Power Supply to the Square Kilometre Array

Assessment of the Australian Site Submission - Power

For SKA Program Development Office, University of Manchester

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CONTENTS

EXECUTIVE SUMMARY

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

ANZSKA proposes to supply the SKA from the extension and reinforcement of the existing Western Power transmission network and distribute power to the core receptors through an appropriate voltage hierarchy. Some spiral arm stations and the remote stations would be supplied from stand alone diesel generation. The SKA 1 is proposed to be powered from a diesel / solar PV hybrid plant that would be used as backup during the operation of the SKA 2. An alternative option to supply power from a CCGT power plant is presented conceptually but is not substantiated or costed in the main response. The super computer is proposed to be located in Perth and supplied from the existing grid network.

Generally, the information provided defines the proposed solution in a moderate amount of detail. However it is clear that major high level design decisions such as whether to supply power from the grid or from a CCGT power station have not been finalised. This may be because of the levels of uncertainty in relation to cost and schedule that exist for both options.

Uncertainty relating to the future generation mix and the capacity of centralised generation, coupled with the lack of a schedule for the full reinforcement of Western Power's 330 kV system raise concerns about the ability of the transmission system to deliver the required power during the early operational stages of the SKA 2. However, a centralised generation fleet with a suitable technology mix would provide a reliable, low emissions, source of power to the transmission grid and hence to SKA so long as there is sufficient capacity planned to meet the demands of SKA and other industrial loads in Western Australia.

The proposed interconnection to the Western Power network has limited redundancy, having a single 330 kV / 132 kV transformer and 350 km single circuit 132 kV overhead line. Failure of any of these parts would result in interruption to SKA operation and prolonged outages could result if major repairs or replacements were required.

The distribution system offered represents a sound engineering solution for a large scheme such as this, which should ensure good power quality and availability. RFI minimisation and mitigation have been addressed comprehensively, with resulting high costs in some areas, for instance extensive buried cable systems.

The power supply to the super-computer systems is only covered in very general terms. Duplicate grid feeds and a diesel rotary UPS unit are included that appear to offer the necessary high level of reliability.

All transmission connections to the SKA are excluded from the capital cost estimate but are assumed to be included in the electricity supply tariff so that these appear as operational costs rather than capital expenditure. The capital cost estimates for electricity generation and distribution are broadly in line with UK costs. The remaining operational and maintenance expenditure for the power system is not broken down and sufficiently substantiated to undertake a detailed appraisal.

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 the provision of power to the SKA for the Australia and New Zealand SKA Submission.

2 Methodology

Parsons Brinckerhoff has reviewed the response from ANZSKA 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 ANZSKA, 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, ANZSKA proposes to supply the SKA from the extension and reinforcement of the existing transmission network and distribute power to the core receptors through an appropriate voltage hierarchy. Some spiral arm stations and remote stations would be supplied from stand alone diesel generation. The SKA 1 is proposed to be powered from a diesel / solar PV hybrid plant that would be used as backup during the operation of the SKA 2. An alternative option to supply power from a CCGT power plant is presented conceptually but is not substantiated or costed in the main response.

3.1.1 SKA 1

ANZSKA proposes to supply the SKA 1 from the extension of a diesel / solar PV hybrid plant called Horizon Power hybrid project. The plant currently has funding for the delivery of a 1.1 MW plant with approximately 500 kW of solar PV capacity to supply the Murchison Radio Observatory (MRO). ANZSKA proposes to extend the power station capacity to supply the SKA 1 core load of 5 MW.

3.1.2 SKA 2

ANZSKA proposes to supply the SKA 2 via a new 350 km single circuit 132 kV connection fed from the existing Western Power 330 kV transmission network. This connection would supply the core receptors, an operations centre approximately 30 km from the core, the data processor and the first five clump stations within each spiral arm. Power would be distributed through these areas via 33 kV, 6.6 kV and 415 V buried distribution cables with a high degree of RFI shielding.

The five outer clumps for each spiral arm would be supplied from stand alone shielded diesel generators of 250 kVA capacity. The remote stations would be supplied by stand alone diesel generators or local grid connection, although it is currently unclear as to how many would be supplied by each method.

3.1.3 Super computer

The super computer is proposed to be located in Perth and supplied from the existing grid network.

3.2 Key observations

- Apparent limited input from Western Power
- Great effort and cost attributed to RFI minimisation and mitigation
- Conceptual high level design decisions remain undetermined
- Supply to SKA 1 relatively vague
- Excessive reliance on and expense of diesel fuel

3.3 Quality of information

Generally, the information provided defines the proposed solution in a moderate amount of detail; however it is clear that major high level design decisions such as whether to supply power from the grid or from a CCGT power station have not been finalised. This may be because of the levels of uncertainty in relation to cost and schedule that exist for both options.

ANZSKA has stated that cost information specific to the provision of power is provided from Aurecon who have extensive experience in power and infrastructure consultancy across the globe. The base data provided is therefore likely to be reliable and sufficiently accurate for the current stage in the design process except where highlighted in Section 7 of this report.

There are some discrepancies within the information provided which could be misinterpreted. However these generally relate to relatively small cost items and do not have a significant impact on operation or availability. Discrepancies are expected at this stage of the design process due to internal variations in design and calculations and the involvement of numerous parties.

