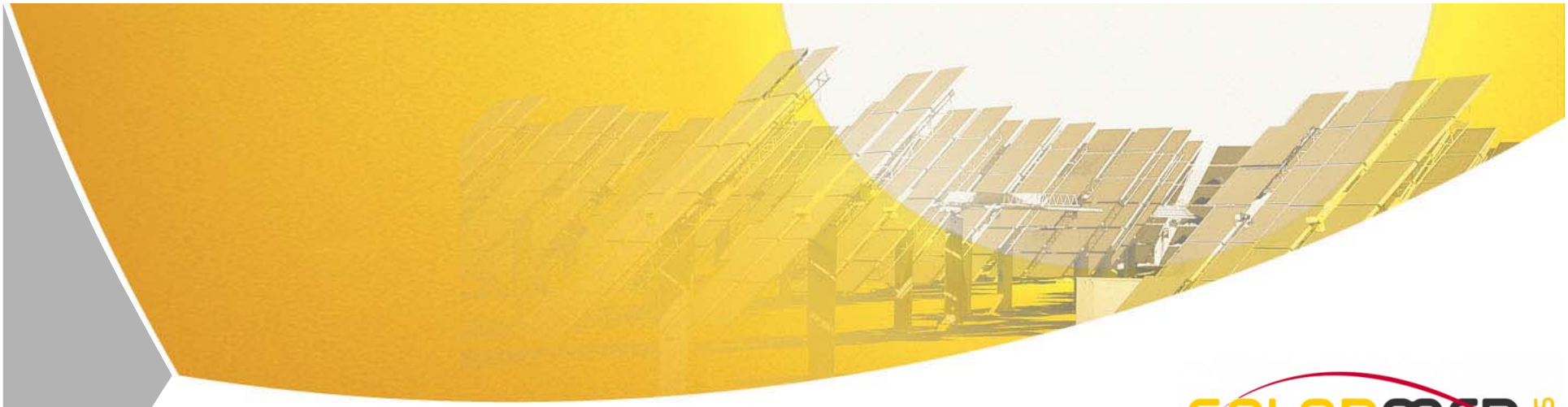


Introduction to Solar Resource Assessments

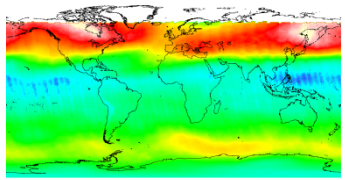
Carsten Hoyer-Klick

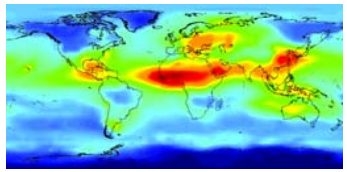
German Aerospace Center

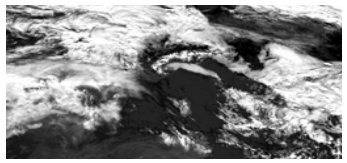
Institute of Technical Thermodynamics

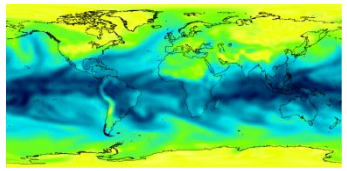
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

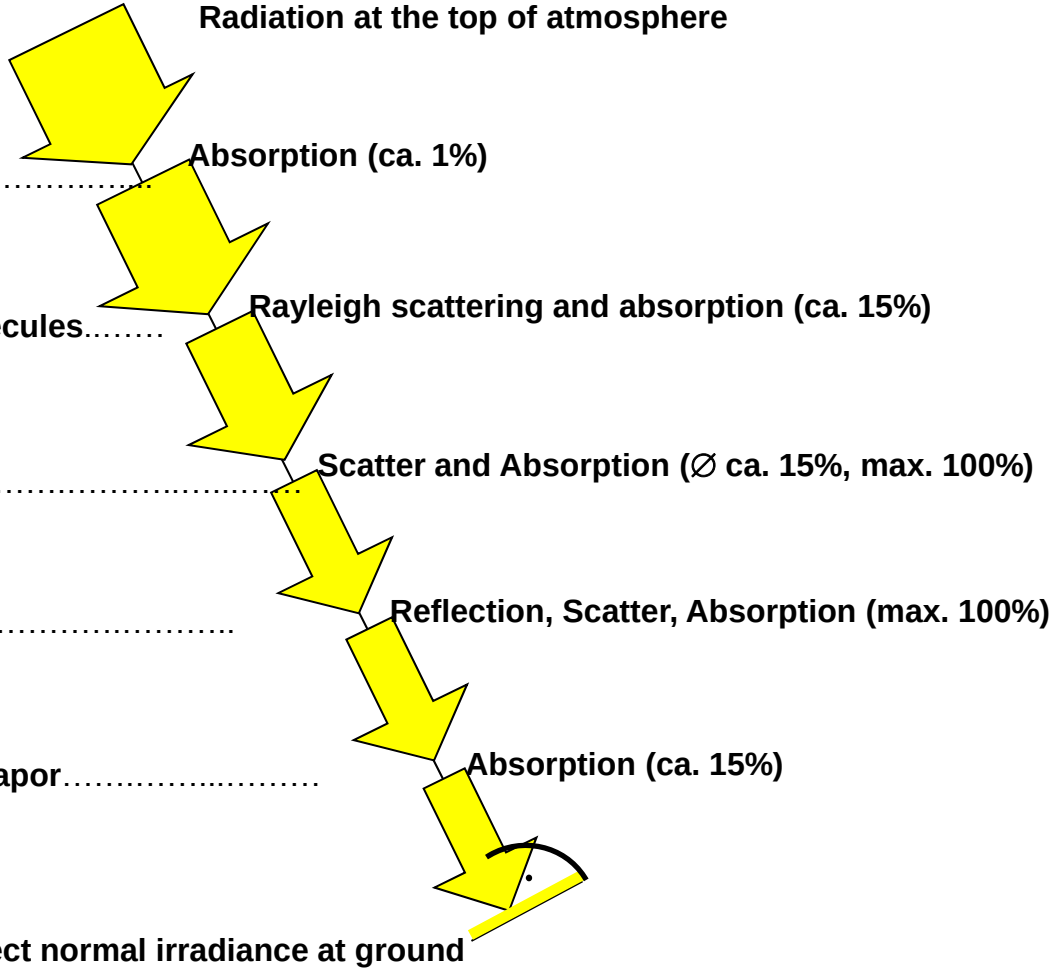
Transfer of Solar Radiation through the Atmosphere





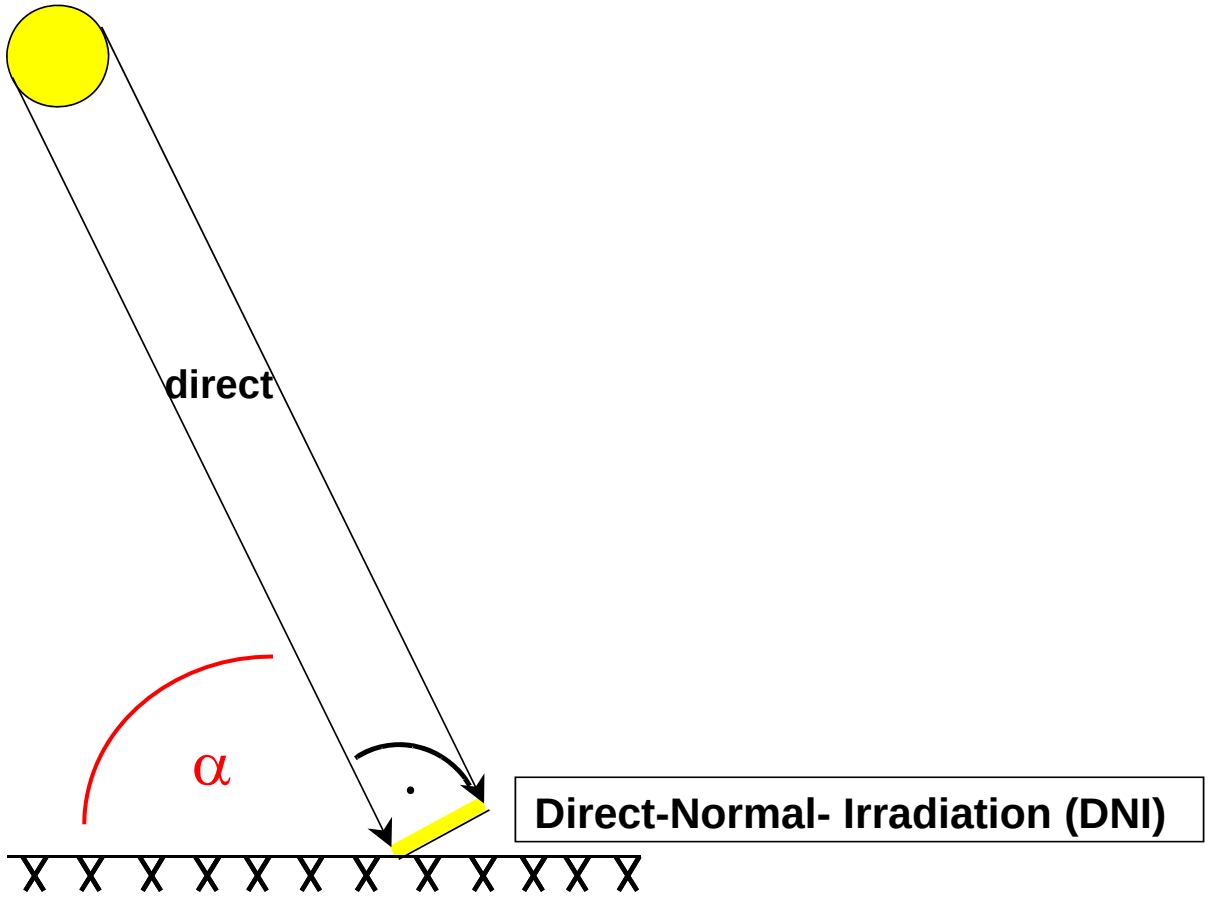




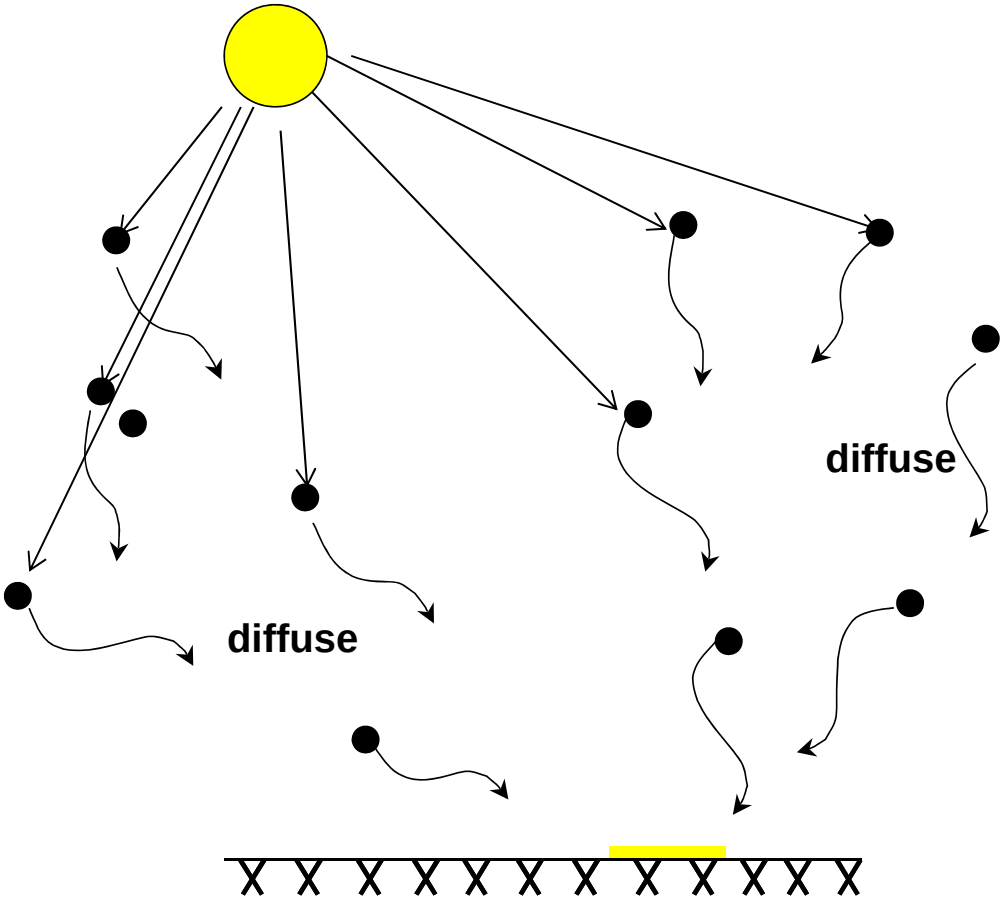


Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety — based on a decision of the Parliament of the Federal Republic of Germany

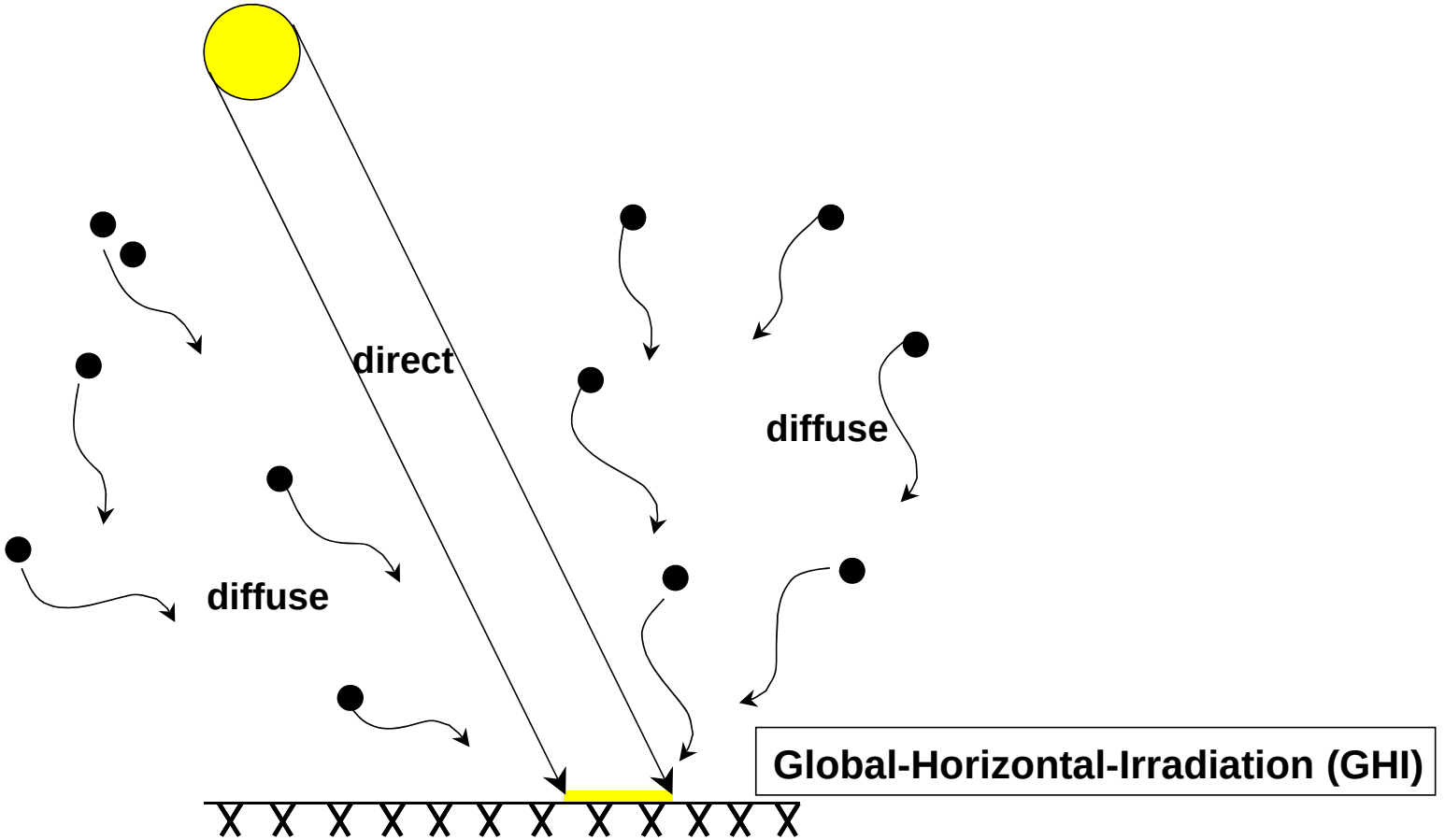
Direct Normal Irradiation (DNI)



Diffuse Horizontal Radiation



Global Horizontal Irradiation (GHI)

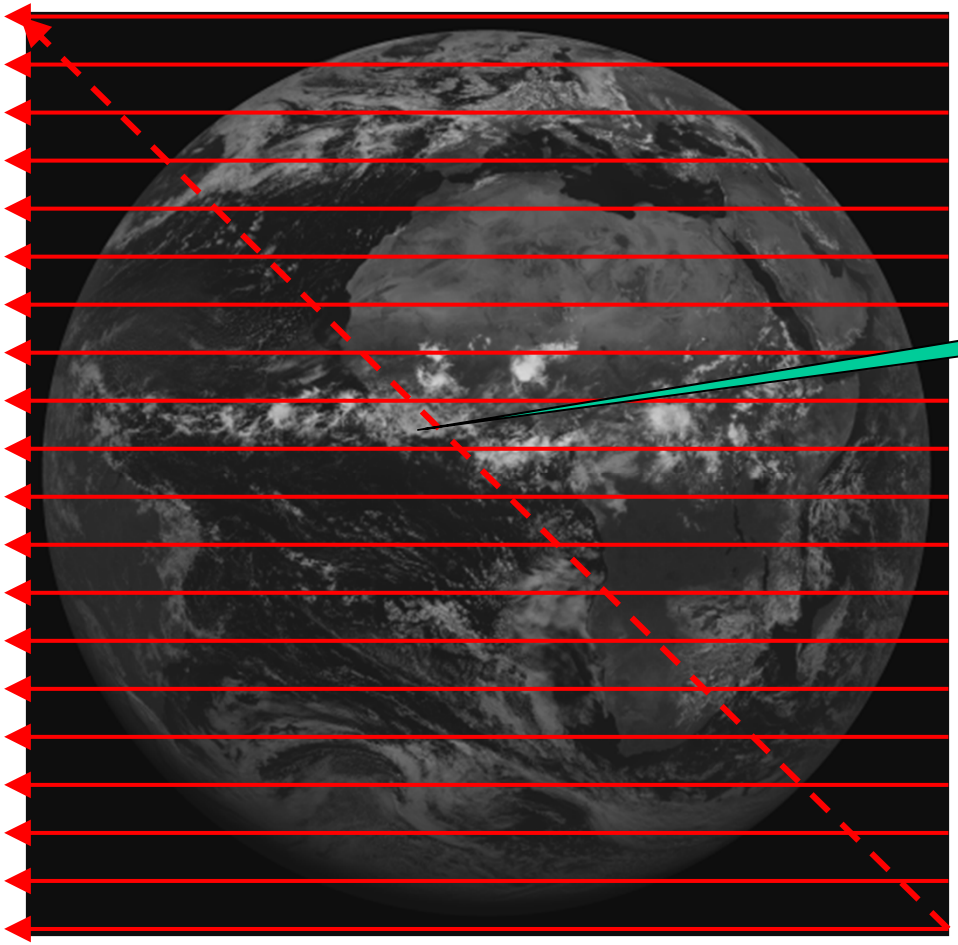


How two derive irradiance data from satellites

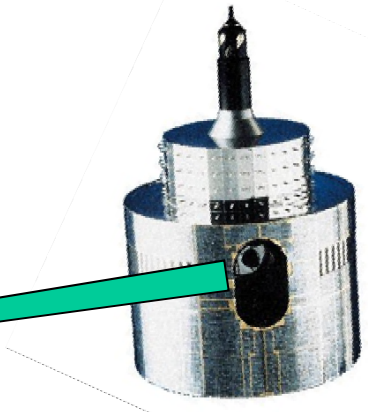
- The Meteosat satellite is located in a geostationary orbit
- The satellite scans the earth line by line every half hour

