# Power Supply for the Square Kilometre Array

## Assessment of the South African Site Submission - Power

For SKA Program Development Office, University of Manchester

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## Version 2

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CONTENTS

## EXECUTIVE SUMMARY

Parsons Brinckerhoff has reviewed the response from SKA Africa to the "*Request for Information from the Candidate Sites*" produced by the SKA Siting Group.

SKA Africa proposes to supply the SKA from the extension of the existing 400 kV transmission network via a substation and 132 kV substation and distribute power to the core receptors through the combination of 33 kV overhead line circuits and cabling within 2 km of any receptor. Some remote stations would be supplied from stand alone solar PV systems backed up by diesel generation. The super computer is proposed to be located approximately 30 km from the SKA core on the "Astronomy complex" which would also house an operations centre, accommodation, the data processor and the 132 kV / 33 kV main supply substation.

The supply of power to the SKA was proposed to be undertaken by either grid connection, wheeling of renewable energy or connection to a dedicated solar power plant. Only a grid connection was presented and costed in any detail, and is therefore considered as the main Submission on which conclusions are based.

Many areas of the design are developed to a high level of detail with evidence that multiple options have been explored at various levels of the design. However, the electrical distribution design within the array is defined in principle only, without adequate detail of scope or configuration for proper assessment.

South Africa is currently undertaking an extensive program of increasing centralised generation and renewables. This would increase the margin between the system capacity and peak demand and reduce or eliminate the current need for frequent load shedding.

The South African transmission system is well established within the vicinity of the site, such that a suitable connection to the core can readily be made. The transmission system assets (132 kV and above) would be owned and operated by the national utility ESKOM. The Submission gives confidence that radio frequency interference (RFI) issues for the transmission system would be well managed by ESKOM and mitigated to some extent through careful selection of the 132 kV OHL route to utilise natural shielding.

A general lack of definition of the distribution system (33 kV and below) raises questions regarding scope of equipment, power availability, power quality and RFI. In particular, the use of 33 kV overhead lines up to 2 km from the receptors would increase the incidence of RFI compared with that from buried cables, although costs would be reduced.

The reliability of power delivery across the array cannot be properly assessed without further details of the distribution network configuration. Irrespective of the distribution arrangement, the transmission connection depends on a single circuit 132 kV overhead line. It appears that breakdown or maintenance of this line could cause infrequent but extended shutdown of the array.

The transmission and generation capital cost estimates are reasonably complete and broadly comparable with the equivalent costs from previous PB projects in Europe. The distribution capital cost estimate does not include an adequate scope of supply for it to be assessed properly; however unit costs appear reasonable.

With regard to the operational and maintenance costs, the breakdown of the cost beyond the headline figures is not clear and it has therefore not been possible to provide a comprehensive appraisal of the operational costs or to identify any areas that have not been included.

# 1 Introduction

The SKA Project is evaluating the alternative locations for the SKA. Parsons Brinckerhoff was engaged to assess the Submissions made by the alternative sites on the provision of power to the various parts of the SKA facilities. The objective of this review is to highlight issues of uncertainty and risk to the SKA from the proposed arrangements.

This report summarises the findings of the review of for the provision of power to the SKA for the SKA Africa Submission.

# 2 Methodology

Parsons Brinckerhoff has reviewed the response from SKA Africa to the "*Request for Information from the Candidate Sites*" produced by the SKA Siting Group.

The following document presents PB's findings in relation to the following areas:

- Feasibility of the solution
- Credibility of information provided
- Reasonableness of the costs and costing methodology
- Areas of design that have not been considered
- Sequencing of the roll-out

The information below is based on PB's interpretation of the information presented by SKA Africa, industry knowledge, best practice and the experience of the reviewing engineers.

Documentation was split into specific areas of expertise including large scale generation, transmission, distribution, small generation and renewables, RFI and costing for study, whilst consideration of the overall proposed system was achieved through close collaboration of the engineers involved.

Due to the relatively short period in which the Submission was reviewed, it was not possible to comment on every aspect covered in the Submission. Areas of the Submission that are not commented on in this report should be considered either suitable and not requiring comment, or superfluous detail for the current stage of the project. PB has focused within this report on areas of risk and uncertainty in an attempt to highlight these to the SSG and SPDO.

A list of the specific documents and sections reviewed and commented on within this report is available in the appendices. All document references are noted in *Italics*.

# 3 Overview of Site Submission

## 3.1 Approach

In general terms, SKA Africa proposes to supply the SKA from the extension of the existing ESKOM transmission network and distribute power to the core receptors through the combination of 33 kV overhead line circuits and cabling within 2 km of any receptor. Four remote stations would be supplied from stand alone solar PV systems backed up by diesel generation.

### 3.1.1 SKA 1

SKA Africa proposes to provide a supply for the construction of the SKA 1 via a 33 kV overhead line connection to the existing ESKOM 66 kV / 33 kV Carnarvon substation. The SKA 1 shall be connected to the 132 kV / 33 kV Astronomy complex substation which is proposed to be complete by the end of 2015.

#### 3.1.2 SKA 2

SKA Africa proposes to supply the SKA 2 via a 132 kV overhead line connection to the existing ESKOM transmission network. This connection is proposed to supply the core receptors, the data processor, the super-computing facility and operations centre located within the Astronomy Complex approximately 30 km from the core. Power would be distributed through these areas via 33 kV overhead line and cable and 415 V distribution cables.

Four of the remote stations would be supplied by stand alone solar PV systems that are proposed to supply a 96 kW load during the day and charge a battery system that would supply the load during the night. A diesel generator is proposed to be included to supply the load in case of the unavailability of the solar PV system.

#### 3.1.3 Super computer

The super computer is proposed to be located approximately 30 km from the SKA core on the "Astronomy complex" which would also house an operations centre, accommodation, the data processor and a 132 kV / 33 kV main supply substation.

