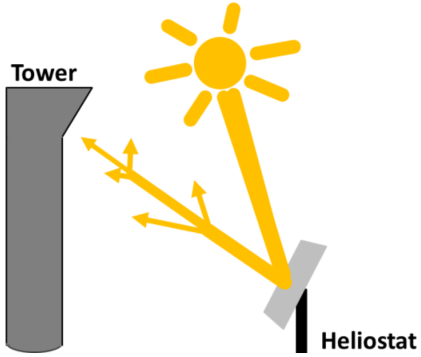
Atmospheric Extinction/Attenuation in Simulation Tools for Solar Tower Plants

Natalie Hanrieder, Stefan Wilbert, Marion Schroedter-Homscheidt, Franziska Schnell, Diana Mancera Guevara, Reiner Buck, Stefano Giuliano, Robert Pitz-Paal

DLR

Outline



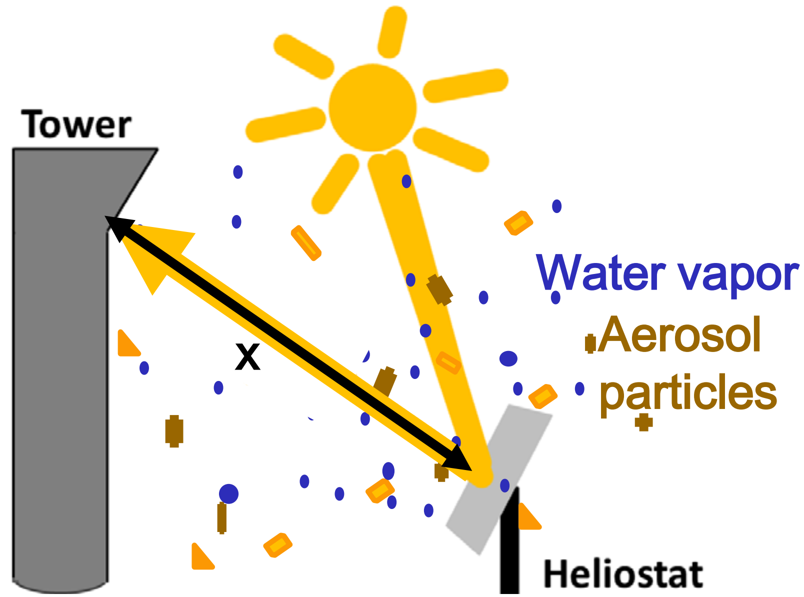
1. **Why is atmospheric extinction interesting for CSP?**
   → Motivation

2. **State of the art:**
   - How is extinction estimated in selected ray-tracing and plant optimization tools?
   - What methods have been developed to determine extinction for tower plant?

3. **How large is the annual plant yield loss due to atmospheric extinction?**
   → Results of an exemplary plant yield simulation with on-site extinction measurements

4. **Conclusion and future research needs**

Why is atmospheric extinction interesting for CSP?