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Das Meteosat System – Image recording

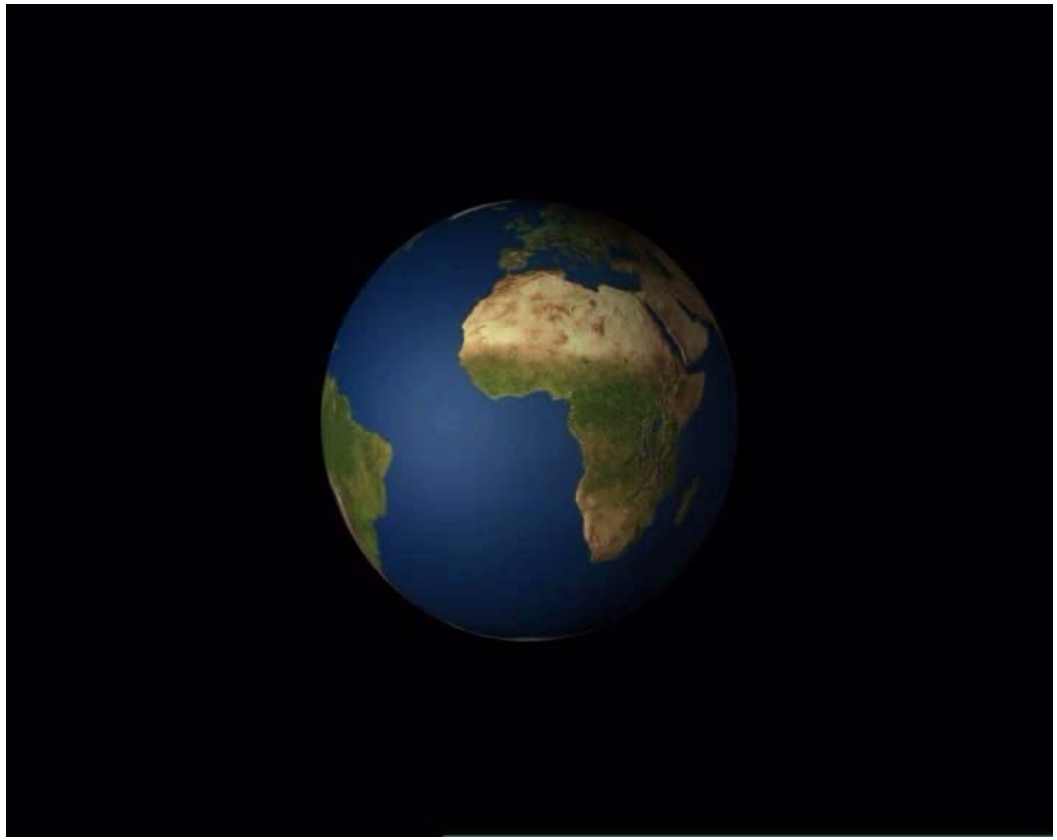


Scan



- The satellite rotates at 100 rpm
- Line by line scanning of the earth from south to north
- Pixels by sampling of the analog sensor signal
- Field of view of the sensor e.g. in Europe 3 x 4 km due to geometric distortion

How two derive irradiance data from satellites



- The Meteosat satellite is located in a geostationary orbit
- The satellite scans the earth line by line every half hour
- The earth is scanned in the visible …

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

How two derive irradiance data from satellites

- The Meteosat satellite is located in a geostationary orbit
- The satellite scans the earth line by line every half hour
- The earth is scanned in the visible and infra red spectrum

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

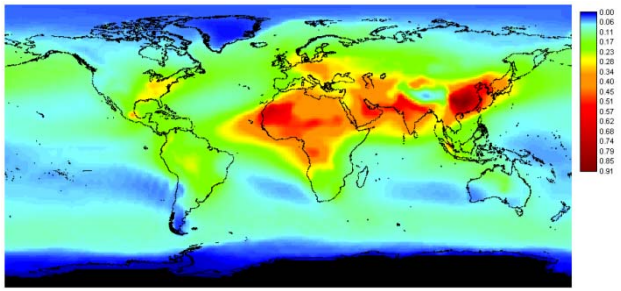
How two derive irradiance data from satellites

- The Meteosat satellite is located in a geostationary orbit
- The satellite scans the earth line by line every half hour
- The earth is scanned in the visible and infra red spectrum
- A cloud index is composed from the two channels

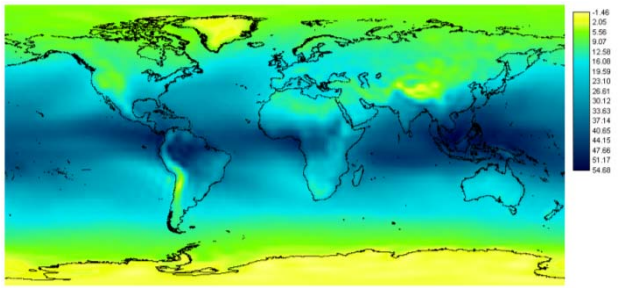
Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Clear sky Model input data

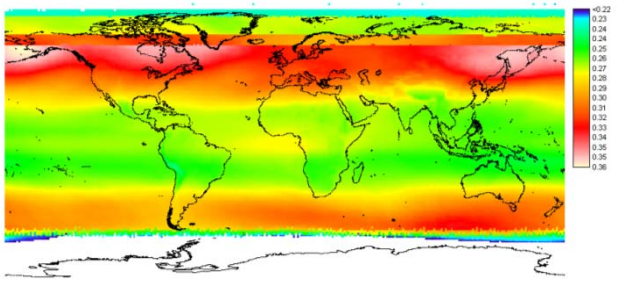
- Aerosol optical thickness
  GACP Resolution 4°x5°, monthly climatology
  MATCH Resolution 1.9°x1.9°, daily climatology



- Water Vapor: NCAR/NCEP Reanalysis
  Resolution 1.125°x1.125°, daily values



- Ozone: TOMS sensor
  Resolution 1.25°x1.25°, monthly values



Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Remote Sensing of Aerosols

- Usually split channel / dark target approach:
  - A dark target is searched in a long-wave channel
  - The reflectivity is observed in a short wave channel (usually aerosol backscatter increases with frequency)
  - The difference is translated into a AOD

- Problems:
  - Dark targets a land: Forrests, lakes – only a very few available almost none in deserts

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Chemistry Transport Models for Aerosol Data

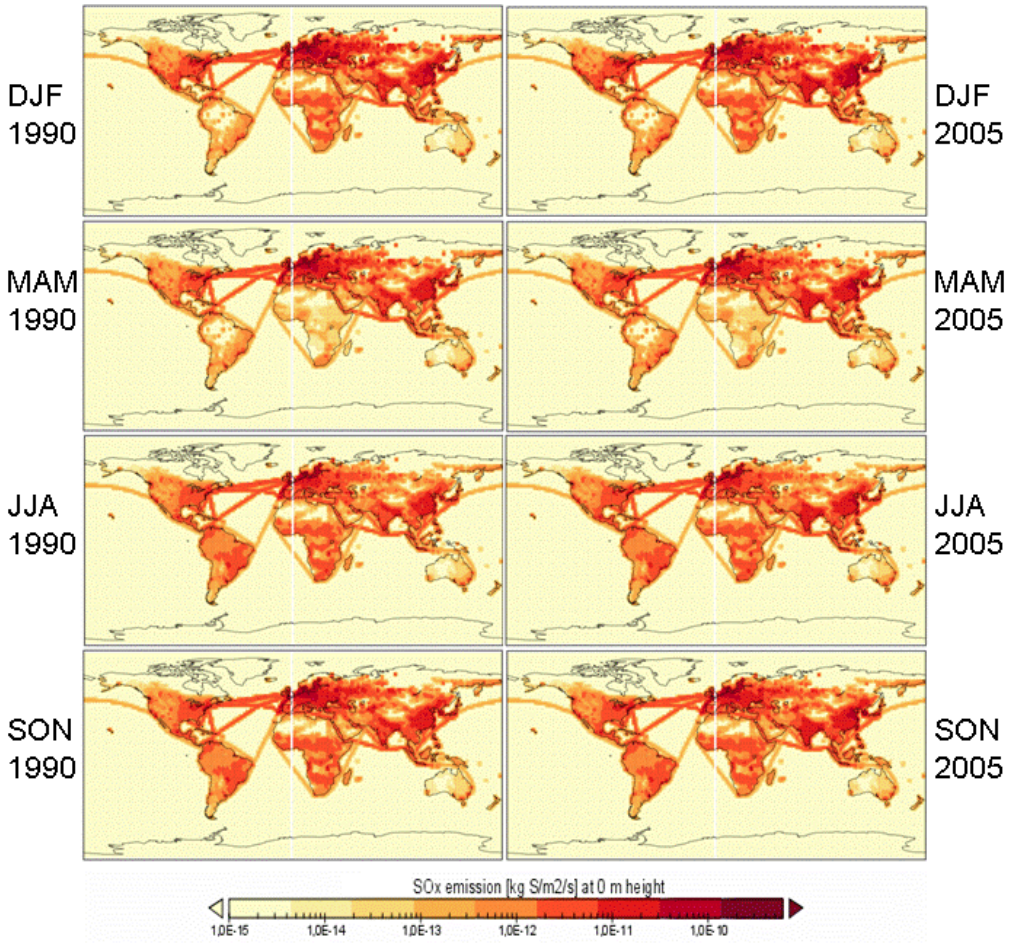
Modeling of aerosol uptake, transport, chemical change and deposition in a numerical model

- Input:
  - Surface properties
  - Emission data bases
  - Numerical weather models (especially wind fields, rain).
- Modeling:
  - Aerosol uptake
  - Aerosol transport with wind
  - Aerosol outfall
  - Aerosol chemistry, change in properties with time
- Output:
  - Mass concentrations
    - converted to optical properties

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

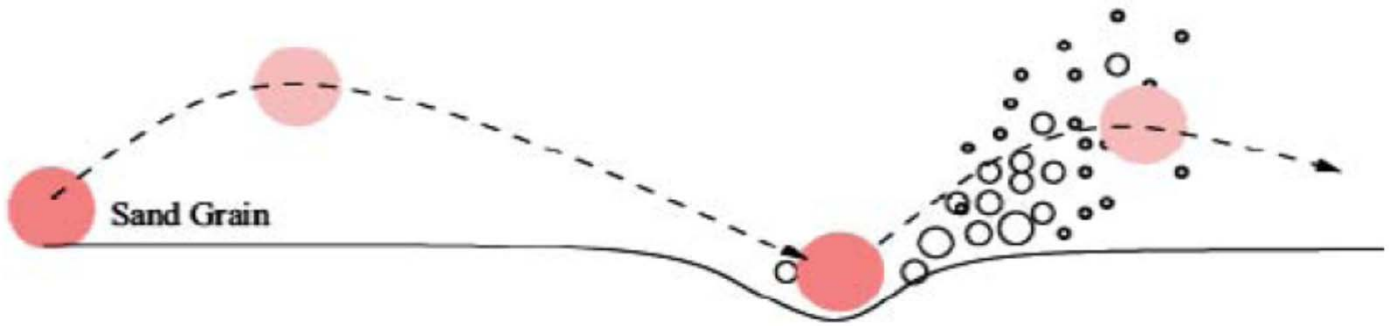
Chemistry Transport Models – Emission data bases

- Emission data bases, e.g. SOx emissions



Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Chemistry Transport Models - Dust

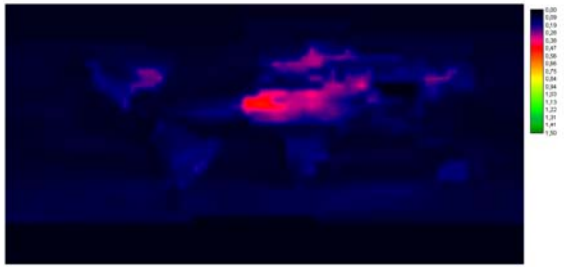


- Mineral dust mobilisation is initiated by strong winds blowing over bare ground and erodible particles.
- Medium range sand-sized particles above 60 µm particle diameter are lifted up, but also fall quickly down again to the ground.
- The momentum of the landing particles results in the loosening of small and fast moving particles which are known as sandblasting particles.
- Dust particles are mixed into higher atmospheric layers by turbulent processes and transported in the atmospheric flow over larger distances.

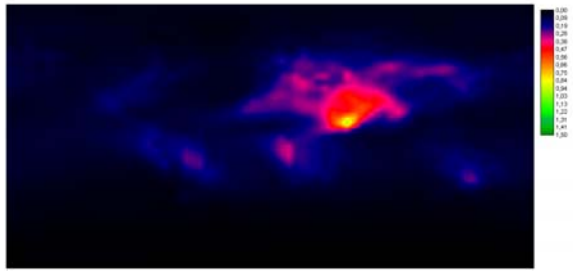
Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Uncertainty in Aerosols

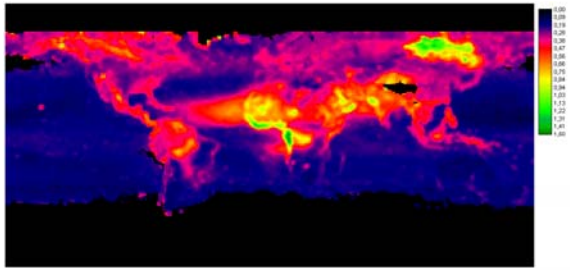
- All graphs are for July
- Scales are the same! (0 – 1.5)
- Large differences in Aerosol values and distribution



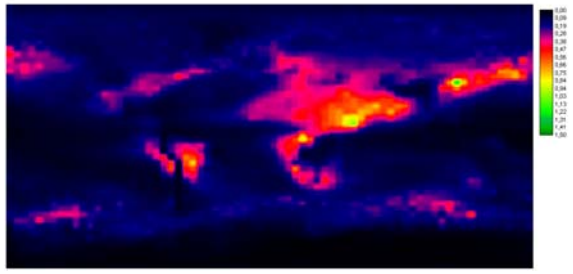
GADS



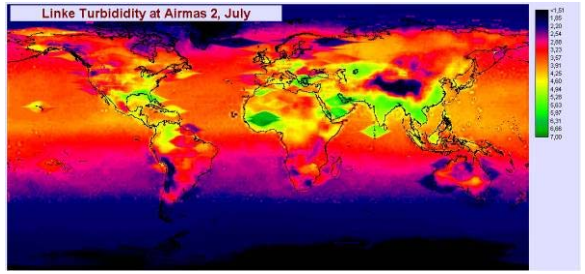
NASA GISS v1 / GACP



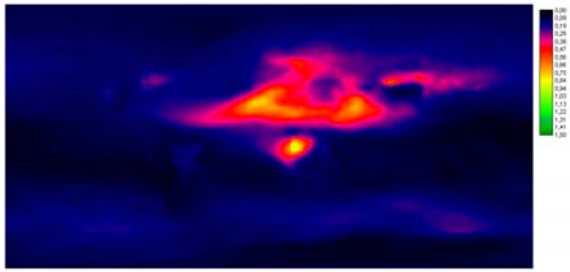
Toms



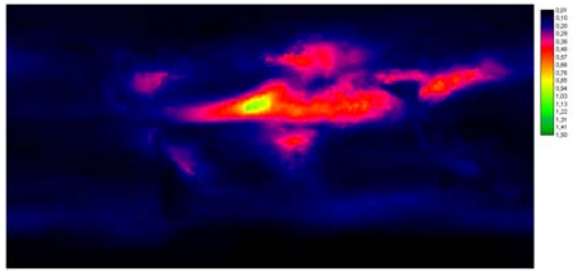
NASA GISS v2 1990



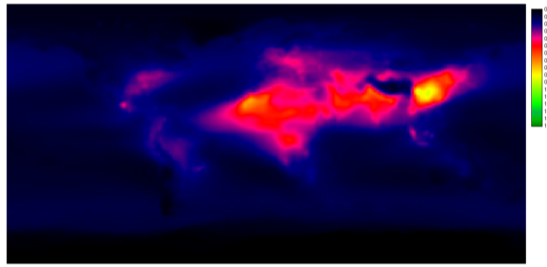
Linke Turbidity



GOCART

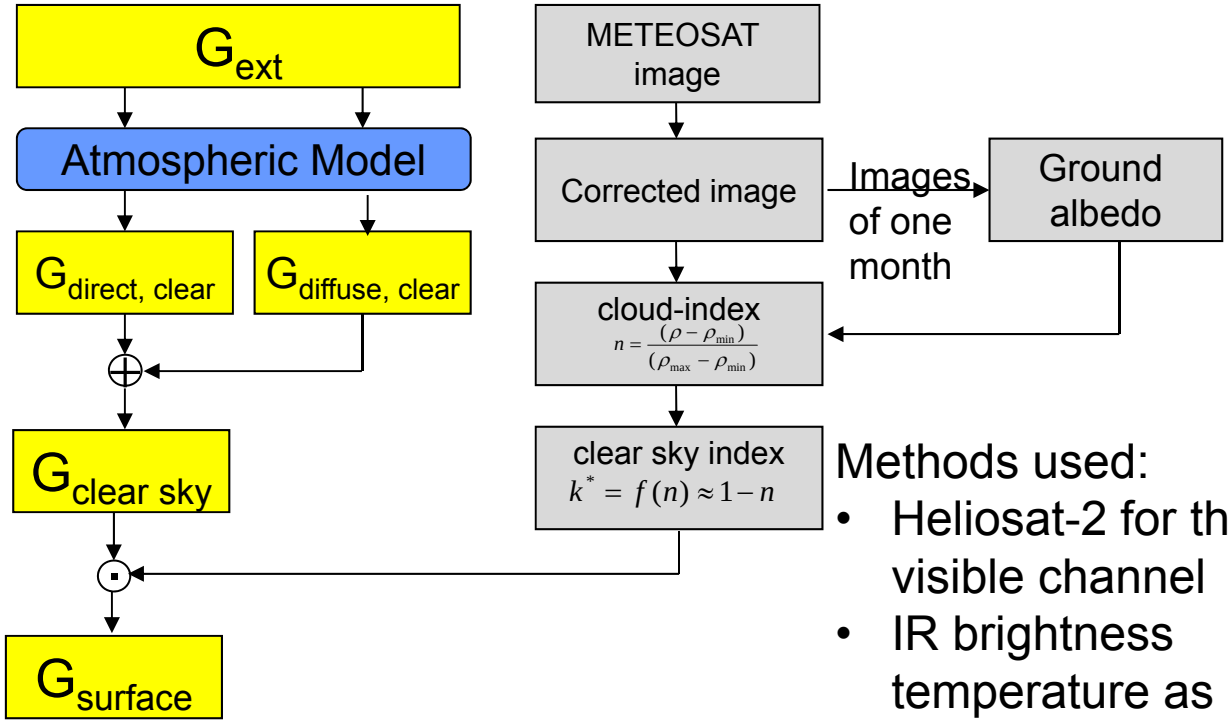


AeroCom



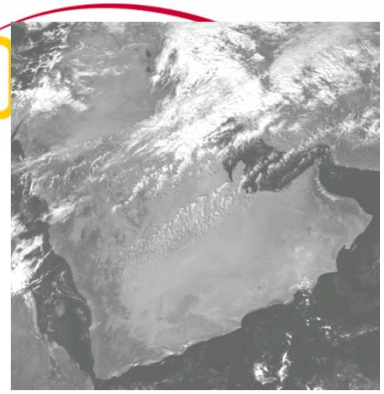
MATCH

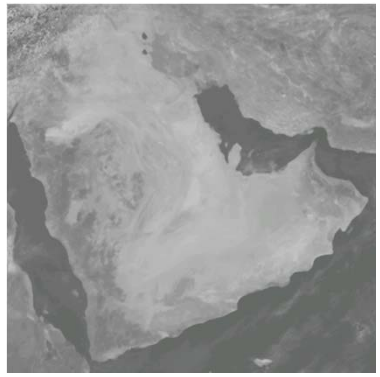
Calculation of solar radiation from remote sensing