### 3.2 Key observations

- Many areas of the design are developed to a high level of detail with evidence that multiple options have been explored at various levels of the design.
- Costs for major equipment are based on manufacturer quotes and a quantity surveying method has been utilised to develop the overall cost estimate.
- The supply of power to the SKA was proposed to be undertaken by either grid connection, wheeling of renewable energy or connection to a dedicated solar power plant. Only a grid connection was presented and costed in any detail, and is therefore considered as the main Submission on which conclusions are based.
- The distribution design within the array is described in principle only without a detailed network configuration or scope to allow the availability of power or cost estimates to be evaluated.
- An alternative location for the super-computer in Cape Town was evaluated, but was not presented as part of the main Submission.

### 3.3 Quality of information

The information provided defines the proposed solution at varying levels of detail. In some instances (for example, the topology of the 132 kV system and the backup generation philosophy) considerable study is evident. In others high level concepts are not further developed into a documented design.

SKA Africa has obtained much cost information from quotations from reputable suppliers; however the scope of supply in the array power distribution is not adequately described.

No suitable breakdown of the components of the operational costs other than electricity tariffs is provided.

Adequate cost data related to the power generation and transmission equipment has generally been included in the Submission.

# 4 Feasibility of solution

## 4.1 Feasibility of supply from national generation

Since SKA Africa are proposing to supply power to the SKA site via the extension and reinforcement of the existing transmission network, consideration of the ability of the future generation fleet to meet the SKA power requirements as well as the existing demand is required.

South Africa is currently undertaking an extensive program of increasing centralised generation and renewables. Current generation capacity of around 45 GW is expected to increase significantly to around 58 GW due to the commissioning of committed new build over the coming decade, with a further increase by 2030 from additional planned capacity. This would increase the margin between the system capacity and peak demand from just 6 GW in 2010 to 11 GW by 2020 and reduce the necessity and frequency of load shedding. The following table illustrates the predicted generation mix within South Africa. Note that this data was derived by PB from graphical information in "*Annexure D4 – IRP2010*".

| Generation type | New capacity by 2030 (GW) | Existing and committed capacity (GW) | Percentage energy in 2030 | Energy in 2030 (GWh) | Estimated capacity factor in 2030 |
|---|---|---|---|---|---|
| Coal | 6.3 | 34.8 | 65.0 % | 295100 | 81.96 % |
| Nuclear | 9.6 | 1.8 | 20.0 % | 90800 | 90.92 % |
| Hydro (imported) | 2.6 | 2.2 | 5.0 % | 22700 | 54.55 % |
| CCGT | 2.4 | 0.0 | 1.0 % | 4540 | 21.59 % |
| OCGT | 3.9 | 3.4 | 0.1 % | 454 | 0.71 % |
| Wind | 8.4 | 0.8 | 3.5 % | 15890 | 19.72 % |
| CSP | 1.0 | 0.2 | 0.5 % | 2270 | 21.59 % |
| PV | 8.4 | 0.0 | 3.8 % | 17252 | 23.45 % |
| Pumped storage | 0 | 2.9 | 1.0 % | 4540 | 17.87 % |
| Other | 0 | 0.9 | 0.1 % | 454 | 5.76 % |

*Predicted generation capacity, energy and capacity factor of generation types*

The increased capacity is proposed to comprise of large coal stations, nuclear power stations and renewables such as concentrated solar and wind power. ESKOM generation would remain heavily dependant on coal-fired power plant although growing renewable generation would increase the sustainability of power generation somewhat.

The estimated aggregated emissions for electricity generation in South Africa according to "*Annexure D3 – ESKOM Annual Report 2011*" are:

- $CO_2$ = 0.97 kg per kWh
- $NO_x$ = 0.00411 kg per kWh
- $SO_2$ = 0.00762 kg per kWh

Although the total $CO_2$ emissions is expected to increase as new large coal power stations are commissioned to keep pace with demand, the specific emissions of the generation fleet are expected to fall due to the provision of electricity from new stations that are more efficient. The total and specific $CO_2$ emissions are expected to fall in the future as the penetration of renewable generation increases.

## 4.2 Feasibility of supply from the existing transmission system

The Submission is based on a connection to the ESKOM system at Kronos 400 kV / 132 kV substation. One 400 kV / 132 kV 250 MVA transformer is planned for 2012 and a second identical transformer would be provided as part of the SKA project. This information is taken from "*Annexure D5 - Eskom Report SKA Africa Radio Telescope Grid Infrastructure Requirements.*"

There is no mention of possible deeper reinforcement work that may be needed on the 400 kV system. Otherwise, this represents a fully viable solution.

### 4.3 Feasibility of the proposed new transmission system

The SKA project Submission includes an additional 400 kV / 132 kV 250 MVA transformer at Kronos substation and a new single circuit 132 kV 115 km line to the Astronomy substation near the SKA core. ESKOM would own the assets up to and including the Astronomy substation (power utility interface to SKA).

The voltage drop down the incoming 132 kV transmission line would be at the limit when delivering 105 MW at 0.98 power factor. This calculation would have to be reviewed once the final load and power factor are known, with a view to possibly providing voltage support at the receiving end in the form of shunt capacitors.

The above information is taken from "*Annexure D5 - Eskom Report SKA Africa Radio Telescope Grid Infrastructure Requirements.*"

The alternative of a duplicate 132 kV line is considered in the Submission but rejected on the grounds that it has an insignificant effect on the overall power availability.

The Astronomy substation is proposed to be located approximately 30 km from the centre of the array. It comprises an arrangement of 132 kV double busbar GIS switchgear supplying three 80 MVA 132 kV / 33 kV transformers. The 132 kV / 33 kV transformers are proposed to be fitted with on-load tap-changers[1]. This information is taken from "*Annexure D5 - Eskom Report SKA Africa Radio Telescope Grid Infrastructure Requirements.*"

Apart from the dependence on a single 132 kV line, the system described above represents a prudent and conventional utility design.

