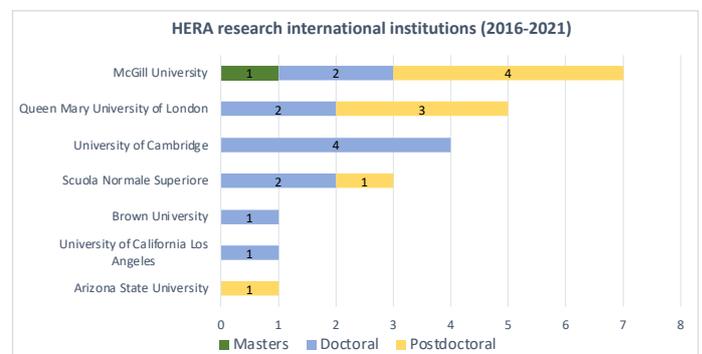


Figure 14: Postgraduate students and postdoctoral research fellows at international institutions undertaking or who have undertaken a research topic related to HERA.

The overall number of postgraduate degrees (masters and doctoral) and postdoctoral fellowships that are affiliated with international institutions forming part of the HERA collaboration is shown in Figure 15. Most of the postgraduate degrees were towards a doctoral level of study (12 PhD candidates in total), with only 1 masters degree undertaken on a HERA research topic. A total of 9 postdoctoral fellowships were undertaken on research related to HERA at the international institutions.

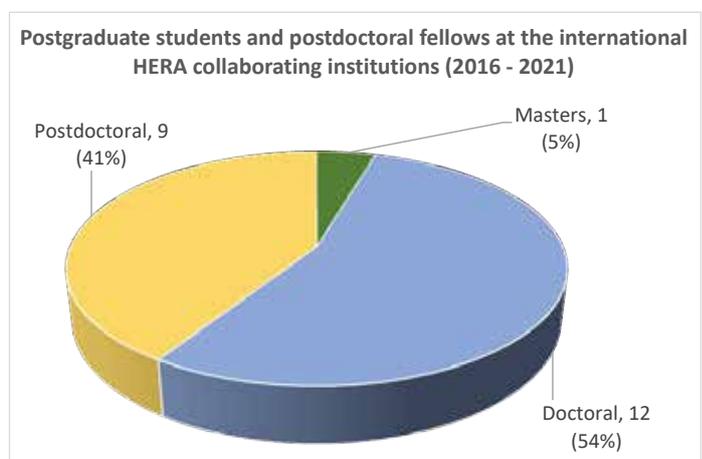


Figure 15: The distribution of postgraduate students (masters and doctoral) and postdoctoral fellows undertaking research topics related to HERA since 2016.

<sup>21</sup> Institutions forming part of the international HERA collaboration were requested to provide their respective HCD numbers to ensure their inclusion in the HERA impact study. The HCD numbers for international institutions presented in section 3.3 represents the collated information as provided in the database at the end of February 2022. Institutions who have not submitted their respective HCD numbers by the latter date are not represented in this section of the HERA impact study.

### 3. HERA'S CONTRIBUTION TO DEVELOPING SKILLED SCIENTISTS AND ENGINEERS IN SOUTH AFRICA

Figure 16 shows the starting year for undertaking the postgraduate degree or postdoctoral fellowship at the respective international institution. On average, 2 doctoral degrees have been undertaken each year on HERA related research since 2016 to 2021. From 2018, more postdoctoral fellowships have been awarded on topics related to HERA with a larger number of fellowships awarded for the years 2018 and 2020. It should be noted that some of the doctoral students are currently in the final stages of their degree, with graduations of these students expected in 2022 and in the next few years. The single masters degree student completed the degree in 2021.

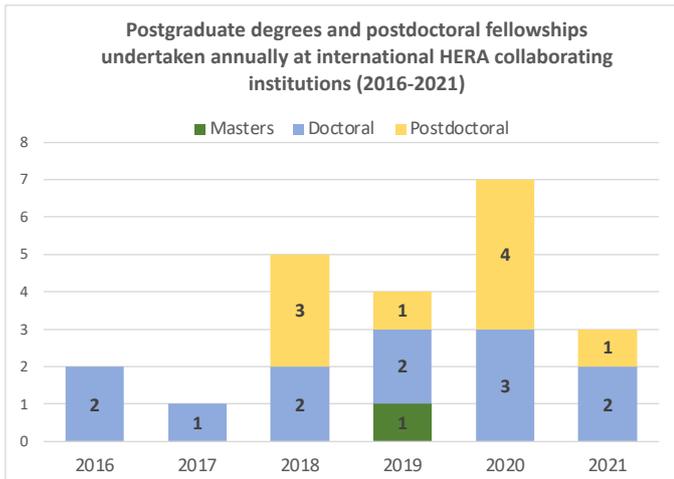


Figure 16: Number of postgraduate degrees (masters and doctoral) and postdoctoral fellowships undertaken annually on research related to HERA. The starting year for the degree or research fellowship is shown for the period 2016 to 2021.