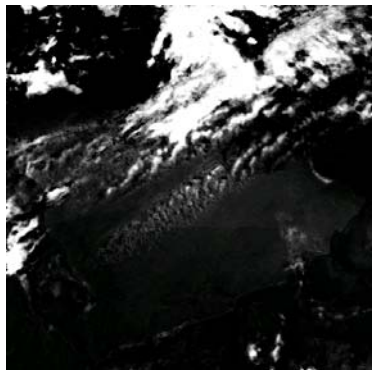


Methods used:

- Heliosat-2 for the visible channel
- IR brightness temperature as indicator for high cirrus clouds (T < -30°C, DNI = 0)

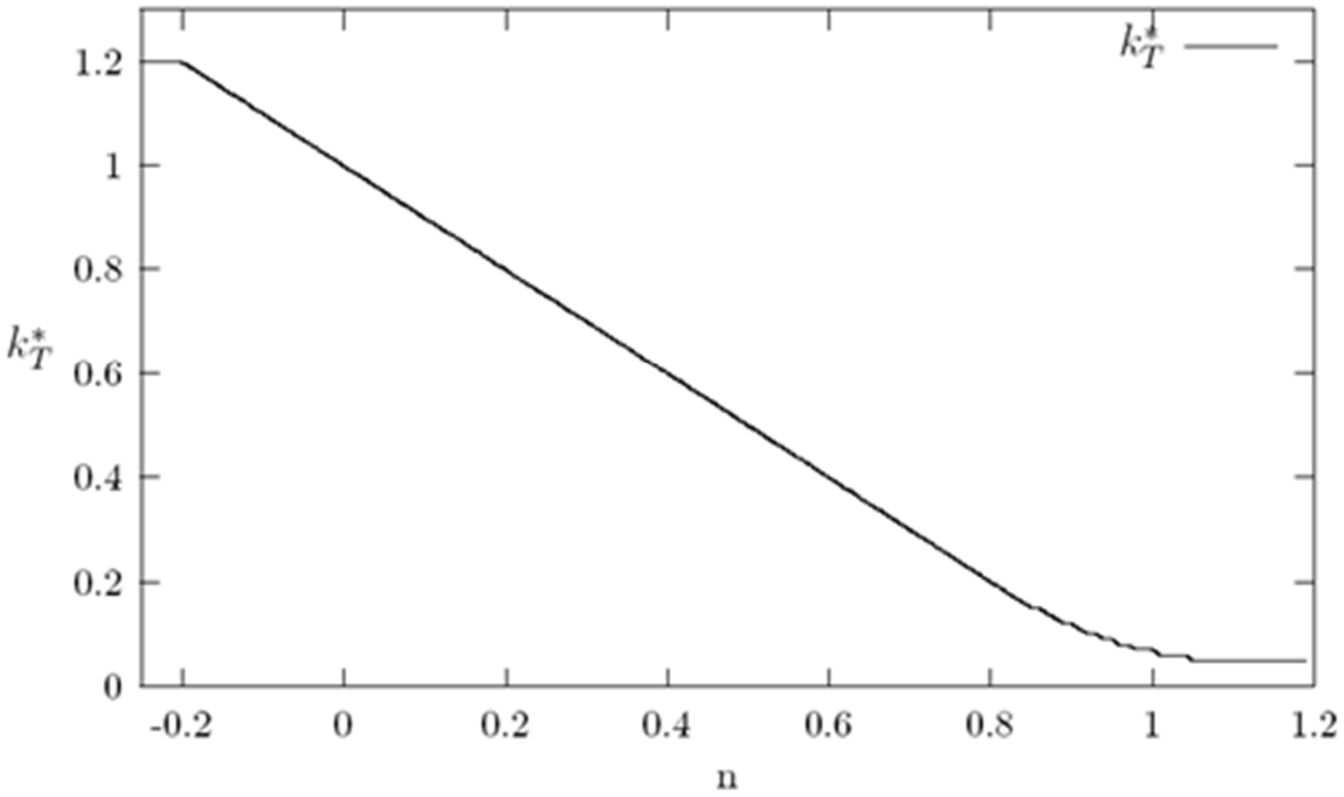






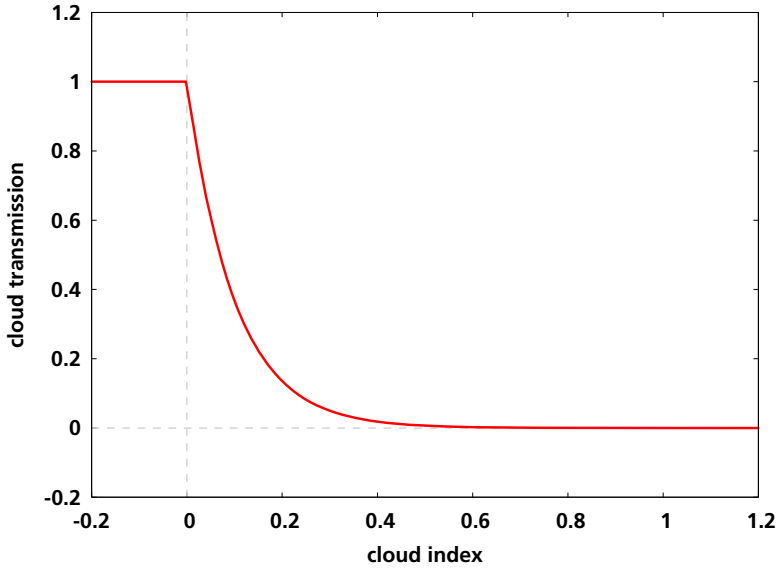
Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety — based on a decision of the Parliament of the Federal Republic of Germany

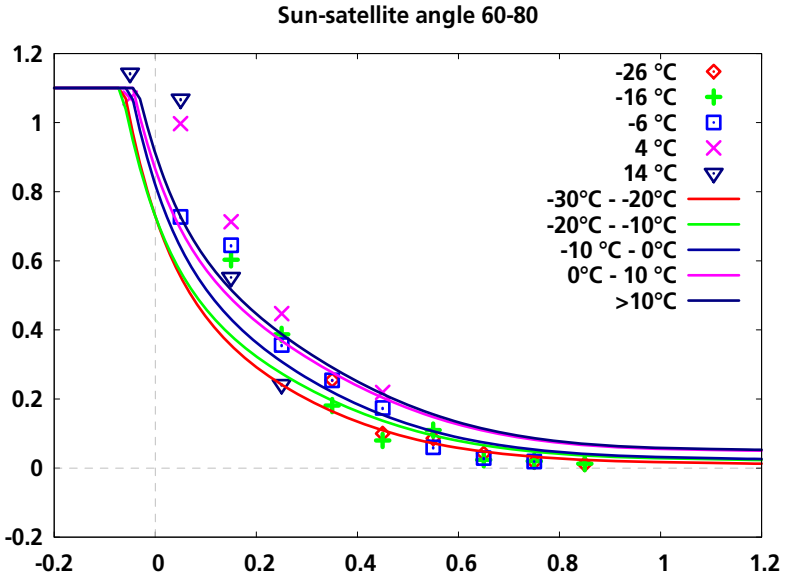
Cloud Transmission for GHI



Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Cloud Transmission for DNI



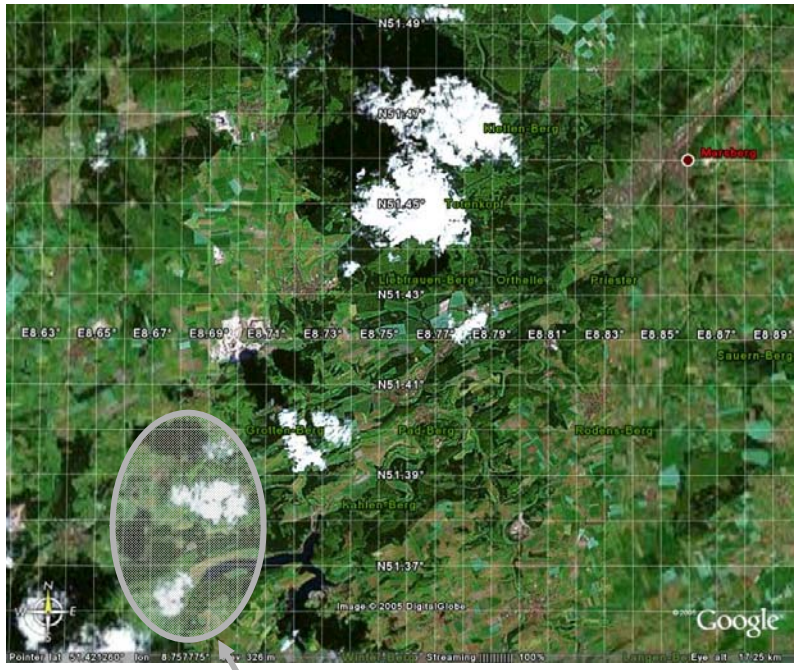


Simple function $\tau = e^{-10*ci}$

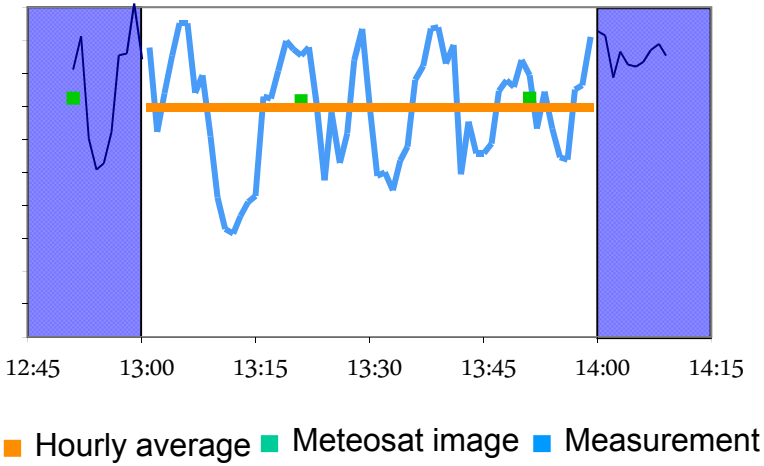
Complex functions:
Different exp. function for various viewing angles and brightness temperatures

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Comparing ground and satellite data: time scales



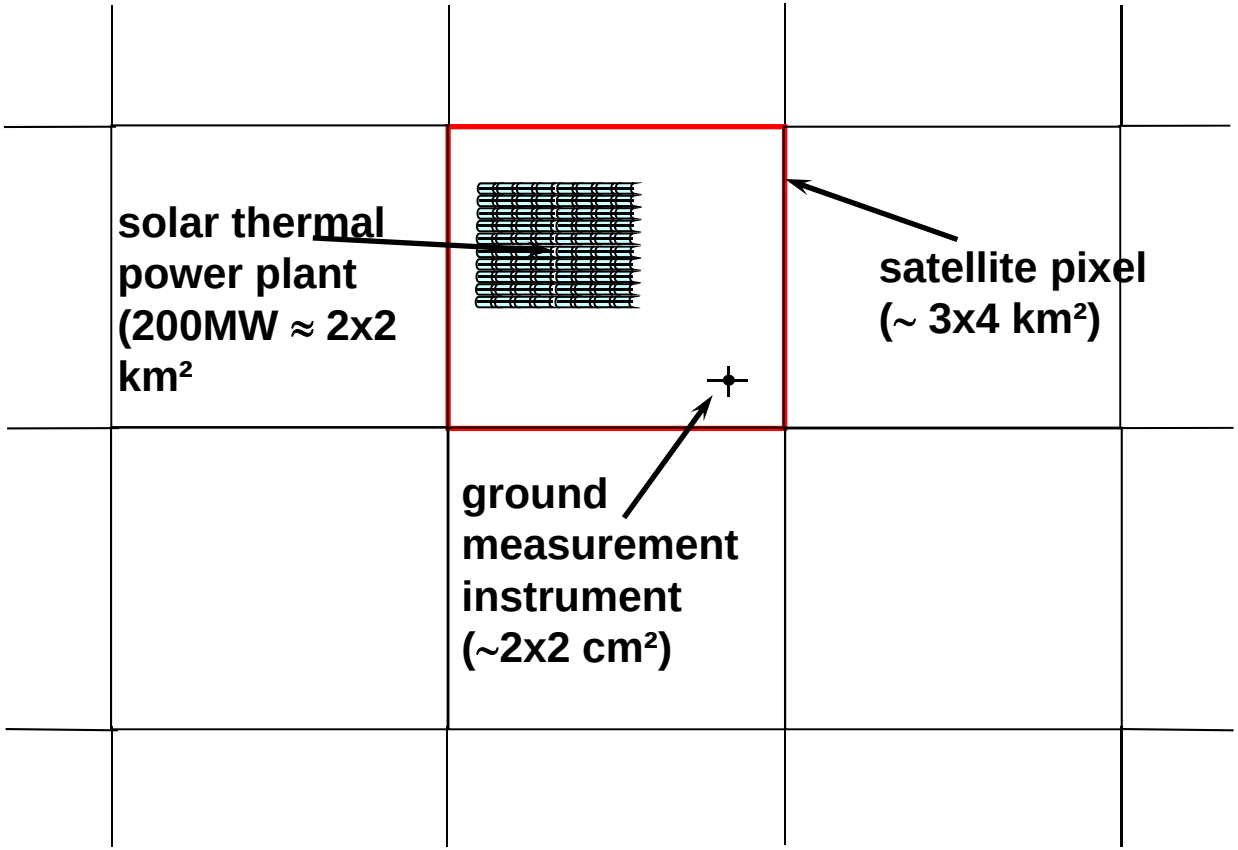
Hi-res satellite pixel in Europe



- Ground measurements are typically pin point measurements which are temporally integrated
- Satellite measurements are instantaneous spatial averages
- Hourly values are calculated from temporal and spatial averaging (cloud movement)

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

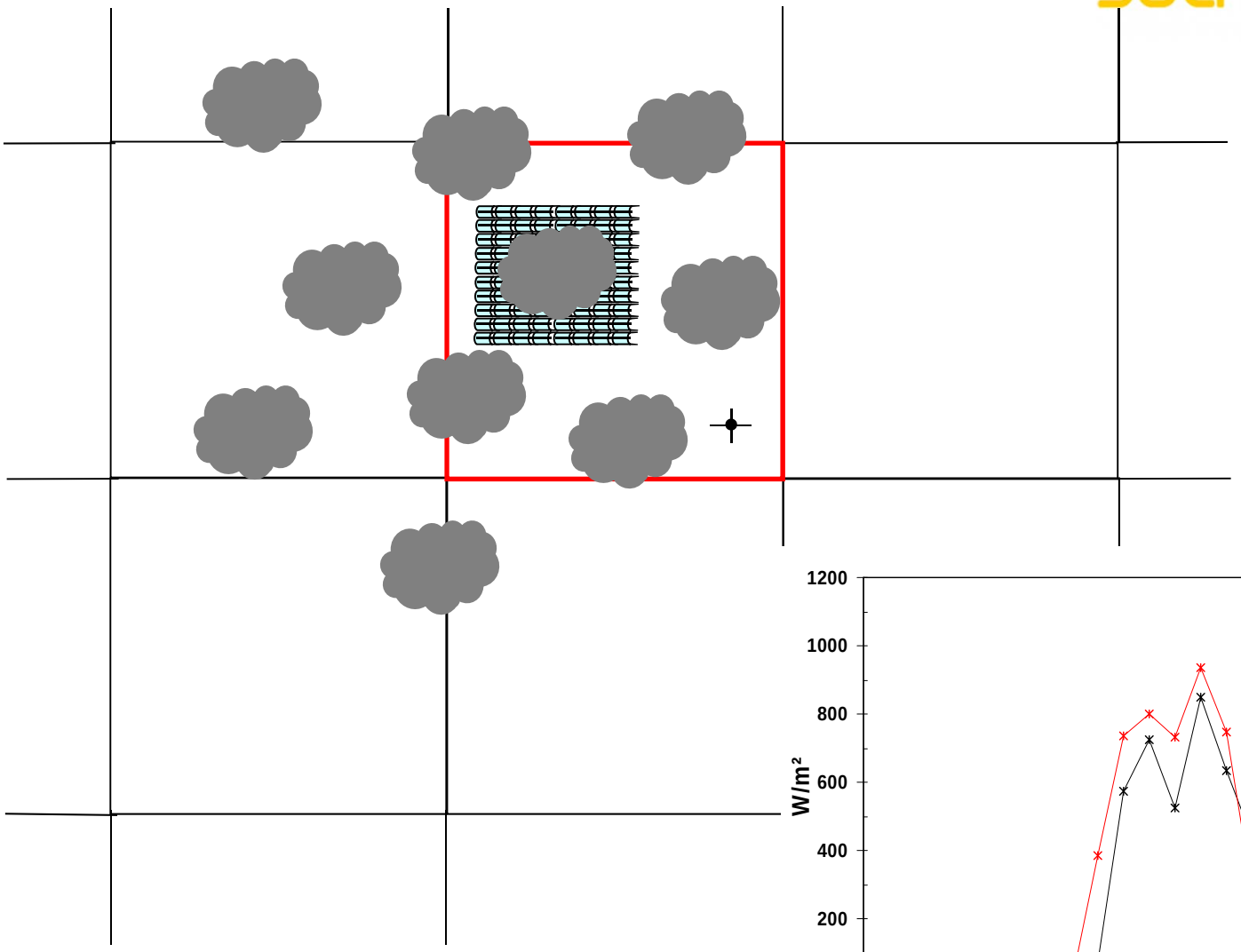
Comparing ground and satellite data: “sensor size”

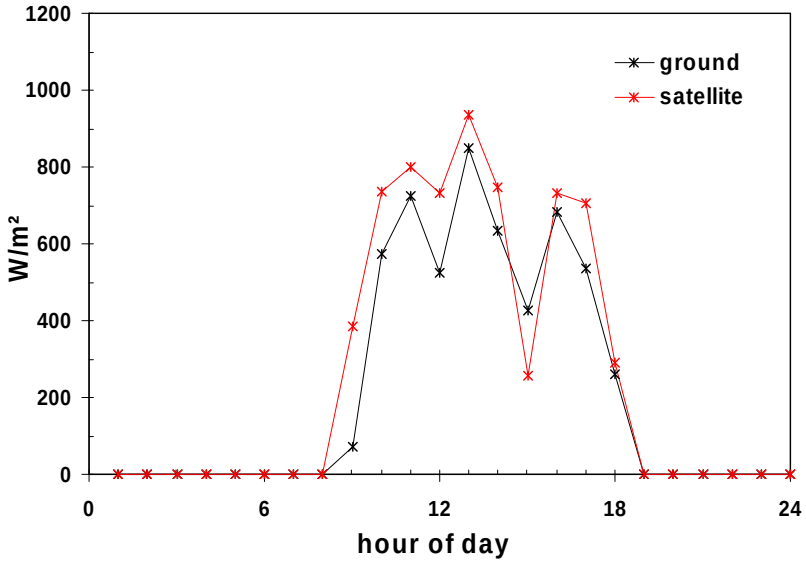


Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Comparison with ground measurements and accuracy

general difficulties: *point versus area* and *time integrated versus area integrated*

