THE SOLAR TOWER: LARGE-SCALE RENEWABLE ENERGY POWER STATION DEVELOPMENT

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1.0 Introduction – The Prototype

For many years Professor Jorg Schlaich and his team at Schlaich Bergermann und Partner (SBP) of Stuttgart, Germany, prominent European structural consulting engineers, have been vitally interested in large scale solar energy applications. In the late 1970's and early 1980's the team developed a detailed proposal for a Solar Tower, eventually gaining funding support for a prototype from the German Federal Ministry of Research and Technology (BMFT).

An experimental 50kW capacity pilot plant, illustrated below, was then built to SBP's design in Manzanares, Spain, some 50km south of Madrid, on a site provided by the Spanish utility Union Electrica Fenosa. The tower and collector, constructed of simple materials to minimise cost, was 195m high with a single vertical axis propeller turbine and a collector of 240m diameter. The plant was highly instrumented with more than 180 sensors to record system behaviour second by second. The pilot plant was in operation from 1982 with only the occasional shutdown for development modifications up to 1986. From mid-1986 to the beginning of 1989 when it was decommissioned it operated continuously for a period of 32 months at an availability exceeding 95 % (J.Schlaich, J.Kern 1995).

The Manzanares 50kW Solar Tower

Various collector materials were tested, the performance of the plant was closely monitored with results interpreted. In parallel with plant testing, SBP commenced numerical modelling of the thermodynamic behaviour of the generic Solar Tower. Calculation methods were confirmed by expert opinion (B.Gerwick (1995) and S Jansen, G.Rockendorf et al (1996)) and the simulation results verified on the basis of measured values from Manzanares. Taking account of all relevant physical plant parameters it is now possible accurately to computer model tower performance with capacities up to 300MW.

During the nineties worldwide commercial and scientific interest was shown in the technology and, with the acquisition of the licence in the late nineties by EnviroMission's founder, Roger Davey, who is also chair of SolarMission Technologies Inc., the story outlined in this paper had its origins.

2.0 EnviroMission Limited

2.1 Origins of the Company

EnviroMission Limited was formed in July 2000. Formally majority owned by SolarMission Technologies Inc., (US), EnviroMission merged with Perth based Prudential West Limited to become a majority Australian owned company, listing successfully on the Australian Stock Exchange in August 2001 - ASX code EVM. EnviroMission's structure and progress can be found on the company's website at www.enviromission.com.au

2.2 The Solar Tower Licence

EVM is developer of the exclusive Australian licence to Solar Tower technology. German designer of the concept, Professor Jorg Schlaich and his firm, Schlaich Bergermann und Partner, continue to be involved as design engineers to EnviroMission. Further details of SBP and examples of their work can be found at www.sbp.de

Nearly US$40M has been invested to date to develop and prove the technology through research and development, pilot plant operations and feasibility studies for commercial plant construction. An independent technical review was undertaken prior to the ASX float by leading Australian engineering consultants, Sinclair Knight Merz. SKM confirmed that the proposed solar thermal power station design concepts and construction methods are adequately proven and the plant could be built in Australia.

2.3 Management and Staff

Melbourne based EVM has a small operations team responsible for day to day company management and development, facilitation and input into the design and engineering development, marketing and commercial management, site selection and negotiation, public relations and company secretarial and administrative management.

2.4 Consultants and Government support

Apart from ongoing design input from EVM's lead design consultants, SBP, selective use is made of specialist Australian and international consultants where additional resources, specialist expertise or local knowledge is needed. A number of consultancies have been commissioned and, while findings must remain commercial in confidence, they have been drawn upon to support this paper.

EVM has actively sought and continues to seek government support that in time will also include funding assistance at State and Federal levels to ensure the commercial prospects of the development.

In other areas of Federal, State and Local Government support the interest shown and assistance offered has been most encouraging and is an essential requirement for eventual success. In all negotiations with the three levels of Government EVM has maintained scrupulous openness about the status of design, expectations of performance and costs and the anticipated impacts on the communities involved. EVM is preparing for the necessary environmental impact assessment procedures before project construction can proceed.