The gender distribution for the postgraduate students and postdoctoral fellows who have undertaken research on a HERA topic can be seen in Figure 17. Overall, representation by females have been low with a total of 6 postgraduate and research fellowship opportunities (corresponding to 27%) taken up by females between 2016 and 2021. The low number in female representation is seen at both the doctoral and postdoctoral levels, with 3 out of 9 doctoral degree placements (corresponding to 33%) and 2 out of 7 postdoctoral placements (corresponding to 29%) taken up by female researchers. The gender distribution observed at the postgraduate and postdoctoral levels do, however, correspond to the gender distribution for female researchers globally, where it has been estimated that female researchers make up less than one third of researchers in STEM [3, 4].

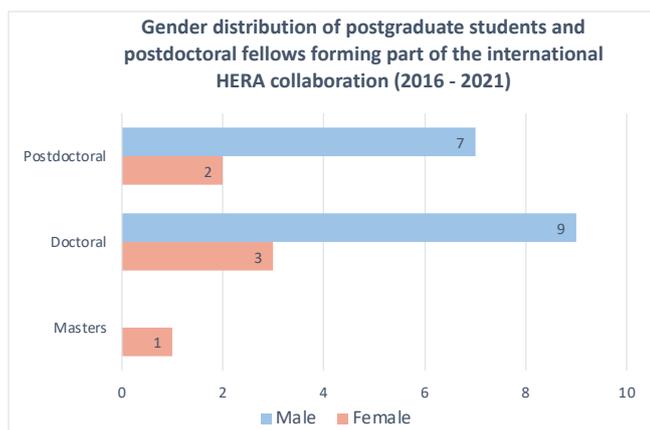


Figure 17: The gender distribution of postgraduate students and postdoctoral fellows that undertook HERA research topics at an international HERA collaborating institution (2016 - 2021).

The research topics of the postgraduate students and postdoctoral fellows who have undertaken research relevant to HERA at an international institution are listed in Table 6. As observed for the South African HCD assessment, most of the research topics at the international institutions are science topics related to HERA rather than engineering focused topics.

Starting Year	Level of Qualification	Research Topic / Thesis Title	Research Area (Science / Engineering)	Affiliated Institution
2016	Doctoral	Bayesian power spectrum analysis of 21-cm observations	Science	Brown University
		HERA Phase II wide band feed: Design and Analysis	Engineering	University of Cambridge
2017	Doctoral	Robust statistical techniques in radio interferometry	Science	University of Cambridge
2018	Doctoral	Density-ionization correlation forecasts and machine learning for HERA	Science	McGill University
		Systematic signals in HERA: prediction and calibration	Science	University of Cambridge
	Postdoctoral	Null tests for HERA power spectrum limits	Science	McGill University
		HERA theory interpretation and cross-correlations	Science	McGill University
		Validation of HERA analysis pipeline	Science	Arizona State University
2019	Masters	HERA power spectrum window functions	Science	McGill University
	Doctoral	Bayesian statistics and covariance estimation for 21-cm intensity mapping surveys	Science	Queen Mary University of London
		HERA pipeline validation and cross-correlations with line intensity mapping	Science	McGill University
	Postdoctoral	Power spectrum estimation and simulation of systematic effects for HERA	Science	Queen Mary University of London
2020	Doctoral	Statistical signatures of Cosmic Dawn galaxies	Science	Scuola Normale Superiore
		Identification of Neutral Islands During Reionization	Science	University of California Los Angeles
		Searching for the Epoch of Reionisation using high-filling factor interferometers	Science	University of Cambridge
	Postdoctoral	Visibility simulations and power spectrum estimation for HERA	Science	Queen Mary University of London
		HERA power spectrum window functions	Science	McGill University
		End-to-end Bayesian data analysis pipeline for 21-cm cosmology	Science	McGill University
		Joint forward models of systematics and cosmology for 21-cm inference	Science	Scuola Normale Superiore
2021	Doctoral	Statistical inference of radio foreground components	Science	Queen Mary University of London
		Data science and 21-cm parameter inference	Science	Scuola Normale Superiore
	Postdoctoral	Statistical inference of instrumental and sky model parameters for HERA	Science	Queen Mary University of London

Table 6: Research topics of postgraduate students and postdoctoral research fellows affiliated with international institutions (outside South Africa) forming part of the HERA collaboration.