A high level overview of the capital costs is provided within the Submission, however there is no information relating to specific sources or a breakdown of how the summary costs were derived.

No breakdown of the majority of the components of the operational expenditure is provided.

Very little information regarding the origin of costs and evidence of calculations related to the power generation equipment has been included in the Submission. This makes it very difficult to evaluate the data to ensure the right sized equipment had been used and to check the credibility of data.

4 Feasibility of solution

4.1 Feasibility of supply from national generation

Since ANZSKA 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.

The Submission includes the assumption that “generation capacity would be driven by other customers and thus suitable power would be readily available by the time it is required for the SKA”. Although the SKA load is small compared to the system demand, it should be considered when planning for future generation.

Figure 2 in “*Attachment 33*” shows the energy supplied by various generation technologies in Western Australia between 2010 and 2050. It should be noted from this diagram that the predicted future increase in energy demand is proposed to be met by distributed renewable generation such as rooftop PV and micro wind power. The percentage of the energy demand supplied by distributed generation is expected to increase from around 9 % in 2010 to nearly 40 % in 2050 as energy demand increases. However, the amount of energy supplied by larger centralised generation is predicted to remain at a relatively stable level. Values assumed from analysis of Figure 2 in “*Attachment 33*” are given for reference in the following table.

Generation type	Energy 2050 (GWh)	Energy 2010 (GWh)	Energy 2020 (GWh)	Energy 2030 (GWh)
Coal	0	17500	16600	10000
Coal CCS	14000	0	0	0
Biomass	3000	2500	2500	2500
CCGT	0	0	0	1000
OCGT	500	1000	1000	1000
Wind	5500	2500	3000	5000
Solar	3500	0	0	0
Rooftop PV	11000	0	500	5000
Hot fractured rocks	5000	0	0	0
Other distributed generation	7000	1200	6500	11500

Predicted annual energy split by generation type for Western Australia

The maximum annual energy demand of the SKA is likely to represent between 3 % and 5 % of the energy supplied by centralised generation to the Western Power transmission system, which although small, is not insignificant. Future strategic generation planning should include the SKA demand in order to ensure sufficient central generation capacity exists to supply the SKA.

The aggregated emissions for the Western Australia network are:

- CO_2 = 0.81 kg per kWh
- NO_x = 0.0021 kg per kWh
- SO_2 = 0.0039 kg per kWh

These emissions are primarily attributable to a significant penetration of coal pulverised fuel stations (approximately 60 %); however Figure 2 in “*Attachment 33*” suggests that by 2040, all coal stations would be decommissioned and replaced by coal with carbon capture and storage (CCS), large scale wind power and large scale solar power. A centralised generation fleet of this technology mix would provide reliable power with low emissions to the transmission grid and the SKA so long as there is sufficient capacity planned to supply the SKA and other industrial loads in Western Australia.

4.2 Feasibility of supply from new generation

ANZSKA proposes to supply the SKA 1 from the extension of the Horizon power solar PV hybrid station that is currently funded to supply 1.1 MW to the Murchison Radio-astronomy Observatory (MRO). The currently funded plant is proposed to consist of four diesel generating units and a solar PV array of 500 kW; no battery systems are specified. Under this arrangement and if the demand is constant throughout the day and night, the proportion of energy supplied by solar PV would be around 25 %, not 50 % as stated in the Submission. Discussions relating to the planned plant and possible extension are still on going, so the potential exists for the level of solar PV to increase.

Following the commissioning of the power supply system for SKA 2, the generating capacity of the Horizon power hybrid plant is proposed to be utilised as backup power, although there are few details supporting or explaining this decision within the Submission. A more economical solution may be to run the PV part of the station to offset some of the imported electricity and to utilise the diesels as backup. No evidence of any consideration of this option is provided, although there may be reasons as to why this solution has not been proposed.

4.3 Feasibility of supply from the existing transmission system

The Submission is based on an assumed future reinforcement of the Western Power transmission system, involving a 330 kV line from Three Springs to Geraldton and a new 330 kV substation at Moonyoonooka. The Western Power "*2010/2011 Annual Planning Report*" indicates that this reinforcement is not yet funded and that until it is complete, the system would not be able to accept any large blocks of load without load shedding agreements.

Hence the supply from the Western Power network is technically feasible but there is a risk associated with the timing of the 330 kV system reinforcement. Network reinforcements can have long lead times due to planning issues and procurement of long delivery equipment. The likely design and installation period is approximately five years.

4.4 Feasibility of the proposed new transmission system

The SKA project Submission includes an extension to the Moonyoonooka substation. The exact nature of this extension is not specified in the Submission but it is assumed to comprise a single 330 kV / 132 kV transformer and line feeder. This would supply a 350 km single circuit overhead line to the SKA power utility interface (main substation).

On account of the preliminary nature of the 330 kV reinforcement project, the layout of the 132 kV system has not been developed. This leaves further uncertainty about its feasibility and cost.

The ownership of the 132 kV assets is not altogether clear in the Submission. The overhead line is apparently leased from Western Power but it is also stated that the last 20 km of 132 kV overhead line would be owned by the SKA project, in order to ensure a suitable design for RFI.