2.5 Business Collaborators

As the Solar Tower project has progressed, EVM has sought the involvement of business collaborators who can contribute to project viability and credibility. Key project collaborators and the arrangements into which EVM has entered are described below.

Leighton Contractors

As announced to the Australian Stock Exchange in November 2002, EnviroMission entered into Heads of Agreement with Australia's largest infrastructure developer, Leighton Contractors Pty. Ltd., together with technology provider SolarMission Technologies Inc. to pursue jointly profitable large scale renewable energy power stations for the Australian and international electricity markets. This partnership, with a number of supporting consultants and prospective specialist suppliers, has added significantly to the management, contracting and engineering skills available for commercial realisation of the project.

With Leighton involved in the major issues of project development, both technological and commercial, a number of specialist consultants and prospective suppliers have further been attracted to contribute professional expertise. Laing O'Rourke, for example, is providing advice on the tower structure and its optimal configuration. GE Plastics is providing design input on the collector. GE Turbines and TLT of Germany are providing input on the blading and turbine generator design. Schlaich Bergermann und Partner continue to provide ongoing engineering input. A number of other specialist suppliers and prospective contractors are also assisting the Leighton – EVM Joint Venture in project development.

Results to date are singularly encouraging. Several significant detail design and constructability improvements have been made or are still being evaluated; all of which continue to enhance project economics. Leighton has confirmed that the design can be built and with successful completion of the pre-feasibility study the project is now advancing through the detailed financial modelling and project financing stage of development.

Australian Gas Light Electricity (AGLE) Limited

After negotiations with a wide range of retailers throughout 2002 and early 2003, EnviroMission signed a Memorandum of Understanding with Australian Gas Light Electricity (AGLE) Ltd in June 2003. The MoU provides for AGLE's exclusive arrangements to take up 100% of the green energy and Renewable Energy Certificates generated by the project.

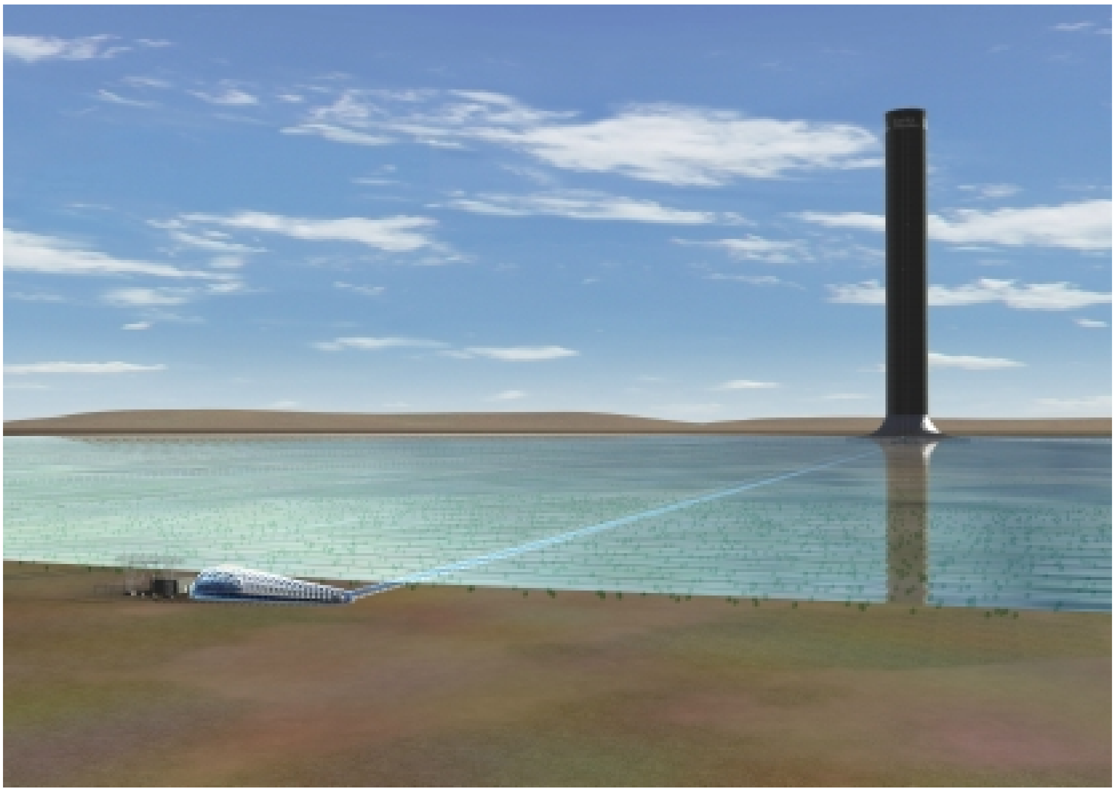
3.0 Solar Tower Design – From Concept to Optimisation