## 3. HERA'S CONTRIBUTION TO DEVELOPING SKILLED SCIENTISTS AND ENGINEERS IN SOUTH AFRICA

### 3.4 Key outcomes on HERA's contribution towards Human Capacity Development in South Africa

1. South Africa has invested over R12 million (R 12, 071, 142) towards the funding of masters and doctoral scholarships, as well as postdoctoral fellowships focused on HERA research topics over the period of 2013 to 2021. A total of 24 awards were made through this investment with 16 scholarships awarded at the masters and doctoral levels, and 8 postdoctoral research fellowships awarded.
2. Half of the recipients of awards were South African who were funded at the masters and doctoral level of study. This investment in postgraduate scholarships has assisted with building a local skills base for South African participation in the HERA collaboration and 21-cm science experiments more generally.
3. The HERA impact study has shown that South Africa maintained a continuous level of financial support for the funding of masters and doctoral degrees together with postdoctoral fellowships over the period of 2013 to 2021. This commitment of funding towards HCD was achieved throughout the construction period of HERA. South Africa's commitment towards HCD through its early participation in HERA research has led to increased participation of researchers based at South African universities in the HERA collaboration.
4. HCD awards made to females is observed to be very low with 3 awards (approximately 12.5% of the total number of awards) made at the masters, doctoral and postdoctoral level over the period of 2013 to 2021. Less scholarship and research fellowship opportunities have been taken up by females at South African universities when compared to the findings from the international HERA collaborating institutions (approximately 30% female representation). It is clear that more needs to be done by all the HERA collaborating institutions to attract female participation in HERA research.
5. South African institutions that have researchers actively participating in the HERA collaboration have benefitted the most from the support towards postgraduate students and postdoctoral research fellows. In particular, the HERA impact study has revealed that 3 South African universities have benefitted the most from this support. These universities are Rhodes University, the University of the Western Cape and the University of KwaZulu-Natal, who are leading the South African participation in HERA research conducted nationally.
6. The research topics funded over the period of 2013 to 2021 were mostly directed towards science topics related to HERA. This has grown South Africa's scientific participation in research using low-frequency telescope arrays and contributed to building a community of researchers focusing on results from 21-cm experiments such as HERA.
7. At the time of publishing this report, a total of 7 masters degrees and 1 doctoral degree was awarded based on HERA research. The HERA project has therefore contributed to both developing the local skills base of scientists that can participate in this international project, and the development of high-level skills that will contribute to building South Africa's knowledge economy.
8. South Africa has used the hosting of the HERA instrument as a platform to build HCD in specialised science and engineering areas within the radio astronomy domain. This dual approach of developing skilled expertise in tandem with infrastructure is a result of South Africa's unconventional approach to critical skills development in science and engineering, with a broader view of building local expertise while attracting investment for infrastructure development. An example of the success of this approach is clearly demonstrated by SARAO's HCD programme, which has used the development of radio astronomy infrastructure through MeerKAT and the SKA to build an internationally recognised community of radio astronomy researchers in South Africa.



# 4 Socio-economic impact of HERA in the Northern Cape Province



## 4. SOCIO-ECONOMIC IMPACT OF HERA IN THE NORTHERN CAPE PROVINCE

The socio-economic impact assessment of HERA presented in this section mainly focuses on local employment opportunities, which were created through the hosting of the instrument in the Northern Cape province. More specifically, these were employment opportunities associated with on-site activities through the construction, operations and maintenance of the instrument. The employee survey presented as part of the socio-economic impact assessment was conducted with individuals who were employed on-site as part of the HERA project over the period of 2016 to 2021.

### 4.1 Local employment created by HERA

The HERA project has created employment for 24 individuals to work on-site over the period 2016 to 2021, with most workers from the town of Carnarvon. The majority of employees were assigned job roles or duties that were related to the construction and operations of the instrument, which was managed and overseen by a single supervisor. The total number of employees working on-site annually from 2016 to 2021 can be seen in Figure 18. With the bulk of the construction work for HERA beginning in 2017, most of the workers were employed in this particular year. Slightly reduced numbers are observed in 2020 and 2021 as the construction of HERA neared completion. However, it is worth noting that the total number of on-site employees was reduced even further to 11 by March 2021 after completing the construction of HERA<sup>22</sup>. The remaining employees are mainly responsible for operations and maintenance to ensure a well operating instrument is provided to the HERA collaboration.

The gender distribution of on-site employees working on HERA is shown in Figure 19 for the period 2016 to 2021. It can be seen that less than a quarter of the workers were female for any given year during this period. Overall, the HERA project has recruited 13% females into job roles related to on-site activities, whereas 87% males were predominantly recruited over the period of 2016 to 2021. The significantly higher number of male employees may be due to the nature of the job. It is, however, acknowledged that more needs to be done to recruit and retain women in roles conventionally seen by society as males jobs.

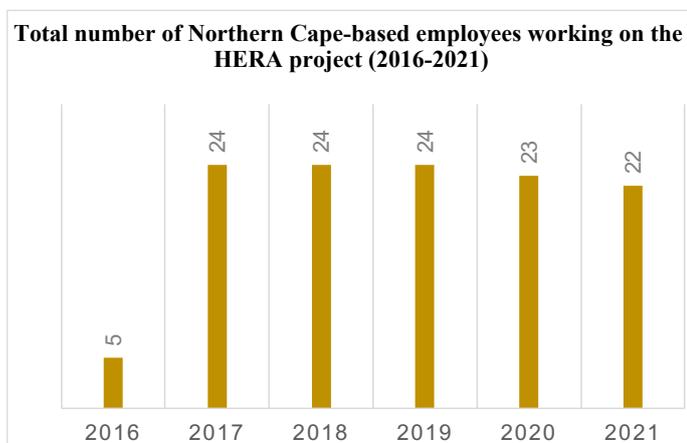


Figure 18: Total number of on-site employees recruited for the HERA project over the period of 2016 to 2021. This period corresponds to the construction period for HERA with construction completed in 2021.