Because of the length of line and power flow required (65 MW), it has been identified that voltage support would be required at the receiving end. This is stated to consist of switched shunt reactors but in practice a combination of reactors and capacitors is likely to be required. A line voltage drop calculation would be required, once the load variations and power factor are better known. On-load tap-changers would need to be specified on the 132 kV / 33 kV transformer(s) to control the distribution voltage.

The SKA power utility interface is proposed to be located approximately 50 km from the centre of the array. The proposed location is not detailed in the Submission.

A single 132 kV / 33 kV transformer rated at 85 MVA is proposed, with a possible alternative of two 50 MVA transformers which would give partial redundancy.

The system described above diverges from a standard engineering solution with regard to the long length of single circuit overhead line and lack of redundancy within the line and transformer configuration. The solution is feasible, subject to the key risks identified below.

4.5 Feasibility of the proposed new distribution system

All the distribution, right back to the SKA power utility interface 50 km from the core is proposed to be buried cable in order to minimise RFI interference.

The primary distribution at 33 kV is proposed to supply the following:

- Three power hubs (33 kV / 6.6 kV substations) supplying the cores and inner spiral arms
- A ring main supplying twenty five clump nodes (packaged 33 kV / 6.6 kV substations) to the outer spiral arms (first 5 clumps on each arm)
- A 33 kV / 6.6 kV substation supplying the operations centre (no single line diagram provided)

The remaining five clumps on each outer spiral arm are proposed to be supplied from autonomous diesel generators.

The remote stations are proposed to be supplied either from the local grid or from autonomous diesel generators plus renewable generation; however, it is unclear as to how many stations would be supplied by each method.

The power hubs would be equipped with duplicate 33 kV / 6.6 kV transformers, providing a good level of reliability.

The secondary distribution at 6.6 kV and 415 V is proposed as follows:

- From the power hubs to the core arrays using open 6.6 kV ring circuits
- From the clump nodes to the clumps using radial feeders
- Within the operations centre

The 6.6kV ring circuits would be interconnected between the three power hubs to provide additional backup. The system would be remotely reconfigured.

The connections from the diesel generators to the outer clumps are proposed to be 415 V buried cables over approximately 2 km, presumably to reduce RFI levels.

The grid-supplied system described above represents a large distribution scheme, using classical engineering solutions for such systems. With the proposed layout, satisfactory voltage control should be achievable, subject to the necessary cable sizing calculations. The only significant risks that have been identified are the lack of definition in the operations centre power supply and a possible requirement for harmonic filtering.

4.6 Local and backup generation

The three power hubs are proposed to be equipped with diesel rotary UPS units rated at 0.5 MVA per hub. The operations centre is also proposed to be equipped with a diesel rotary UPS unit.

These systems appear to be sized to back up critical loads within the substation such as lighting and cooling systems.

The generators within the 180 km central area would be located along the outer spiral arms and be constructed within a shielded enclosure, several hundred metres from any major equipment. This is thought to be suitable protection from RFI. Fuel storage for each of the generators is to be sufficient for three months of continuous operation. At an estimated fuel usage rate of 50 litres per hour, the underground fuel storage tanks would have to be sized to approximately 108,000 litres. Although the civil works cost would be high (the tank is to be located underground) there are no practical limitations on the tank size, subject to adequate bunding arrangements. Practical refuelling of such large storage would require several visits by a large fuel tanker.

As 230 kW is the required load, a generator sized above the standard 250 kVA is required. This would allow for transmission losses and would account for a power factor of 0.9. A relatively small increase in generator capacity is however unlikely to have a significant impact on cost.

The exact number of diesel generators required for the remote stations is not known but from the Submission it is estimated to be between five and twenty five. In the case where a diesel generator is required, the distance from the point of generation and the remote station is believed to be less than 2 km, so the transmission losses would be minimal. The Submission states that up to two months of fuel is to be provided. This is a suitable amount when considering the distances from the major towns.

It is envisaged that whenever a diesel generator is to be used for power it would be running continuously to provide the required load. Usually under these conditions, it is good practice to have 100 % redundancy (i.e. 2 x 250 KVA sets) in case of unit failure. This should be even more the case due to the remote desert location, leading to regular maintenance of the machines.

4.7 Super computer

The 40 MW load requirement for the supercomputer building is to be provided by the grid. The use of a heat source associated with nearby power generation with absorption chillers is being considered to provide cooling and to reduce the electrical demand. This may reduce the costs associated with cooling the supercomputer. For backup of the grid supply, a diesel rotary UPS system is proposed. This is considered standard on such high powered computers.

The power supply to the super-computer systems is only covered in very general terms. Duplicate grid feeds are included to enhance reliability.

4.8 General aspects of SKA system

All equipment is designed for continuous operation at 45 °C ambient. (The absolute maximum ambient temperature is given as 44.9 °C.)

All cables are stated to be termite resistant. Cables are buried 1 m deep to reduce the effects of seasonal variations in temperature.

Earthing and lightning protection for the arrays is described in "*Attachment 32 – Preliminary Design & Costings of Power Systems for SKA*". The proposed systems are considered to be adequate, as far as can be judged at this stage of the project.