3.1 Technology Principles

The technology is characterised by a combination of three physical principles, namely the greenhouse effect, the chimney up-draught effect (natural buoyancy) and the pressure stage turbines. The air underneath a circular translucent roof open around the periphery forms a hot air collector where air is heated by incident solar radiation. In the middle of the translucent structure is a tall tower that resembles a chimney.

Due to the density difference between the warm air in the tower and the colder ambient air, the warmer lighter air column rises up the inside of the tower. At the same time, the tower draught draws in warm air from the collector, while colder ambient air flows into the collector outer periphery. Thus the incident solar radiation produces a continuous updraught in the tower. Moreover the ground below the collector absorbs solar energy during the day which is released at night, so that the rising air column is continuous. This wind energy will drive 32, 6.25MW pressure staged turbines located around the base of the tower and the resulting mechanical energy is converted in a conventional generator into electric energy.

The tower will be around 1000m tall making it the tallest engineered structure in the world. The translucent collector roof has been optimised up to 3500m in radius and will be one of the largest covered areas ever constructed. The artist's impression below shows a conceptualisation of an operational Solar Tower power station.

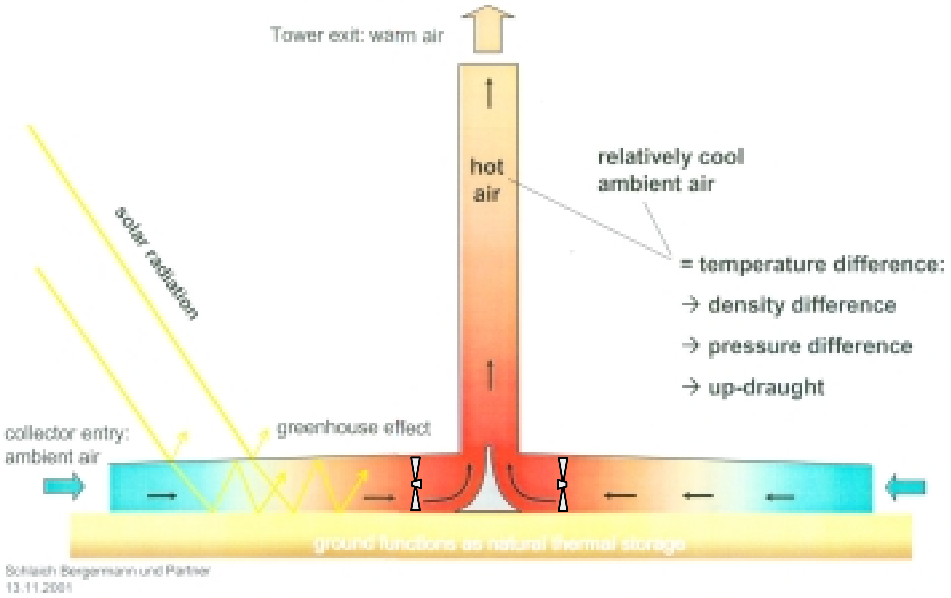


Solar Tower Power Station Conceptualisation

The 200MW generating plant can be connected into the electricity grid like any other form of energy generation, with the advantage noted that some power can be generated at night in off-peak periods from re-radiated heat stored in the ground during the day. Storage capacity can be further increased, should it prove economic to further modify or flatten the power curve, by adding thermal storage under the collector.