### 4.4 Feasibility of the proposed new distribution system

The Astronomy substation is proposed to include a 33 kV primary switchboard and two secondary switchboards supplying:

1. The array via five double circuit 33 kV lines
2. The super-computer, processor and operations centre via three cable circuits.

There are conflicts between the various diagrams provided regarding the arrangements of the 33 kV switchgear and the number of outgoing lines to the array.

The feeders to the array would be 33 kV double circuit lines, reverting to buried cables 2 km from the receiving end. They would be terminated at "miniature substations" from which power is distributed at 33 kV and 415 V to the load. This information is taken from "*Annexure B: Provision of Electrical Power SECTION 1".*

The information regarding the 33 kV / 415 V distribution system is somewhat piecemeal. A set of system layout drawings ("*D9_14 107102-SSG-ELE-0014*" sheets 1-6 in Annexure D9) are provided but the information is not clear. Standard diagrams of the connections to the receptors are also provided but there is no overall distribution diagram. There is also insufficient description of the equipment.

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[1] These are described in the text but not shown on single line diagram "*D9_2 107102-SSG-ELE-0002*".

The thirteen remote stations in South Africa would be supplied from the ESKOM grid. In-line UPS systems are proposed.

Twelve remote stations outside South Africa would be supplied either from the local utility grid or from autonomous solar PV and battery systems backed up by diesel generation.

The distribution system design is generally feasible but better definition is necessary to make a proper assessment. The design appears to have some drawbacks regarding RFI and availability as detailed in the sections below.

### 4.5 Local and backup generation

Various alternatives for backup power to the SKA core receptors in the event of the loss of the 132 kV supply are offered. The recommended alternative consists of five diesel generators rated at 2 MVA each to provide power to allow dishes to return to a neutral position; however this is not included in the final cost calculations.

In four of the remote stations where it is not possible to obtain power from the grid, a hybrid system of a 500 kW photovoltaic array with battery bank and a back-up diesel generator is proposed to supply the required 96 kW load.

The calculation sheet provided by Rentech ("*Sizing-MPPT New Ver v6 irradiance*") calculates an equivalent number of hours per day during which the array is expected to deliver peak power based on irradiance data for each country in which a hybrid system is proposed. The total daily energy demand is estimated assuming losses of 15 % and the calculated battery charging energy. The array is sized to allow the daily energy demand to be delivered during the estimated period of peak power delivery. A worst case month for irradiance is utilised for calculations, thus resulting in a robust size estimate.

In the Submission it is estimated that the battery bank (charged by the PV array) would provide the required power 99 % of the time. When the PV array is unable to provide the required load, a backup 250 kVA diesel generator has been proposed with a standard 350 litre storage tank.

In order to supply the load of 96 kW, the generator would need to be run at approximately 50 % load. This equates to a fuel usage rate of approximately 17 to 20 litres per hour[2] which would consume the capacity of fuel storage in 17.5 to 20 hours. This may be sufficient to cover the failure of the PV and battery system for short periods due to insufficient irradiance, but is not a suitable backup for a prolonged outage of the system.

Within the Submission, there is no mention of RFI protective enclosures for the power generating sources and power electronics. It is however stated that generation for the remote stations would be located 2 km away from the receptors and connected via underground cable.

### 4.6 Super computer and data processor

The power supply to the super-computer systems is only covered in very general terms. Various alternatives for backup power are offered, the recommended one being 5 MVA of rotary diesel UPS, which is included in the cost estimate. The size and cost of this system should be reviewed once the critical load is better defined.

[2] Calculated on fuel use at full load of 29 litres per hour quoted from diesel generator specification sheet, "*GEH275*"

### 4.7 General aspects of SKA system

Transformers are stated to be designed for the appropriate ambient temperatures (see *"Annexure D1 - Response to Annex 2 of the SSG RfI"*). There is no general statement on design ambient temperatures.

Earthing and lightning protection for the arrays is not covered in the Submission.

## 5 Credibility / reliability of information

### 5.1 Information on national generation

Information on national generation is provided in "*Annexure D3 - Eskom Annual Report 2011*" and from the South African Department of Energy in "*Annexure D4 - IRP2010*" and so is considered reliable.

### 5.2 Information on power transmission

The "*Annexure D3 - Eskom Annual Report 2011*" included in the Submission does not contain any specific data on the planned extensions to the transmission system.

Regarding the new assets for the SKA project, the information provided in the Submission is generally complete and consistent. The information is largely based on "*Annexure D8 - Aurecon Assistance for the SKA South Africa Site Bid Submission*" and "*Annexure D5 - Eskom Report SKA Africa Radio Telescope Grid Infrastructure Requirements*", both of which are from reliable sources considered to have sufficient industry knowledge and experience.

### 5.3 Information on the distribution system

The information provided in the Submission is sparse and in some points contradictory; however unit costs for major distribution equipment appear to be based on manufacturers' quotes and are therefore considered credible.

### 5.4 Other sources of information

A costing for the hybrid generating equipment at the remote sites has been performed by Redtech. The cost calculation is robust and complete and likely to be credible as Rentech supplies such systems.

## 6 System performance

### 6.1 Availability

#### 6.1.1 Availability of power for the core, processor, super-computing centre and operations centre

Availabilities of 99.6 % to 99.9 %, corresponding to an annual average downtime of 8 to 35 hours are quoted in "*Annexure D5 - Eskom Report SKA Africa Radio Telescope Grid Infrastructure Requirements."* for 132 kV supply points similar the one proposed for SKA. However, availability figures for low voltage consumers are not quoted, although these are likely to below the level at the 132 kV supply point.

Redundancy is provided for the 400 kV / 132 kV and 132 kV / 33 kV transformers. The option of a duplicate 132 kV line was rejected on the grounds that the increase in line availability would be marginal for the additional cost. This assessment needs further examination in view of the impact on the overall system availability, particularly for infrequent extended outages.