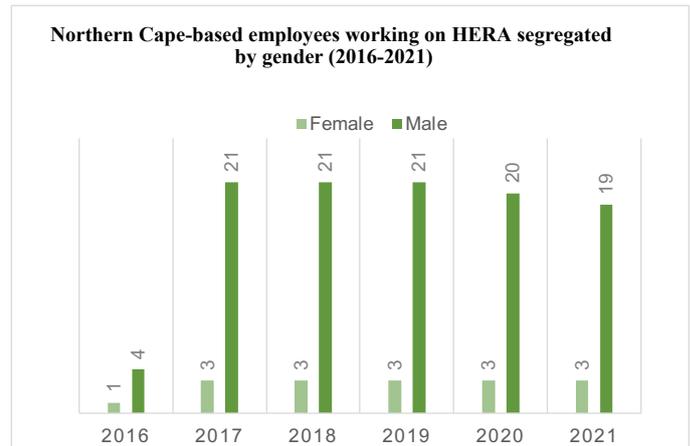


Figure 19: Gender distribution of on-site employees recruited for the HERA project over the period of 2016 to 2021.

### 4.2 The HERA Employee Survey

A survey was conducted as part of the socio-economic impact assessment to gain insight into the demographics of workers employed locally to work on HERA, in addition to their skills development while working on HERA, their views and perceptions of HERA, as well as their living conditions / social environment to better understand the impact of the project on these individuals. The survey was designed to target all 24 HERA employees who have worked on-site over the period of 2016 to 2021.

The aim of the HERA impact study and the survey was explained to each participant before administering the survey questionnaire. It was also explained that their identity will remain anonymous throughout the study and in the final report. A total of 20 employees completed the survey out of a total of 24 HERA employees, giving an 83% response level for the survey. The results from the employee survey are presented below.

#### 4.2.1 Demographic representation of survey participants

The demographics related to gender, age, current employment status, and average household income of the survey participants is shown in Table 7. Four of the survey participants were female employees representing 20% of the overall responses, with the remaining responses from male employees. Most of the survey participants fall into the 30 to 39-years age category (14 out of 20 respondents). 6 survey participants are of younger age falling into the 20 to 29-years age category. At the time of carrying out the survey, 9 of the survey participants were employed on a full-time basis while 11 of the respondents were unemployed. Those employed at the time of carrying out the survey were employed as part of the HERA project. The average household income for most respondents who were unemployed at the time of the survey was below R5, 000 with many individuals receiving their sole income from a social services grant.

The survey found that most employees (19 out of 20 respondents) were born in the Northern Cape province except for one respondent who was born in the Limpopo province. For those survey participants from the Northern Cape, 18 were born in Carnarvon, while one participant was born in the town of

<sup>22</sup> This lower number corresponds to the total number of on-site employees at the time of carrying out the HERA employee survey presented in section 4.2. All current and previous on-site employees who have worked on the HERA project were contacted when conducting the survey.

## 4. SOCIO-ECONOMIC IMPACT OF HERA IN THE NORTHERN CAPE PROVINCE

Pofadder. The former 18 respondents grew up in Carnarvon with all these respondents attending Carnarvon High School during their senior education and schooling years.

A total of 14 survey participants (corresponding to 70% of respondents) indicated that they have a National Senior Certificate and have thus completed their final year of schooling (a Grade 12 / matric). The remaining 6 respondents have either Grade 10 (5 out of 6 respondents) or Grade 11 (1 respondent) as their highest level of education. Only 2 survey participants indicated having a post-school or tertiary education, with one respondent holding a National Diploma and one having a certificate in Human Resources Management. The basic level of education of most workers is mostly related to the nature of the work on-site that required general skills for building of the instrument. However, the professional development and views on upskilling of survey participants while employed as part of HERA are presented in the next section.

Characteristics	Total number of respondents	%
<b>Willing to participate</b>	<b>20 out of 24</b>	<b>83</b>
<b>Gender</b>		
Female	4	20
Male	16	80
<b>Age</b>		
20-29 years	6	30
30-39 years	14	70
<b>Current employment status</b>		
Employed Full-time <sup>23</sup>	9	45
Unemployed-actively looking for employment	11	55
<b>Average household income (in ZAR)</b>		
Below R5, 000	9	45
R6, 000 - R10, 000	2	10
R11, 000 - R15, 000	8	40
R16, 000 - R20, 000	1	5

Table 7: Demographics of survey participants who were employed on-site as part of the HERA project (2016 - 2021).

### 4.2.2 Professional development of employees while working on the HERA project

Survey participants were asked to indicate the main reason for applying for a job position with the HERA project. The responses from participants were grouped into various categories such as the basic need to earn an income, an opportunity to grow their skills and the ability to work for a large science / engineering organisation, which were all viewed as the main reasons by employees for applying for jobs. Figure 20 shows the main reasons why survey participants applied for jobs with HERA as grouped into the different categories. 40% of respondents indicated that their main reason for applying for a job was to earn an income. This was followed by 35% of respondents indicating that it was an opportunity to grow their skills, which could lead to better work prospects in the future. A few individuals (15% of respondents) indicated that the attractiveness of working for a large science / engineering organisation such as SARAO was the main reason for their job application.