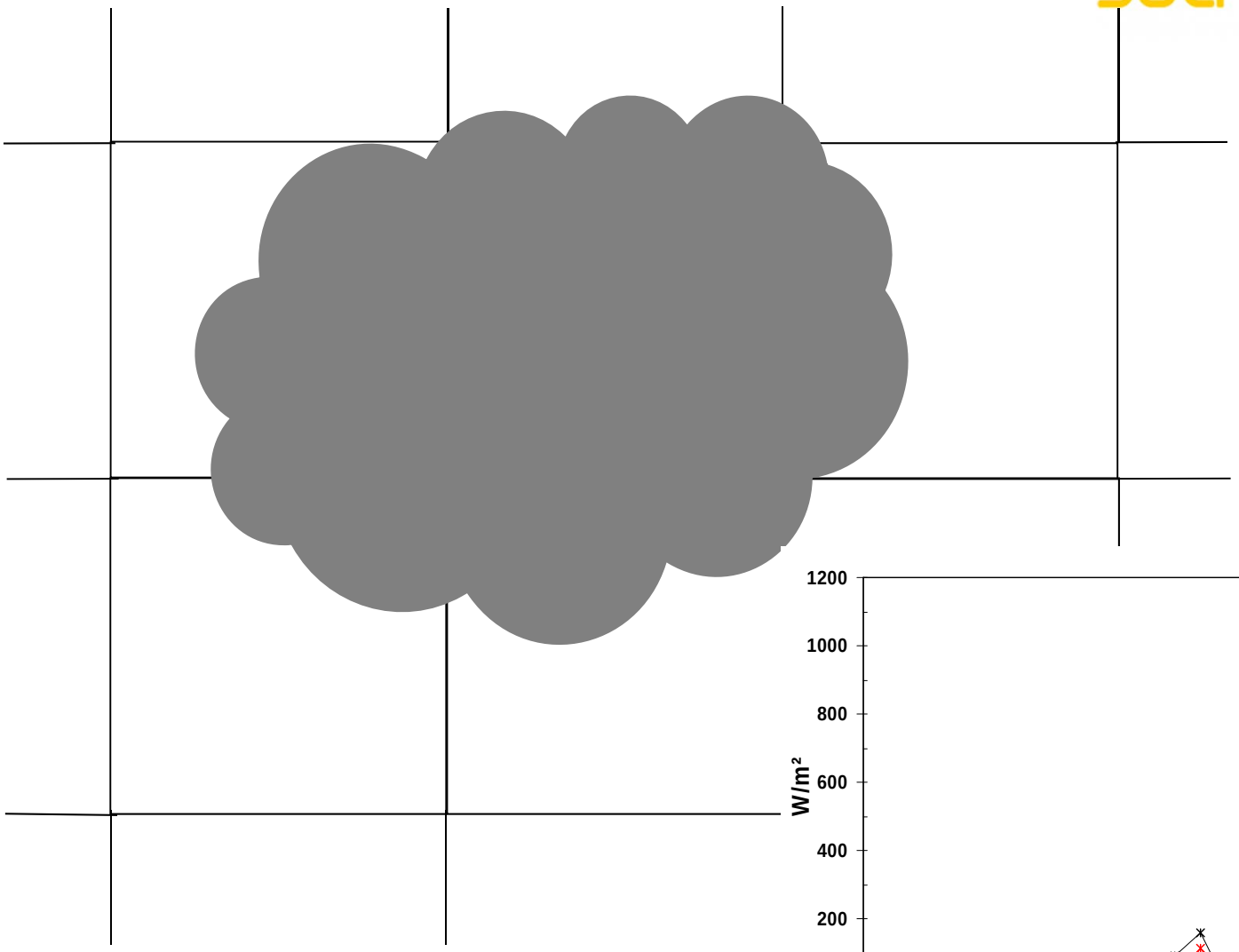


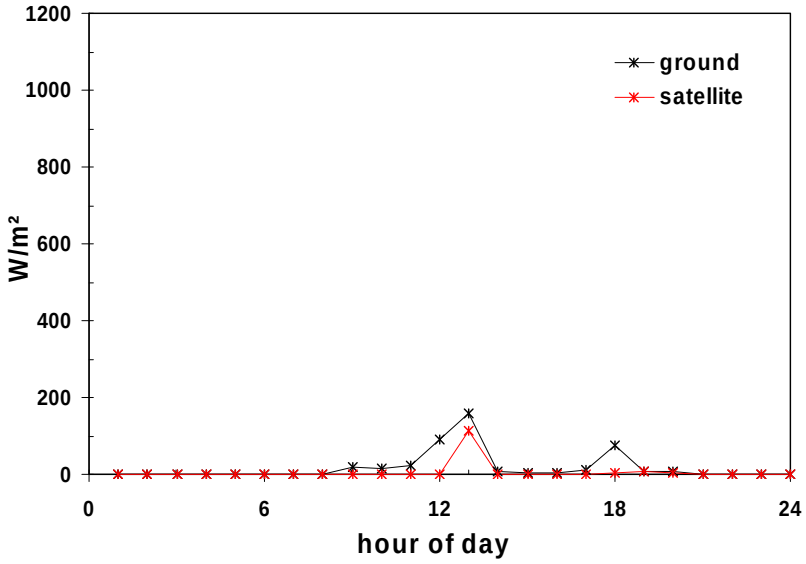


DNI time serie for 1.11.2001, Almería
Partially cloudy conditions, cumulus humilis

Comparison with ground measurements and accuracy

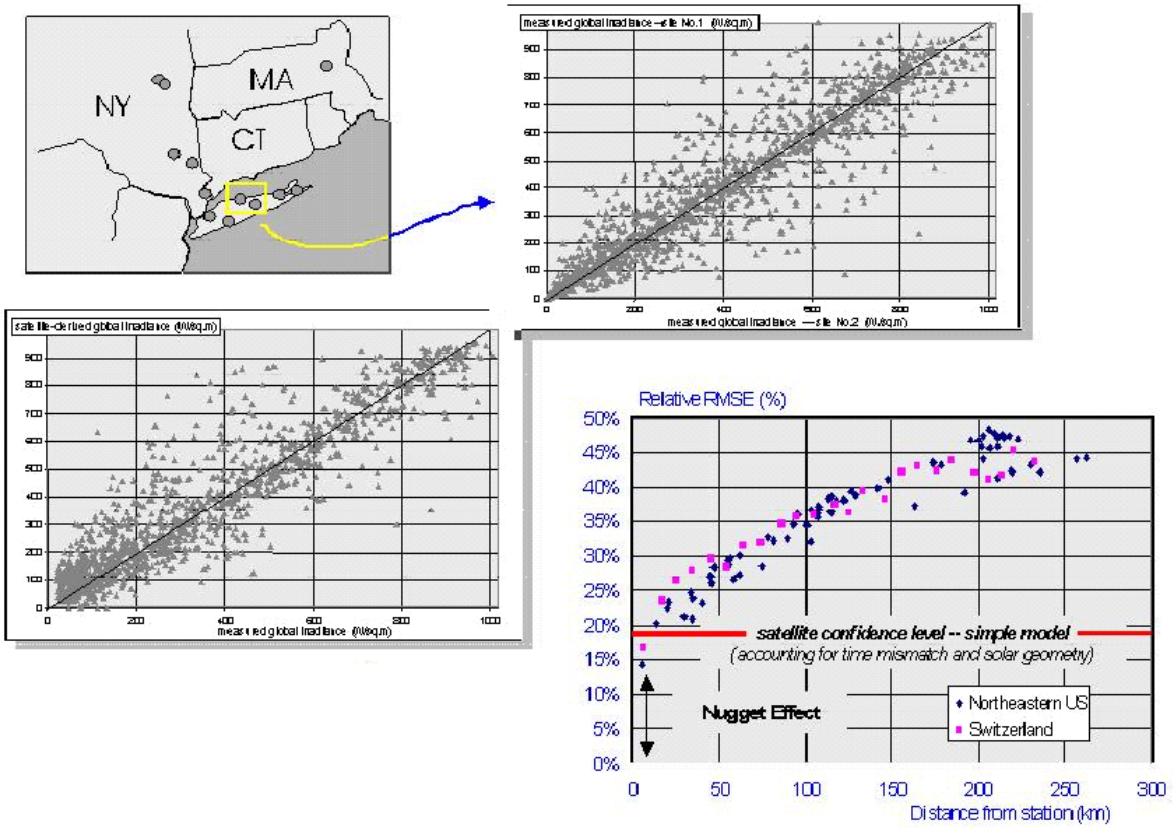
general difficulties: *point versus area* and *time integrated versus area integrated*





DNI time serie for 30.4.2000, Almería
overcast conditions, strato cumulus

Satellite data and nearest neighbour stations

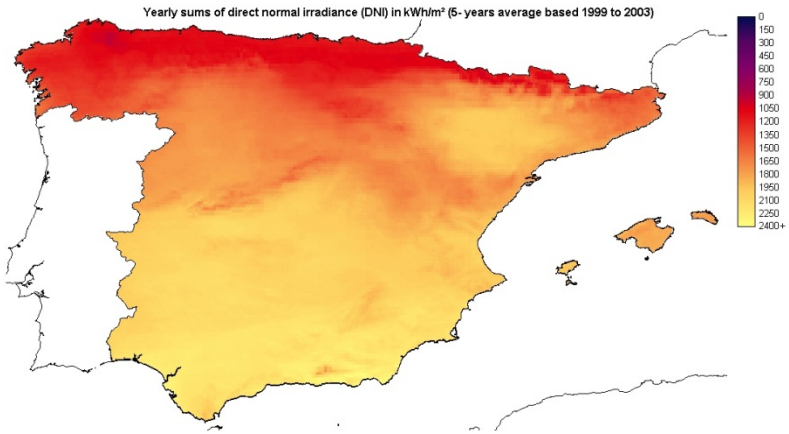


Perez et al., ASRC

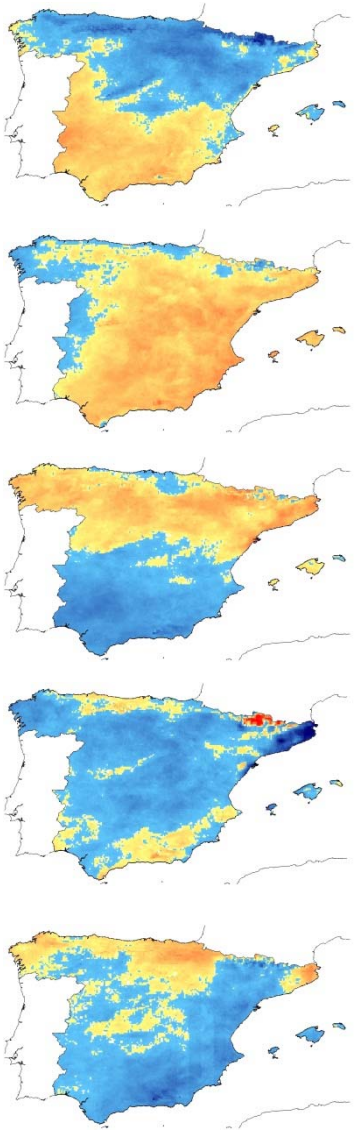
- Satellite derived data fit better to a selected site than ground measurements from a site farther than 25 km away.

Inter annual variability

- Strong inter annual and regional variations



Average of the direct normal irradiance from 1999-2003



1999

2000

2001

2002

2003

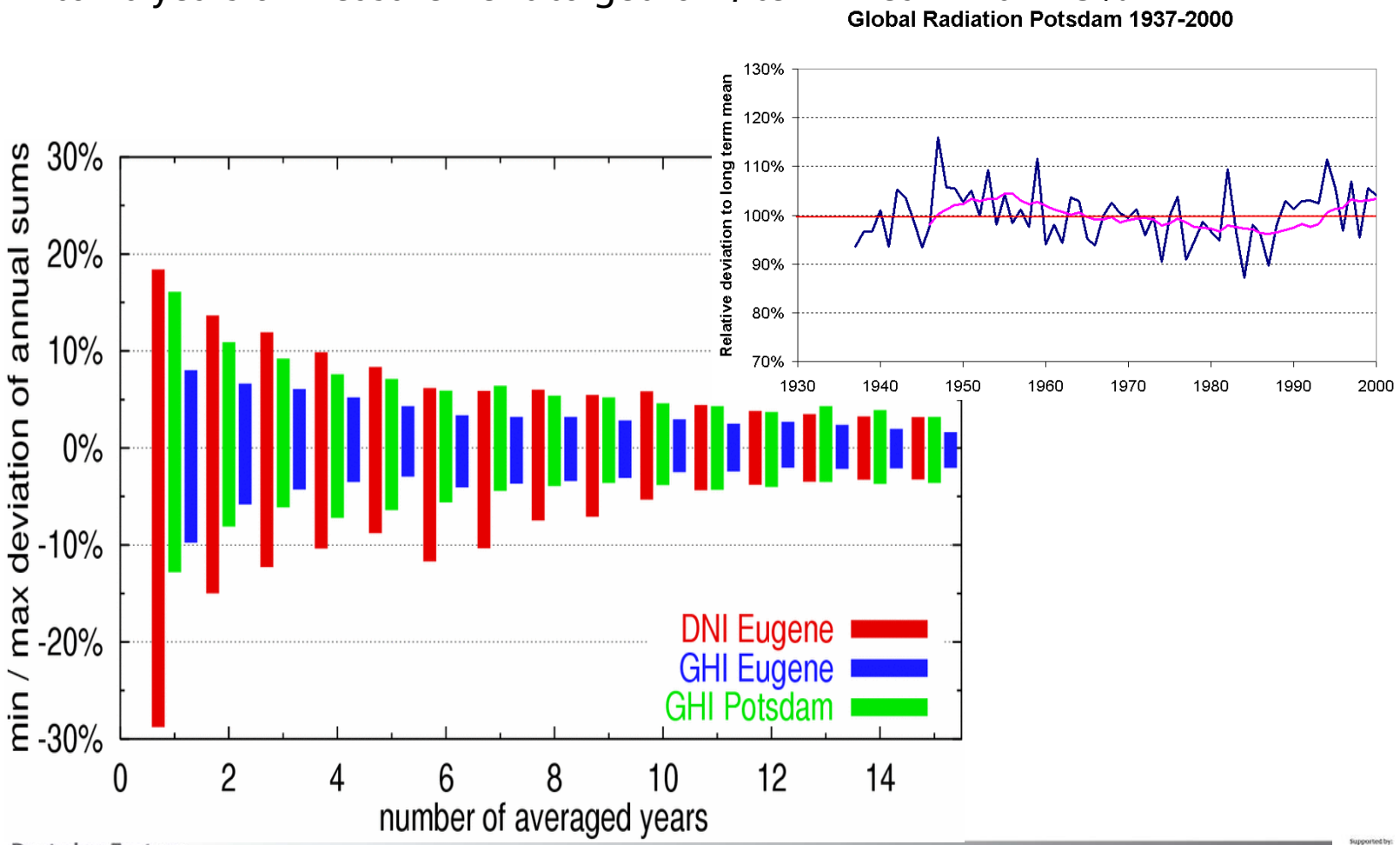
deviation to mean

<-350
-306
-263
-219
-175
-131
-88
-44
0
44
88
131
175
219
263
306
350
kWh/m²a

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Long-term variability of solar irradiance

- 7 to 10 years of measurement to get long-term mean within 5%



Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety — based on a decision of the Parliament of the Federal Republic of Germany

Ground measurements vs. satellite derived data

Ground measurements

Advantages

+ high accuracy *(depending on sensors)*
+ high time resolution

Disadvantages

- high costs for installation and O&M
- soiling of the sensors
- sometimes sensor failure
- no possibility to gain data of the past

Satellite data

Advantages

+ spatial resolution
+ long-term data *(more than 20 years)*
+ effectively no failures
+ no soiling
+ no ground site necessary
+ low costs

Disadvantages

- lower time resolution
- low accuracy at high time resolution

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Combining Ground and Satellite Assessments

- Satellite data
  - Long term average
  - Year to year variability
  - Regional assessment

- Ground data
  - Site specific
  - High temporal resolution possible
    (up to 1 min to model transient effects)
  - Good distribution function

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Matching Ground and Satellite Data

Why do ground and satellite data not match?

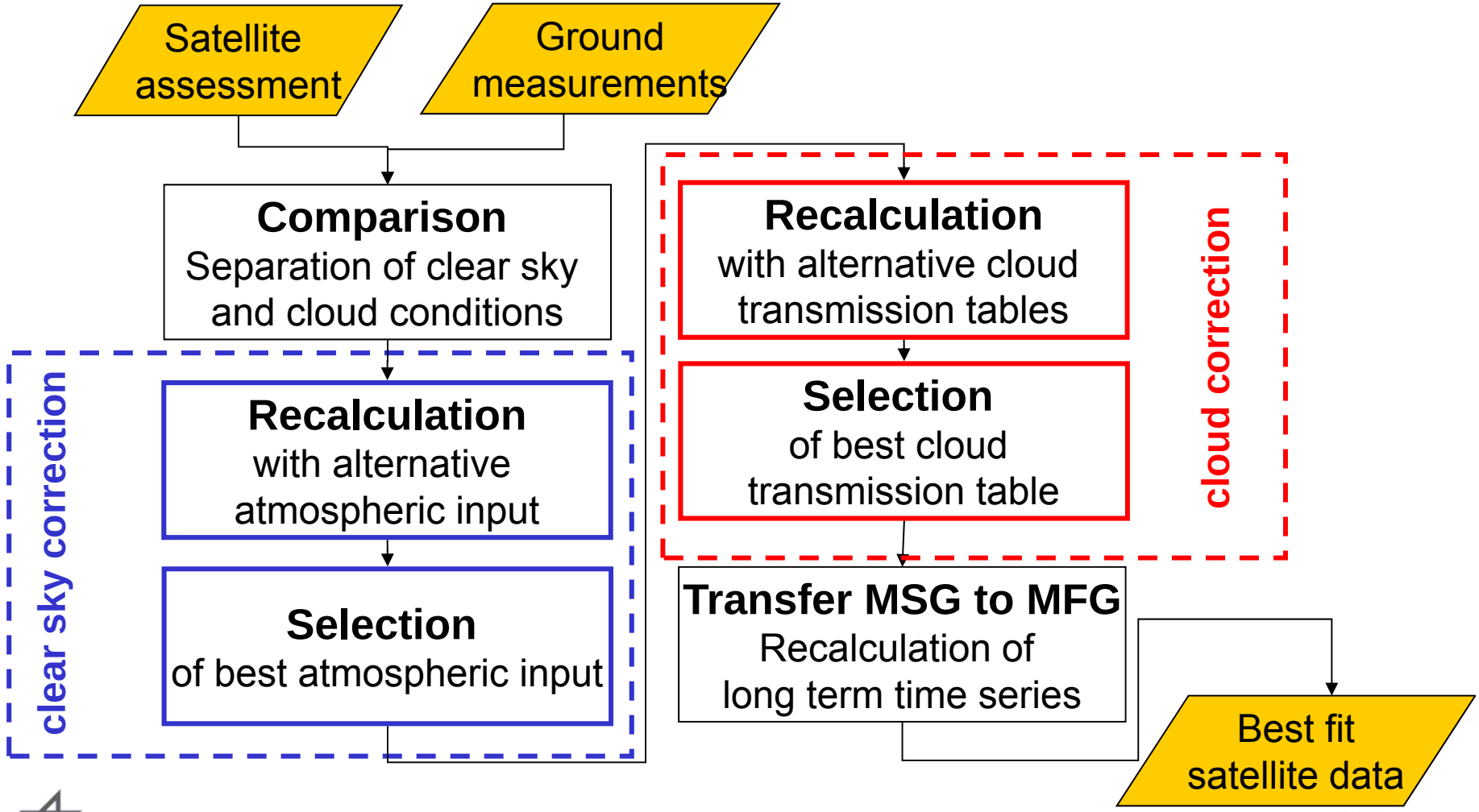
Due to uncertainties in:

- Atmospheric Parameters, most prominent Aerosols

- Cloud transmission:
  - The cloud index is a combination of cloud fraction and transparency. A semi transparent cloud can be distinguished well from a fractional cloud cover.
  - Parameterization may depend on prevailing cloud types in the region.