5 Credibility / reliability of information

5.1 Information on national generation

Information provided within "*Attachment 33 – The Australian Context for Renewables Development*" is considered to be supplied from reliable sources and reflects the high level strategic planning for the development of renewables in Australia.

5.2 Information on power transmission

The information provided in the Western Power "*2010/2011 Annual Planning Report*" can be considered to be reliable. Although this document does not form part of the Submission it is a public document[1].

The extent of Western Power's involvement in the development of the Submission appears minimal. Greater engagement would increase the credibility of the design and reduce risk.

Regarding the new transmission assets for the SKA project, the information is sparse and in some points contradictory (e.g. redundancy of 132 kV / 33 kV transformers).

Costing information for many major items such as the Moonyoonooka substation and the 132 kV / 33 kV substation is not provided.

5.3 Information on the distribution system

The information provided in the Submission is generally complete and consistent. Omissions are:

- Diagrams for the supplies to the operations centre and super-computer
- Routing of existing overhead lines
- Location of existing MRO power plant

These omissions do not have a significant impact on the assessment of the overall Submission.

5.4 Other sources of information

The exact source of information such as unit costs for major equipment, cabling, overhead lines, generators etc. is not specified.

6 System performance

6.1 Availability

6.1.1 Availability of power for the core, processor and operations centre

The predicted downtimes per annum stated in the Submission are as follows:

- Operations centre: 12 hours
- Cores 14 hours

These are compared with 99.974 % availability or 2.3 hours per annum downtime for low voltage customers in the Geraldton area. It is not clear how this estimate was made, but it allows considerable conservatism due to the remote nature of the supply, which seems reasonable.

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[1] http://www.westernpower.com.au/aboutus/publications/Annual_planning_report_.html

The largest single risk involves the long repair times for the main transformers (330 kV / 132 kV and 132 kV / 33 kV) and 132kV overhead line if no backup is provided. No estimates are given for repair times in the Submission. Planned maintenance outages would be required and these should also be taken into account when assessing the system availability.

The distribution system design includes interconnections between circuits and remotely controlled reconfiguration of the system, which would result in a high level of availability.

6.1.2 Availability of power for the spiral arms

The inner spiral arms that are proposed to be supplied from the extension of the core power supply would have similar availability to the core systems.

The remaining spiral arms are proposed to be supplied from diesel generators with very large diesel storage provision, ensuring fuel is likely to always be readily available. Diesel generators are an efficient and reliable stand alone electricity source for the required load.

Maintenance outages for a typical 250 kVA diesel generator run over a 32 month cycle and are displayed in the following table.

Months into cycle	Period of outage (days)
8	2
16	5
24	2
32	10

Maintenance outages for a typical 250 kVA diesel generator

The above maintenance regime corresponds to an availability of 98 %. However, any unplanned or forced outages may result in additional extended periods of unavailability due to the remote location of the generators, thus reducing the overall availability of the system to between 95 % and 97 %.

100 % redundancy is usually good practice to facilitate continued operation through maintenance periods and unplanned outages; however is not specified or costed. An alternative may be to replace the entire set during prolonged outages and repair or maintain off site. This may have been considered however no evidence suggesting that this has been costed is presented in the Submission.

6.1.3 Availability of power for the remote sites

The availability of remote sites supplied from grid is dependant on the strength of the grid to which it is connected. As the exact connection configuration is currently unspecified, therefore the availability of grid connected remote stations is unknown but is expected to be reasonably similar to the availability of the core receptors.

The availability of remote stations supplied by diesel generators is likely to be between 95 % and 97 %, although as with the spiral arm clusters; the inclusion of a second diesel generator of the same capacity would be advantageous.

6.1.4 Availability of the super-computing centre

The availability at the super-computer is expected to be high as the site is proposed to be supplied from dual network feeders. A backup rotary UPS system is also specified although no detail is provided. It is unclear as to what proportion of the 40 MW super-computer load would be backed up by the UPS system and for what period.

6.1.5 Backup systems

Emergency backup supplies are included as follows;

- diesel rotary UPS unit (0.5 MVA) per power hub to supply essential load
- diesel rotary UPS unit (unspecified rating) for operations centre
- diesel rotary UPS unit (unspecified rating) for supercomputer
- possible supply from MRO power station (proposed 33 kV supply to SKA 1)
- possible supply from existing local system to operations centre

6.2 Power quality and regulation

Steady state voltage control would be by on-load tap-changers on the 132 kV / 33 kV transformers with switched shunt reactors to provide additional reactive power compensation as required. 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 however the effect of such events on the operation of the receptors is not described within the RfI.

Voltage variations for each delivery point of the SKA are not specifically stated in the Submission; however it is stated that the voltage at the LV side of the 132 kV / 33 kV transformers would be controlled to within 2 % of nominal. Voltage variation would be significantly affected by the long transmission connection to the core and remains an important uncertainty. Frequency variations would only be significant in the diesel fed remote clusters. These should be maintained at an acceptable level if modern generator controls are used.

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 can be expected to be within standard limits for Australia.