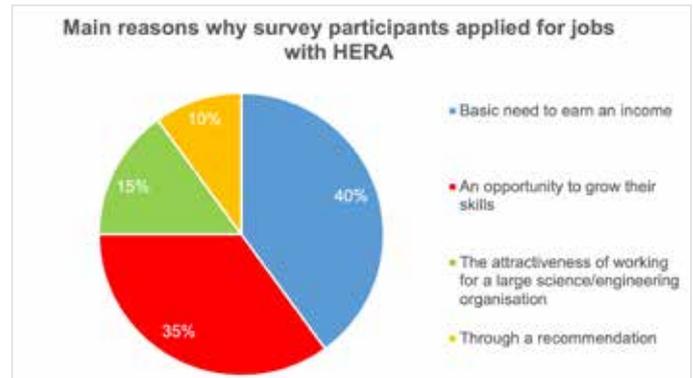


Figure 20: The main reasons given by survey participants for applying for a job with the HERA project.

The professional development of the employees was assessed through targeted questions on courses they have undertaken while working on the HERA project. The survey found that 75% of respondents have completed at least one skills development course while working on the HERA project. The skills development courses undertaken by the employees included fibre optics training, first aid training, working on heights, and firefighting, amongst others. Survey participants were asked to indicate the technical courses they would like to undertake if given an opportunity to upskill or reskill themselves. A range of responses was received from survey participants which included obtaining a qualification in radio frequency engineering, optical engineering or electronic engineering. Survey participants were also interested in computer programming and project management courses. The knowledge areas of interest of these employees are an indication of the science, engineering and management areas they have been exposed to through their work with HERA. This is seen as a positive outcome in increasing the knowledge and awareness of possible careers to employees, who may have not been exposed to these career choices through their schooling and in their communities. Soft skills were additionally mentioned as vital to the professional development of employees, with respondents indicating courses or programmes that build on teamwork, communications and health and safety being important to their overall professional development in the workplace.

The survey participants were asked what aspects of the job they liked most while working on the HERA project. A variety of responses was given to this question that included their ability and exposure to "Assembling feeds and splicing fiber"; "Building antennas"; "Learning and gaining experience in astronomy"; "Building feed springs"; "Working with radio receivers" and "Learning about the importance of the universe".

Survey participants were asked what in their opinion is the significance or value of the HERA project. Responses included, "To observe the universe, stars, and galaxy", "To pinpoint when the first stars were formed"; "To understand how the universe was formed"; "To study the universe"; "Radio waves"; "Research data" and "Big data". These responses indicate that the employees have gained a broad level of understanding on the objectives of HERA and astronomy concepts while working on the HERA project. This again is another positive outcome given the little knowledge and exposure of employees to science / engineering before taking up employment on HERA. To add to this, more than half of the survey participants (approximately 60%) indicated that they would have liked to

<sup>23</sup> Total number of individuals employed on-site working on HERA at the time of the survey (August to October 2021) was 11. Only 9 of these employees participated in the survey.

## 4. SOCIO-ECONOMIC IMPACT OF HERA IN THE NORTHERN CAPE PROVINCE

receive more background or general information on HERA and its objectives from SARAO and the HERA collaboration while undertaking the job.

Further findings from the survey indicate that most of the respondents (70%) felt proud of working for an international project, with just over half of respondents (55%) indicating that they do understand the significance or value of the HERA project. The career aspirations of most survey participants were mainly focused on job security, with most respondents indicating that they would like to have some sort of permanent employment in the future. Regardless of not having permanent employment, the majority of survey respondents (70%) did agree that the HERA project has contributed to the employment growth within their community.

### 4.2.3 Social living environment of survey participants

The survey participants were asked a few questions on their social living conditions to gain further insight on how employment has contributed to the income of households of these individuals. These questions were considered as optional to survey participants and only represent those individuals who were willing to disclose information related to their living environment.

The survey results revealed that 18 out of 20 participants have at least one dependent, with a dependent being defined as a child or children, a parent or parents, or any other family member(s) who are financially supported by the survey participant. The number of dependents that were supported by participants at the time of the survey were as follows:

- one dependent (15% of participants);
- two dependents (40% of participants);
- three dependents (15% of participants);
- four dependents (15% of participants);
- and more than five (5% of participants).