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Procedure for Matching Ground and Satellite Data



Benchmarking of Time Series Products

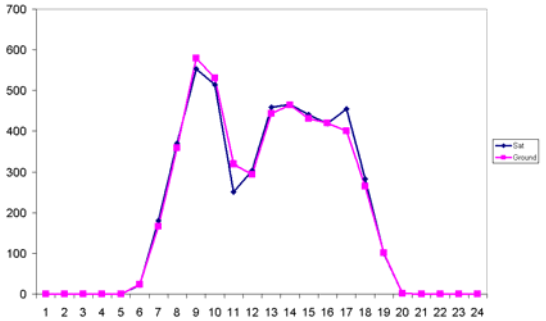
- **First order measures:**
  Bias, root mean square error, standard deviation

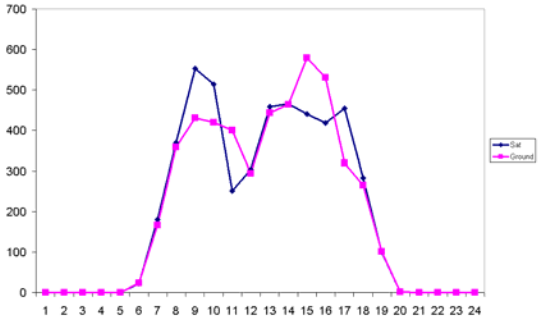
  Exact match of data pairs in time

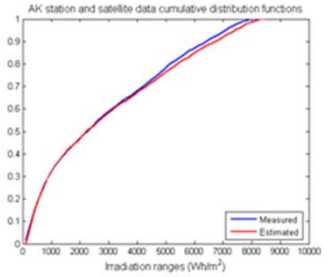
  Sometime this match is not necessary (e.g. system layout with historical data)

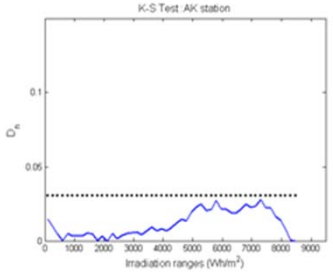
- **Second order measures:**
  Based on Kolmogrov-Smirnov Test

  Match of distribution functions







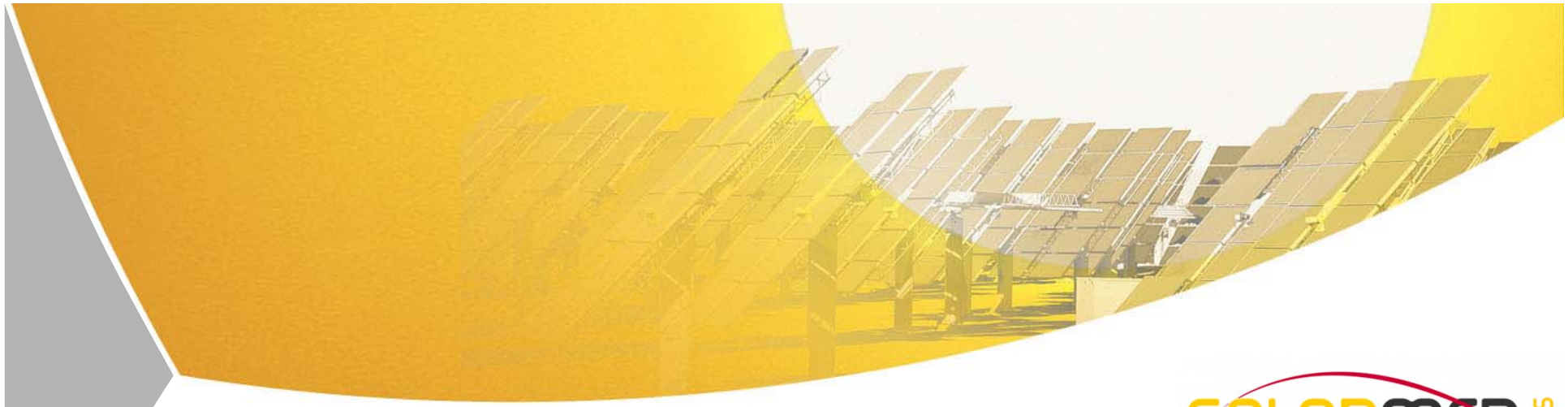


Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Validation of the MFG data base

DNI	Bias	RMSE	Correl. Coeff
overall	-3.78%	27.52%	0.86
PSA	0.65	30.25%	0.89
SedeBoqer	-6.86%	29.01%	0.84
Tamanrasset	-5.83%	25.22%	0.84

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany



Using Solar Resource Data for Policy Analysis

Policy questions

- How potential is there for a certain technology?
- Are there prime areas to develop a technology?

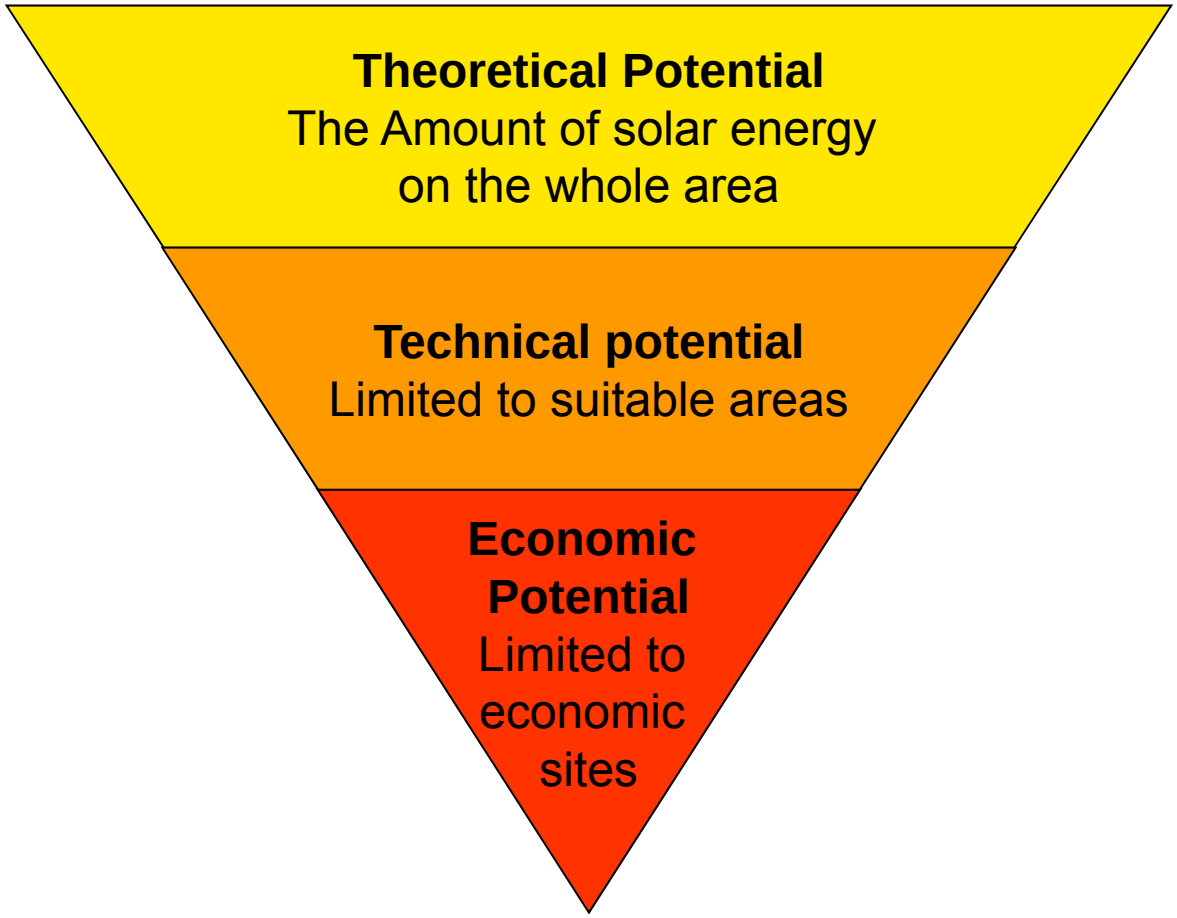
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

1st Question: How much Potential?

- Is the technology feasible, are there enough resources?
- Is there sufficient area to depoly the technology?
- To which share of the (national) demand can they contribute?

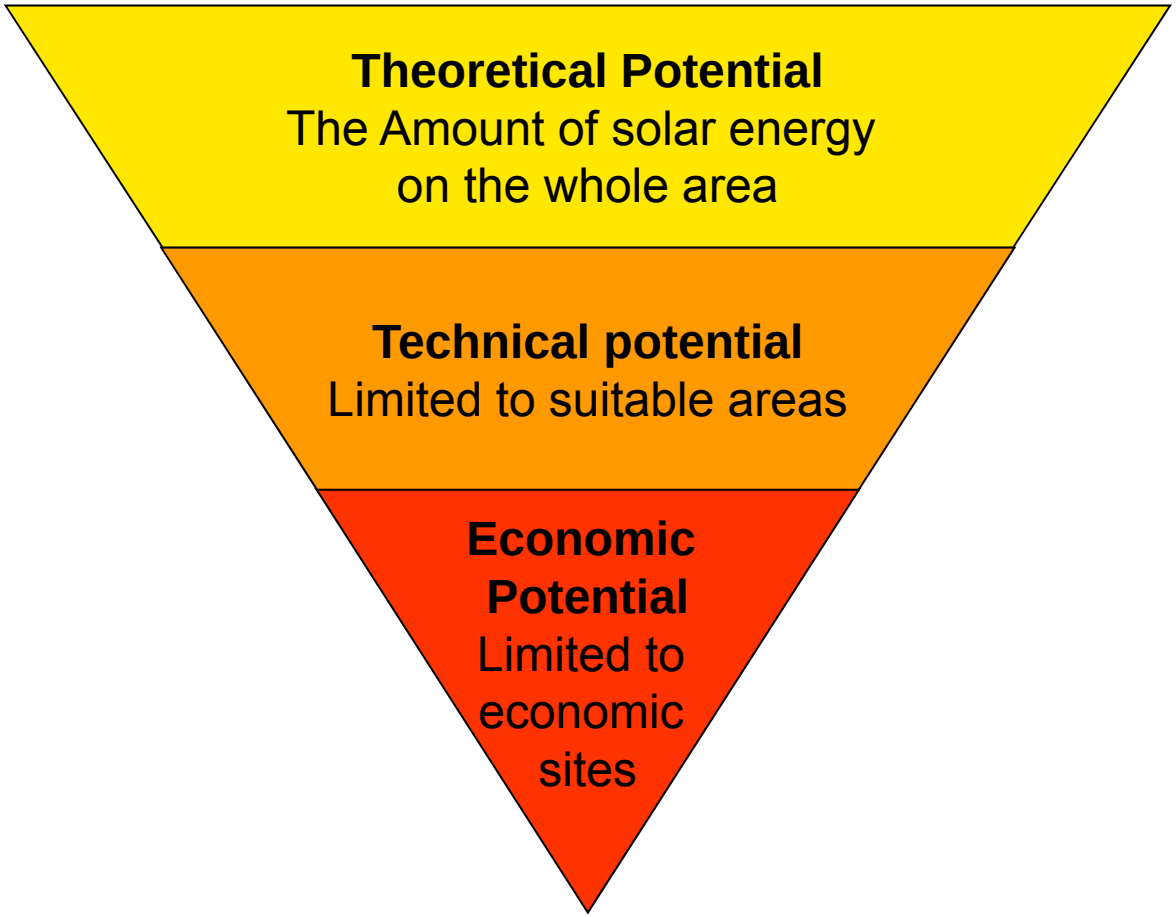
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Assessing Potentials - Outline



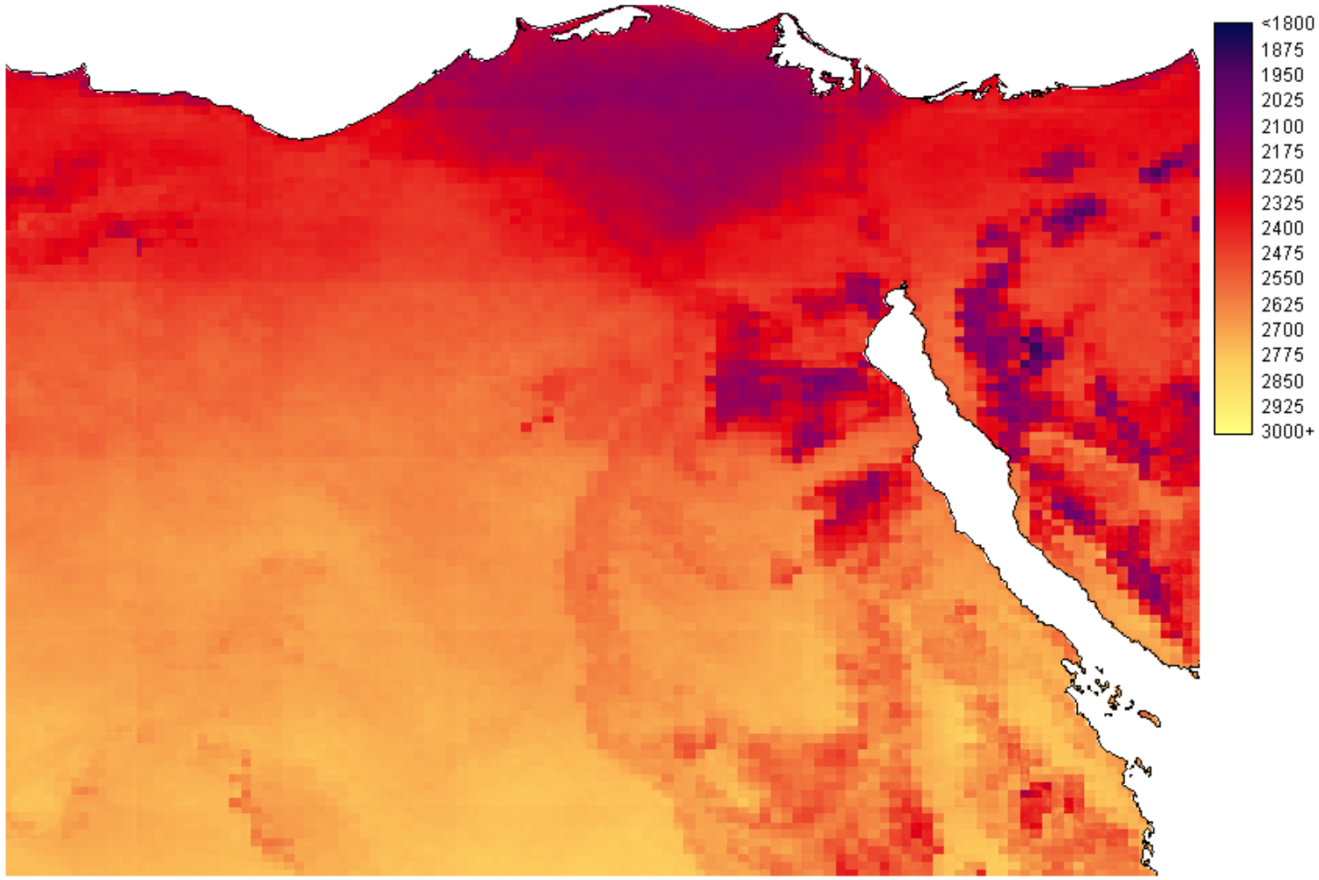
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Assessing Potentials – CSP Sample



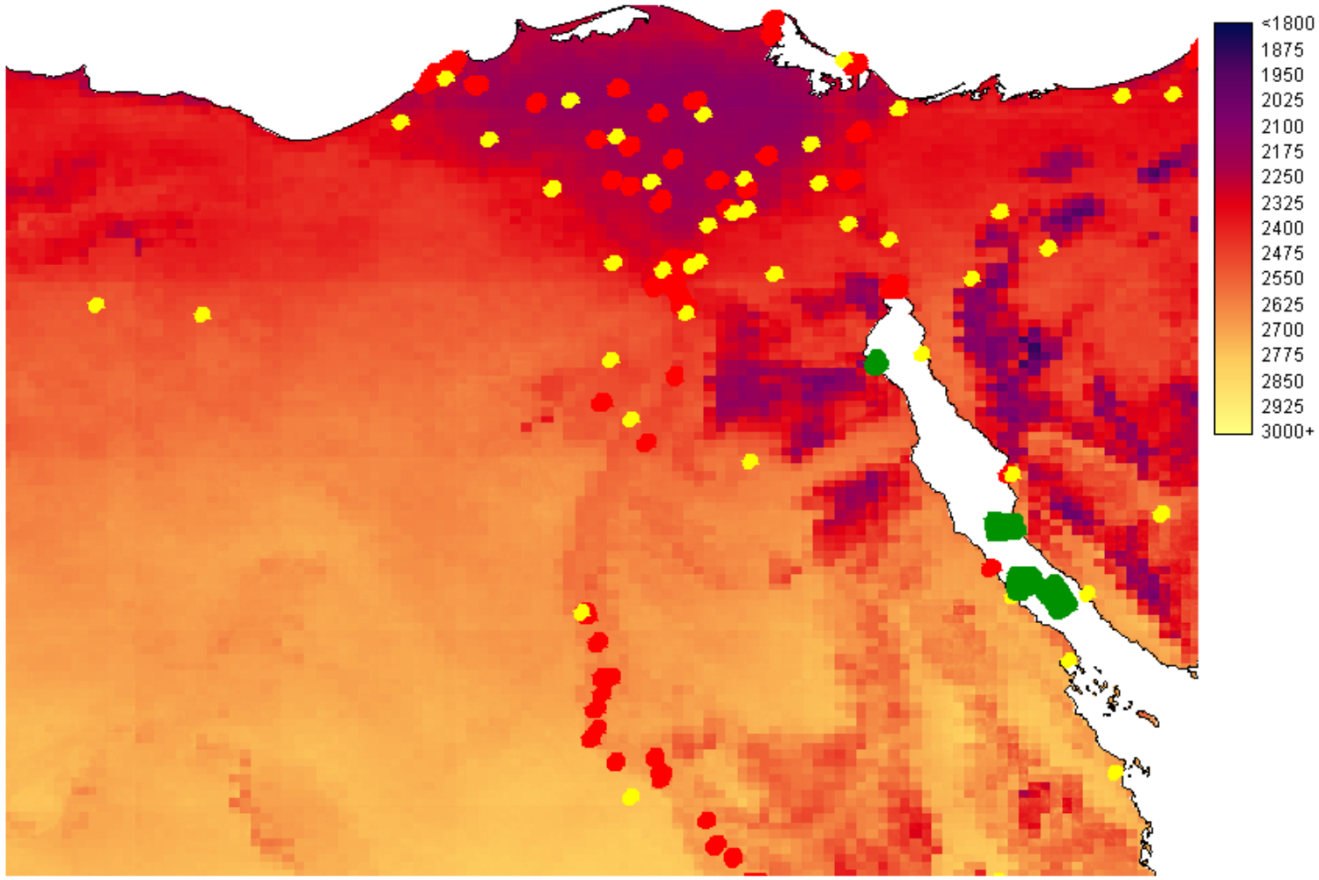
- DNI map of the region
- DNI map minus excluded areas
- Technical potential only for DNI e.g. above 2000 kWh/m²

