Pre-Feasibility Study for the Establishment of a
Pre-Commercial Concentrated Solar Power Plant in Namibia

Presentation of the First Draft for final version

June 2012

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CSP TECHNOLOGY OVERVIEW

NAMIBIA SOLAR RESOURCE AND DNI ANALYSIS

ENVIRONMENTAL ANALYSIS AND SITE SELECTION

TOP 5 SITES SELECTION AND FINANCIAL ANALYSIS

GROUND MEASUREMENTS

CSP DEVELOPMENT AND IMPLICATIONS FOR NAMIBIA

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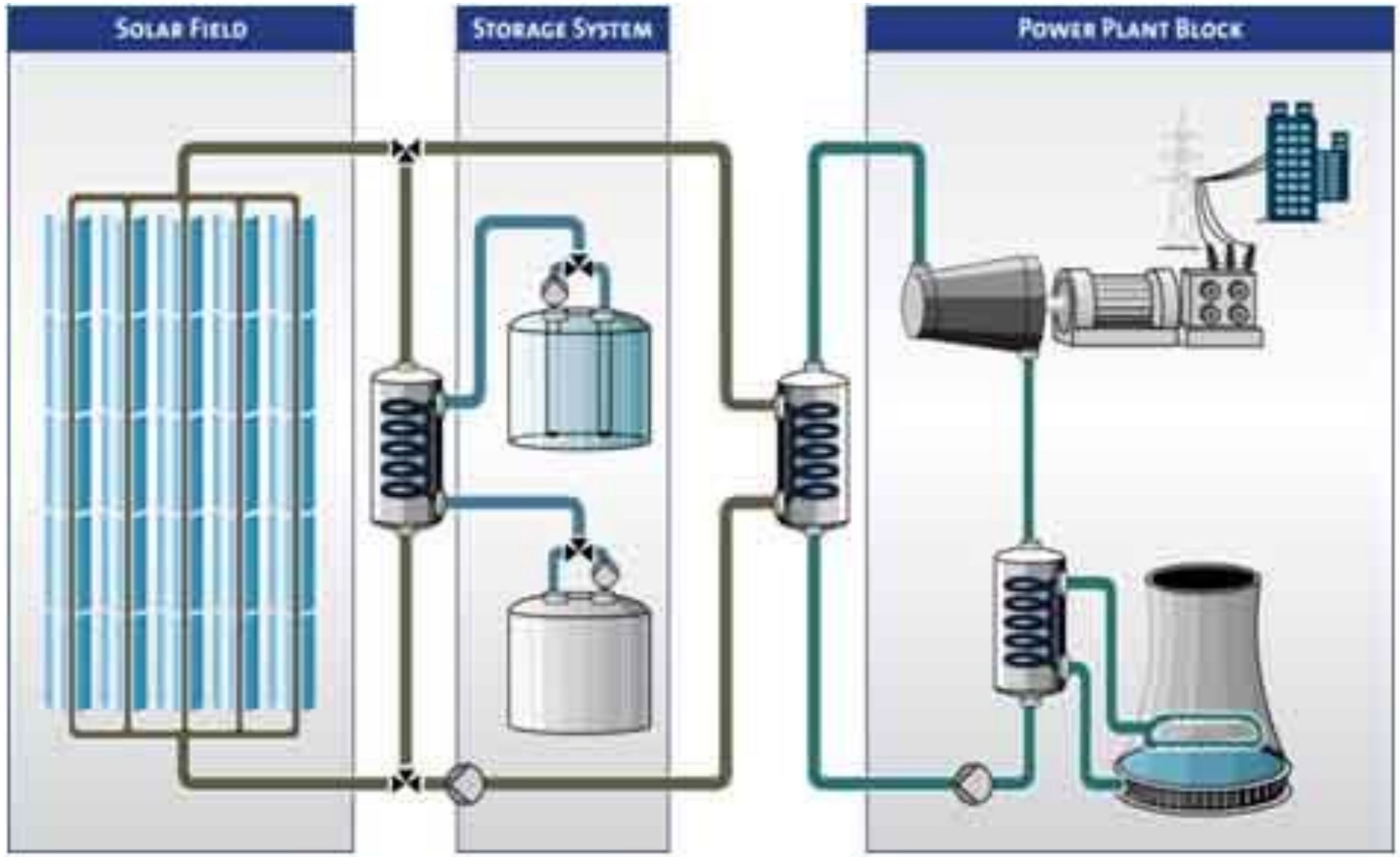
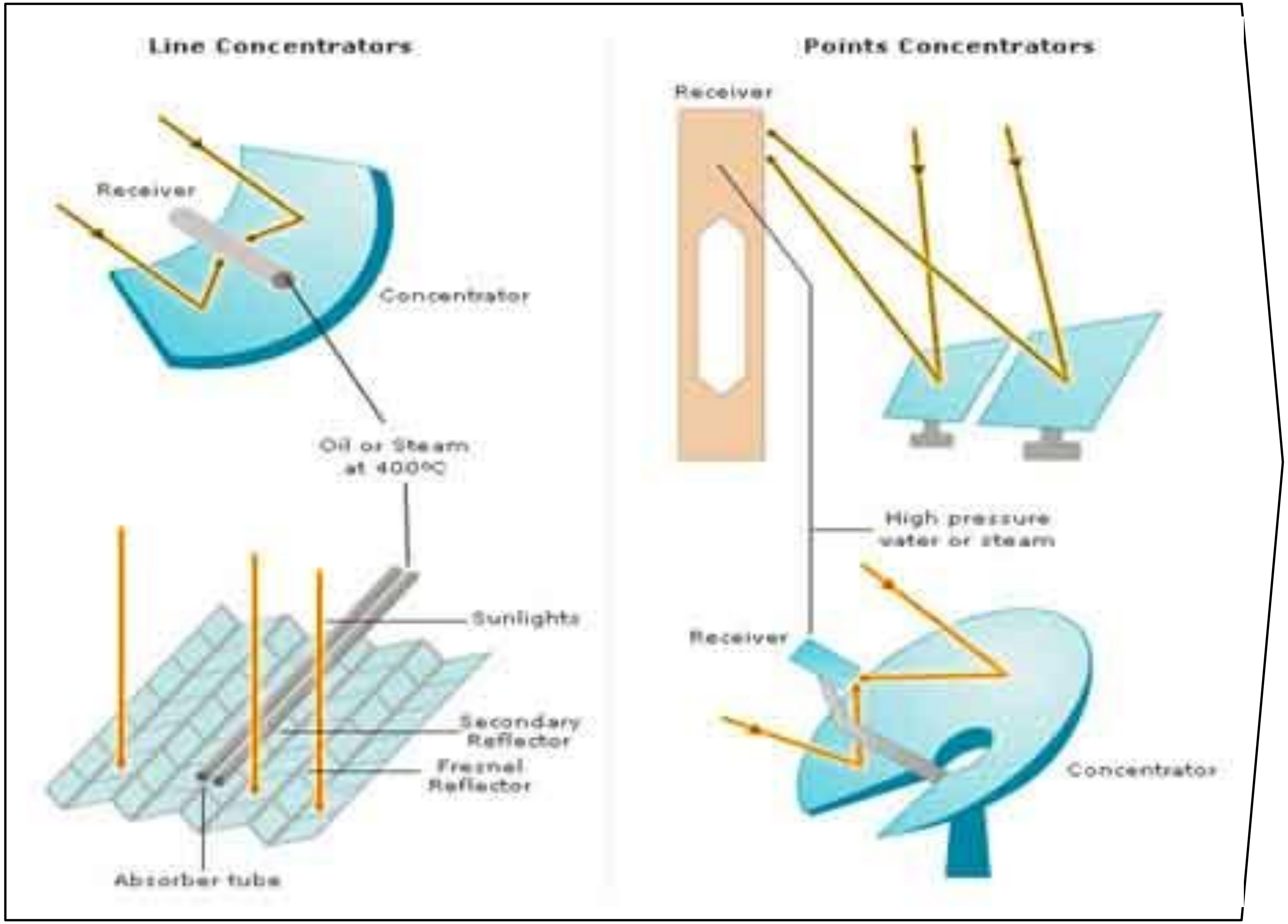
CSP Technology Review – Introduction and technology outline



A typical CSP solar plant

- Solar field
- Heat transfer fluid system and heat exchangers
- Optional back-up parallel boiler or storage system
- Steam cycle feeding into the turbine
- Power block and ancillary wet/dry condenser, deaerator, feedwater and pumps
- Grid connection

CSP Technology Review – Introduction and technology outline



Main types

- Linear focus systems (Parabolic troughs and linear Fresnel reflector systems)
- Point focus systems (towers and dish systems)

CSP Advantages

- Easy and cost effective implementation of thermal storage
- Easy combination with combustion fuels (hybridization)
- Slower response to short-term fluctuations of solar irradiation (thermal inertia)
- Other applications: solar cooling, process heat, seawater desalination

CSP Technology Review – Parabolic troughs

The operating principle of a parabolic trough power plant :

- Parabolic mirrors track the sun about one axis, usually north-south, and focus its rays, with typical concentration factors of 70-80, onto linear, specially coated, heat collecting elements (**HCE**).
- HCE are coated steel pipes with a surrounding evacuated glass tube that minimizes heat losses
- Heat transfer fluid (**HTF**) is circulated through the HCEs to carry the heat from the solar field to the power block.
- Superheated steam is used to run the turbine.
- The plant includes conventional sub-systems – the power block steam turbine and generator, wet cooling towers or dry air cooled condensers, feedwater pumps and deaerator for the steam cycle and a steam drum.
- Optional storage and/or auxiliary gas burners can be used to cover transient weather conditions and for production during night time or to protect the HTF against freezing.