The pressure staged turbine generators will be mounted horizontally around the air inlets at the base of the tower. Operation is as encased pressure staged turbines rather than free-running open wind turbine generators with airflow more consistent and at higher velocity. Electrical output is up to eight times that of an equivalent diameter open wind generator. Blade pitch can be adjusted to regulate power output.

The Solar Tower can simplistically be likened to an inverted hydroelectric plant. The sun is analogous to rain (except it is more regular), the collector and ground storage analogous to water, the tower analogous to the penstock and the turbines broadly similar to hydroelectric machines with air as the working fluid. The diagram on the page following illustrates the broad working principles and the station successfully operates even on cloudy days.



Solar Tower Working Principles

The leading dimensions of the Sunraysia Project, following optimisation, are set out below.

Solar Tower power plant rated capacity	200 MWe
Tower height	1000 metres
Tower internal diameter (constant over full height)	120 metres
Collector diameter	7000 metres (inclusive of tower)
Number and configuration of turbine generators	32 units horizontally mounted
Maximum continuous rating (MCR) of each turbine	6.25 MWe
Plant land usage (footprint)	3,800 hectares

3.2 Tower

Design analysis

The tower is a 1000m tall thin concrete shell of 120m internal diameter. It is based on a slab foundation and promises to be the highest structure ever built. Wall thickness at the top is expected to be around 30cm, dictated by construction requirements, increasing exponentially to around 1.1m at the bottom. The first 80m of the tower comprise 32 radial support buttresses arranged circumferentially, between each of which is a single turbine exhaust duct.

This represents a huge design and construction challenge that has required exacting studies especially with respect to wind loadings. The tower shell has been analysed by linear elastic analyses, buckling analyses, non-linear analyses and dynamic analyses. The complete non-linear calculation includes geometrical and physical non-linear effects for the limit state.

The size and design of the slab foundation and the complex structural base of the tower is not only dependent on the wind loads but on the soil properties of the selected site that has been found to be geotechnically appropriate.

Load assumptions

The main tower induced loads are self-weight and wind. However temperature loads and construction imperfections may contribute to induced stress and have all been carefully studied. Earthquake loads are not however expected to govern the selected site. The lesser effects of creep and shrinkage, differential settlement, construction and maintenance loads and possibly catastrophic loads (eg aircraft impact) have been included in analysis.

Wind loadings

Wind loads are based on Australian standards and have been carried out preliminary wind tunnel tests. The optimised design will be validated using Australian wind tunnel facilities. Design data including hourly mean wind speeds, hourly mean wind pressures, turbulence intensity, wind gust amplification factors, circumferential pressure distribution for different heights, global analysis of the cantilever, drag coefficients, wind induced dynamic transverse response factors and the dynamic ovalling response (vortex shedding) has been evaluated to ensure an inherently stable structure.

Temperature

The Bureau of Meteorology has calculated temperature loadings from actual measurements at Mildura over 4-6 years. Since these cover typical rather than extreme years, they cannot be used directly for the limit state design. However they provide an acceptable basis for preliminary design. From the measurement of daily air temperatures and simulation of plant operation the maximum design values for the Tapio site have been determined.

Earthquake

In the Mildura region the maximum horizontal earthquake tower loads are only one eighth of those from wind, based on Australian codes. Earthquake resistance is thus well covered by other more dominant design criteria, especially wind, although the loads are additive.

3.3 Collector

Design

The collector is essentially a very large circular greenhouse with a radius of 3500m designed to maximise the absorption and minimise the re-radiation of incident solar energy.

The collector is open for the entry of ambient air at the periphery where the translucent surface is some 3.5m above the ground. At this point the air velocity is low and the air under the collector has adequate time to heat up by about 14°C on average, although the maximum temperature rise has been calculated at up to 46°C. The maximum design collector exit temperature at the turbine generators, where the roof rises to around 25m as it joins the tower, is calculated at 73°C and around 83°C at the tower base. The minimum is around 5°C, giving the range for which exposed plant must be designed. The air temperature falls progressively up the tower due to expansion, not thermal loss through the walls.