6.3 Radio frequency interference (RFI)

The 132 kV incoming line route has not been finalised but the Submission states that it would be routed such that it is at least 50 km from any receptor and that terrain shielding would be maximised. There is a risk that these objectives may not be met when the route is finally developed.

Increased insulation levels would 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 may also improve the line performance in this respect.

The Submission also states that “no public power asset is closer than 20 km from the antennas”. Presumably this refers to existing overhead lines but no documentary evidence is provided of such lines and their routes in relation to the array.

All distribution from the power utility interface to the final supply point is proposed to be buried screened cable, in accordance with the SSG RfI. This is the optimum solution for reduced RFI emissions. The Submission also states that 11 kV rated cables would be used for the 6.6 kV system to reduce the voltage stress and hence ageing which could otherwise “increase their RFI over time due to microscopic partial breakdown of insulating material”. References to relevant technical papers were not included to support the benefits of this approach.

Transformers would be oil-immersed with welded tanks and tap-changers enclosed in the tanks. These measures would be effective in minimising RFI emissions.

RFI filters would also be fitted to the 6.6 kV systems. These filters were apparently developed in the previous MRO project.

All 6.6 kV / 415 V transformer protection is proposed to be fuses to reduce RFI from electronic protection components. Such an approach may give cruder protection but would be effective.

The Submission includes a statement that any HV switching operation would cause an RFI burst but that such operations are "not expected to occur more frequently than once every few years". In PB's experience this is optimistic and switching operations can be expected every few months on a distribution system of this size and complexity. It is not clear how switching noise would be avoided from switched reactors proposed for voltage control at 132 kV.

For those remote stations that are supplied from public networks, the last 2 km of the supply circuit would be underground cable to minimise RFI.

A preliminary calculation of the required buffer distance for overhead lines is included in "*Attachment 32*". This concludes that a buffer distance of 4 km would be adequate for a 66 kV line. The above measures give a good level of confidence that RFI emissions would be well managed.

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 Western Power.

The distribution system to the central zone of the array is proposed to be controlled by a SCADA system.

6.4.2 Generation

The diesel generators in the central area and in the remote stations have 3 months and 2 months fuel storage respectively. This ample fuel storage reduces the need for frequent visits to the sites; however regular maintenance on the units is still required and is currently not specified. Standard maintenance activities include regular filter cleaning, possible filter change and removal every 500 hours, fuel injection equipment maintenance and timing and tappet checks every 6000 hours and full inspection every 24,000 hours. It is not clear as to the extent of maintenance activities that have been included in the cost evaluation.

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. However it is estimated that planning, development, design, approval and installation of such assets could take over five years and risk a delay to the start of operation of the SKA 2.

6.5 Scheduling and roll-out

The Submission states that in addition to the extension of the MRO hybrid power station, the construction of one power hub, some parts of the distribution system and a temporary 33 kV underground cable would be undertaken as part of the roll out of power infrastructure for the SKA 1. No schedule is presented for these activities; however the time frames suggested in Table 3 of the Submission are tight but would be achievable with sufficient resources. PB estimates the lead time and installation period for a solar PV array of around 500 kW are approximately four weeks and five weeks respectively.

The Submission estimates the total period for the approval, development, procurement and installation of the 132 kV cable to be 3.5 years. Given the extended time period required to install the receptors, it is unlikely that this would be on the critical path. The stated time period is reasonable for the installation of a 132 kV OHL and could also include the installation of a substation at each end in parallel, although this assumption is not stated.

No time frame is provided within the Submission in relation to the completion of the "stage 2" 330 kV upgrades from Three Springs to Moonyoonooka.

7 Cost review

7.1 Summary of Capital Costs

The following table summarises the cost components broken down by PB using the data provided in 2011 AUD from "*SKA CRA 5 Sep compliant Config calc sheet*" of the Submission and converted to 2007 Euros using the conversion factors given on page 4 of "*Attachment 30*". The total does not exactly match that stated in the main report as a full calculation was not available. However the totals are reasonably similar and the breakdown has allowed PB to evaluate some cost components.

Category	Cost	Comment
HV transmission	€ 68,900,000	Quote for 132 kV OHL only – 330 kV / 132 kV substation and 132 kV / 33 kV transformers not included. Cost of transmission system down to the 33 kV side of the 132 kV / 33 kV transformers is assumed to be amortised and included in the operational expenditure
Extension of the MRO solar PV hybrid station	€ 11,300,000	
MV distribution	€ 181,800,000	33kV and 6.6 kV equipment and cabling
MV/LV transformers	€ 32,600,000	6.6kV/415 V transformers, including main 415 V switchgear
LV distribution	€ 28,400,000	415 V cabling and equipment
Generation	€ 54,000,000	Autonomous and backup
Commissioning	€ 2,700,000	
Total	€ 310,800,000	Exclusive of HV transmission

Note: Super-computer and temporary 33 kV cable not included in the above. See also comments in sections 7.2-7.4 below.

7.2 Transmission

All transmission items are excluded from the capital cost estimate i.e.

- Extension to Western Power Moonyoonooka substation
- 132 kV line to SKA power utility interface
- 132 kV / 33 kV substation

The capital costs of the 132 kV line and 132 kV / 33 kV substation are understood to be included as a amortisation charge in the electricity supply tariff, based on a 15 % return on investment. The Submission highlights the uncertainty associated with the return on investment that would be required for this method of funding. Alternatively, some or all of the capital cost could be paid directly by SKA.