The 33 kV lines to the core distribution are double circuit, providing 100 % backup. However, it is not clear how far down into the distribution system this philosophy extends. Interconnections between circuits and control arrangements for reconfiguring the system, both of which would improve power availability, are not described.

#### 6.1.2 Availability of power for the spiral arms

The majority of the spiral arm stations are proposed to be supplied from an extension of the core distribution system. The remainder are proposed to be supplied from connections to other parts of the transmission system. Again insufficient information is given to assess the power availability to these areas of the array.

#### 6.1.3 Availability of power for the remote sites

The availability and efficiency of the PV array is dependent on the solar intensity. Subject to adequate battery capacity, the solar array and battery system would have a very high availability. The down time figure for low irradiance stated in the Submission of 1 % appears reasonable for the location and proposed system configuration. During any outages the supply would be taken over by the backup diesel for a period of up to around 20 hours, giving a very high overall availability.

Prolonged outages for maintenance or an outage of the entire system is unlikely due to the modular nature of the system; however common mode failures such as extreme weather events or failure of the supply cable could cause an extended outage.

#### 6.1.4 Backup systems

The extent of back-up power coverage is not clear and as a result it is difficult to assess its impact on overall availability. In view of the limited information on the distribution network design from the core it is not possible to estimate the benefit of the core back-up systems.

### 6.2 Power quality and regulation

The Submission refers to the South African standard “*NRS 048-2*” for power quality issues.

Steady state voltage control would be by use of on-load tap-changers on the 132 kV / 33 kV transformers. Provided the cable sizing is correct, this should keep long-term voltage excursions within normal limits of ± 5 % at low voltage. There would be deeper short-term (< 200 ms) voltage dips due to transmission system faults as shown in the Submission; however the effect of such events on the operation of the receptors is not described within the RfI.

Depending on the proportion of the load that is supplied via power electronics and the nature of the converter equipment, there may be a requirement for harmonic filtering. This is not addressed in the Submission. Background harmonics from the transmission system are expected to be within South Africa’s standard limits as defined in “*NRS 048-2*”.

### 6.3 Radio frequency interference (RFI)

The 132 kV incoming line route is detailed in the Submission. The Submission mentions an agreed 11 km buffer zone for 132 kV overhead lines. The thinking behind this figure is not explained and may have been provided to ESKOM as guidance for the design work (see also ”*Annexure D5 - Eskom Report SKA Africa Radio Telescope Grid Infrastructure Requirements*”, clause 5.1).

Increased insulation levels are proposed to be used on the final 20 km of the 132 kV line and the conductors would be designed to minimise corona. These measures are suitable for reducing RFI emissions. The line poles would be cylindrical, which is stated to be “more RFI quiet” than the lattice type structure (see ”*Annexure D5 - Eskom Report SKA Africa Radio Telescope Grid Infrastructure Requirements*”). The line route has been chosen to maximise the use of terrain shielding which is stated to be 20 dB, although this figure is not substantiated. No references are given to relevant technical papers to justify the extensive use of 132 kV and 33 kV overhead lines in the design.

"*Annexure D7 - Eskom Electromagnetic Compatibility Associated with the Power Supply of the SKA*" gives some useful information on the thinking on RFI for transmission systems.

The Astronomy substation transformers would be screened using mesh. Screening for the substation building is separately reviewed in the PB infrastructure report.

The use of 33 kV overhead lines within the array area deviates from the RfI which specifies that all distribution from the utility power interface should be by underground cable. This deviation is not justified by reference to any technical papers and radically affects the costs of the power distribution network.

It is stated in "*Annexure B: Provision of Electrical Power SECTION 1"* that the miniature substations and distribution kiosks do not contain any electronic equipment. However, circuit breakers are included, which presumably include some form of electronic protection relaying. The protection philosophy is not explained. Shielding measures for the distribution system equipment are not described.

The emergency diesel generators that may be located within the core to provide backup power during an outage of the 132 kV supply are not proposed to be shielded, on the grounds that they would only be used when the array is not in use. However, shielding would be necessary to permit the regular test running of these engines to assure their readiness for emergency use.

Some of the remote stations within South Africa are relatively close to the utility supply lines, the closest being 555 m (see "*2011.09.01_CostEstimate_Rev7"*). This would have an adverse effect on RFI.

The proposed measures for the 132 kV overhead line and Astronomy substation give a measure of confidence that RFI emissions would be well managed by ESKOM at the transmission level. However, there is a severe lack of definition of RFI management issues within the distribution system.

RFI screening of buildings is separately reviewed in the PB infrastructure report.

## 6.4 Operations

### 6.4.1 Transmission and distribution

It can be assumed that the transmission system would be competently operated by ESKOM.

The Submission does not mention any of the necessary control and supervisory systems for the distribution system to the central zone of the array and to the Astronomy complex.

### 6.4.2 Generation

Generation in the SKA Africa design is limited to solar PV hybrid systems at four remote sites and standby diesel generators elsewhere.

Routine weekly visits are proposed when the hybrid power system is in operation. This is a suitable frequency for maintenance on the diesel generator and, subject to adequate fuel storage tank sizing, would allow refuelling as required. However, a solar PV system of this size would usually require the presence of two technical personnel during the day and remote monitoring during the night, neither of which are proposed. Two to three on site cleaning staff may also be required in order to maintain availability.

As the proposed location of the units is to be in the remote desert, extra consideration should be given to air inlet filters. This may include installing special filters so any air that is passed through is fine filtered and/or is passed through an oil bath type self cleaning arrangement to avoid any particle entry into engine. No mention of such arrangement is given in the Submission.

### 6.5 Scheduling and roll-out

An existing 33 kV line is available for the power supply for the start of the SKA1 construction. The main phases of construction of SKA1 and SKA2 would be supplied from the Astronomy substation, once this is completed and energised in 2016. The programme for this main power supply is acknowledged in the Submission as being "tight". The remainder of the construction programme (2016 to 2024) does not pose any particular challenges.