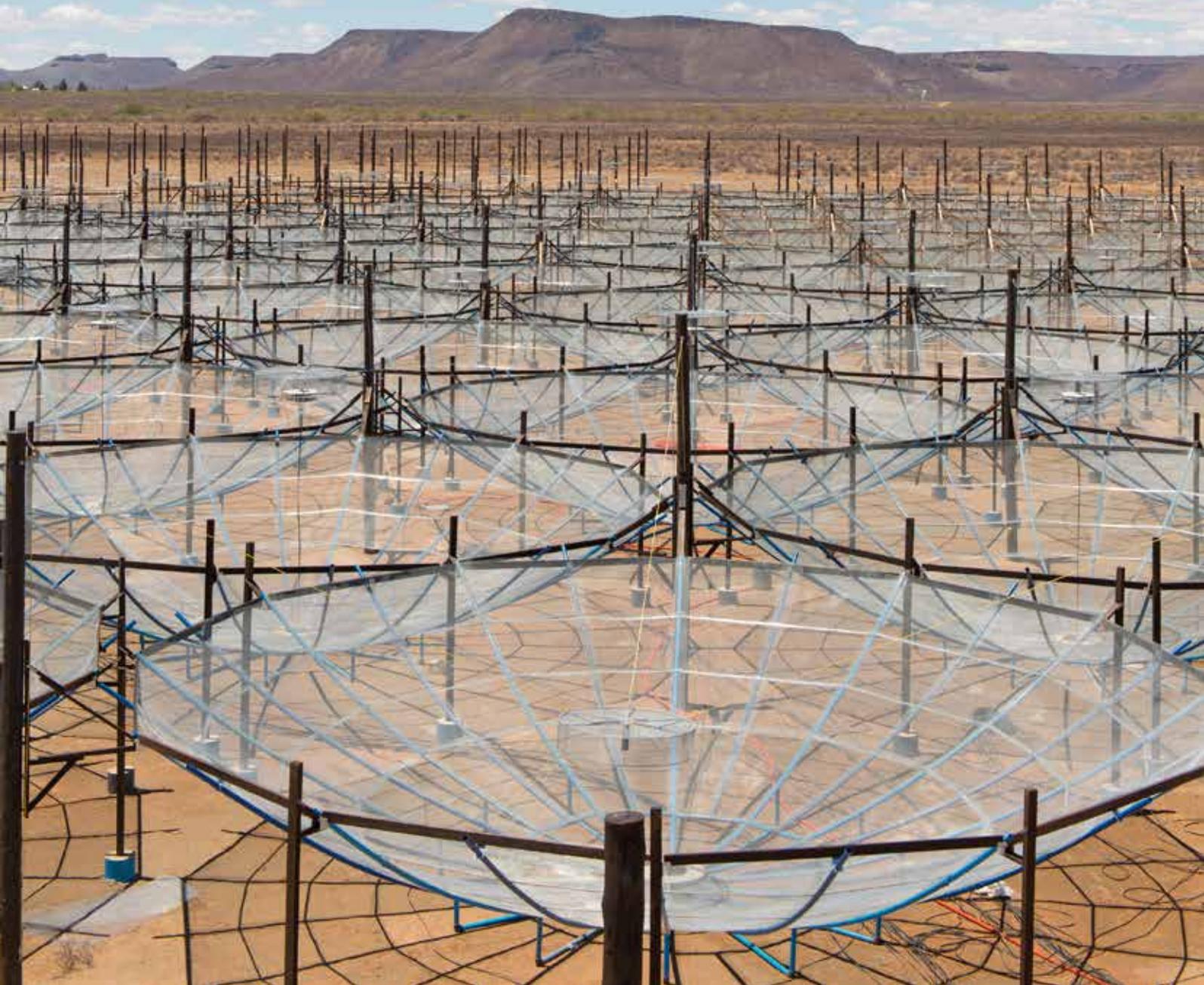
It was found that 7 out of 18 survey participants have more than two dependents, with one of these individuals having more than 5 dependents. More than half of the survey participants (60%) revealed that the dependents are currently living with them and that the dependents are children. The children were either at pre-school / kindergarten level and in need of child care, or at primary or high school level of education. Most households were single income households with 17 out of 20 respondents indicating that they were single (never been married) at the time of the survey.

Given the average number of dependents for the survey participants, it can be inferred that the average household size for participants was 3.5 at the time of conducting the survey. This value is lower than the average household size of 4.3 measured for Carnarvon in 2015 through the *Northern Cape SKA Socio-economic Impact Assessment 2015* report [2]. The lower estimate in the average household size may be simply due to the small sample size of individuals participating in the HERA employee survey and might not be a true reflection of the average household size when compared to the overall population statistics for Carnarvon. Nevertheless, the average household size for participants is comparable to the national average with Statistics South Africa giving an estimate of 3.3 as the average household size in South Africa in 2016 [5].