CSP Technology Review – Linear Fresnel Reflectors

- Can reach solar concentrations of 30 – 100 suns
- Open the possibility of using simple, non-industry specific, commodity materials
- Use flat rather than curved mirrors, low profile construction, leading to rapid on-site assembly.
- rotating reflectors
- non-evacuated standard steel tubes protected by plain glass sheets.
- Special evacuated tubes in some solutions

- Collector frame structures are fixed in place, dispensing with high temperature moving joints and implement direct steam generation (DSG i.e. water as HTF) in the receivers

CSP Technology Review – Power towers (or central receiver)

- The collecting optics are called heliostats
- Individual 2-axis sun tracking heliostats concentrate direct beam sunlight onto an absorber, called receiver, which is fixed atop a tower.
- Possible to have thermal energy storage system and/or a fossil fuel firing system to enable round-the-clock operation of the plant if required.
- Possibility of very high solar concentration ratios of up to 1000 suns

- Allowing for very high HTF operating temperatures (565 to 1000°C), depending on which technology is used
- Enormous potential for achieving the highest Carnot efficiencies among the CSP thermal power plants

CSP Technology Review – Dish Stirling

- Relatively small power generation systems when compared with other CSP technologies
- Power ratings are between 3 to 25 KW though recently larger systems are being attempted
- The system is a stand-alone, which tracks the sun in two axes and concentrates the direct solar irradiation onto a receiver - the focal point of the paraboloid reflector or dish - where an engine using a Stirling cycle converts heat into mechanical energy through a piston engine, which in turn is transformed into electricity
- Highest peak conversion efficiencies among solar tecnologies of above 30% solar to electricity and a daily average of up to 25 %, however
- High concentration ratios up to 3000x and high working temperatures of above 750ºC

- Requires a relatively "cold side" which is the case in some cold deserts with clear skies

CSP Technology Review – Projects

• SEGS I-IX, parabolic troughs, California, USA (completed 1981-1990), 354 MW
The SEGS (Solar Electricity Generating System) plants in California were the first commercial CSP plants in the world. The largest plants have a capacity of 80 MW.

• Liddel coal power plant boosting, Linear Fresnel Reflectors, Australia (June 2004), 1 MWth
First coal augmentation LFR solar power plant

• PS10, Power tower, Seville, Spain (2006), 11 MW
First commercial power tower power plant to be online in the world

•Nevada Solar One, Parabolic troughs, USA (completed 2007), 64 MW
This plant was the first parabolic trough plant to be built almost two decades after the SEGS systems.

• Andasol 1, Parabolic troughs, Andalusia, Spain (completed 2008), 50 MW
Andasol 1 was the first commercial CSP plant in Europe and the first one with a large storage for 8 hours of full load operation without sun.

• Maricopa, Stirling engines, Arizona, USA (March 2010, 1,5 MW
First Stirling dishes based CSP power plant

• Gemasolar, Power towers, Andalusia, Spain (May 2011), 19,9 MW
First Power tower to use direct molten salts and first CSP power plant to do base load generation

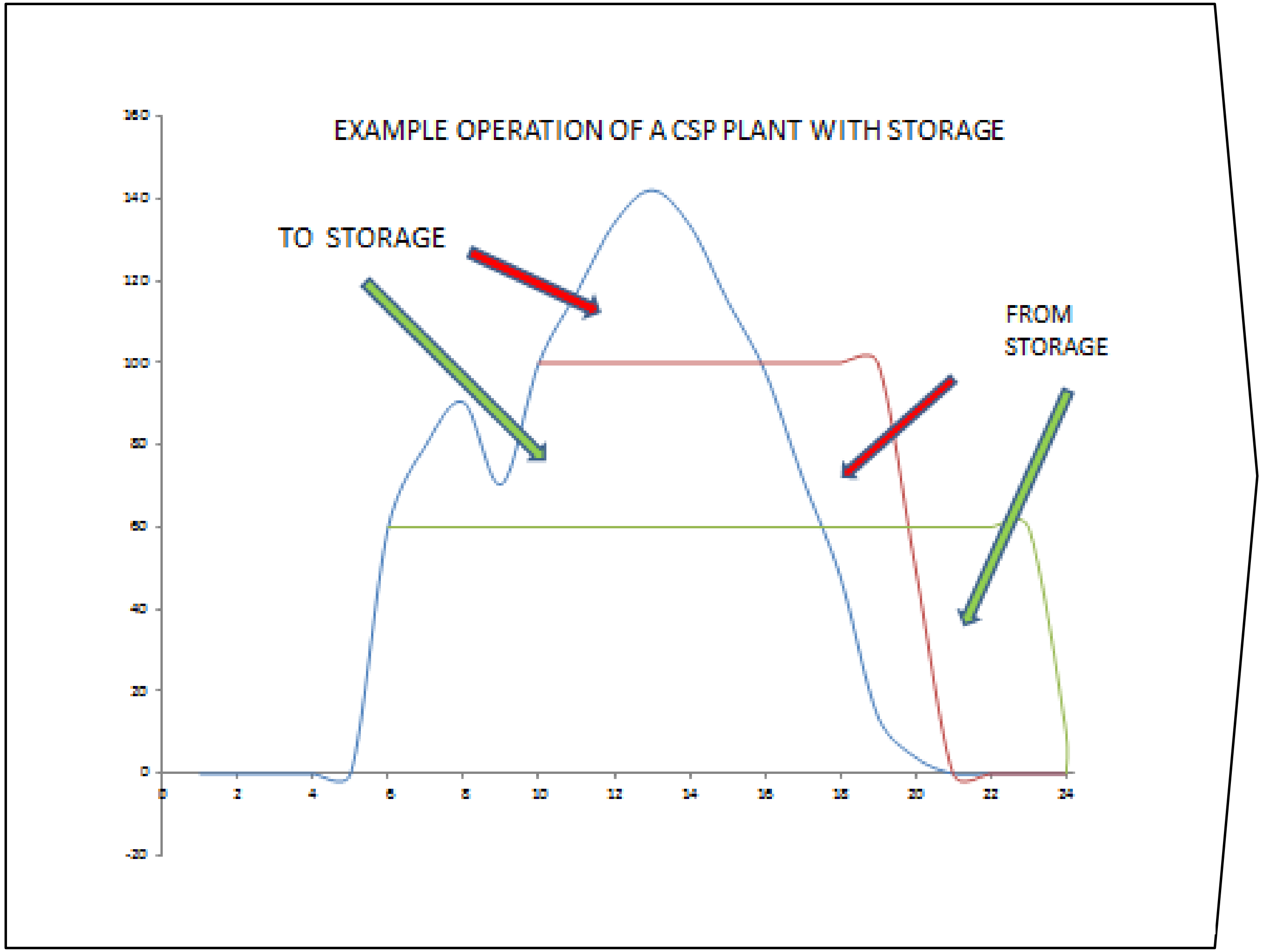
• ISCC Morocco, Ain Beni Mathar, Morocco (completed 2011), 470 MW (20 MW solar)
First large scale ISCC power plant, where waste heat from a gas fired turbine is combined with heat from a solar field to drive a steam turbine.

• Puerto Errado II, Linear Fresnel reflectors, Spain, (completed March 2012), 30 MW
First large scale LFR power plant with direct steam generation in the world

CSP Technology Review – Storage

- If the solar field size can provide more than the heat needed to drive the power block at maximum rating (solar multiple greater than 1), by selecting an operating point for the power block at 100% of its rating, or say 60% of its rating, electricity production can be maintained for a number of hours beyond sunset or through into the evening.

- Solar multiples for CSP plants with storage are typically greater than 2.



- This allows extended operation and eventually, 24/7 operation of the power plant. CSP plant may be operated as peaking plant or as base load power plant.

CSP Technology Review – Storage

Storage

Molten salts

60% sodium nitrate, 40% potassium nitrate Indirect two tank molten salt storage system, direct two tank storage system. In the latter, the molten salt acts as both heat transfer fluid and storage medium, while in the former molten salts are only used as storage medium. Single-tank molten salt system is being developed, using thermocline or sharp vertical temperature transition from cold to hot.