## 7 Cost review

### 7.1 Summary of capital costs

The following table shows the approximate splits of the capital cost for various areas of power provision for the SKA. There exists a slight discrepancy between the total below and that quoted in the Submission as the costs were broken down by PB and re-constituted using slightly different assumptions to those used in the Submission.

| Category | Cost | Comment |
|---|---|---|
| HV transmission | € [redacted] | 400 kV / 132 kV system and 132 kV / 33 kV transformers, including main 33kV switchgear |
| MV distribution | € [redacted] | 33kV lines, cabling and equipment |
| MV/LV transformers | € [redacted] | 33kV/415V transformers, including main 415V switchgear |
| LV distribution | € [redacted] | 415V cabling and equipment |
| Generation | € [redacted] | Autonomous and backup |
| Total | € [redacted] | |

*Note: The connection of the super-computer included in the above. See also comments in sections 7.2-7.4 below.*

### 7.2 Transmission

The cost estimates for the transmission assets appear to be reasonably complete. Assessment of these costs indicates that they are broadly comparable with the equivalent costs from previous PB experience in UK. It should be confirmed by SKA Africa that any consequential 400 kV system reinforcement costs are considered.

### 7.3 Distribution

The unit rates quoted for buried cables are comparable to those from PB experience in UK

The remainder of the distribution costs are difficult to evaluate because of the lack of definition of the distribution system architecture.

### 7.4 Local and backup generation

Component costs quoted in USD for the PV array, the battery cells and related UPS, battery chargers and standby diesel generator for a hybrid solar PV system can be found in "*Sizing-MPPT New Ver v6 irradiance*" and are detailed in the following table.[3]

| Component | Quoted value USD 2011 | Quoted value Euros 2007 | PB estimate value | PB estimate value Euros 2007 |
|---|---|---|---|---|
| Supply and installation of PV system and inverters | $ [redacted] | € [redacted] | € [redacted] | € [redacted] |
| UPS system | $ [redacted] | € [redacted] | £ [redacted] | € [redacted] |
| UPS battery chargers | $ [redacted] | € [redacted] | £ [redacted] | € [redacted] |
| Generator | $ [redacted] | € [redacted] | € [redacted] | € [redacted] |
| Battery cells - 2 V, 11400 Ah | $ [redacted] | € [redacted] | £ [redacted] | € [redacted] |
| Battery stands | $ [redacted] | € [redacted] | £ [redacted] | € [redacted] |
| TOTAL | | € [redacted] | | € [redacted] |

*Cost breakdown for solar PV hybrid system*

The above table shows that the component cost quotes for the PV system, inverters, UPS system, battery chargers and battery stands are highly comparable. There is a slight discrepancy in the cost of the batteries themselves; however the difference is within expected margins for this stage of design. The only notable discrepancy is the cost of the diesel generator.

A cost of € [redacted] for a backup generator to back up the super computer and data processor at the Astronomy Complex has been included in the Submission. The generator is sized at 5 MW. Based on PB's experience, a generator cost of approximately € [redacted] would usually be expected. It is not clear whether the priced scope includes other equipment such as switchgear and fuel storage.

### 7.5 Operating costs

The operational costs are presented in the main part of the Submission as headline figures and as a specific cost in € per kWh. The cost based on 2011 ESKOM tariffs (as per the RfI) was presented, along with an escalated cost based on a predicted tariff for 2014. All other operational and maintenance costs are assumed the same for the 2011 calculation and the 2014 calculation.

| | |
|---|---|
| Annual expenditure on ESKOM electricity based on 2011 tariff | € [redacted] |
| Annual expenditure on ESKOM electricity based on 2014 tariff | € [redacted] |

In addition to the ESKOM tariff, the Aurecon report contained within "*Annexure D8 - Aurecon Assistance for the SKA South Africa Site Bid Submission*" states that the operations and maintenance cost estimate includes staffing costs relating to the power system and materials for planned and unplanned maintenance of the power system. However, it is unclear as to the breakdown of the operational cost beyond the headline figures shown below. It has therefore not been possible to provide a comprehensive appraisal of the operational costs or to identify any areas that have not been included.

| | |
|---|---|
| Annual expenditure on operations other than electricity supply | € [redacted] |
| Annual expenditure on maintenance | € [redacted] |

[3] The cost of the hybrid system is quoted as € [redacted] in "*Annexure D2 - SKA Power Cost Summary*" and as $ [redacted] in "*Sizing-MPPT New Ver v6 irradiance*", therefore the conversion factor between 2011 USD and 2007 EUR used for each component is 0.671.

# 8 Discussion

## 8.1 Areas of uncertainty

- Uncertainty exists within the exact topology and level of redundancy within the distribution system for the cores.

## 8.2 Risks associated with the design

The following points summarise the key design risks. A complete risk register can be found in the appendices.

- The lack of redundancy in the 132 kV incoming overhead line may result in brief total power outages in the event of a fault and extended but infrequent outages for planned maintenance.
- The use of 33 kV overhead lines up to 2 km from any receptor would increase the incidence of RFI compared with that from buried cables.
- A general lack of definition of the distribution system raises questions regarding power availability, power quality and RFI.
- The proposed SKA core emergency diesel generators omit RFI shielding which would mitigate against RFI during testing.
- Harmonic filtering is not addressed.
- Voltage and frequency variations are not specified.

## 8.3 Clarifications required

- The rating and present load flow on the local 400 kV system should be provided to verify the capacity of the existing system and estimate the capacity following the implementation of the proposed reinforcements.
- A single line diagram and description of the distribution system should be provided.
- The RFI strategy at distribution level should be justified.
- Further detail on the breakdown of the operational and maintenance costs and components included should be sort.

## 8.4 Subsequent work required

- An availability study should be carried out.

# 9 Conclusions

1. The proposed design for the core and spiral arms of the SKA Africa site is based on a conventionally designed 33 kV grid distribution system fed from a dedicated 132 kV connection from the existing ESKOM network.