Testing at the Manzanares pilot plant in the late 1980's showed that glass roofing supported by a light weight steel structure would prove to be a durable and economic solution in the cost benefit terms of the time. Part of the Manzanares experimental work trials were conducted on a wide range of collector and support materials, including glass and a variety of synthetic plastic film materials. The latter, have since been developed to the point of being sufficiently robust for the long term collector application.

In terms of cost versus durability and optical properties, such as IR-reflection and light transmission, tempered glass is still preferred for the inner perimeter. Recent advances in polycarbonates and polymer materials that also require lighter support systems are proving an attractive technical and economic alternative for the outer collector perimeter.

Design issues which impact on collector material economics at all radii include physical strength, transportability, storageability, ease of erection, fastening details, drainage arrangements, hail resistance, cleanability, joint air tightness, erection safety and handling and price. The areas to be covered are so vast that the materials required will require special manufacturing arrangements to the supply chain.

Materials

It is likely the inner collector surfaces will use conventional annealed glass. Advantages are that the bearing capacity is some four times that of float glass with higher hail resistance. Toughened glass would suffer less breakage during transport and erection.

More recent optimisation and performance analysis of newer synthetic sheetings has suggested that the optimal design for the first plant will be a materials hybrid, with glass closer to the inner collector ring where temperatures are high and heat retention is paramount. In the outer sections of the collector air temperatures, although well above ambient, are not high enough to warrant the much higher cost of low 'E' glazing. This huge is proposed to use synthetic polymer film with thermal and UV performance properties. A variety of materials have been evaluated with consulting manufacturers.

3.4 Turbine generators

The 32 shrouded axial turbines proposed for the 200MWe Solar Tower have yet to be produced commercially. International suppliers working with Leighton are developing customised designs. The advantages claimed for shrouded turbines are greater power output for a given rotor diameter (up to 8 times with double the on-blade air velocity) and higher efficiency (up to 80% compared with 20% to a maximum of 30% for conventional open wind turbines). Computational fluid dynamics (CFD) modelling techniques are being used and SBP predict eventual efficiencies up to 85%.

Individual turbine peak ratings of 6.25MWe would meet the 200MWe plant design output. However performance predictions show that in prolonged and very hot conditions the energy available may exceed peak generator capacity for 3 months of the year. Accordingly, to avoid spillage of the most valuable energy, given that prolonged high level insolation is likely to coincide with peak system demand due to air conditioning, consideration is being given to increasing generator short term peak ratings, possibly to a nominal 10MWe.

Temperature at the tower base is normally around 60°C to over 80°C. Current design envisages open ventilation of the generator with ambient cooling air being drawn from outside, ie air/water cooled generators. In climates hotter than the Sunraysia region such cooling may not be sufficient and alternative cooling systems may need to be considered.

The generators proposed are 11kV synchronous machines with either static or brushless excitation. Static has a better response although response time variation is unlikely to be an issue. However there may be a need to provide sustained fault current due to network protection requirements. In this case a separately excited brushless system may be needed.

Synchronising to the grid will most likely be at grid voltage to reduce costs, particularly as generator auxiliaries will be minimal. Depending on the final electrical system arrangement synchronising at a generator circuit breaker (11kV) remains the most likely option.

Wind velocity over the turbine blading cross section will range between approximately 4m/s and 18 m/s with the highest frequency between 7m/s and 10m/s. The 32 horizontal axis turbines are arranged radially outside the tower support walls, equally spaced and concentric. This arrangement makes it easier to optimise machine layout with tower base design, while using machines which can be manufactured, transported to site, erected and maintained.

3.5 Electrical Services

Grid connection

The proposed Tapio Station site lies to the north east of Mildura. The two closest bulk electricity supply points are Buronga in NSW at a distance of 8km and Red Cliffs in Victoria on the outskirts of Mildura at a distance of 29km. Connection options have been evaluated.

Generator connection

Grid connection of the 32 Solar Tower generators will require step up transformers with on load tap changing facilities to meet voltage regulation and reactive power requirements. At the 10MWe peak rating the generators can be connected through the 11kV station busbars.