Ceramic with air as heat transfer fluid

It combines the use of a gas as the heat transfer fluid and a ceramic material for heat storage at these temperatures. The hot gas, specifically air, is blown through an insulated bed of ceramic materials (silicate sand or aluminosilicate ceramic bricks have been used)

Pipes in solid media + PCM

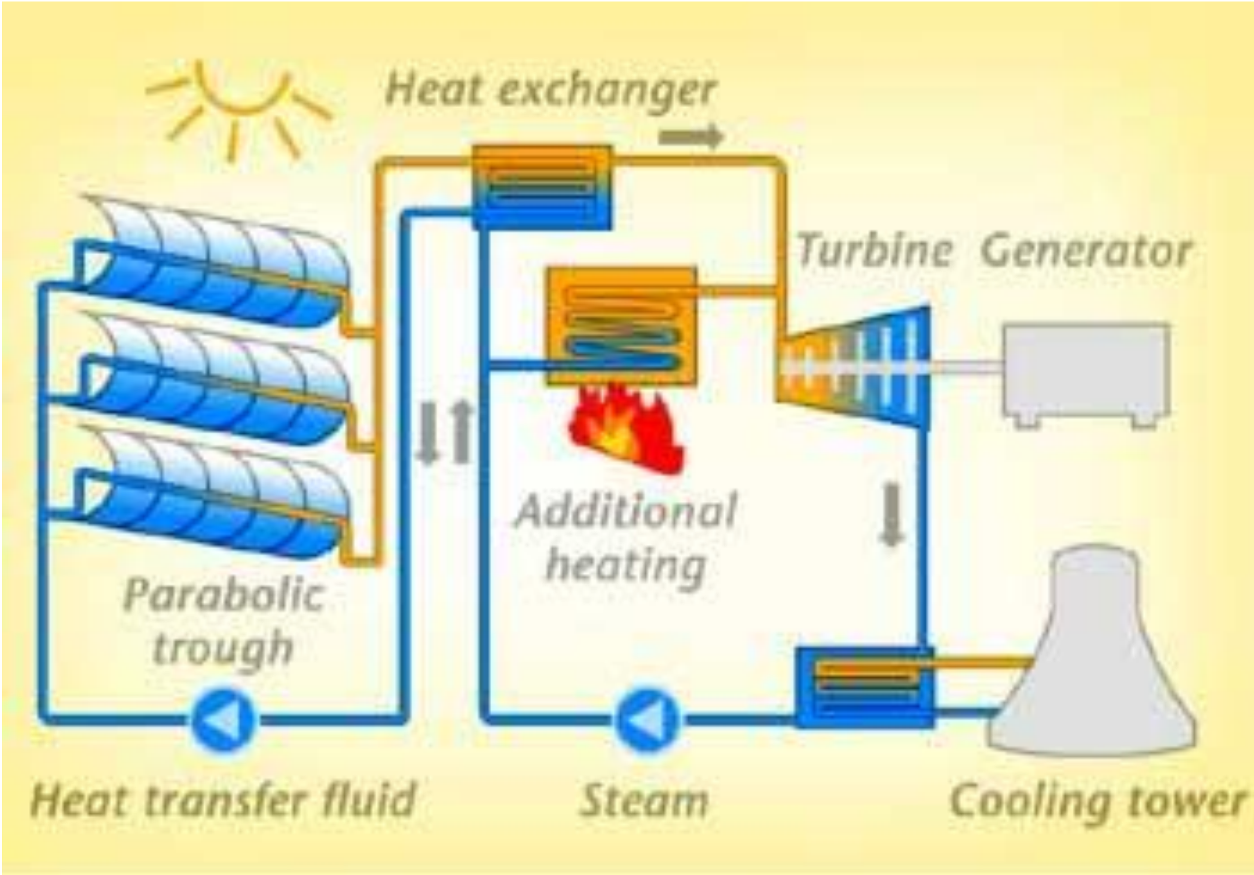
Comprise three sub-systems operating at low, medium and high temperatures respectively. Both low and high temperature ranges are provided by, for example, pipes-in-concrete subsystems relying on sensible heat of the cast concrete. The medium temperature subsystem uses latent heat storage in a PCM which has a phase change temperature close to that of the steam input to the turbine.

Sand

Sand is used as heat transfer and storage fluid. In this case, the sand is directly irradiated by the solar beam as a falling particle curtain inside the receiver, and stored for later use. This is under research.

CSP Technology Review – Backup with Natural Gas

- The current CSP power plants in Spain have an auxiliary backup natural gas boiler to mitigate the number of shutdowns of the turbine as well as the intermittency associated with the solar radiation and consequently the steam generation.
-The use of small amounts of gas Backup may be justified by the investment in the Balance of Plant infrastructure namely the turbine
- The backup via natural gas boiler has a relatively low investment cost and is mature, low risk technology.



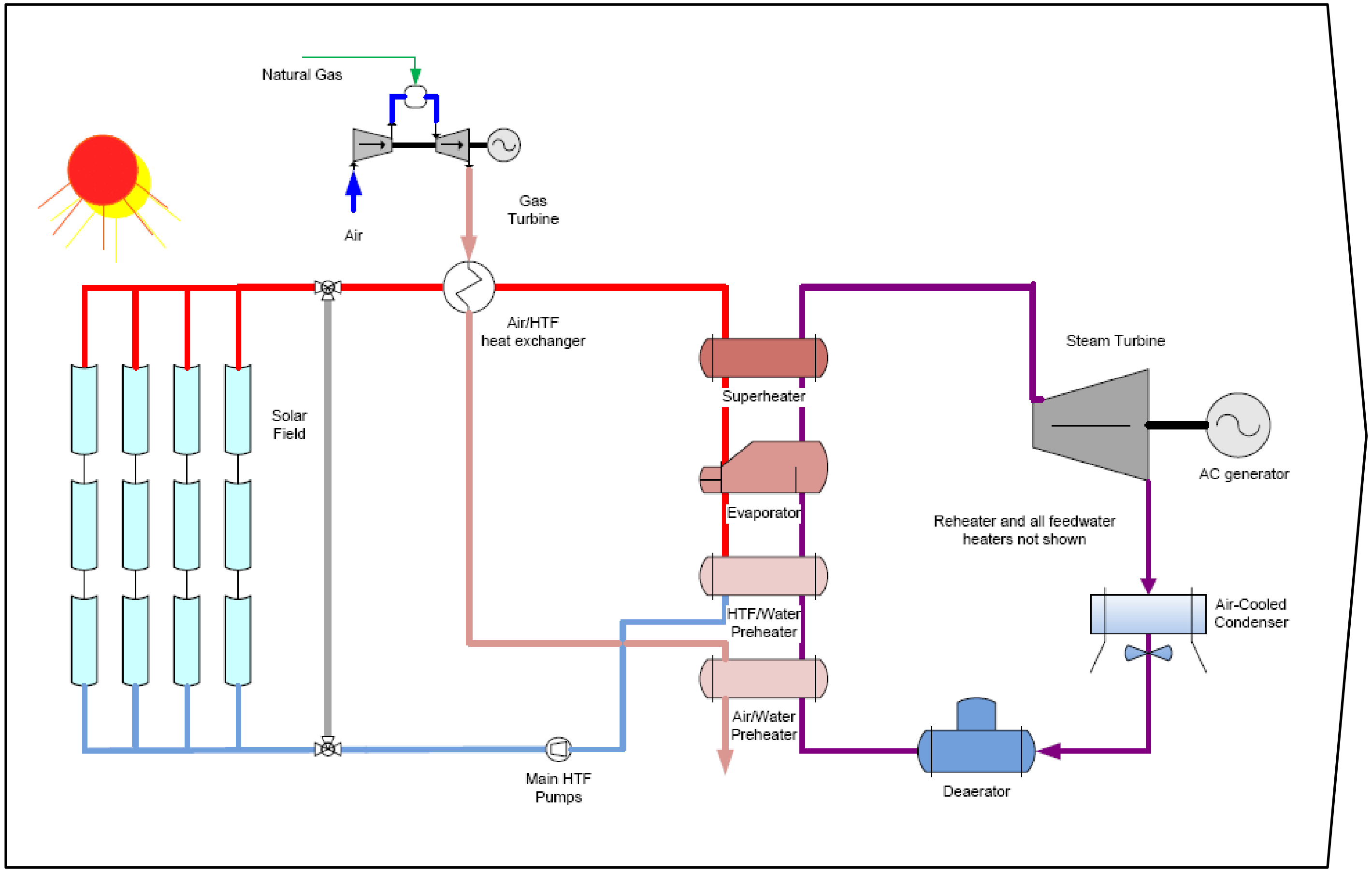
The concept of backup is simply explained in the following diagram

CSP Technology Review – Integrated Solar Combined Cycle - ISCC

- The integration of CSP technology with a combined cycle power plant is referred to as integrated solar combined cycle systems (ISCCS)

- Examples in the world: Morocco, Algeria and Egypt

- The gas turbine generates electricity and at the same time heat which is coupled with the heat from the CSP solar field to generate power through a steam based turbine.