Assessment of Potentials, e.g. Large Solar



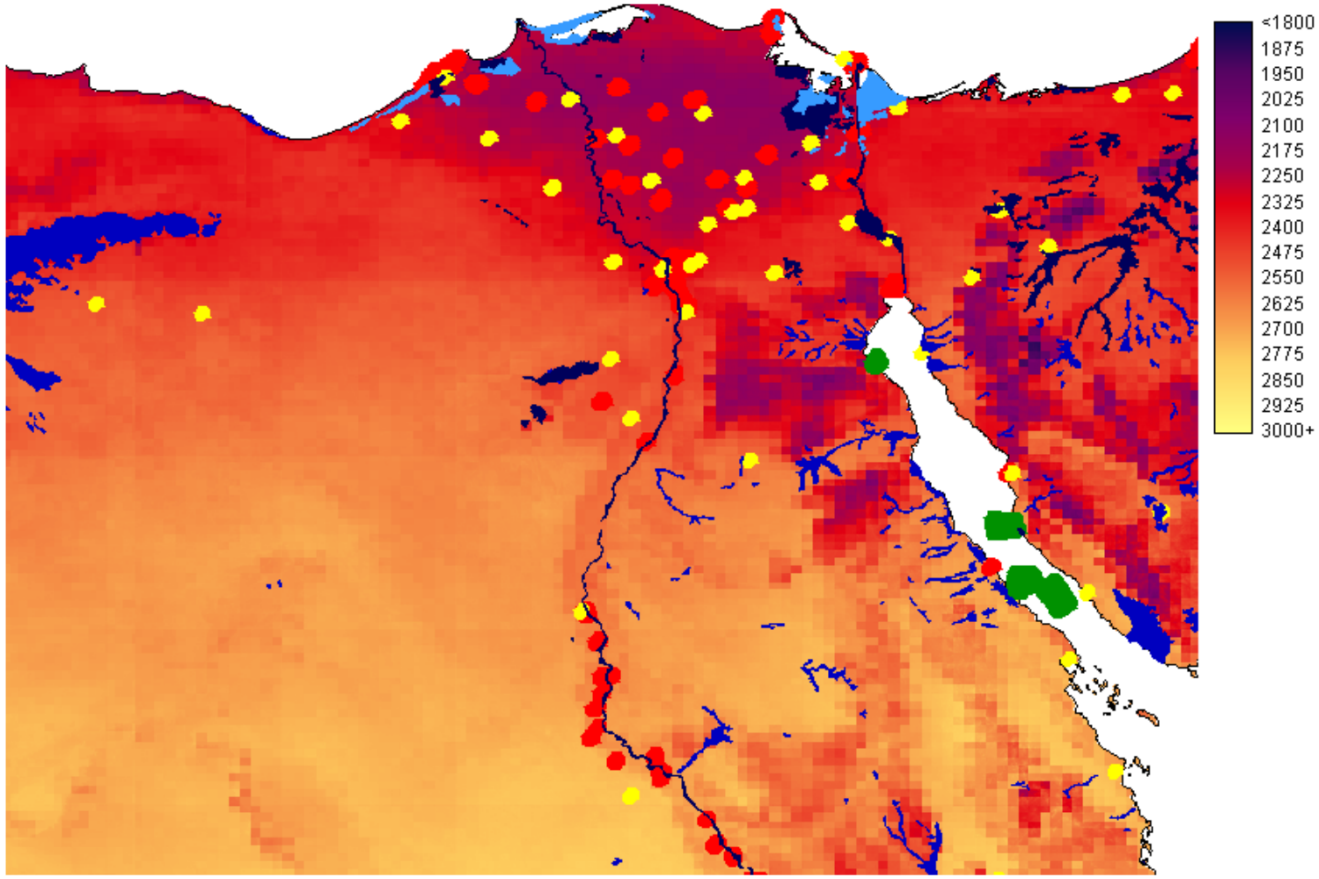
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Assessment of Potentials, e.g. Large Solar



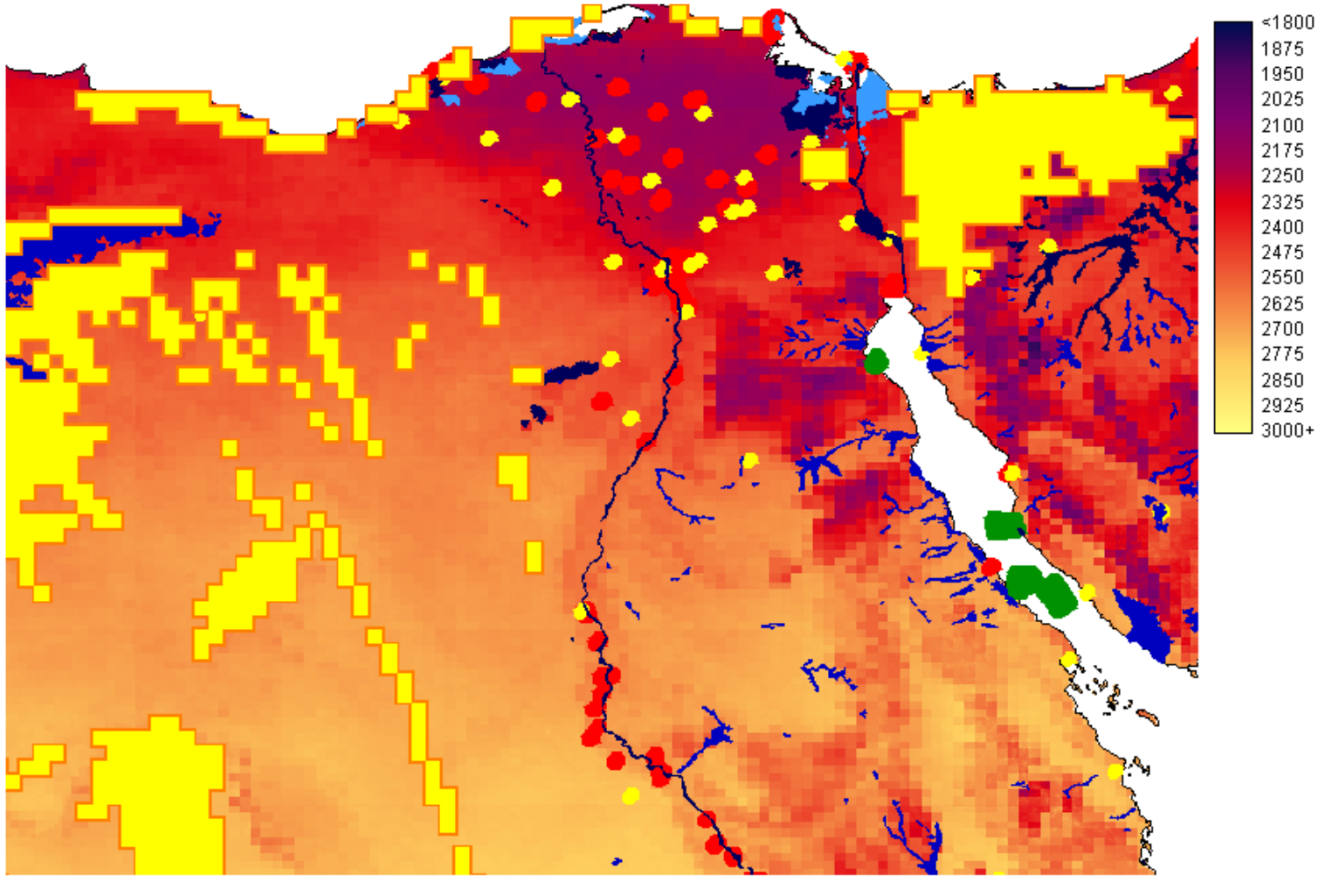
+ Industry, settlements

Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology

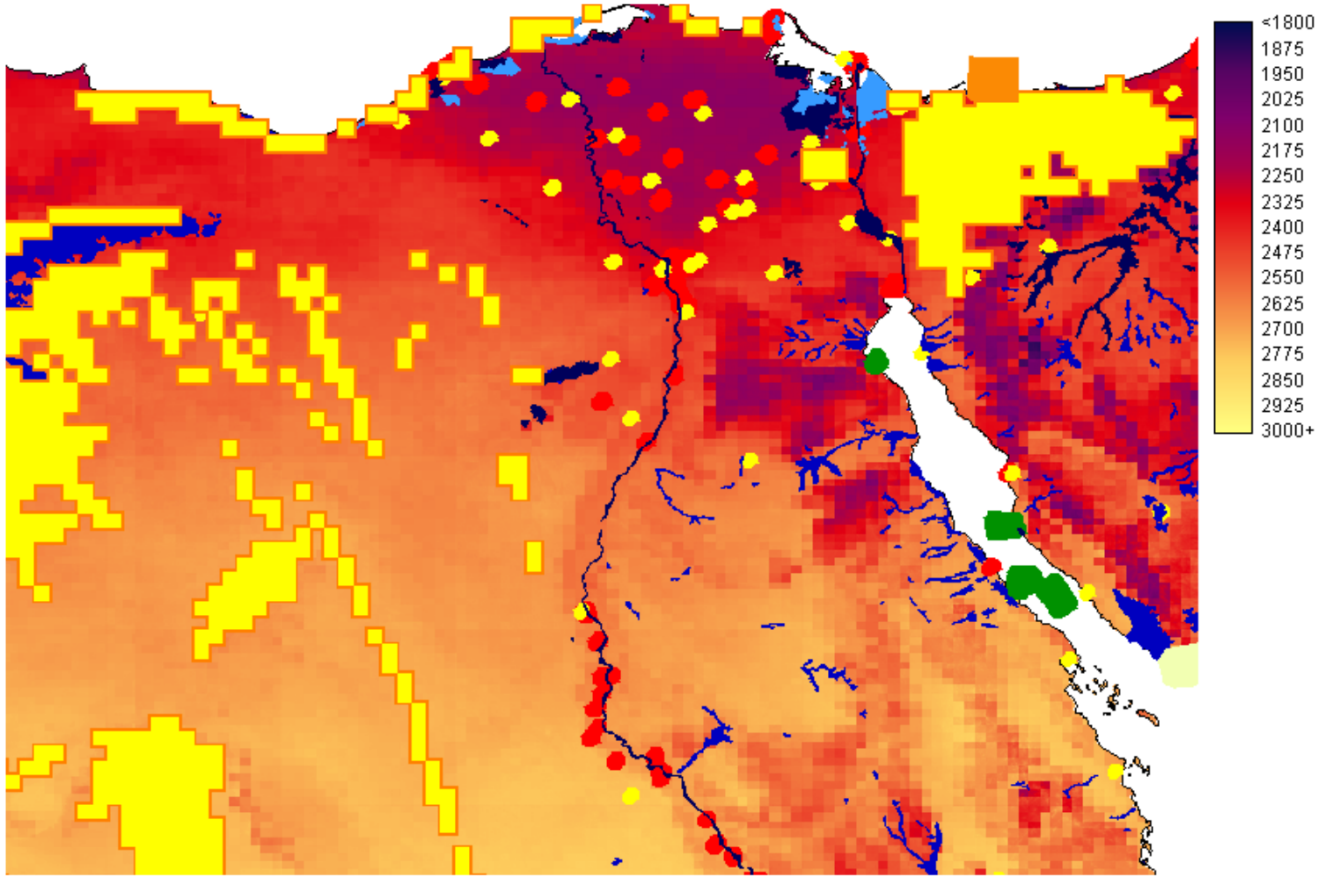
Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology
+ Geomorphology

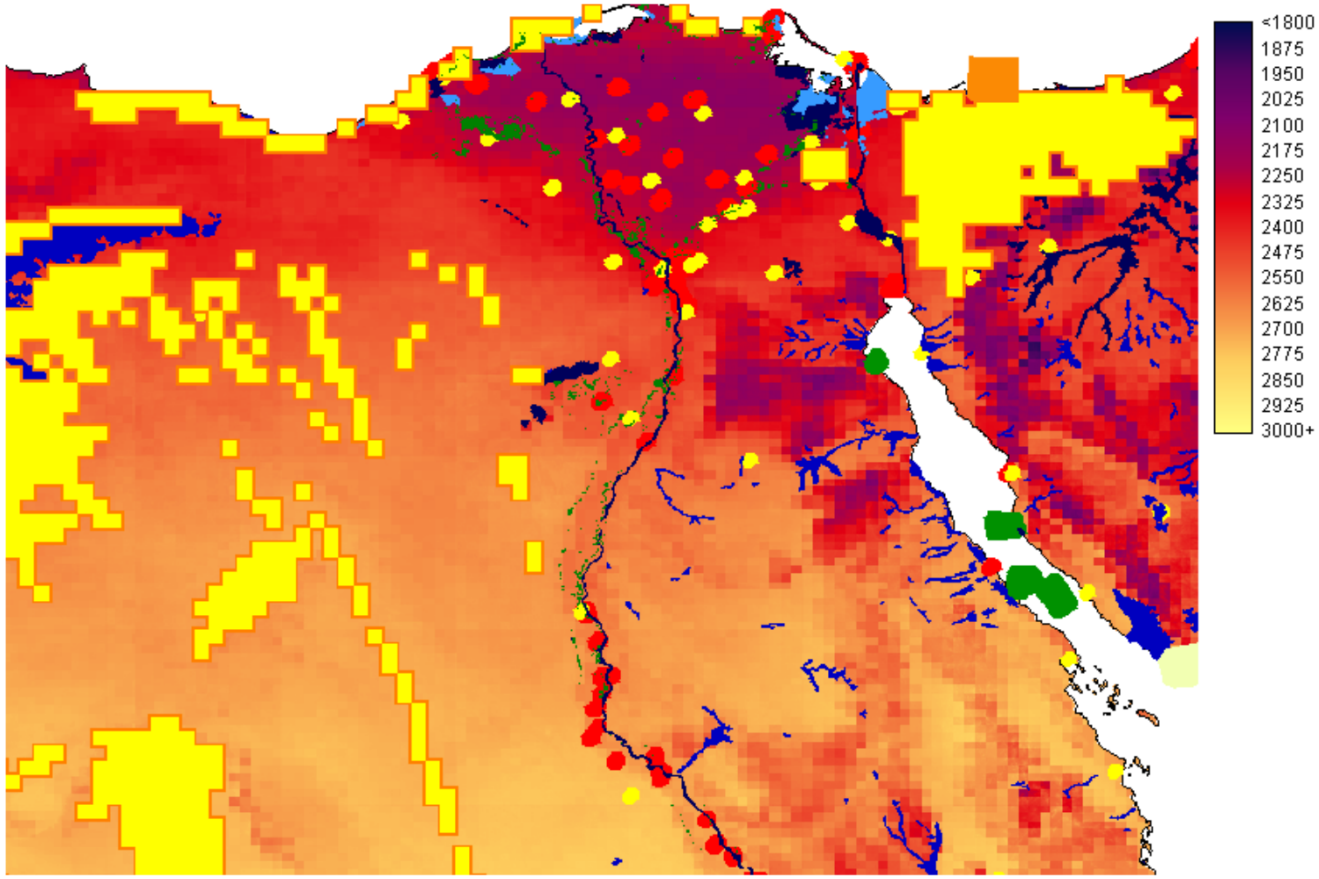
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology
+ Geomorphology
+ Protected Areas

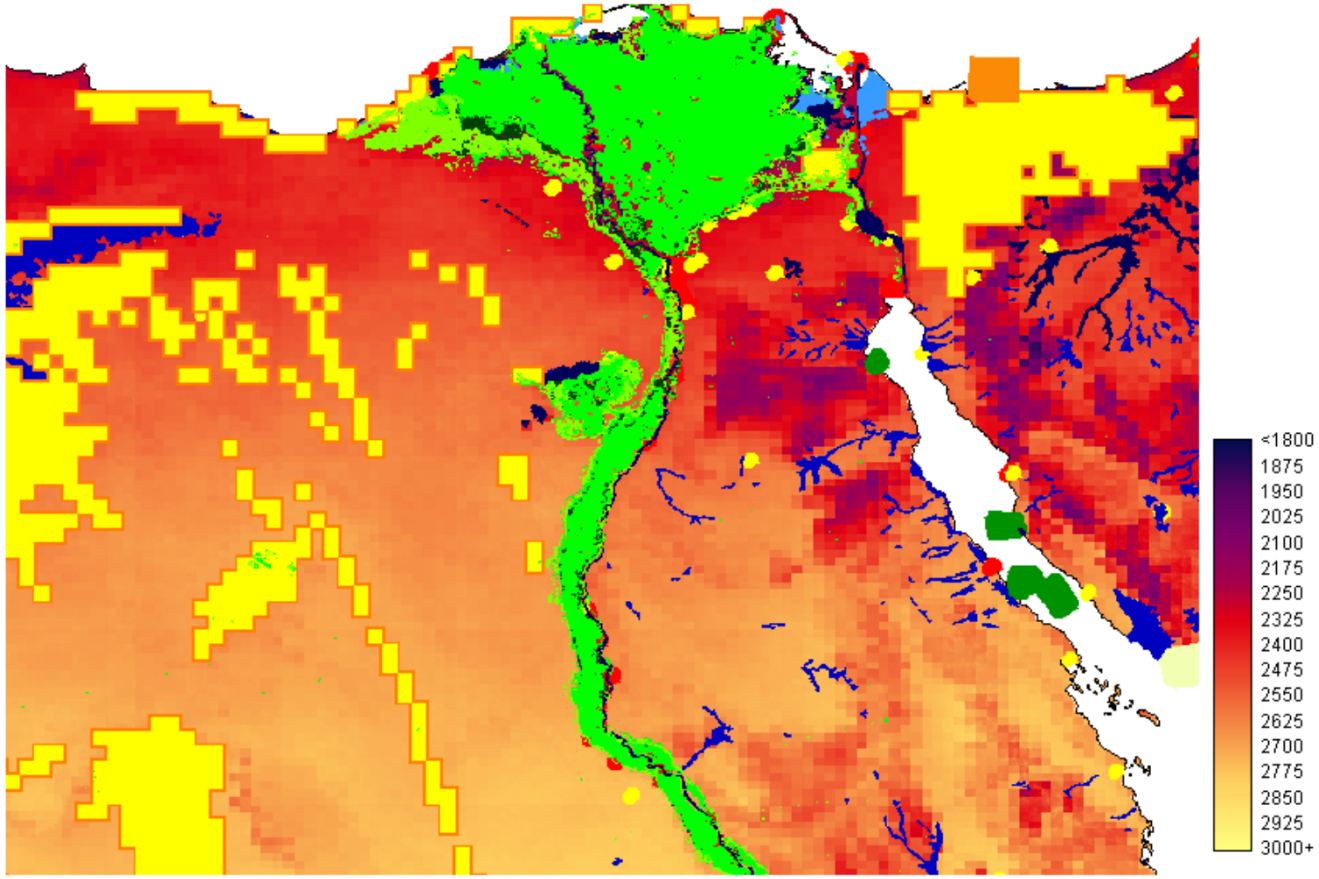
Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology
+ Geomorphology
+ Protected Areas
+ Wood

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

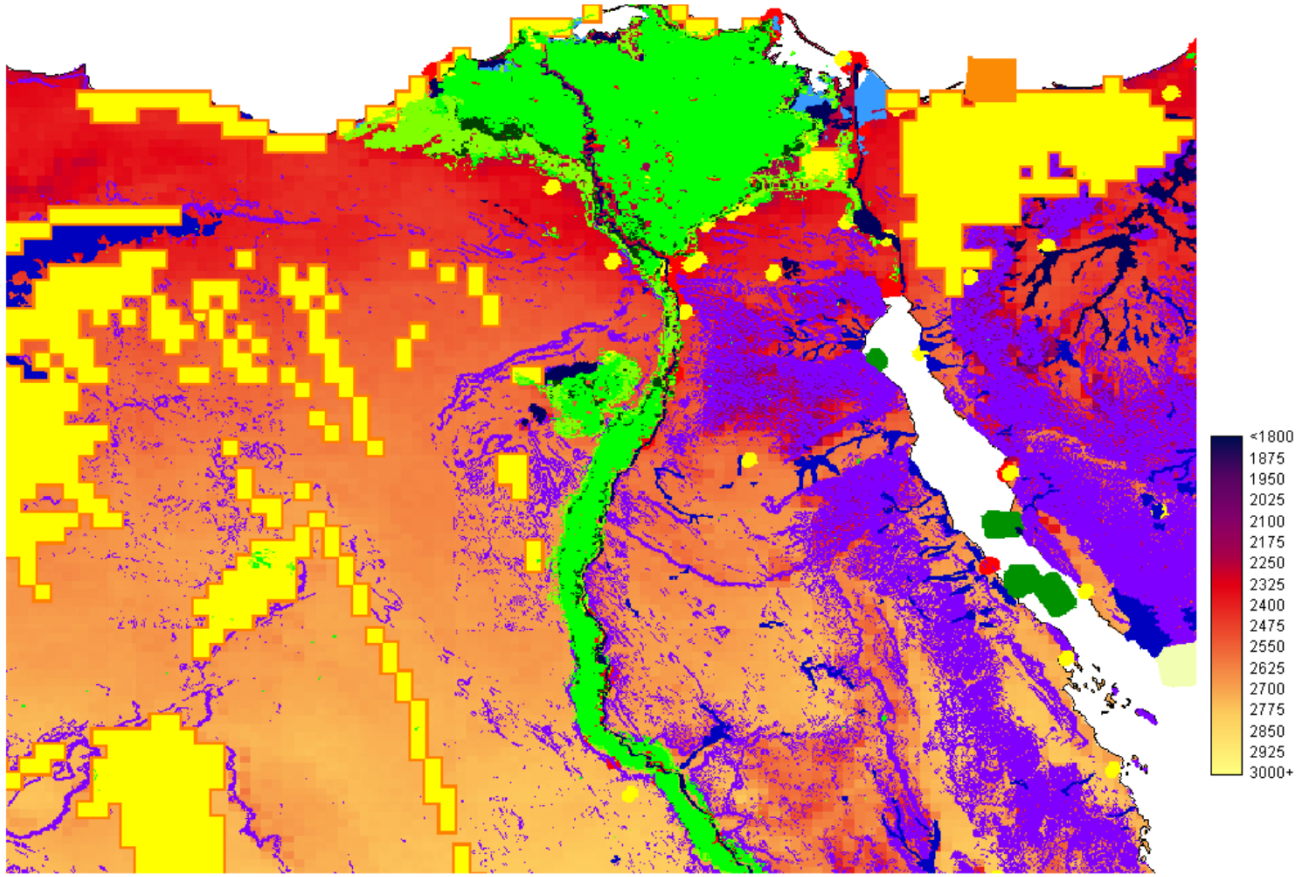
Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology
+ Geomorphology
+ Protected Areas
+ Wood
+ Agriculture