### 4.3 Main Findings from the Northern Cape socio-economic impact assessment of HERA

1. The construction of HERA in the Northern Cape province has created employment for a total of 24 individuals over the period 2016 to 2021 with most individuals recruited from Carnarvon. These employees were mainly involved with the construction of the instrument with an average of 23 workers employed annually from 2017 to 2021.
2. *The Northern Cape SKA Socio-economic Impact Assessment 2015* report [2] gives an estimate of 1, 576 for the number of households in Carnarvon in 2015. From this, it can be roughly inferred that the HERA project has created employment for 1.5% of households in Carnarvon over the construction period of the instrument, with the assumption that there has been little change to the number of households over this period.
3. Less than a quarter of the 24 locally based employees working on HERA were female, which was likely due to the nature of work with construction perceived as a male's job. More inclusivity into these job roles can be attained by providing the appropriate training and skills development for women interested in these roles. Marketing and promoting these roles to a younger generation of women can additionally change these perceptions in society, and allow for more diversity and inclusiveness in similar job roles that may come about in the future.
4. The survey found that the average household size for most of the employees is 3.5. The employees were often single income households with children at pre-school / kindergarten or school level of age being the main dependents on this income. Unemployment remains a challenge in these households with more than half of these individuals indicating they were not working at the time of the survey (post construction of HERA) making it difficult to support a household. The average household income for 82% of individuals who were unemployed was below R5, 000 with most individuals dependent on social grants for an income. To address the job security of low-skilled workers, it is recommended that focus be placed on the upskilling of these workers to increase their prospects of getting work opportunities in the future.
5. Nearly all of the employees have completed a skills development course while working on the HERA project. However, a combination of skills development courses and more specialised technical courses need to be taken up by individuals in order to upskill themselves to a defined knowledge area. It is recommended that individuals showing an affinity and drive towards a particular knowledge area in the technical / engineering aspects of radio astronomy instrumentation be supported for upskilling through professional courses offered part-time at a tertiary institution.
6. The survey has found that HERA has played a positive role in increasing the knowledge and awareness of possible careers in technology / engineering areas related to radio astronomy instrumentation to employees. Most of these individuals have not been exposed to these career choices through their schooling and in their communities. This awareness will contribute to wider knowledge transfer of possible careers in technology / engineering through the interaction of these individuals with the youth in the community.

# 5 Summary of findings from the HERA Impact Study



## 5. SUMMARY OF FINDINGS FROM THE HERA IMPACT STUDY

A summary of the main findings from the HERA impact study is provided in this section.

### ***Economic benefits of hosting HERA in South Africa:***

1. The findings from the financial assessment of the impact study indicate that the total direct investment made towards the HERA project is well over R70 million (R 74, 090, 948), which was invested by the US, South Africa and the UK over the period of 2013 to 2021. South Africa, as the hosting country, received approximately R40 million in international investment for the construction of HERA. This investment was made over a period of 6 – 7 years, which resulted in longer term economic benefits for the country through its role in managing the project and creation of employment opportunities for construction of the instrument.
2. South Africa as the hosting country has additionally contributed significantly to the HERA collaboration with over R32 million contributed towards the total DFI of the project. This contribution was mostly towards the human resources (52%) needed for the project management, construction, maintenance, and operations of the instrument, together with financial support for HCD initiatives (37%) in building radio astronomy science and engineering capacity in South Africa.
3. Through the construction of HERA, over R25 million (R 25, 464, 016) in direct investment has been awarded to suppliers in South Africa through the award of financial tenders. The Northern Cape, Gauteng and Western Cape are the provinces that have directly benefitted from the tender awards for the construction of HERA.
4. It was found that the hosting province of the instrument benefitted the most out of all provinces in South Africa from direct investment made during the construction of HERA. Over R15 million (R15, 226, 295) in expenditure towards goods and services was made to suppliers based in the Northern Cape province during the construction of the instrument.
5. Local suppliers based in the town closest to the HERA instrument benefitted the most from the investment during the construction period when compared to other towns in the Northern Cape province. It was found that Carnarvon benefitted 95% (corresponding to R 14, 574, 169) in DFI through spends during the construction period, which were made to local suppliers.
6. The economic sector assessment found that the hosting of HERA in the Northern Cape has made a significant contribution to the construction sector in this province through the use of local contractors in supplying materials and services. This has assisted in building the construction sector in the province so that local companies and skills can be used for planned construction projects within the region, rather than outsourcing these projects to companies in other provinces.
7. The HERA project has created employment for 24 locally based individuals over the construction period of the

instrument from 2016 to 2021. These employees were mainly involved with the construction of the instrument with an average of 23 workers employed annually. Approximately half of these employees have been retained post-construction of the instrument to assist with the maintenance and operations of HERA. The hosting of HERA has therefore led to increased job opportunities for individuals from town closest to the infrastructure.