Grid connection will comply with the National Electricity Code (NECA), the local Transmission Network Service Provider (TNSP) or Distribution Network Service Provider (DNSP) requirements and all applicable local codes and standards. For the Buronga site these are TransGrid and Australian Inland respectively. Preliminary system load flow, fault level and stability studies have determined design parameters for the generator/generator transformer and related grid system modifications.

The control system will be simple and no unusual risks are foreseen. It will comply with NECA requirements for remote control and monitoring to enable the generators to participate in the National Electricity Market (NEM).

3.6 Balance of plant services and infrastructure

Construction power

Australian Inland, the regional power utility, has been advised of EVM’s plans to build on a site over which low voltage power lines currently pass. AI is evaluating line relocation and the provision of construction and standby power.

Water

EnviroMission is working with the Wentworth Shire Council, the NSW Department of Land and Water Conservation and Western Murray Irrigation to identify sources of fresh and saline water supplies for the construction and ongoing needs of the project, especially fire protection. Some 200kl/d of water will be required during plant construction.

Road access

Access is via Arumpo Road, starting at the Silver City Highway at Buronga and running through the project site. The road will be upgraded to take the anticipated construction traffic and a portion re-located around the collector perimeter and sealed to minimise dust. Pooncarie Road around the site from the Arumpo Road intersection will also be re-located.

Telecommunications

Telstra has indicated that no telecommunication service lines or cables run through the site.

4.0 Site Selection

4.1 Locational factors

The adequacy of solar radiation and proximity of power transmission infrastructure generally govern Solar Tower location. The following siting criteria were established:

- Classified as non-cyclonic located in a region with a low design wind speed as defined by Australian Standard AS1170-2,
- Preferably non-seismic in a reasonably low risk area with an acceleration coefficient of about 0.05 as defined by Australian Standard AS1170-4,
- Ideally with underlying rock strata for economic tower foundation design and adequate bearing safety and stability, and
- Not subject to excessive precipitation as hail or desert sandstorms.

4.2 Selected site

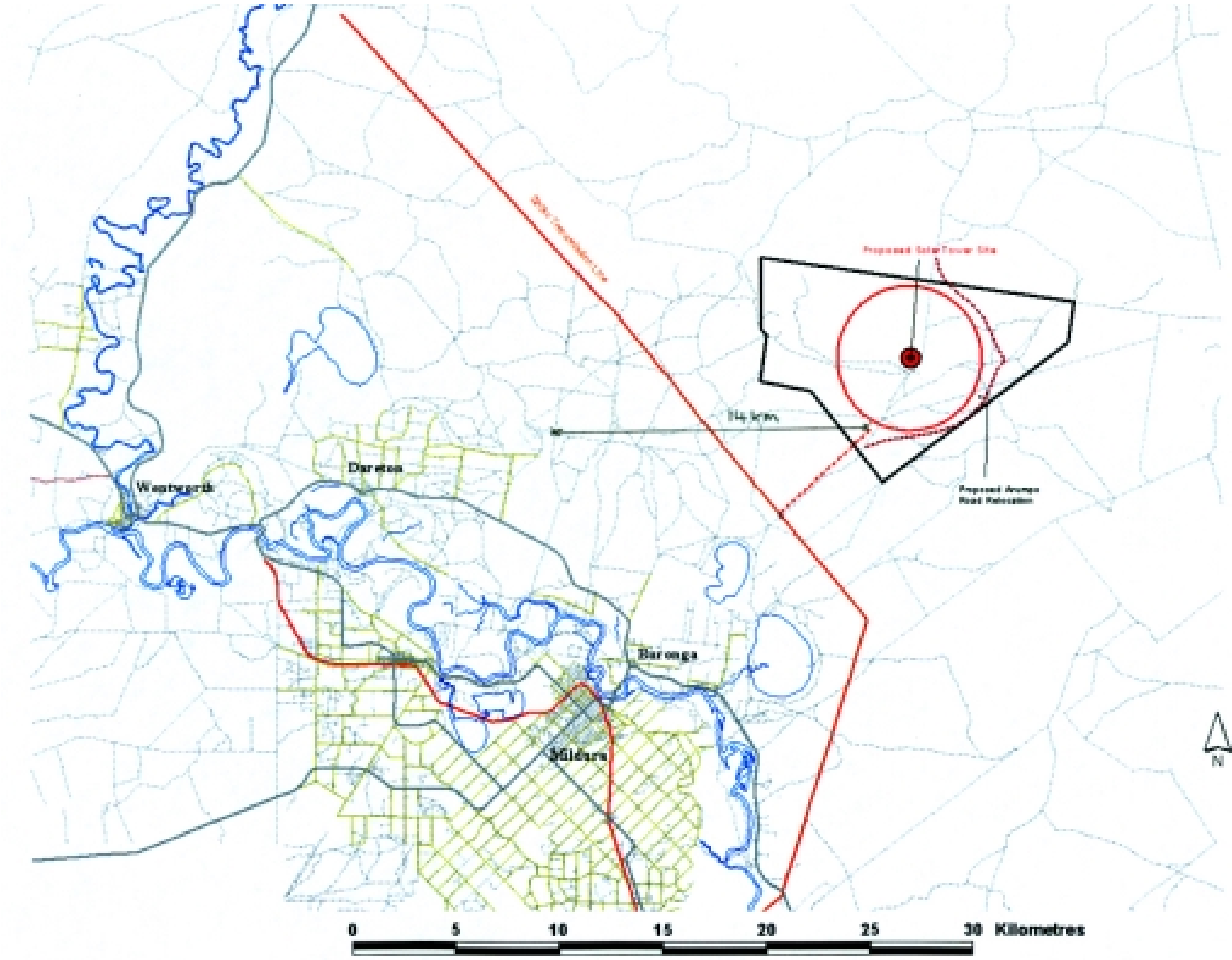
EVM assessed potential sites in Victoria, New South Wales, Western Australia, South Australia and Queensland. Of these Tapio Station at Buronga was considered financially and technically viable for Australia's first Solar Tower.