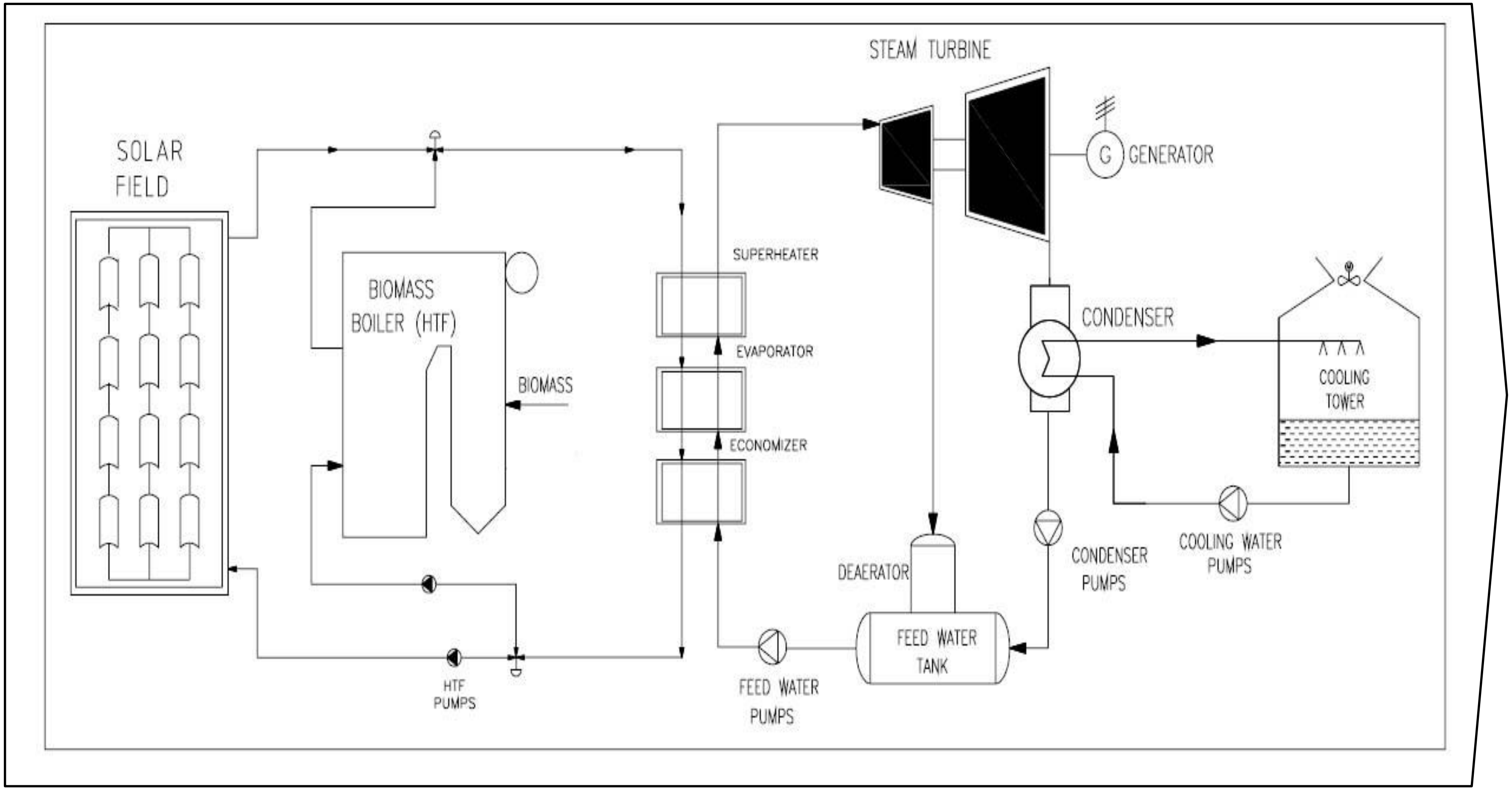
- The idea is to increase or augment the output of the power plant

CSP Technology Review – Hybridization with biomass

- Mature technology

- Cost of hybridization is low – boiler and burner

- CSP generally require a considerable power rating to be economically viable, so boiler is in the MW range



The combination of these two technologies benefits from increased overall efficiency of the power plant, reduced number of shutdowns of the turbine and reduced investment per unit of power generated compared to CSP with molten salts heat storage, for example

CSP Technology Review – Coal Augmentation

- CSP solar field is much cheaper than a CSP power plant and in a conventional power plant the whole power plant is available

- CSP solar field generates steam for a conventional power plant will yield interesting paybacks as it has been shown by Hu, David Mills, Graham Morrison and Peter Le Lievre in the paper *Solar power boosting of fossil fuelled power plants* (published in ISES back in 24th May 2003).

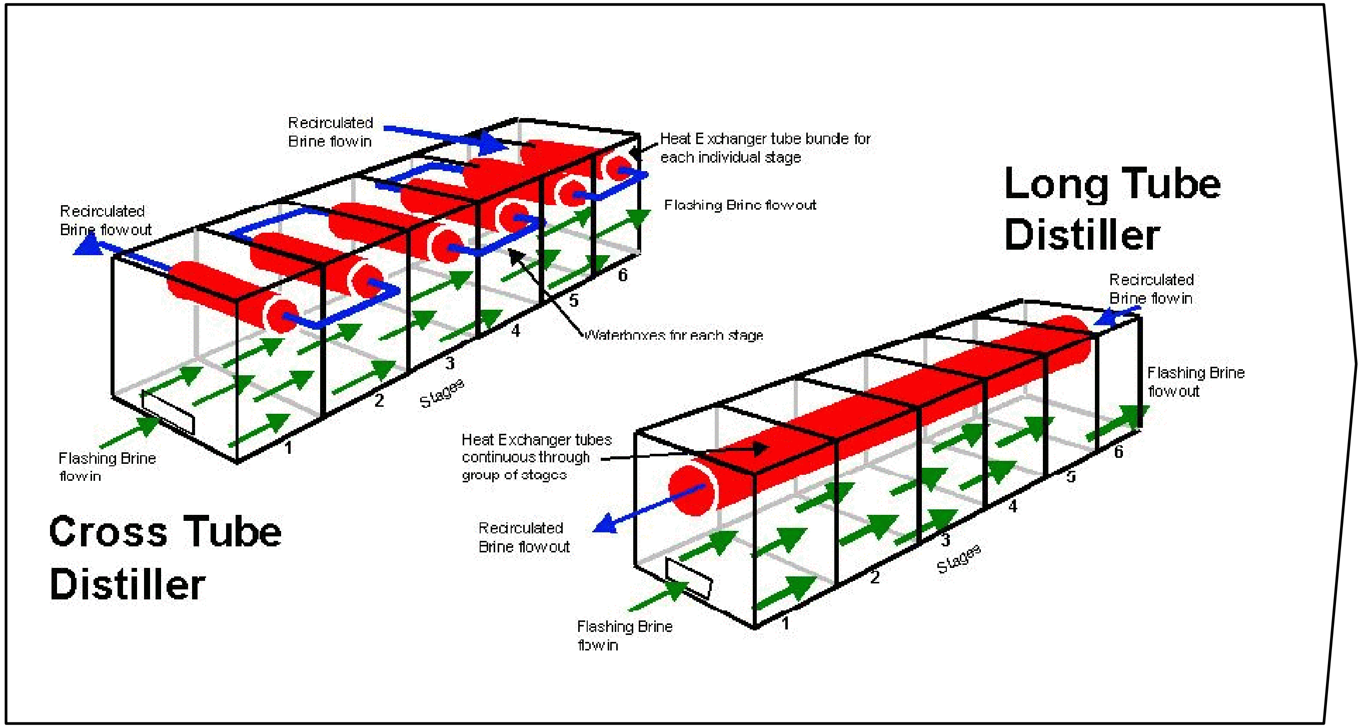
- Liddel CSP solar field to augment a coal power plant as one of the first projects of this nature in the world.

Multi-stage Flashing (MSF)

-Series of stages in which "flash" evaporation takes place from the flow of salt water or brine that occurs in the lower part of the evaporator

- The vapour released in flashing is filtered to remove brine droplets and condenses to yield water on heat transfer tubes at the top of the evaporator

- The seawater or brine flowing through the tubes is heated by the transfer of latent heat from the condensing vapour, giving a temperature rise equal to the temperature drop in "flashing"