### ***HERA's contribution to developing HCD in science and engineering in South Africa***

1. The financial assessment conducted for HCD found that South Africa invested over R12 million (R 12, 071, 142) to fund masters and doctoral scholarships, as well as postdoctoral fellowships focused on HERA related research topics. A total of 24 awards were made towards these HCD initiatives (corresponding to 8 masters, 8 doctoral and 8 postdoctoral awards) over the period of 2013 to 2021.
2. The HERA impact study has shown that South Africa maintained a continuous level of financial support for the funding of the masters and doctoral degrees together with postdoctoral fellowships over the period of 2013 to 2021. This commitment of funding towards HCD was achieved throughout the construction period of the instrument. South Africa's commitment towards HCD through early participation in HERA research has led to increased participation of researchers based at South African universities in the HERA collaboration.
3. Half of the recipients of HCD awards were South African who were funded at the masters and doctoral level of study. This has assisted in building a local skills base for South African participation in HERA and 21-cm science experiments more broadly.
4. South African institutions that have researchers actively participating in the HERA collaboration have benefitted the most from the support towards postgraduate students and postdoctoral research fellows. In particular, the impact study has revealed that the 3 universities benefitting most from this support are Rhodes University, the University of the Western Cape, and the University of KwaZulu-Natal, who are leading the South African participation in HERA research conducted nationally.
5. The research topics funded over 2013 to 2021 were mostly directed towards science topics related to HERA rather than engineering topics. This has grown South Africa's scientific participation in research using low-frequency telescope arrays and building a community of researchers focusing on results from 21-cm experiments such as HERA.
6. At the time of publishing this report, a total of seven masters degrees and one doctoral degree was awarded based on HERA research. The HERA project has therefore contributed to both developing the local skills base of scientists that can participate in this international project, and the development of high-level skills that will contribute to building South Africa's knowledge economy.

## 5. SUMMARY OF FINDINGS FROM THE HERA IMPACT STUDY

### ***Socio-economic impact of hosting HERA in the Northern Cape province of South Africa***

1. The construction of HERA in the Northern Cape province has created employment for a total of 24 individuals over the period 2016 to 2021 with most individuals recruited from, Carnarvon, which is the town closest to the instrument. Most of the individuals recruited were born and grew-up in Carnarvon. Local employment created through HERA has therefore mostly benefitted individuals residing in the town closest to the infrastructure.
2. The survey forming part of the HERA impact study found that the average household size for most of the employees is 3.5. The employees were often single income households with children at pre-school / kindergarten or school level of age being the main dependents on this income. With more than half of the individuals indicating they were unemployed at the time of the survey (post-construction of HERA), the majority of households had an income of below R5, 000 with most individuals dependent on social grants for an income. The provision of longer term, more sustainable job opportunities for locally based individuals therefore remains a challenge through the co-hosting of smaller telescopes and instrumentation.
3. The HERA impact study found that nearly all of the locally based employees have completed a skills development course while working on the HERA project. However, a combination of skills development courses and more specialised technical courses need to be taken up by individuals in order to upskill themselves to a defined knowledge area and improve their prospects of job security.
4. HERA has played a positive role in increasing the knowledge and awareness of possible careers in technology / engineering areas related to radio astronomy instrumentation to locally based employees. Most of these individuals have not been exposed to these career choices through their schooling and in their communities. This awareness will contribute to wider knowledge transfer of possible careers in technology / engineering through the interaction of these individuals with the youth in the community.





## 6. CONCLUSION

To understand the economic and socio-economic benefits of co-hosting smaller telescopes, instrumentation and experiments in South Africa, an impact study was undertaken for the HERA experiment, which is co-located on the MeerKAT / SKA site in the Northern Cape province. The impact study found that the hosting province has benefitted most out of all provinces in South Africa from the investment made in construction of the instrument in the Northern Cape. This is evidently seen through expenditure towards mainly the construction sector, with most materials sourced and fabricated locally in the province. The Gauteng and Western Cape province have additionally benefitted from this investment, particularly, if goods or materials could not be locally sourced in the Northern Cape.

The impact study found that the Northern Cape town of Carnarvon benefitted most from the investment during the construction period of HERA. This has stimulated business development in the town closest to the infrastructure through the use of local suppliers for goods and services. To add to the local economic development, the construction of HERA has created employment for 24 individuals with most individuals recruited from Carnarvon. This has increased the job prospects of individuals living in the town, where unemployment and lack of access to job opportunities remain a challenge within these rural areas. Half of the individuals employed have been retained into job roles post-construction of HERA to assist with the maintenance and operations of the instrument. The creation of sustainable employment through co-hosted instrumentation remains a big challenge, especially after the construction of the infrastructure when fewer staff may be needed, or existing staff is used to maintain the infrastructure.

South Africa has used the hosting of the HERA instrument as a platform to build human capacity in specialised science and engineering areas within the radio astronomy domain. This dual approach of developing skilled expertise in tandem with infrastructure is a result of South Africa's unconventional approach to critical skills development in science and engineering, with a broader view of building local expertise while attracting investment for infrastructure development. More notably, South Africa maintained a continuous level of financial support for the funding of the masters and doctoral degrees together with postdoctoral fellowships throughout the construction period of the instrument which has led to increased participation of researchers based at South African universities in the HERA collaboration. A total of seven masters degrees and one doctoral degree was awarded based on HERA research, with most of these degrees awarded to South Africans. South Africa's contribution to the HERA collaboration has therefore led to developing the local skills base of scientists that can participate in this international project, and the development of high-level skills that will contribute to building its knowledge economy.



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**SARAO**  
South African Radio  
Astronomy Observatory

# An Impact Study of South Africa's hosting of the Hydrogen Epoch of Reionization Array (HERA)



**science & innovation**

Department:  
Science and Innovation  
REPUBLIC OF SOUTH AFRICA