2. The reliability of future ESKOM supplies is justified on the basis of the published programme of new power plant which would fill the current capacity gap and eliminate the need for extensive load shedding. Most new capacity would be coal-fired, although a programme of renewable generation development would improve the sustainability of electricity somewhat.

3. The transmission design, subject to specific reservations detailed in section 4.3 of this report, is conventional and appropriate and appears to offer reasonable availability at cost levels consistent with European experience.

4. The supply at 132 kV would be derived by extension of an existing 400 kV substation. However, only a single circuit connection would be provided for the 115 km line to the Astronomy substation near the core. From there redundant transformers would supply power at 33 kV to supercomputer, the data processor and the array. The single circuit connection would expose the whole array to brief interruptions on transient faults and to extended outages for infrequent maintenance works on the line. A duplicate overhead line was considered in the Submission but not included in the selected configuration.

5. Most remote stations are proposed to be fed from local grid connections with UPS back-up. Four remote stations are supplied by photovoltaic arrays and batteries with local diesel generator back-up, which represents an adequate solution.

6. The design of the SKA Africa distribution network conflicts with the RfI by proposing the use of 33 kV overhead distribution within the array area to within 2 km of receptors and the location of a number of the remote stations at less than 2 km from existing 22 kV and 11 kV overhead lines. Further, the distribution network design is not detailed sufficiently to allow an assessment of its availability or cost to be made.

7. Detailed review of some features was not possible because of lack of detail or inconsistencies in the Submission. This limited the review of the supplies to the super-computer and assessment of standby generation. The absence of information also restricted the assessment of availability and lower level costs.

8. The availability claimed for the design is reasonable at 99.6 % to 99.9 % equating to annual downtimes of the order of 20 hours across the system. Insufficient information is provided to check this quantitatively. There are concerns that the average figure does not reflect the risk of infrequent but extended shutdowns from outages on the 132 kV transmission connection. Insufficient or conflicting information also impeded the assessment of the likelihood and extent of partial outages of the SKA.

9. Radio frequency interference from the power system is addressed by limiting 132 kV overhead lines to areas more than 11 km from the array and exploiting terrain shielding. The 33 kV overhead lines would be routed at least 2 km away from any receptor. Additional measures include increased insulation for the overhead lines closer to the array and shielding of the Astronomy substation. These measures may not be adequate to meet the RFI objectives. Elsewhere in the proposed design RFI measures are omitted e.g. for the diesel generators, despite the need for test operation while the array is active.

10. Unit rates for capital cost items within the distribution system provided in the Submission appear to be comparable with expected levels. Insufficient information was however provided to relate the total costs with the scope of supply and total costs appear to be below expected values for the extent of the system. The lack of detail on the distribution network scope represents a substantial uncertainty in the cost of the system.

11. it is unclear as to the breakdown of the operational costs and has therefore not been possible to provide a comprehensive appraisal of the operational costs or to identify any areas that have not been included. This introduces significant uncertainty into the operational cost estimate.

# 10 Appendix A – Abbreviations

| | |
|---|---|
| CAPEX | Capital Expenditure |
| CCGT | Combined Cycle Gas Turbine |
| CO2 | Carbon Dioxide |
| CSP | Collecting Solar Power |
| ° C | Degrees Centigrade |
| GW | Giga Watt |
| GWh | Giga Watt-hour |
| HSE | Health, Safety and Environment |
| HV | High Voltage |
| km | kilometre |
| kV | Kilo Volt |
| kVA | kilo Volt-Amp |
| kW | kilo Watt |
| kWh | kilo Watt-hour |
| LV | Low Voltage |
| m | metre |
| ms | millisecond |
| MV | Medium Voltage |
| MVA | Mega Volt-Amp |
| MW | Mega Watt |
| MWh | Mega Watt-hour |
| NOx | Nitrous Oxides |
| NRS | National Standards |
| OCGT | Open Cycle Gas Turbine |
| OHL | Overhead Line |
| OPEX | Operational Expenditure |
| PB | Parsons Brinckerhoff |
| PV | Photovoltaic |
| RfI | Request for Information |
| RFI | Radio Frequency Interference |
| s | second |
| SCADA | Supervisor Control And Data Acquisition |
| SKA | Square Kilometre Array |
| SO2 | Sulphur Dioxide |
| SSG | SKA Siting Group |
| UPS | Uninterruptable Power Supply |
| USD | United Stated Dollars |
| V | Volt |
| VA | Volt-Amp |
| W | Watt |
| Wh | Watt-hour |

# 11 Appendix B – Document List

| | | Section numbers of this report that contain comments on or information derived from each report or section of the Submission | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Report** | **Section title** | **3.1** | **3.2** | **3.3** | **4.1** | **4.2** | **4.3** | **4.4** | **4.5** | **4.6** | **4.7** | **5.1** | **5.2** | **5.3** | **5.4** | **6.1** | **6.2** | **6.3** | **6.4** | **6.5** | **7.1** | **7.2** | **7.3** | **7.4** | **7.5** |
| South African Response to the SSG Request for Information | Chapter 3, Provision of Electrical Power - Section 3.1, Introduction | x | | | | | | | | | | | | | | | | | | | | | | | |
| | Chapter 3, Provision of Electrical Power - Section 3.2, Electricity in South Africa | x | | x | x | x | | | | | | x | | | | | | | | | | | | | |
| | Chapter 3, Provision of Electrical Power - Section 3.3, Provision of Power to the SKA Core | x | x | x | | x | x | x | x | x | x | | s | | | x | x | | | | | | | | |
| | Chapter 3, Provision of Electrical Power - Section 3.4, Provision of Power to the Remote Stations | x | | x | | | | | x | | | | | | x | x | | | | | | | | | |
| | Chapter 3, Provision of Electrical Power - Section 3.5, RFI Mitigation | | | x | | | x | x | | | x | | | | | | | x | | | | | | | |