Example of a MSF process

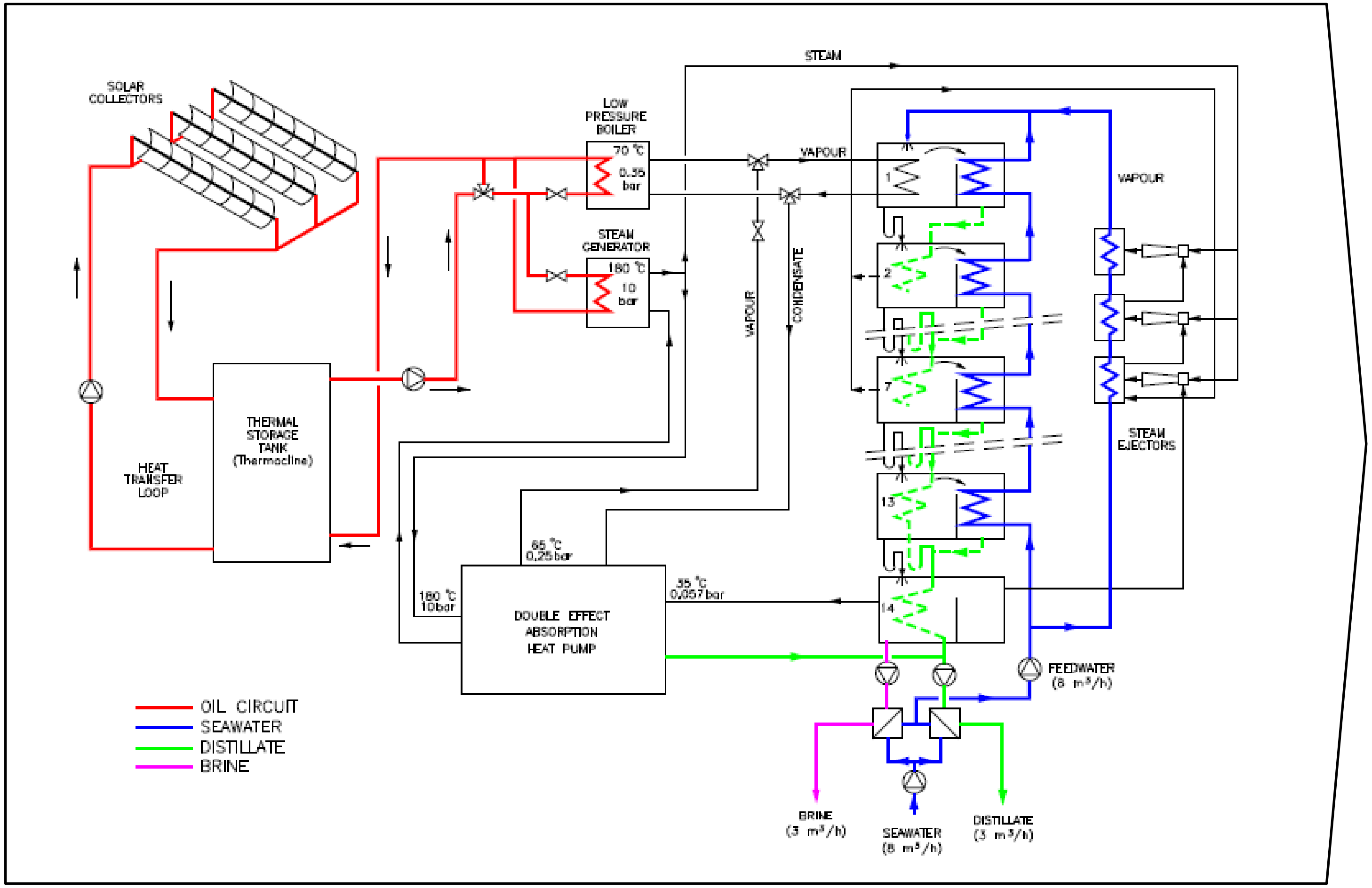
CSP Technology Review – Desalination

Multi-effect distillation (MED)

- Vapour formed in each effect flows to the condensing side of the heat transfer surface in the next (lower temperature) effect

- The latent heat of condensation is transferred through the tube wall to evaporate part of the saltwater or brine flowing across the surface.

- Evaporation is from a seawater film in contact with the heat transfer surface



Schematic diagram of the solar MED system installed at PSA

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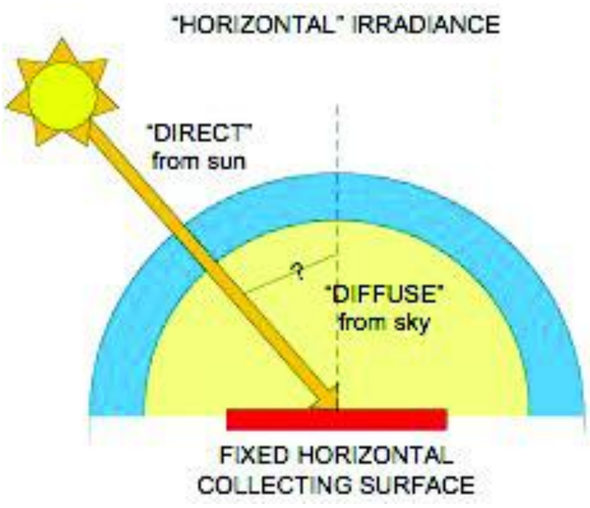
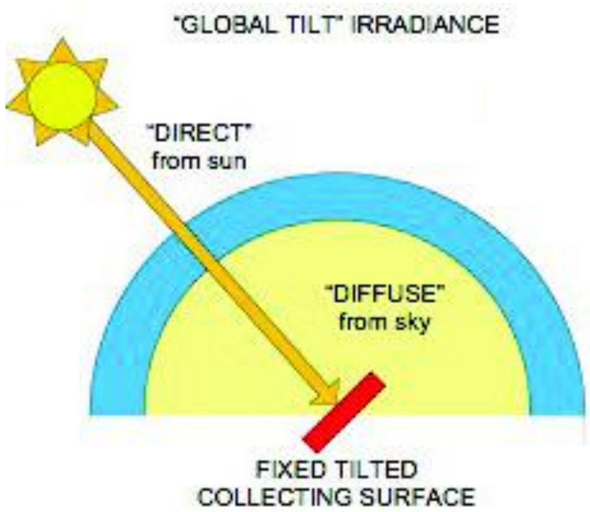
SOLAR IRRADIATION

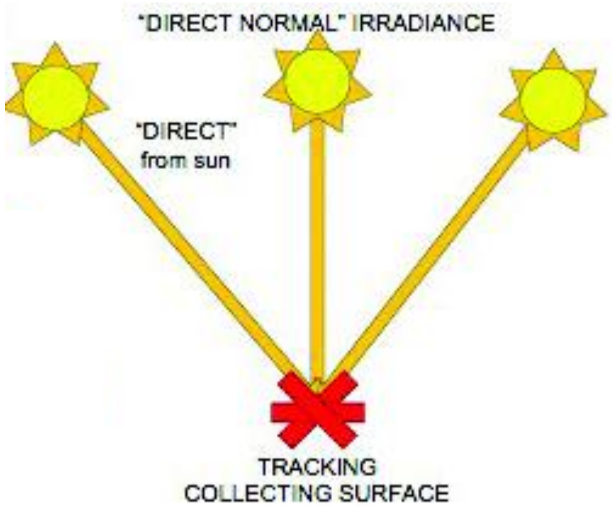
- **Concentrating solar power (CSP) plants must focus sunbeams on a collector to generate high temperatures**. **Only direct radiation from the sun can be concentrated this way**. This makes CSP plants more sensitive to atmospheric conditions than if they could also use diffuse radiation, as with flat-plate collectors (PV or thermal).

- Diffuse radiation normally varies in the opposite direction of direct radiation. Therefore, **direct normal irradiance (DNI) is much more sensitive to clouds or aerosols in the atmosphere than global irradiance**, which is the "fuel" for fixed mounting collectors.

- **An area with a good solar resource in global horizontal irradiance (GHI) is not necessarily suitable for CSP projects**.







Direct normal irradiance (DNI) is the fraction of the downward flux directly emanating from the sun disk that is incident on a plane normal (i.e., perpendicular) to the sunbeams, and that has not undergone any extinction in the atmosphere

Global horizontal irradiance (GHI) is the sum of the projected DNI on a horizontal surface and of diffuse horizontal irradiance

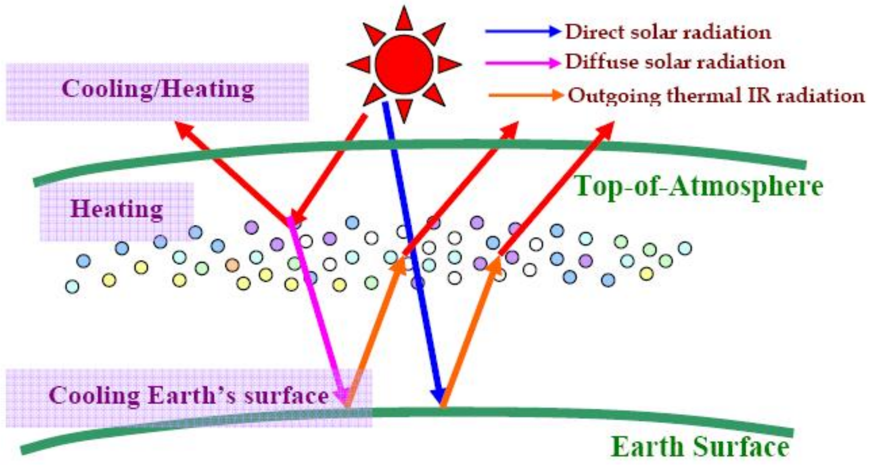
Diffuse horizontal irradiance (DHI) is the downward flux emanating from the sky vault, excluding the sun.

AEROSOLS

- Aerosols are composed of various particles in a large range of sizes. They include sea salt in suspension, sand dust, and many other particles generated by vegetation (e.g., pollen), volcanic activity, anthropogenic emissions (pollution), smoke, etc.

- Under low-aerosol conditions, horizontal visibility is excellent (more than 50 km) and the sky color is dark blue. On days with much higher aerosol loads, the sky becomes hazy (whitish) and visibility decreases significantly.

- Aerosols move much slower than clouds, so that both very clear and very hazy conditions may last hours, if not many days.



- Proper quantification of the solar resource in the absence of local irradiance measurements requires precise information on clouds, aerosols and humidity at any instant. Models do exist to turn this information into estimates of DNI, and such radiative models are widely used in solar resource assessments.

- The limitations in the accuracy of the DNI estimates offered by data providers is the inherent uncertainty in the underlying data—cloudiness and aerosols most importantly. Improved information on the quality, quantity and variability of aerosols is among the essential goals in current solar resource research

AEROSOL OPTICAL DEPTH (AOD) – GROUND OBSERVATIONS

AOD measurement stations in Southern Africa – AERONET network

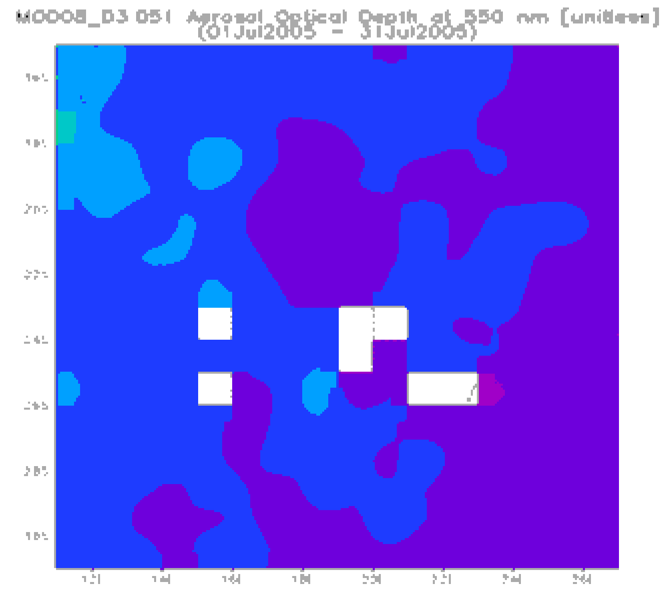
The AOD at multiple wavelengths can be derived from spectral irradiance measurements obtained with ground-based sun photometers.