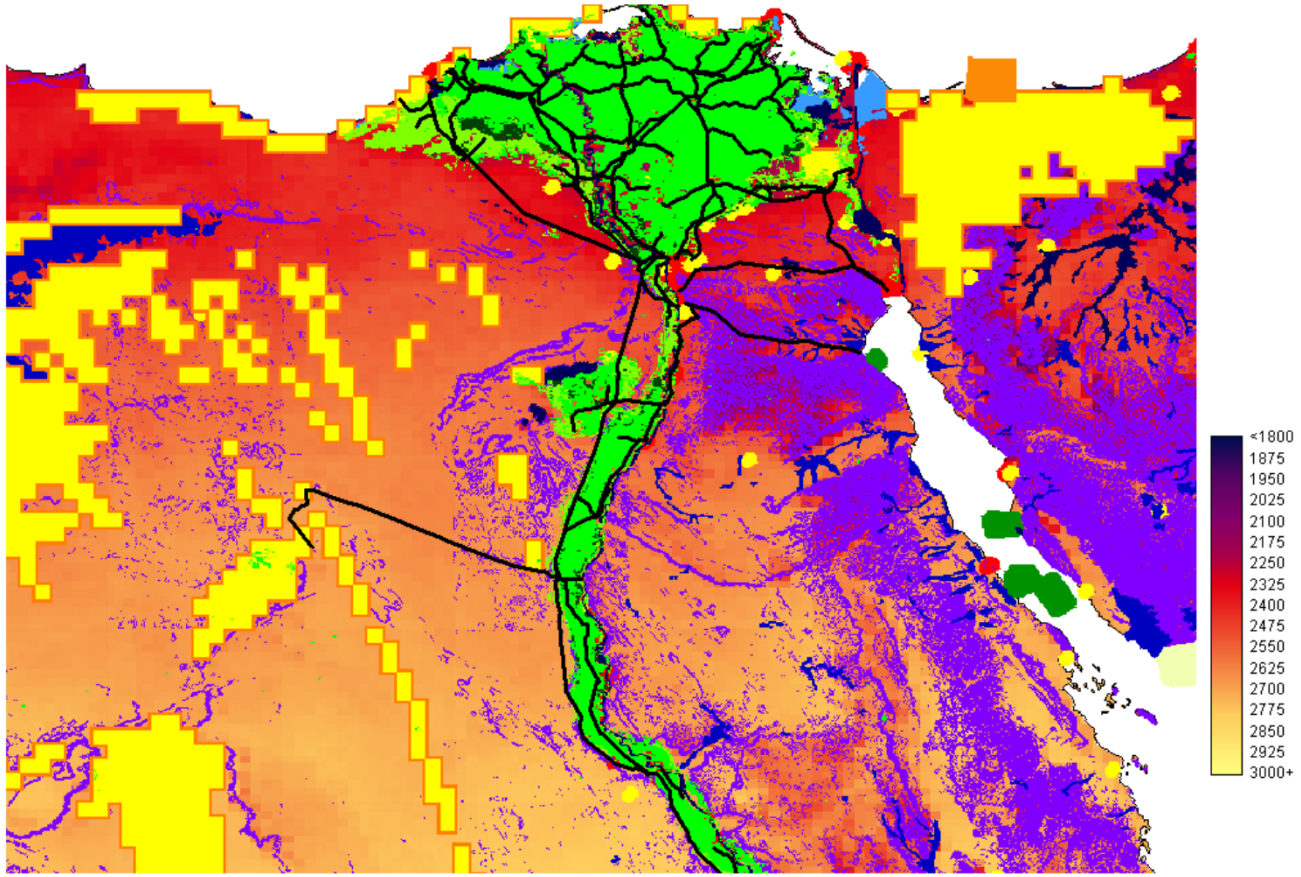
Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology
+ Geomorphology
+ Protected Areas
+ Wood
+ Agriculture
+ Slope

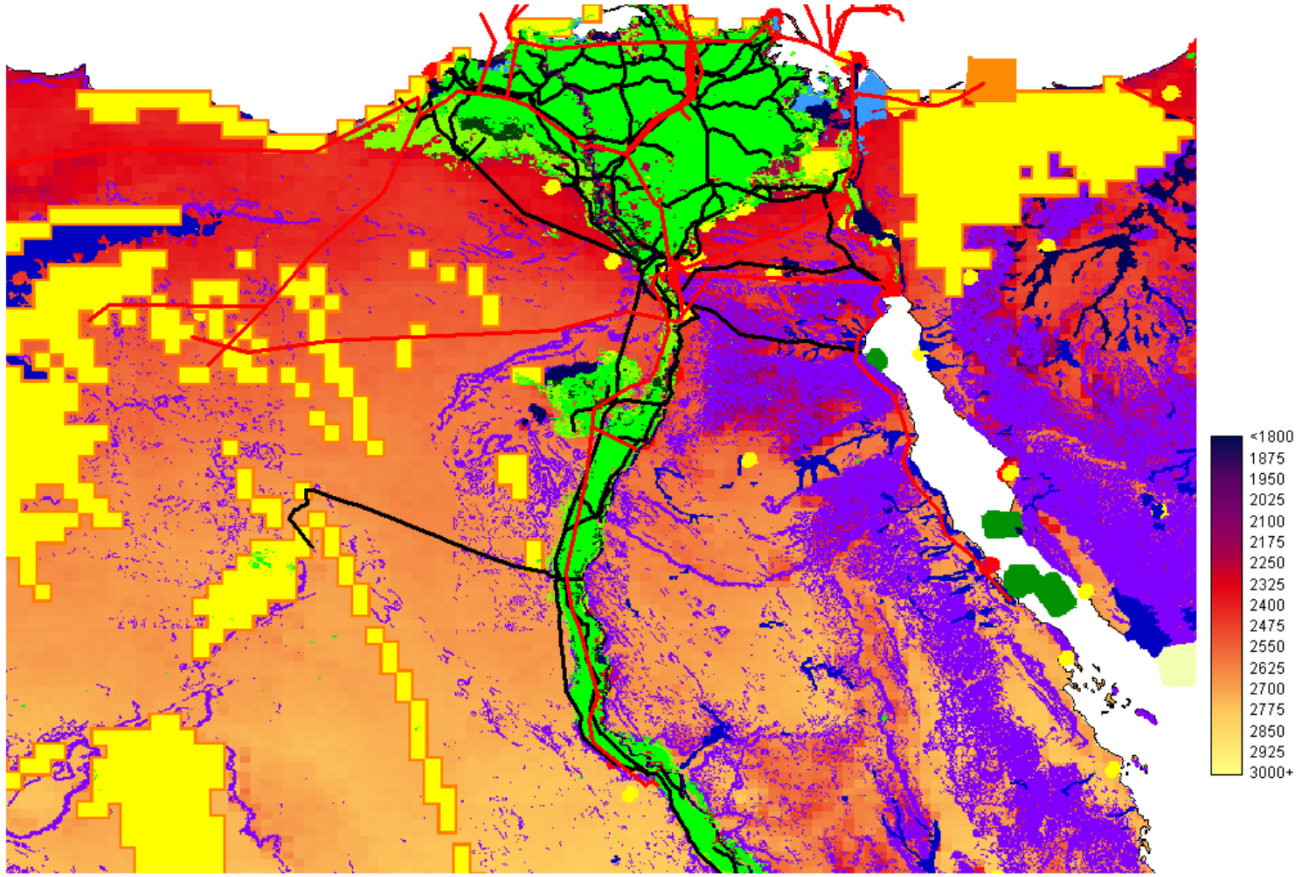
Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology
+ Geomorphology
+ Protected Areas
+ Wood
+ Agriculture
+ Power lines

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

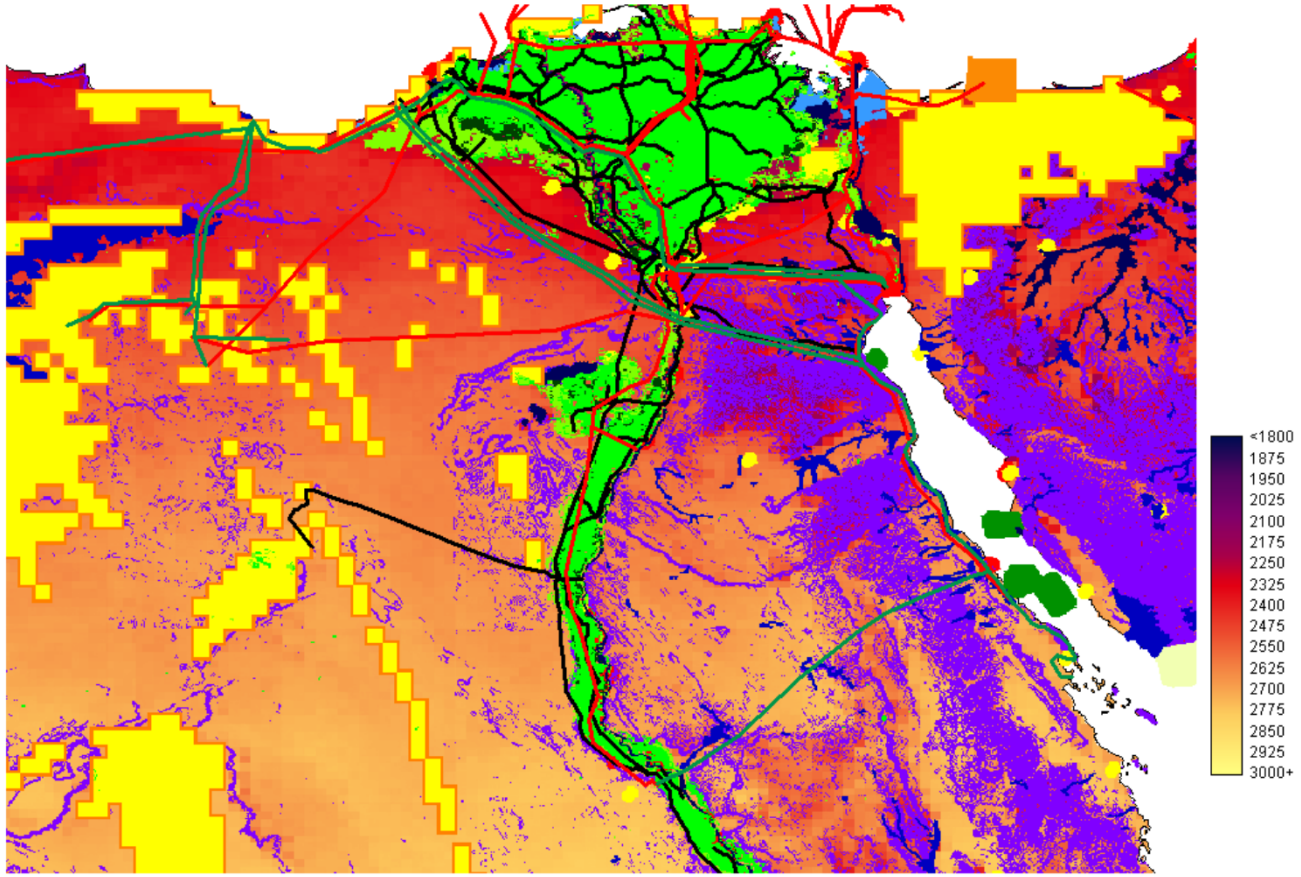
Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology
+ Geomorphology
+ Protected Areas
+ Wood
+ Agriculture
+ Power lines
+ Gas pipelines

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

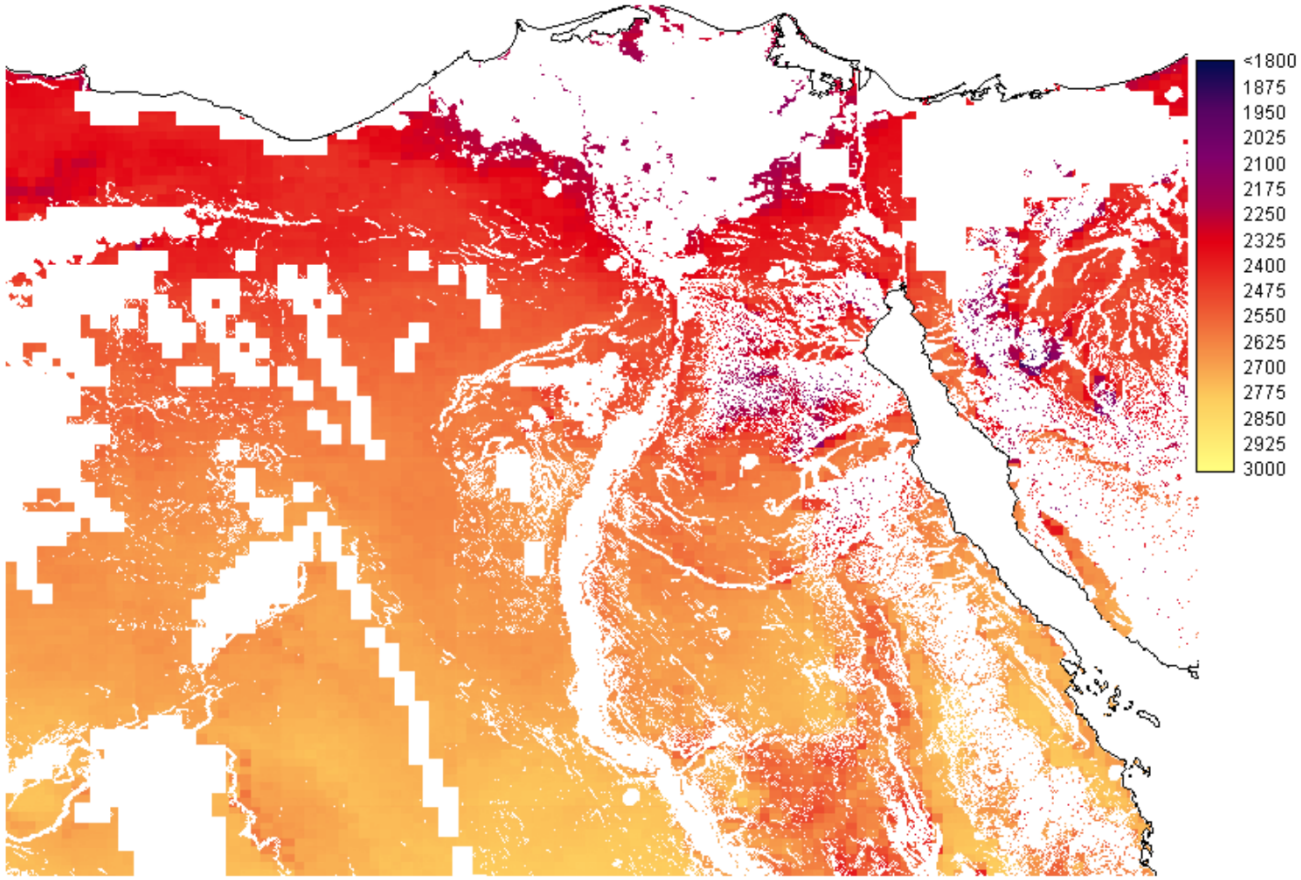
Assessment of Potentials, e.g. Large Solar



+ Industry, settlements
+ Hydrology
+ Geomorphology
+ Protected Areas
+ Wood
+ Agriculture
+ Power lines
+ Gas pipelines
+ Oil pipelines

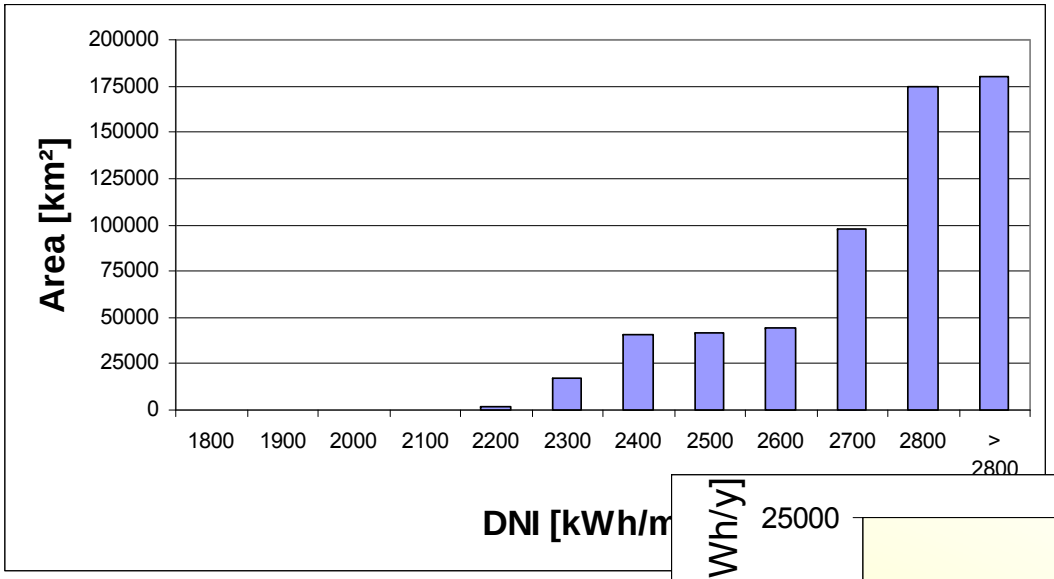
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Solar Radiation at Usable Areas



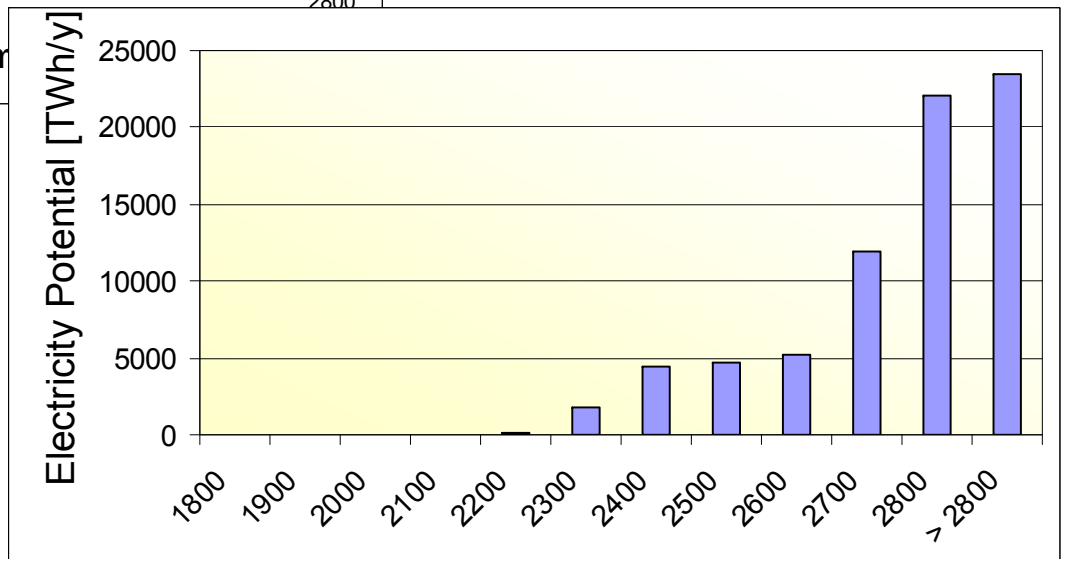
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