| | | Section numbers of this report that contain comments on or information derived from each report or section of the Submission | | | | | | | | | | | | | | | | | | | | | | | |
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| **Report** | **Section title** | **3.1** | **3.2** | **3.3** | **4.1** | **4.2** | **4.3** | **4.4** | **4.5** | **4.6** | **4.7** | **5.1** | **5.2** | **5.3** | **5.4** | **6.1** | **6.2** | **6.3** | **6.4** | **6.5** | **7.1** | **7.2** | **7.3** | **7.4** | **7.5** |
| | Chapter 3, Provision of Electrical Power - Section 3.6, Existing "SKA Ready" Infrastructure | | | x | | | x | | | | | | | | | | | | | x | | | | | |
| | Chapter 3, Provision of Electrical Power - Section 3.7, Cost Summary | | x | x | | | | | | | | | | | | | | | | | x | x | x | x | x |
| | Chapter 3, Provision of Electrical Power - Section 3.8, [redacted] | | | x | | | | | | | | | | | | | | | | | | | | | x |
| | Chapter 3, Provision of Electrical Power - Section 3.9, Schedule of Power Provision Roll-Out | | | x | | | | | | | | | | | | | | | | x | | | | | |
| | Chapter 5, Physical Characteristics of the Site - Section 5.3, SKA Core and Skirt Region | | | x | | x | x | x | | | | | | | | | | | | | | | | | |

| | | Section numbers of this report that contain comments on or information derived from each report or section of the Submission | | | | | | | | | | | | | | | | | | | | | | | |
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| **Report** | **Section title** | **3.1** | **3.2** | **3.3** | **4.1** | **4.2** | **4.3** | **4.4** | **4.5** | **4.6** | **4.7** | **5.1** | **5.2** | **5.3** | **5.4** | **6.1** | **6.2** | **6.3** | **6.4** | **6.5** | **7.1** | **7.2** | **7.3** | **7.4** | **7.5** |
| Annexure D1 - Response to Annex 2 of the SSG RfI | 2.1. Transmission of power to the central area of the array, remote stations, and super computer building | x | x | x | | x | x | | | | | | | | | x | x | | | | | | | | |
| | 2.2. Generation of power for the central area of the array, remote stations and super-computer building | x | x | x | | | | | x | | | | | | | | | | | | | | | | |
| | 2.3. A schematic diagram showing the power distribution network structure | x | x | x | | | | x | | | | | | | | | | | | | | | | | |
| | 2.4. RFI mitigation, lightning protection and other control and safety systems | | | x | | | | | | | | | | | | | | x | | | | | | | |
| Annexure D2 - SKA Power Cost Summary | | | x | x | | | | | | | | | | | | | | | | | x | x | x | x | x |

| | | Section numbers of this report that contain comments on or information derived from each report or section of the Submission | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Report** | **Section title** | **3.1** | **3.2** | **3.3** | **4.1** | **4.2** | **4.3** | **4.4** | **4.5** | **4.6** | **4.7** | **5.1** | **5.2** | **5.3** | **5.4** | **6.1** | **6.2** | **6.3** | **6.4** | **6.5** | **7.1** | **7.2** | **7.3** | **7.4** | **7.5** |
| Annexure D3 - Eskom Annual Report 2011 | Additional Information - Tables - Statistical Overview | | | x | x | | | | | | | x | | | | | | | | | | | | | |
| Annexure D4 - IRP2010 | | | | x | x | | | | | | | x | | | | | | | | | | | | | |
| Annexure D5 - Eskom Report SKA Africa Radio Telescope Grid Infrastructure Requirements | | | | x | | x | x | x | | x | x | | x | x | | | | | | | | | | | |
| Annexure D7 - Eskom Electromagnetic Compatibility Associated with the Power Supply of the SKA | | | x | x | | | | | | | | | | x | | | | x | | | | | | | |
| Annexure D8 - Aurecon Assistance for the SKA South Africa Site Bid Submission | Section 3, Provision of electric power - Section 3.1, Transmission of electric power | x | x | x | | x | x | | | x | | | x | | | x | x | | | | | | | | |
| | Section 3, Provision of electric power - Section 3.2, Generation of power | | | x | | | | | x | | | | | | | | | | | | | | | | |

| | | Section numbers of this report that contain comments on or information derived from each report or section of the Submission | | | | | | | | | | | | | | | | | | | | | | | |
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| **Report** | **Section title** | **3.1** | **3.2** | **3.3** | **4.1** | **4.2** | **4.3** | **4.4** | **4.5** | **4.6** | **4.7** | **5.1** | **5.2** | **5.3** | **5.4** | **6.1** | **6.2** | **6.3** | **6.4** | **6.5** | **7.1** | **7.2** | **7.3** | **7.4** | **7.5** |
| | Section 3, Provision of electric power - Section 3.3, Power distribution network structure | x | x | x | | | | x | | | | | | x | | x | x | | | | | | | | |
| | Section 3, Provision of electric power - Section 3.4, RFI mitigation, lightning protection and other control and safety systems | | | x | | | | | | | | | | | | | | x | | | | | | | |
| | Section 3, Provision of electric power - Section 3.5, Schedule of power provision roll-out | | | x | | | | | | | | | | | | | | | | x | | | | | |
| | Section 3, Provision of electric power - Section 3.6, Operations plan for the power network | | x | x | | | | | | | | | | | | | | | x | | | | | | |
| | Section 3, Provision of electric power - Section 3.7, Regulations applicable to the power network | | | x | | x | x | x | | | | | | | | | | | x | | | | | | |