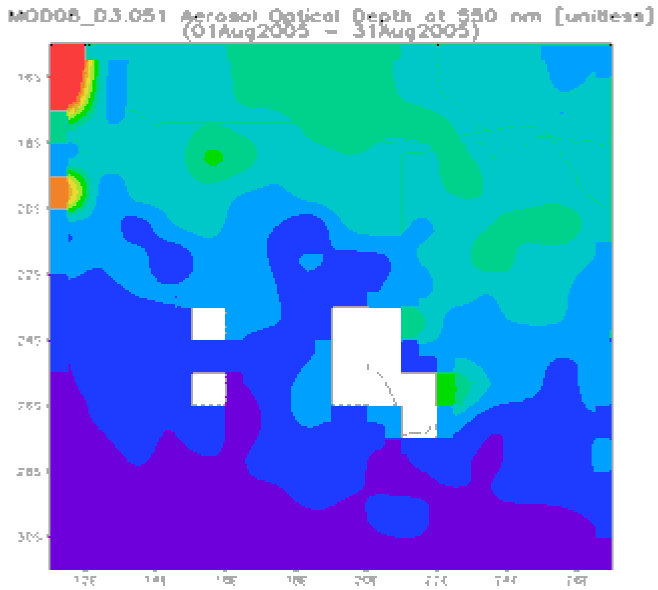
Networks: AERONET (NASA), GAW (WMO), SKYNET

Namibia AERONET stations:
-Etosha Pan - 8/2000 to 6/2001
- Henties Bay - since 11/2011
- Swakopmund - 9/2000
- Sesheke, Zambia - 4 months in 1997

AERONET “data-rich” stations
- Mongu, Zambia (1995–2010)
- Skukuza, South Africa (1998–2011)
- Wits University, South Africa (2002–2009)

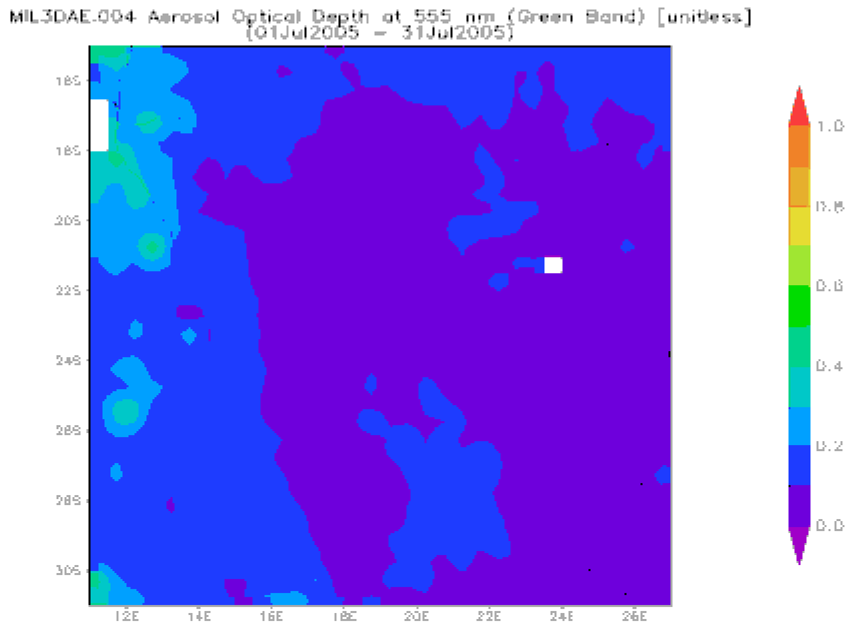
AEROSOL OPTICAL DEPTH (AOD) - SPACEBORN OBSERVATIONS (I/II)

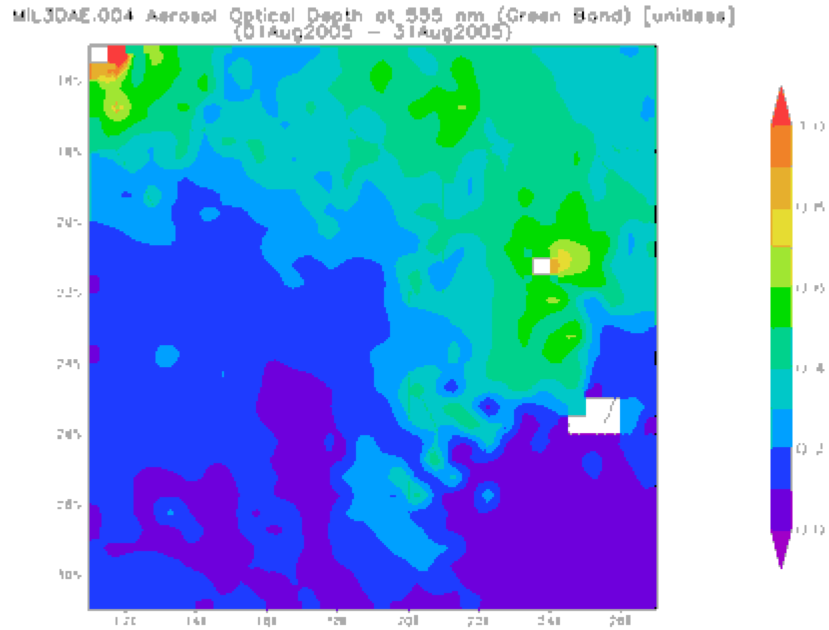




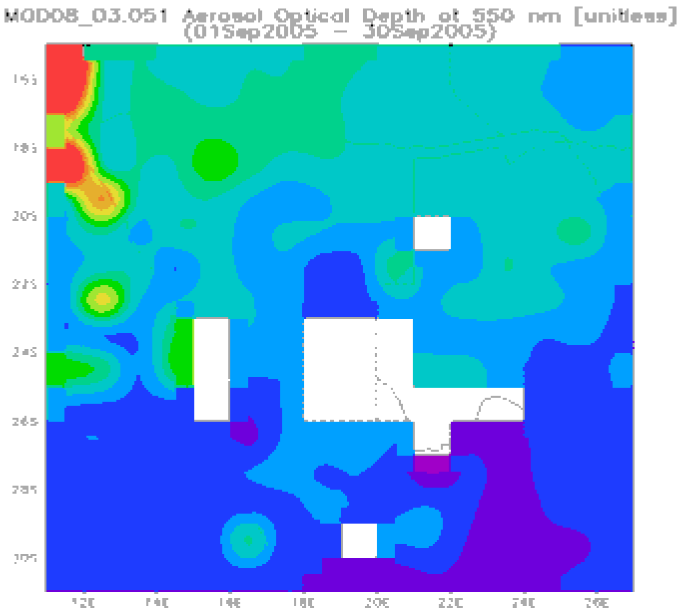
Monthly mean AOD at ≈550 nm as retrieved by MODIS (left plots) and MISR (right plots) during July and August of the 2005 fire season (top to bottom). Source: http://gdata1.sci.gsfc.nasa.gov/

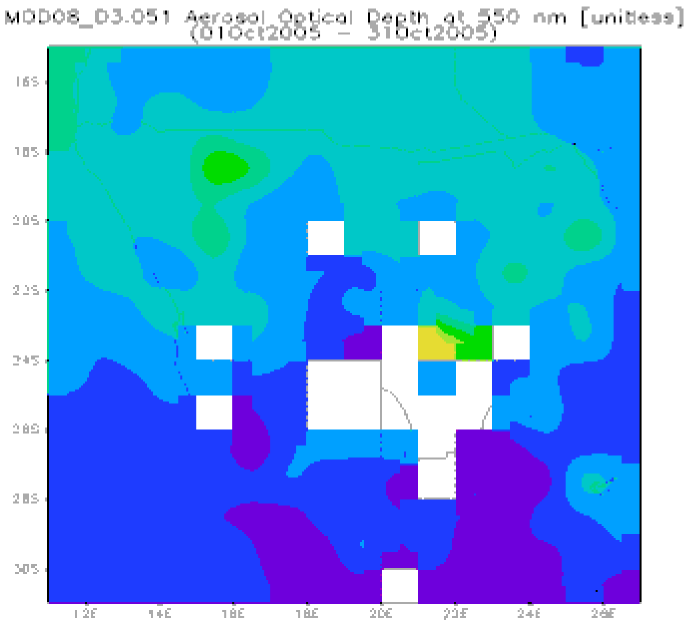
(Resolution of 1×1 km, depending on instrument and processing level; MODIS 1ºx1º and MISR 0,5ºx 0,5º)