The Buronga site north east of Mildura is just inside New South Wales and north of the Murray River. It is some 20km from the town of Buronga at the intersection of the Arumpo and Pooncarie Roads. It comprises an area approximately 10,000 ha on the south east of the Tapio lease. The advantages of the site include:

- A moderate to high level of solar radiation of around 2,000 $kWh/m^2/a$,
- Close to suitable National Electricity Grid HV connection point resulting in lower capital costs and reduced line losses,
- Close to proposed HV transmission line to South Australia,
- Close to existing infrastructure including road, rail and nearby township facilities with quality accommodation,
- Close to suitable aggregate sources and concrete making facilities,
- Potential to support non-energy businesses including tourism, agriculture, aquaculture, telecommunications, etc, and
- Potential to contribute to salinity mitigation and possible salt recovery.

The site is close to the Victorian, NSW and South Australian borders enabling dispatch of green electricity into any one or all three states.

EVM's exercised its option to purchase the site in June 2004 subject to rezoning and planning requirements being met including a change of purpose of the Western Lands lease and approval from the various NSW Statutory and Government bodies.



Buronga Site – Wentworth Shire, NSW

Environmental Considerations

The actual Solar Tower requires around 3,850 ha, enabling the remaining land to be used as a sustainable development precinct including a nature reserve. The land is mainly cleared and used for wheat although around 1,000 ha will require clearing.

While a tower 1,000 m high can be seen up to 80 km away on flat ground, from Mildura or Buronga it would appear the same height as a tree on the horizon from the main street of Mildura.

4.4 Job creation

Plant construction

Up to 1,200 construction jobs will be created over 3 years. The peak is expected between months 12 and 18 with a base force averaging nearly 1,000 over the full period.

Plant and associated businesses

Some 50 employees are estimated for early operation following commissioning, reducing as the plant settles into routine operation. However jobs will be created locally in tourism and agribusiness. Multiplier effects will arise through additional tourists travelling, staying, eating and visiting other tourist attractions. The tower will be a significant regional icon.

4.5 Other site location issues

Aviation

The Civil Aviation Safety Authority (CASA) and Mildura Airport have formally advised EVM there is no objection to the tower subject to appropriate hazard and warning lighting.