| | | Section numbers of this report that contain comments on or information derived from each report or section of the Submission | | | | | | | | | | | | | | | | | | | | | | | |
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| **Report** | **Section title** | **3.1** | **3.2** | **3.3** | **4.1** | **4.2** | **4.3** | **4.4** | **4.5** | **4.6** | **4.7** | **5.1** | **5.2** | **5.3** | **5.4** | **6.1** | **6.2** | **6.3** | **6.4** | **6.5** | **7.1** | **7.2** | **7.3** | **7.4** | **7.5** |
| | Section 5, Cost estimate | | x | x | | | | | | | | | | | | | | | | | x | x | x | x | x |
| 110817 AnnB Sec1 v2 (lr) | | | | x | | x | x | x | | | | | | | | x | x | | | | | | | | |
| D9_14 107102-SSG-ELE-0014 sheets 1 to 6 | | | x | x | | | | x | | | | | | x | | | | | | | | | | | |
| D9_2 107102-SSG-ELE-0002 | | | | x | | | | x | | | | | | x | | | | | | | | | | | |
| Sizing-MPPT New Ver v6 irradiance. | | | | x | | | | | | x | | | | | | | | | | | | | | x | |
| GEH725 | | | | x | | | | | | x | | | | | | | | | | | | | | | |
| Annexure D11 - NRS 048-2 (Ed 3) | | | | x | | x | x | x | | | | | | | | | | | x | | | | | | |
| 2011.09.01_CostEstimate_Rev 7 | | | | x | | | | | | | | | | | | | | x | | | x | x | x | x | |

## 12 Appendix C – Risk Register

| Trigger | Area of SKA | Probability | Period of trigger | Effect | Intensity | Type of effect | Period of effect | Consideration / Proposed mitigation |
|---|---|---|---|---|---|---|---|---|
| Ambient max or average temperature rise due to global warming | All | Medium | Operation | Replacement of electrical infrastructure due to frequent breaches in thermal capacity | Medium | OPEX | Operation | Explicitly excluded from calculations and designs - to be considered at a later design stage. |
| Operation of the telescopes is revealed to be susceptible to short period voltage dips | All | Low | Pre construction | Outages or poor operation due to voltage dips on the transmission network | Low | Availability | Operation | Network designed to regulate voltage at the LV side of the 132 kV to 33 kV transformer to within 5 % of nominal |
| Construction works cause interference with the operation of the SKA1 due to radio / mobile phone use or accidental damage to existing services | All | Medium | Phase two construction | Use of communications devices during construction of the SKA 2 may interfere with the operation of the SKA 1 | Medium | Quality | Phase two construction | None |
| Construction works cause interference with the operation of the SKA1 due to accidental damage to existing services | All | Medium | Phase two construction | Damage to buried services or overhead lines from heavy plant may occur | High | Availability | Phase two construction | None |
| Construction works cause interference with the operation of the SKA1 due to accidental damage to existing services | All | Medium | Phase two construction | Damage to buried services or overhead lines from heavy plant may occur and require replacement | High | CAPEX | Phase two construction | None |
| Core and remote station distribution system RFI protection deficient due to non shielded generators and OHLs | All | Medium | Pre construction | Excessive interference | High | Quality | Operation | Should be clearly defined in the Submission. If unacceptable, revised design may be required resulting in increased CAPEX |
| Harmonic voltage distortion above acceptable limits due to injection from user equipment | All | Medium | Operation | Overloading of some power supply system components, malfunction of some user equipment | Medium | Quality | Operation | Harmonic penetration assessment should be undertaken to establish whether filters are necessary with resulting increased CAPEX |
| Voltage variations outside acceptable limits | All | Low | Operation | Malfunction of equipment | Medium | Availability | Operation | Assessment of voltage excursions should be carried out. Possible increased equipment or cable CAPEX |
| Control and protection philosophy and potential impact on RFI not defined | All | High | Pre construction | Required protection systems may introduce power electronics within the vicinity of receptors that may introduce RFI interference | Medium | Quality | Operation | None |
| Testing of unshielded backup diesels (10 MW dish backup) in core, if included | Backup generation | High | Operation | RFI emissions from operation of unshielded diesels in core interferes with results | High | Quality | Operation | SKA SA concludes that the diesels would only be run when the power supply is down as they are backups but this would not be the case. Scheduled shut down of the SKA / non recording time could be scheduled |
| Core distribution system design deficient | Distribution for the core | Medium | Pre construction | Low availability or power quality | Medium | Availability | Operation | If unacceptable, revised design may be required resulting in increased CAPEX |
| Core distribution system design deficient | Distribution for the core | Medium | Pre construction | Additional capital investment required for suitable distribution system | Medium | CAPEX | Phase two construction | If unacceptable, revised design may be required resulting in increased CAPEX. |
| Excessive RFI emissions from 33 kV overhead lines | Transmission for mid or remote areas | High | Operation | Excessive interference | High | Quality | Operation | Use of overhead lines within RFI quiet zone should be justified by an interference study at the bid stage. Alternatively, underground cables should be used in accordance with the enquiry document (SSG-RFI-001) |
| The cost of electricity supplied by ESKOM to the core appears to be based on the "standard" charge during the summer. Peak rate charges however are more than double. | Transmission for the core | High | Pre construction | If load cannot be shifted out of peak periods then the cost of purchasing power would increase | Medium | OPEX | Operation | The ability of the SKA to load shift is currently unknown |
| 132 kV incoming overhead line fault | Transmission for the core | High | Operation | Short shutdown of power supply to whole site | Low | Availability | Operation | Overall availability to be assessed at the bid stage to establish whether duplicate overhead line is justified |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Delay in the approval or construction of the 132 kV OHL | Transmission for the core | Low | Phase two construction | Operation of the SKA 2 is delayed | High | Delivery | Operation | None |
| Re-enforcement to the deeper transmission system may be required in order to secure supplies to the SKA over life | Transmission for the core | Low | Operation | Power availability may be compromised in the future | High | Availability | Operation | None |
| RFI interference from illegal connections | All | Low | Operation | RFI emissions from unprotected, unshielded illegal connections to the OHLs | High | Quality | Operation | None |
| Some components of the operational costs may be under-estimated or neglected | All | Low | Pre construction | Operational costs are significantly higher than those expressed in the Submission | Medium | OPEX | Operation | Breakdown of operational costs not provided for review |