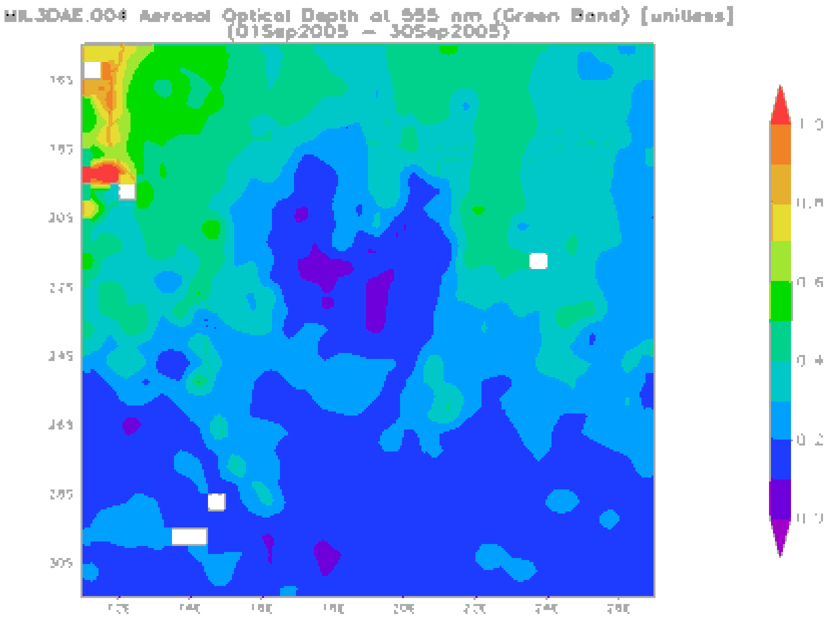
AEROSOL OPTICAL DEPTH (AOD) - SPACEBORN OBSERVATIONS (II/II)

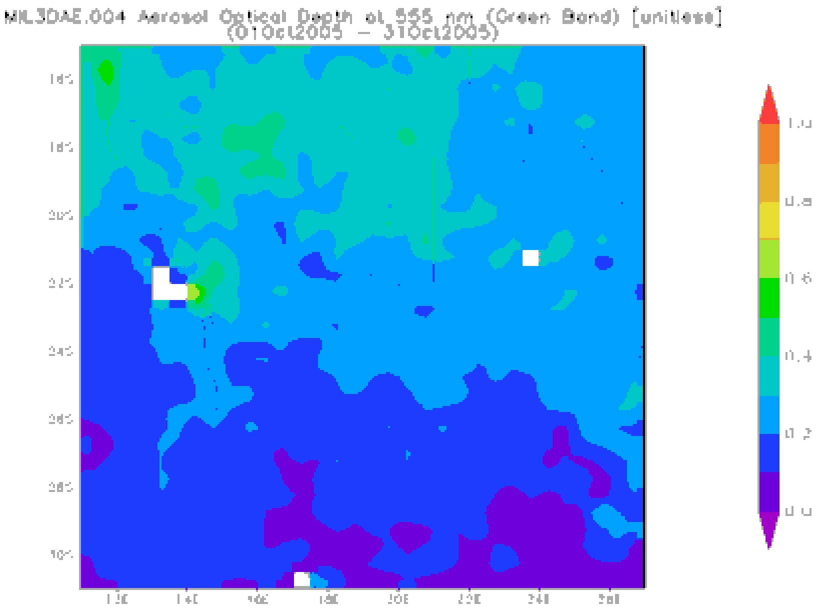




Monthly mean AOD at ≈550 nm as retrieved by MODIS (left plots) and MISR (right plots) during September and October of the 2005 fire season (top to bottom). Source: http://gdata1.sci.gsfc.nasa.gov/

(Resolution of 1×1 km, depending on instrument and processing level; MODIS 1ºx1º and MISR 0,5ºx 0,5º)





AEROSOL OPTICAL DEPTH (AOD) – AEROSOL/CHEMICAL TRANSPORT CHEMICAL MODELS

- AOD is not observed directly, but is calculated by dynamically combining different models and sources of information:
  - (i) estimated time-dependent emission data for various species of particles and aerosol precursors
  - (ii) meteorological information (from general circulation models) related to their transport
  - (iii) descriptions of the chemical processes involved in the formation, ageing and disposition of the different types of particles
- The uncertainties in the inventories of all aerosol precursors released in the past at any location and moment, as well as the complexity of all transport and chemical mechanisms involved, makes the modeled AOD results generally of lower accuracy than those from satellite observations. Moreover, the spatial resolution is coarser, and the AOD is generally derived at only one wavelength.
- Exception - MACC aerosol reanalysis and forecast system developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and it uses an assimilation of MODIS data

SOLARGIS - GEOMODEL

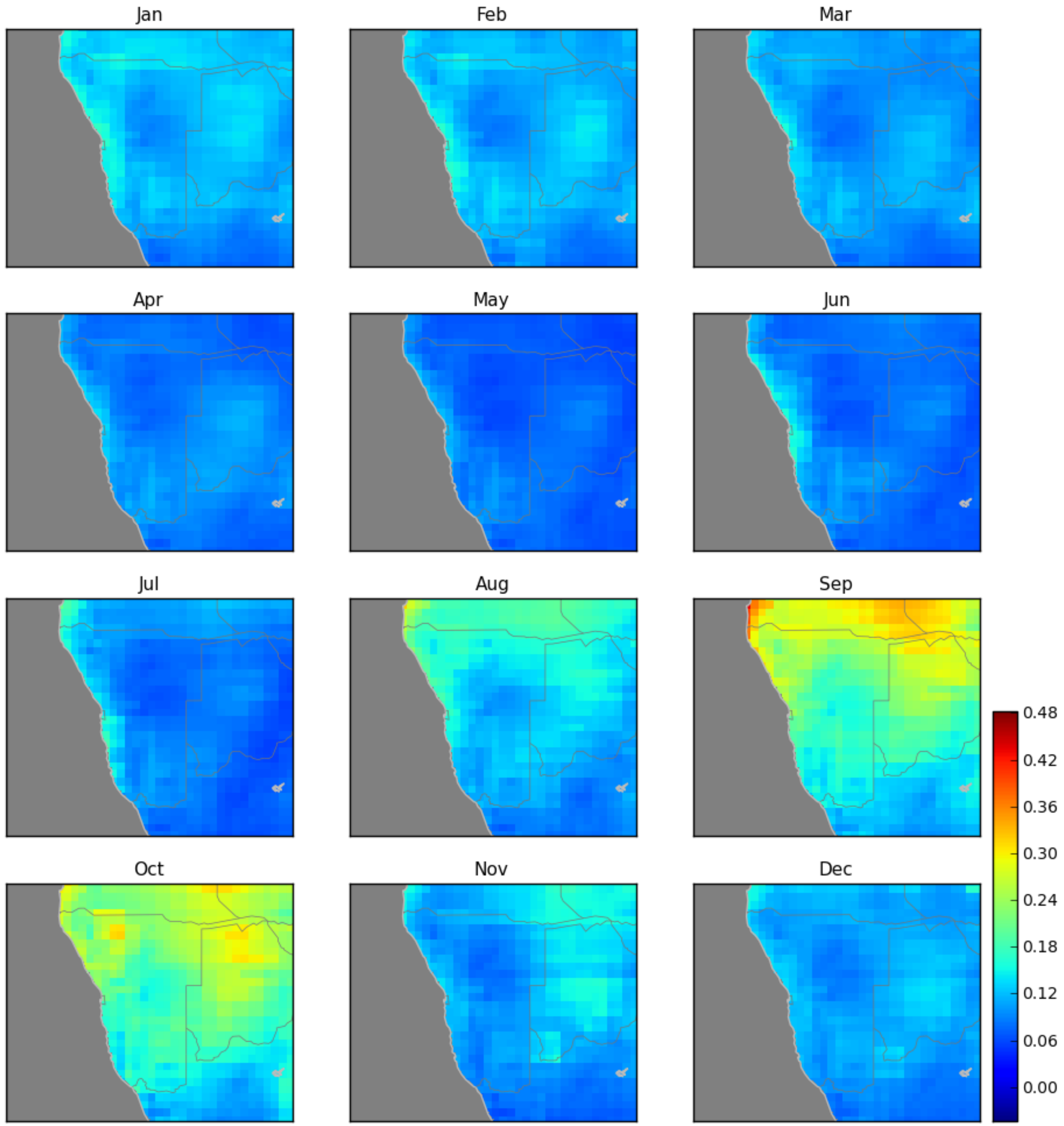
First step consists in using the simplified SOLIS model to evaluate the ideal clear-sky irradiance based on the following parameters:

• Sun position determined by time and astronomical equations
• Variable (over space and time) concentrations of atmospheric constituents, namely aerosols, water vapor and ozone (delivered at a spatial resolution of about 125 km)
• Daily AOD from the MACC model is normally used (daily variability). For Namibia, the AOD obtained from the MACC dataset has been corrected to reflect the lower bias of the monthly AOD specially derived by SCS
• Water vapor is also highly variable in space and time, but has a lower impact on solar irradiance than aerosols (daily data GFS and CFSR)
• Ozone has only a minor effect on broadband solar radiation (monthly values)
• Cloudiness. Cloud extinction is expressed through a parameter called "cloud index", based on meteorological geostationary satellites (MFG and MSG satellites; 4 x 4 km over Namibia). The cloud index is derived by empirically relating the radiance observed by the satellite in four spectral channels and the estimated surface albedo to the cloud optical properties. A number of improvements have been introduced to better cope with specific situations such as snow, ice, or high albedo areas (arid zones and deserts), and also with complex terrain.
• DNI is finally calculated

AEROSOL OPTICAL DEPTH (AOD) AND DNI – IMPACTS AND UNCERTAINTY (I/II)