CSP Potential



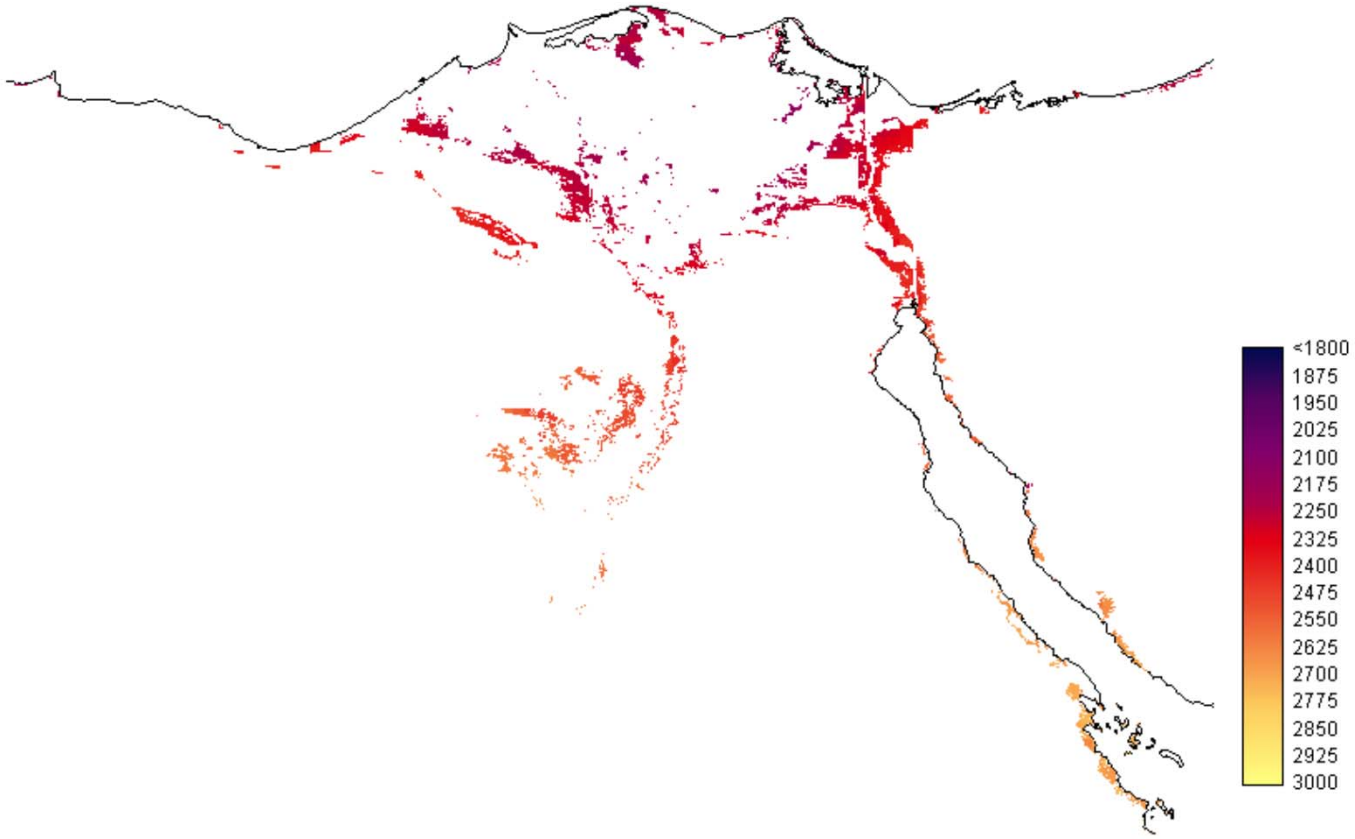
Area with certain level of solar radiation

Technical potential calc. with power plant model



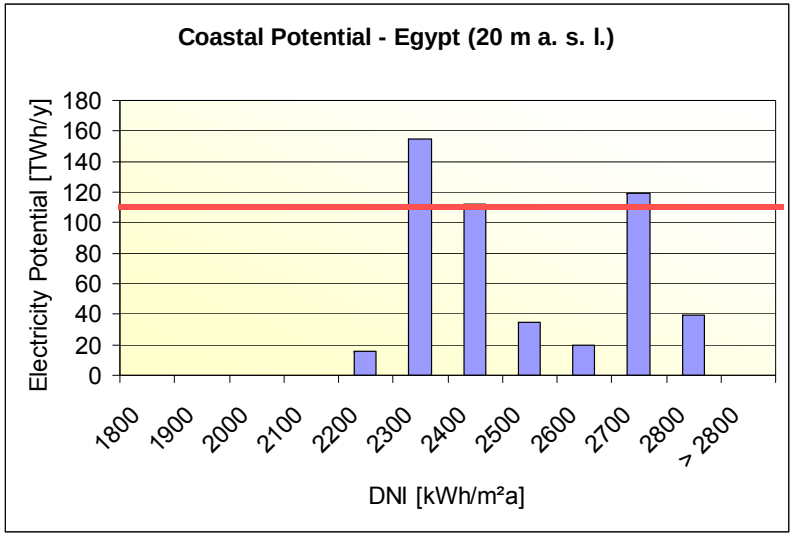
Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Costal Potential (<20m a.s.l.)
e.g. for sea water desalination



Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

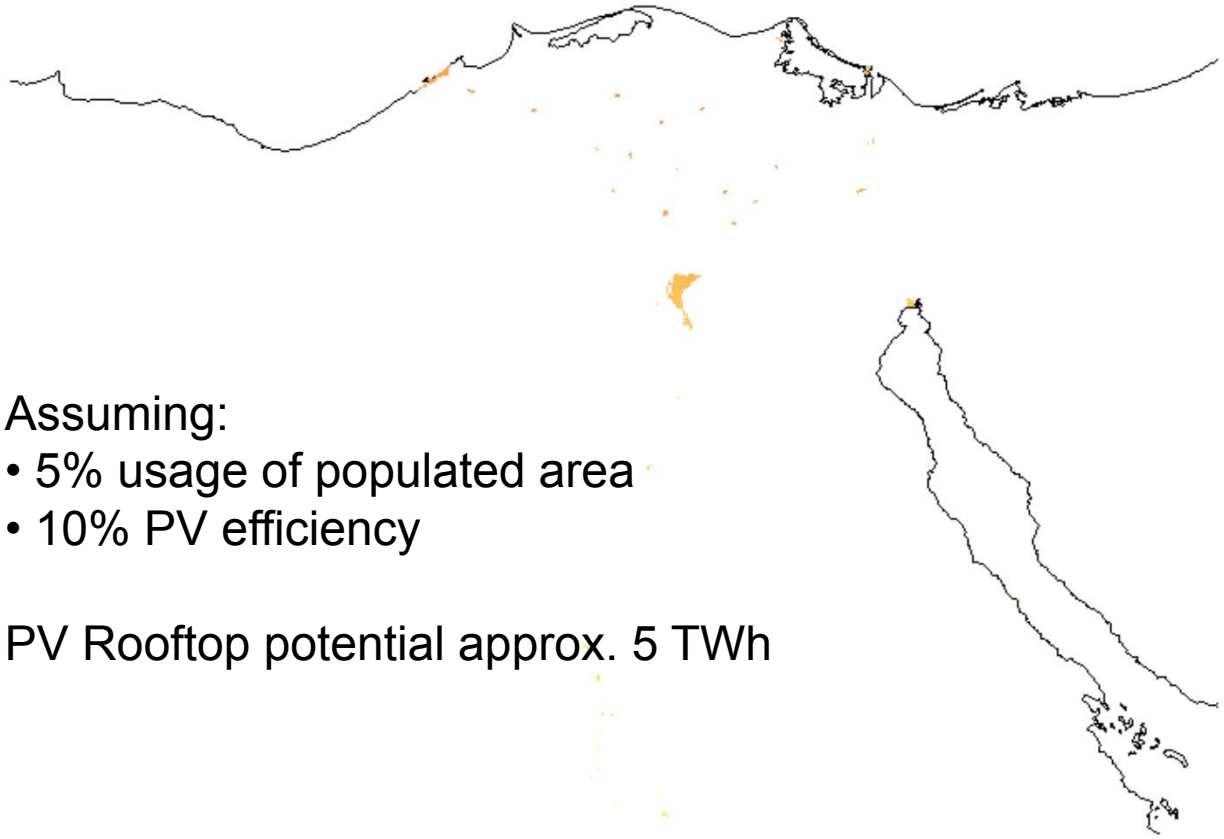
Coastal Potential in Egypt



2008 power demand

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Rooftop Potential



Assuming:
- 5% usage of populated area
- 10% PV efficiency

PV Rooftop potential approx. 5 TWh

Supported by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

2nd Question:
Which areas the most interesting?

- Where are resources available?
- Are they close enough to the demand centers and infrastructure?
- Which resource are available close to demand centers and intfrastructure?
- Can I optimize my spatial planning according to the resource distribution?

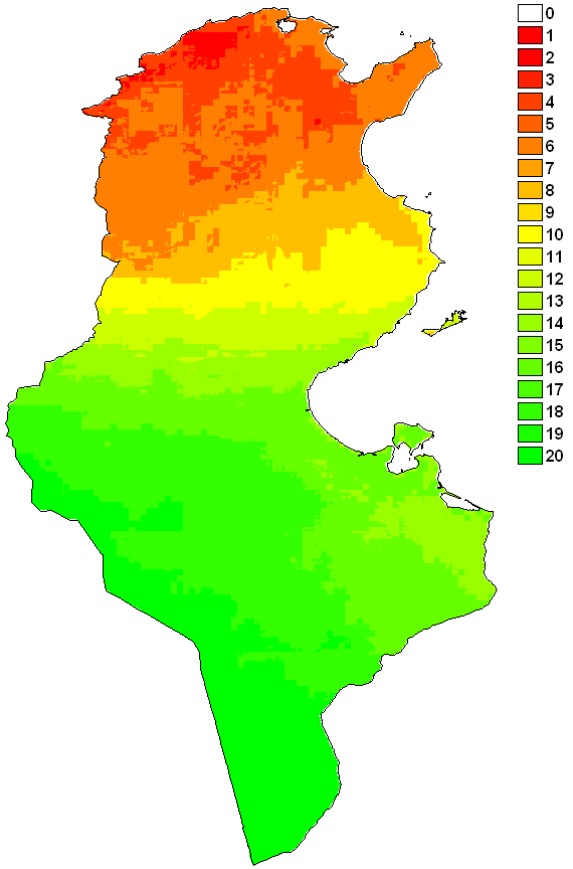
Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

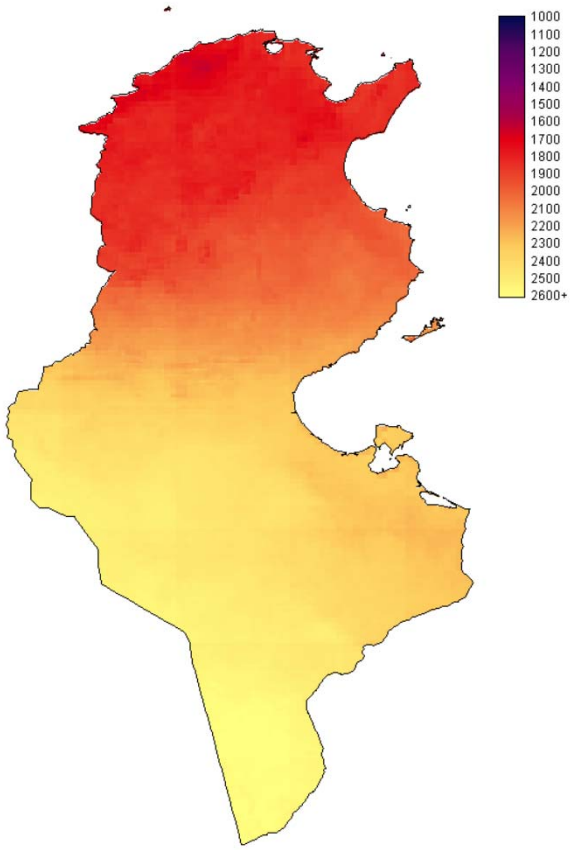
New Approach for Site Ranking

- Prerequisite: GIS data for resources and infrastructure
- Idea, giving Points to:
  - Level of available resource
  - Distance to the electricity grid
  - Distance to settlements
  - Distance to infrastructure
- Ranking based on the sum of points.

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

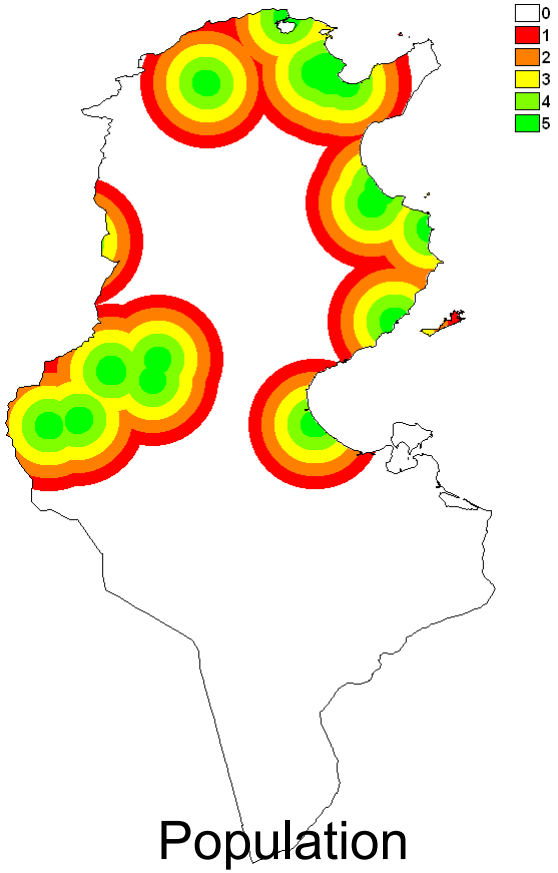
Determination of weights - DNI



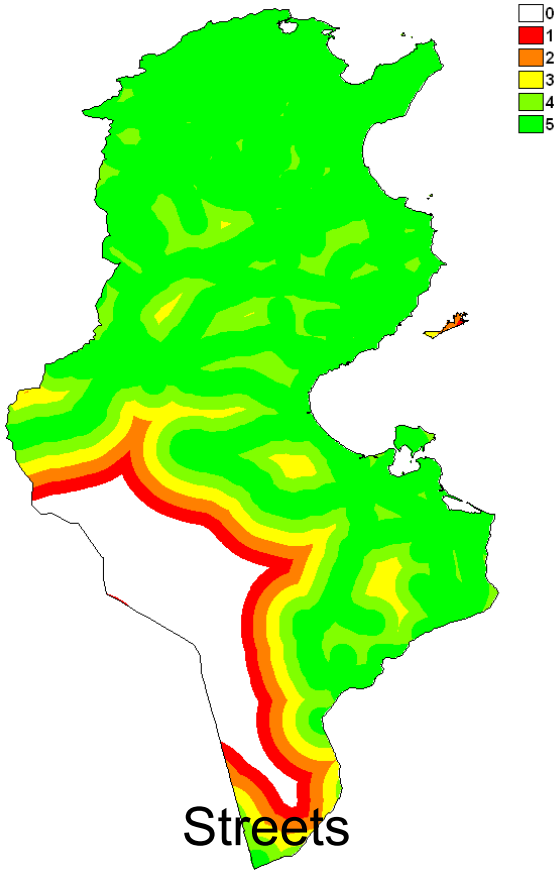


Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

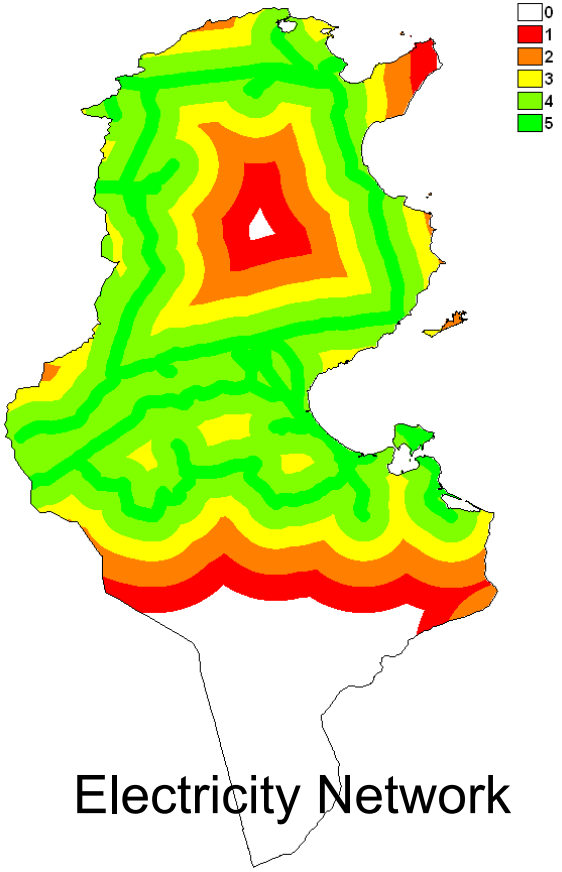
Determination of weights – Population and Infrastructure



Population



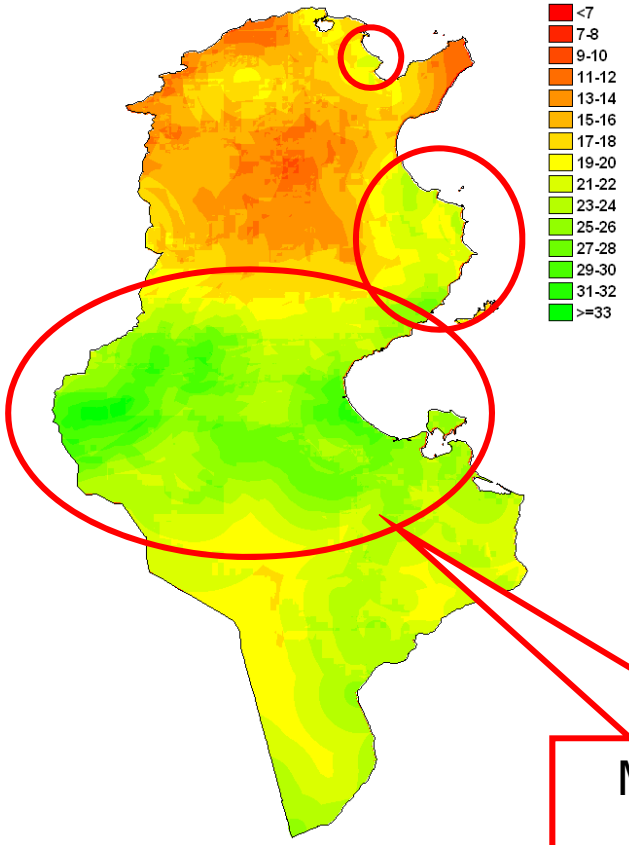
Streets



Electricity Network

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany

Site Ranking for CSP Tunisia



Most interesting area to start development

Site Ranking based on:

	Value		Points	
	Min	Max	min	max
Resource DNI	1900	2300	2	20
Transmission	0	75	5	0
Substations	0	75	10	0
Settlements	0	50	5	0
Roads	0	50	5	0

Thank you for your attention!

Questions & Answers

Either now or carsten.hoyer-klick@dlr.de

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the Parliament of the Federal Republic of Germany