Native Title

The NSW Premiers Department is considering this issue. EVM will undertake the recommended course of action to resolve issues to the satisfaction to all involved. Appropriate cultural exhibitions will be included in the interpretive Visitors Centre.

5.0 Performance Parameters

5.1 Optimisation – performance forecasts

Based on consultants' reports, revenue streams are confirmed from tourism, agribusiness, and naming rights. With its combined revenue streams (energy and non-energy) the project is expected to be economically attractive.

5.2 Renewable Energy Market

The market for renewable energy in Australia will grow in response to the 9,500 GWh/a mandated renewable energy target (MRET), currently under expert review. The Government introduced MRET prior to the 1997 Kyoto conference, the objectives being to focus on the reduction of greenhouse gases and promote Australia's renewable energy industry.

The dominant near term renewable energy driver in Australia will be MRET and associated Renewable Energy Certificates (RECs). The MRET does not discriminate between eligible technologies and resources; the determination being cost. Redding Energy Management reported to the Australian Greenhouse Office (AGO) in December 1998 on relative technology costs. The Solar Tower compares well with other large-scale options.

Growing environmental consciousness has contributed to the emerging market for clean green renewable energy from sources such as the sun, wind, rain and tides. Where the source use produces zero emissions the energy is also truly "clean". The Solar Tower produces both "clean" and "green" energy on a very large scale. The Sunraysia project is estimated to save over 700,000 t/a of greenhouse gases from entering the atmosphere based on avoided brown coal generation. A single Solar Tower power station will generate nearly 7% of the MRET for 2010.

5.3 Other income streams

In addition to green energy a number of other profitable businesses will be incorporated in the project. EnviroMission has undertaken scoping studies to evaluate the broad economic potential of businesses including agribusiness, tourism, telecommunications, naming rights and potential salinity mitigation and associated commercial salt harvesting. Each would bring multiplier effects to regional businesses.

Tourism

Additional project income generation will arise from on-site tours, which it is hoped will include an ascent by lift to the tower summit and inspections of the plant control centre and proposed interpretive Visitors Centre. Significant regional income will also accrue from the estimated 80,000 additional tourists expected in the region. Some 15 tourism related jobs are expected at the tower itself, while related tourist opportunities, mainly accommodation, meals and transport, will arise in the regional communities.

Telecommunications

A study into communications potential has identified the value of high level aerials mounted on the tower for radio, television, mobile telephones, SCADA and radio emergency services.

Agriculture and aquaculture

The periphery of the collector (up to 600m) lends itself to protected high value agriculture. This prospect became evident when it was noted how well weeds and unwanted vegetation grew beneath the Manzanares collector, unlike the seemingly barren soil outside. In this region the wind velocity is gentle, temperature rise is modest, but greenhouse style protection and sheltered access to crops is provided. While no specific aquaculture studies have been undertaken the potential is to be explored.

Salinity credits and salt production

Potential for the productive earning of proposed salinity credits has been considered by EVM through a consultant's report. The topography of the Tapio site, the huge accumulation of near surface saline aquifers and the possible application of thermal storage enhancement all support further examination of groundwater salinity reduction and possible commercial salt production.

Carbon trading

Whilst the carbon trading market is still evolving and is not yet formally ratified in Australia, international indicators suggest added value to the project economics.

6.0 Conclusion – The Next Steps

EnviroMission, together with its business collaborators, investors and management team has progressed development closer towards commerciality in one of the most challenging energy markets. EVM, Leighton and their consultants have staunchly pursued, and will continue to pursue, a path of meticulous engineering analysis and scrupulous disclosure.

To conclude with the words of the great German poet Goethe:

> ***"Whatever you can do, or dream you can do, begin it. Boldness has genius, power and magic in it."***

7.0 Acknowledgments

The authors accept responsibility for the material selected and views expressed. They would particularly mention reliance on sources, some publicly available, from which information has been drawn, a number of which are cited below. Authors include Schlaich Bergermann und Partner; Sinclair Knight Merz; Graham Redding of Redding Energy Management and others. Confidential SBP and EVM internal documents are not cited but have also provided valuable insights and information.

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