- In general, a typical aerosol-induced uncertainty of 10–15% in annual average DNI should be considered at sites with moderate aerosol load.
- Such effects cannot be sorted out without observations from local weather/radiometric stations specially designed for high-quality DNI measurements
- In the atmospheric and geographic conditions of Namibia, the inaccuracies of the aerosol data may account for more than half of the total uncertainty in solar irradiance.
- Over semi-arid and desert zones (which are widespread in Namibia), the accuracy of the modeled solar resource data is mainly determined by the parameterization of the atmosphere, especially the proper quantification of aerosol and cloud attenuation.
- The accuracy of the SolarGIS database, version 1.8, has been compared with high-quality ground observations at almost 100 stations worldwide. The SolarGIS database demonstrated its high reliability and its superior quality compared to other solar databases on the market in a recent IEA-SHC Task 36 data intercomparison study (Ineichen, 2011). -> error of 6 to 10% (we expect to have lowered these values)

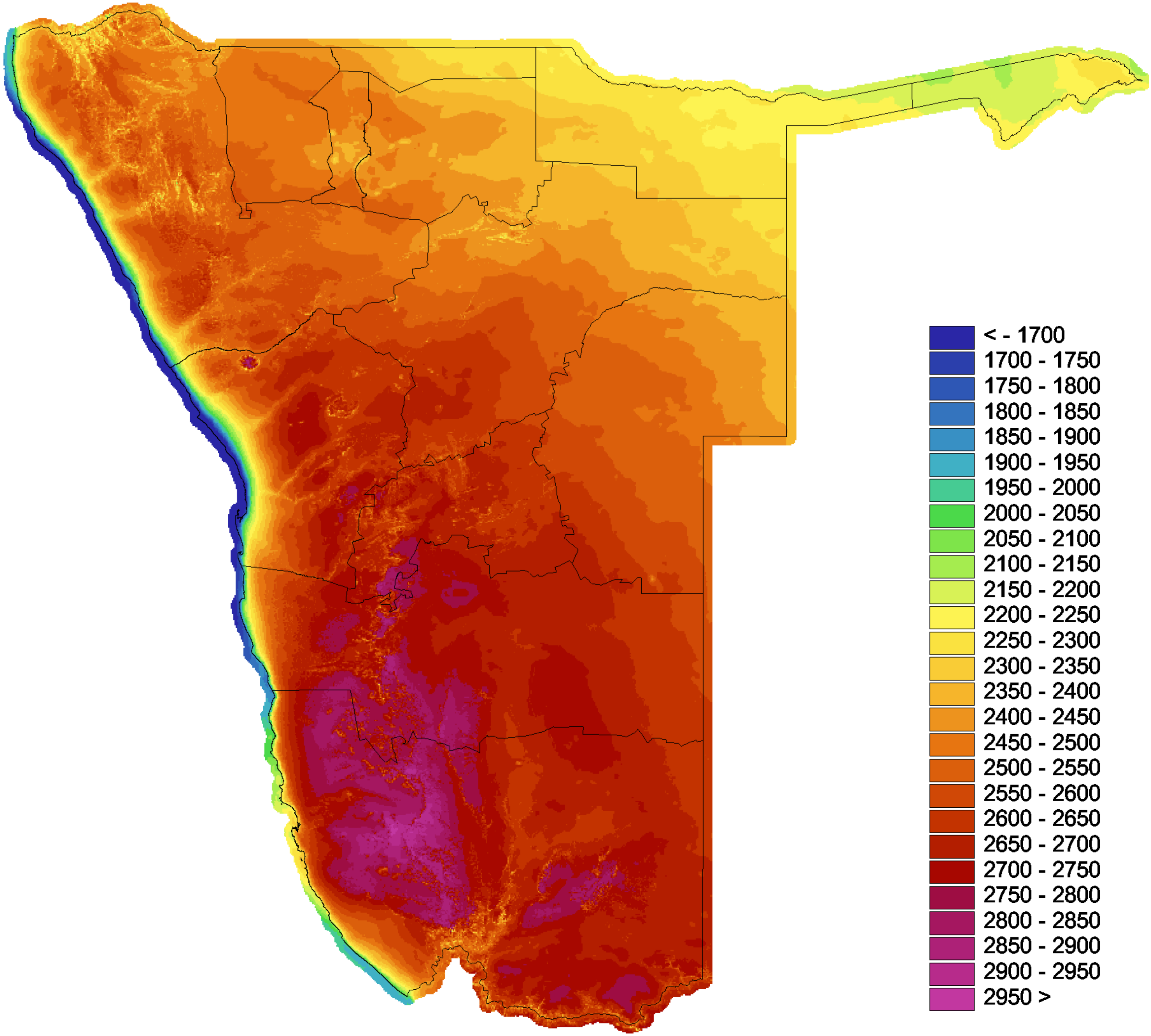
AEROSOL OPTICAL DEPTH (AOD) DATA AND RESULTS (II/II)



Long-term AOD monthly averages for the final dataset used in irradiance calculations for Namibia;

From January (top left) to December (down right)

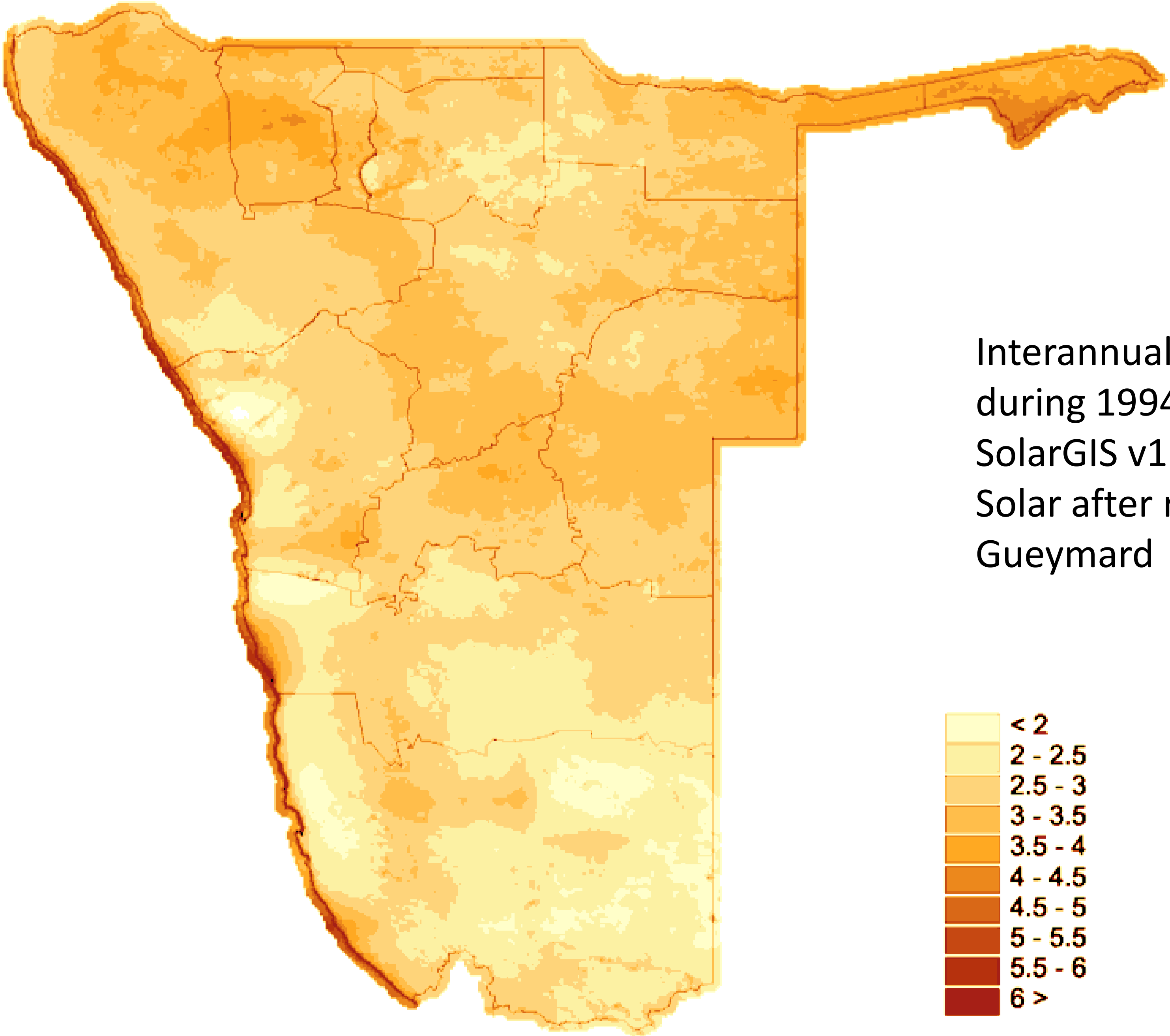
DNI MAPPING OF NAMIBIA - IMPROVED



Long-term annual average of DNI [kWh/m2] over the period 1994-2011, based on SolarGIS v1.8 © 2012 GeoModel Solar with improvements from Dr. Chris Gueymard

For DNI, the bias reaches ±8.0% over arid areas, whereas the hourly Root Mean Square Difference (RMSD) is below 24.0%

DNI ANNUAL VARIABILITY IN NAMIBIA



Interannual variability (in %) of DNI during 1994-2011, obtained with SolarGIS v1.8 © 2012 GeoModel Solar after refinement of Dr. Chris Gueymard