The cost of the proposed reinforcements to the Western Power 330 kV network, including the 330 kV / 132 kV transformer(s) at Moonyoonooka substation are not mentioned in the Submission. It is anticipated that a proportion of these costs would be payable by SKA as part of a connection charge. An estimate of such a charge should be requested from ANZSKA.

A separate estimate for the capital cost of the 132 kV line in "*SKA CRA 5 Sep compliant Config calc sheet*" appears to be broadly in line with UK costs.

7.3 Distribution

Distribution for the super-computer site is omitted from the cost estimate. As for the transmission connection, an estimated connection charge should be requested from ANZSKA to cover the cost of the utility owned assets.

The capital cost schedule for the array site is reasonably complete. The costs appear to be broadly in line with UK costs.

7.4 Local and backup generation

A number of 250 kVA diesel generators for the spiral arm clump stations have been proposed for power generation. From previous experience Parsons Brinckerhoff estimate a cost of € 200,000 for a standard 250 kVA diesel generator. This value includes adequate fuel storage, civil work, switchgear, transformer and control equipment. This value is less than the € 418,400 per unit detailed in the cost evaluation in the Submission. However the proposed design includes large buried diesel storage tanks. The Submission has also factored in a cost for shielding buildings for the generators to prevent RFI emissions. A cost of the shielding per generator of approximately € 656,400 has been included in the Submission. The limited available data on RFI protective enclosures costs suggests that this is a reasonable figure.

A cost for the 250 kVA diesel generators for the remote stations have been included in the Submission although it is not clear how many generators this relates to. According to the technical detail in the Submission, this could be between 5 and 25. If the worst case of 25 units is assumed, the resultant cost per unit would be € 348,700, which is in line with the estimate for the diesel generators for the spiral arms. The cost is again higher than the expected figure of around € 250,000, but again additional facilities are required for the application..

A cost for a backup diesel generator for the data processor area of $1,640,900 has been included in the Submission. The capacity of the back-up generator was not defined. However based on previous experience, PB estimates that a generator or multiple generators of this cost would be able to supply between 5 MVA and 12.5 MVA. The power required to back-up the full 10 MW load of the data processor is 12.5 MVA so this cost appears appropriate.

A cost for the standby diesel generator, batteries and charger for the auxiliary power supply of the SKA site 33 kV main switchboard has been included. The generator has been sized at 0.5 MVA and is just for the switchboards' auxiliaries i.e. lighting, security etc. The cost for the unit is quoted as € 341,300. With the location and mode of operation of the unit this is considered reasonable

7.5 Operational costs

The estimated annual cost of the electricity supply to the array site is quoted in the Submission as € 74.9 million. This is composed of a base supply tariff of 12.7c AUD per kWh plus an additional charge of 7c AUD per kWh to cover the capital cost of the 132 kV line and 132 kV / 33 kV substation (see above). The source of the base tariff and the derivation of the additional charge are not fully explained.

The estimated annual cost of the electricity supply to the super-computer is quoted in the Submission as € 29.7 million, based on the tariff for electricity supply only. It is unclear as to how the supply for the super computer shall be paid for.

The estimated operation and maintenance cost of the distribution system to the central array is quoted in the Submission as € 2.8 million per annum plus € 11.7 million per annum for diesel fuel and maintenance of the remote and spiral arm sites.

For the remote sites, the annual electricity supply cost for the grid connected sites is quoted in the Submission as € 2.4 million. The diesel fuel and maintenance costs for the autonomous sites are quoted in the Submission as € 2.8 million. It is unclear as to how many sites are to be connected using each method.

A comprehensive breakdown of the components of the operating cost is not provided. A detailed appraisal of the operational and maintenance costs can therefore not be carried out.

8 Discussion

8.1 Areas of uncertainty

- Limited explanation relating to the power supply arrangements for the SKA 1 may lead to delays in the operation of the SKA 1.
- Uncertainty relating to the future generation mix and capacity of centralised generation coupled with the lack of a schedule for the reinforcement of Western Power's 330 kV system may reduce confidence in the ability of the transmission system to be able to deliver the required power during the early operational stages of the SKA 2.

8.2 Risks associated with the design

The following points list the key risks associated with the design. A full risk register can be found in the appendices.

- A lack of redundancy in the 330 kV / 132 kV connection, transformer, 132 kV overhead line and 132 kV / 33 kV transformer may result in prolonged outages in the event of a severe fault.
- Lack of definition of the power supply to the super-computer makes a detailed assessment impossible.
- Harmonic filtering is not addressed.

8.3 Clarifications required

- Estimates of utility connection charges should be provided for the main site and super-computer.
- The rating and present load flow on the local 132 kV and 330 kV system should be provided to verify the capacity of the existing system and estimate the capacity following the implementation of the proposed reinforcements.

8.4 Subsequent work required

- Alternative charging methods to cover the capital costs of the 132 kV line and 132 kV / 33 kV substation should be investigated.
- An availability study should be carried out.

9 Conclusions

1. The proposed design for the core of the Australian site is based on a conventionally designed grid distribution system fed from a dedicated 330 kV connection. An alternative CCGT based option is outlined but not presented as a detailed design.

2. The remote sites are proposed to be fed from local diesel generators or distribution from the local grid, although it is unclear as to how many are proposed to be supplied from each option.

3. The overall design, subject to specific reservations below in this report, is conventional and appropriate and appears to offer reasonable availability at cost levels consistent with European experience.

4. The connection at 330 kV depends on other works which are not yet committed to by Western Power; implementation of these works could take around five years and any delay would risk delivery of power for SKA 2.

5. The design of the SKA distribution network is conventional and would offer reasonable levels of reliability within the distribution area. However the single connection at 330 kV and the long single circuit 132 kV connection to the SKA risk supply interruptions that may be extensive in case of line or transformer failure.

6. Detailed review of some features was not possible due to the of lack of detail in some areas of the Submission. These areas include the supplies to SKA 1 and the transition to SKA 2, the supply to the super-computer and some aspects of local generation for the remote sites. The absence of detail also curtailed checks of availability and costs.

7. The availability claimed for the design is high, with annual downtimes of the order of 12 hours across the system. Insufficient information is provided to check this quantitatively but the estimate appears reasonable, although concerns remain that breakdowns in the incoming power connection could cause infrequent but extended shutdowns.

8. Radio frequency interference from the power system is addressed by limiting overhead lines to areas more than 20 km from the array, inserting filters into MV distribution circuits and using shielded generators for the remote stations. These measures seem reasonable but would need detailed modelling and assessment.

9. Capital cost data provided in the Submission includes cost figures consistent with European experience for the transmission, distribution and local generation elements. However, some large cost items such as the connection of the super computer and the 330 kV / 132 kV substation are not detailed.

10. A comprehensive breakdown and evidence supporting the operational and maintenance costs is not provided. It has therefore not been possible to assess what components are included or omitted and whether the cost is reasonable. Great uncertainty therefore exists within the operational and maintenance cost estimate.

10 Appendix A – Abbreviations

ANZSKA	Australia and New Zeeland SKA
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
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
MRO	Murchison Radio Observatory
ms	millisecond
MV	Medium Voltage
MVA	Mega Volt-Amp
MW	Mega Watt
MWh	Mega Watt-hour
NOx	Nitrous Oxides
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
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**	**4.8**	**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**
FINAL Australia New Zealand SKA Coordination Committee - Electrical Power	Report Summary: Electrical Power	x	x	x		x																				
	Power transmission line option for central area of array, remote stations and supercomputer building		x	x			x	x	x	x	x	x		x	x											
	Power generation for central area of array, remote stations and supercomputer building		x	x		x		x	x	x		x		x	x		s	s		x						
	Schematic diagram showing power distribution network		x	x					x					x	x											
	RFI mitigation, lightning protection and other control and safety systems		x	x										x	x				x							
	Schedule of power provision roll out		x	x										x	x						x					
	Operations plan for 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																								
Report	**Section title**	**3.1**	**3.2**	**3.3**	**4.1**	**4.2**	**4.3**	**4.4**	**4.5**	**4.6**	**4.7**	**4.8**	**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**
	Regulations applicable to power network		x	x			x	x	x					x	x											
	Costs to the project for the provision and operation of the power network		x	x										x	x							x	x	x	x	x
Preliminary Design & Costings of Power Systems for SKA		x	x	x		x										x										
The Australian context for renewables development			x	x	x								x													
Electrical power diagrams			x	x			x	x	x	x		x		x	x		x	x								
Capital cost estimate methodology			x	x																		x	x	x	x	x
Risk output report for total project cost			x	x																		x	x	x	x	
2010 / 2011 Annual Planning Report *													x													

* Document produced by Western power and is publicly available. Not part of the Submission.

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
CCS technology is not developed and rolled out to replace existing coal fired stations that may be decommissioned due to age and / or emissions regulations	All	Low	Operation	Approximately 15 TWh (between 1.5 GW and 2 GW of installed capacity) that is planned to be supplied by CCS may be supplied by generation with higher emissions or may not be supplied at all, leading to load shedding.	High	Availability	Operation	Suggested option of supplying the SKA from a large CCGT station as an alternative to grid supply CCS operation is not planned to begin in Western Australia before 2030, by this time the technology and global market should be reasonably well established
Centralised generation development does not keep pace with the growth of large industrial loads including the SKA	All	Low	Operation	Potential for load shedding.	High	Availability	Operation	Suggested option of supplying the SKA from a large CCGT station as an alternative to grid supply
No other industry, e.g. mining within the vicinity of the SKA wishes to share the capital costs of supplying power to the area by local generation.	All	Medium	Pre construction	If grid supplies prove infeasible and the SKA site is supplied from a new CCGT power plant, the significant capital cost may be born solely by the SKA	High	CAPEX	Phase two construction	None
Operation of the telescopes are 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 2% of nominal
Construction works cause interference with the operation of the SKA 1 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 SKA 1 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 SKA 1 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
Operations centre power supply system design deficient	All	Low	Pre construction	Low availability or power quality	Medium	Quality	Operation	Should be clearly defined in bid. If unacceptable, revised design may be required resulting in increased CAPEX
Operations centre power supply system design deficient	All	Low	Pre construction	Low availability or power quality	Medium	CAPEX	Operation	Should be clearly defined in bid. If unacceptable, revised design may be required resulting in increased CAPEX
Super-computer power supply system design deficient	All	Low	Pre construction	Low availability or power quality	Medium	Quality	Operation	Should be clearly defined in bid. If unacceptable, revised design may be required resulting in increased CAPEX
Super-computer power supply system design deficient	All	Low	Pre construction	Low availability or power quality	Medium	CAPEX	Operation	Should be clearly defined in bid. If unacceptable, revised design may be required resulting in increased CAPEX
Existing overhead lines too close to array	All	Low	Pre construction	Excessive interference	High	Quality	Operation	Line routes not shown in bid. Antenna layouts may need to be revised or lines re-located 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	A 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	Quality	Operation	Assessment of voltage excursions should be carried out. Possible increased equipment or cable CAPEX

Trigger	Area of SKA	Probability	Period of trigger	Effect	Intensity	Type of effect	Period of effect	Consideration / Proposed mitigation
Insufficient resources to deliver roll out of all power infrastructure at 33 kV or lower at reasonable cost level in six months	All	High	Phase two construction	Start of operation of phase 2 delayed	Low	Delivery	Phase two construction	None
Delays to planning and approvals process for the 132 kV OHL and Moonyoonooka substation	All	Medium	Phase two construction	Start of operation of phase 2 delayed	Medium	Delivery	Phase two construction	None
Future variation of diesel price	Generation for mid or remote areas	Medium	Operation	Operational costs increased beyond current estimate due to increased diesel prices	Medium	OPEX	Operation	Assumed price of diesel and fuel flow are not clear from data presented
Small scale renewables for spiral arm and remote stations prove to be too expensive or are not developed to a commercial scale	Generation for mid or remote areas	Medium	Pre construction	Energy supply to the SKA from renewable sources remains low	Low	HSE	Operation	Investment from government in renewables development and evidence of a significant level of potential renewables sources across Australia
Small scale renewables for spiral arm and remote stations prove to be too expensive or are not developed to a commercial scale	Generation for mid or remote areas	Medium	Pre construction	Over reliance on diesel fuel	Low	OPEX	Operation	Investment from government in renewables development and evidence of a significant level of potential renewables sources across Australia
Insufficient levels of redundancy within the stand alone diesel generation systems	Generation for mid or remote areas	High	Pre construction	Frequent and / or prolonged loss of power to the spiral arm or remote stations due to maintenance or the forced outage of the diesel generator	Medium	Availability	Operation	None
Output of diesel generators for spiral arm clump stations of 250 kVA is insufficient to cover the load of 230 kW at 0.9 power factor and transmission losses	Generation for mid or remote areas	High	Pre construction	Diesel generators of increased capacity may be required in order to supply the load of each spiral arm clump station	Low	CAPEX	Phase two construction	None
Funding for extension of the MRO hybrid power station is not available	Generation for the core	Medium	Pre construction	Entire capital cost of the extension of the MRO hybrid power station born by the SKA	High	CAPEX	Phase one construction	None
Amount of solar energy provided by the MRO hybrid power station remains at 500 kW	Generation for the core	Medium	Pre construction	Energy supply to the SKA from renewable sources remains low	Low	HSE	Operation	None
Insufficient levels of redundancy within the hybrid power station	Generation for the core	High	Pre construction	Frequent and / or prolonged loss of power to the SKA 1 due to maintenance or the forced outage of all or part of the hybrid power station	High	Availability	Phase two construction	None
Western Power 330 kV system reinforcement not carried out as and when expected	Transmission for the core	Medium	Pre construction	Requires alternative source of power to be found for whole array	High	CAPEX	Pre construction	Discussions with Western Power required and possible development of alternative power source i.e. gas-fired power plant / renewables
330 kV / 132 kV transformer severe fault	Transmission for the core	Medium	Operation	Lengthy shutdown of power supply to whole array	High	Quality	Operation	Single 330 kV / 132 kV transformer assumed to be provided in Moonyoonooka substation (not specified in bid). Duplicate transformers should be provided.
132 kV incoming overhead line fault	Transmission for the core	High	Operation	Short shutdown of power supply to whole site	Low	Quality	Operation	Overall availability to be assessed at the bid stage to establish whether duplicate overhead line is justified
132 kV incoming overhead line too close to antennae	Transmission for the core	Low	Pre construction	Excessive interference	High	Quality	Operation	RFI philosophy is based on line being routed 50 km from any antenna but the line route has not been studied in detail at the bid stage. The route length may need to be increased, resulting in higher CAPEX.

Trigger	Area of SKA	Probability	Period of trigger	Effect	Intensity	Type of effect	Period of effect	Consideration / Proposed mitigation
132 kV / 33 kV 80 MVA transformer severe fault	Transmission for the core	Medium	Operation	Lengthy shutdown of power supply to whole array	High	Quality	Operation	Duplicate 50 MVA transformers offered as alternative, giving partial redundancy. Consideration to be given to this or 100% redundancy and appropriate costs included in estimate at bid stage.