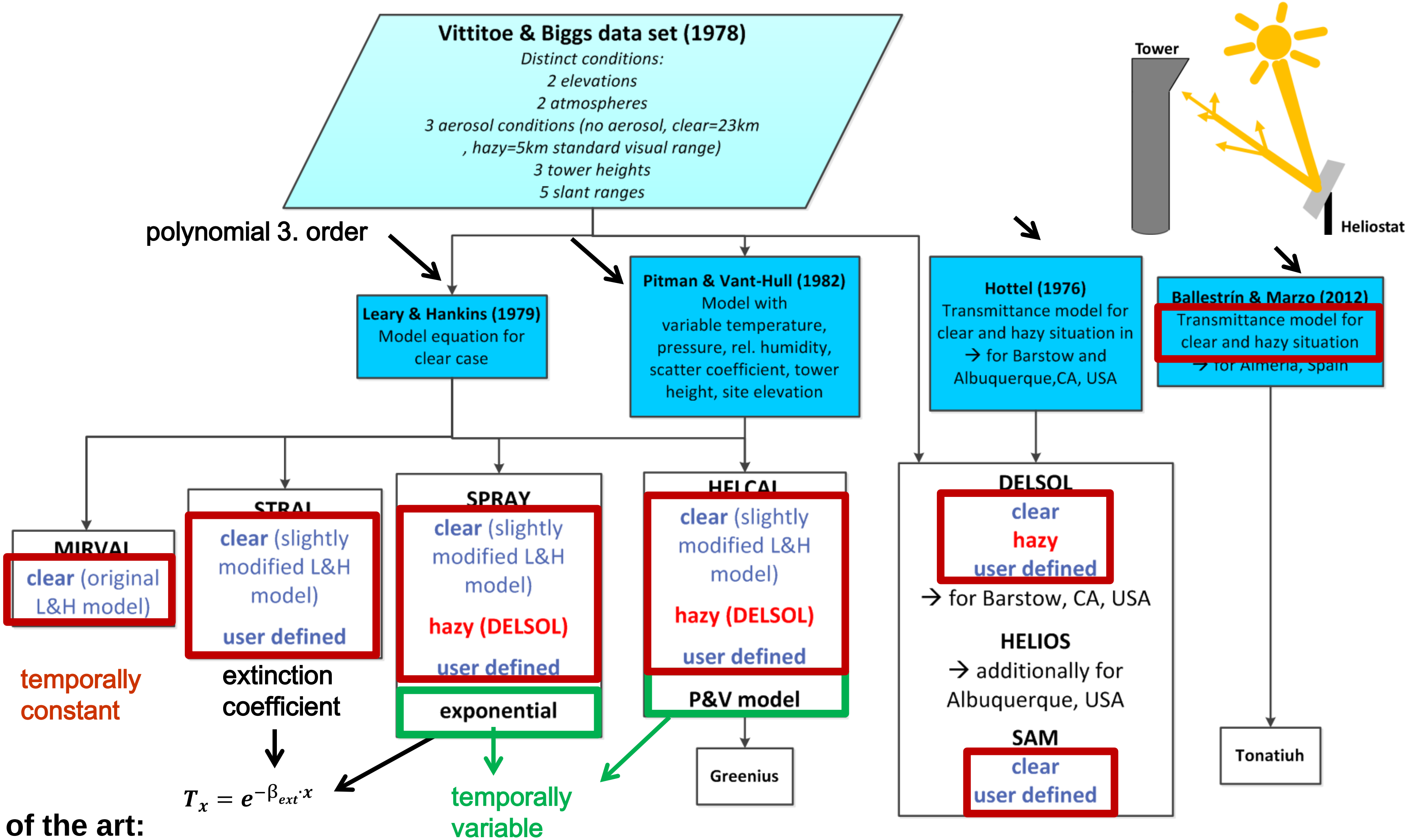


- Solar radiation is lost in lower atmospheric layer
- Atmospheric extinction of solar radiation between heliostat and receiver in solar tower plants can vary strongly with site and time
- Important parameter: transmittance dependent on slant range x → $T_x = \frac{DNI_{rec}}{DNI_{helio}} = e^{-\beta_{ext} \cdot x}$
- This effect reduces the plant yield and cannot be neglected

extinction coefficient

Lambert-Beer-Bouguer law

State of the art: Extinction in Simulation Tools

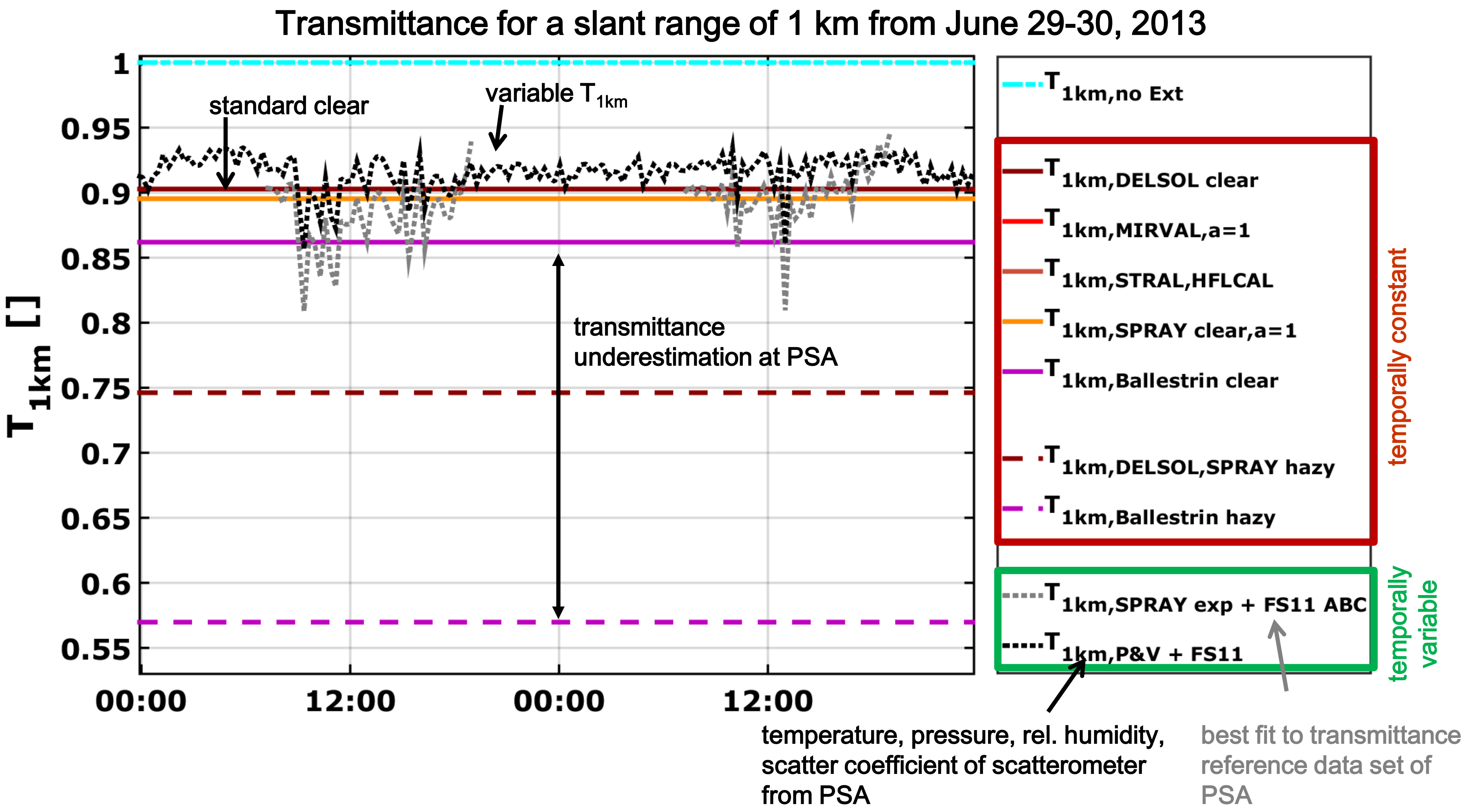


State of the art:

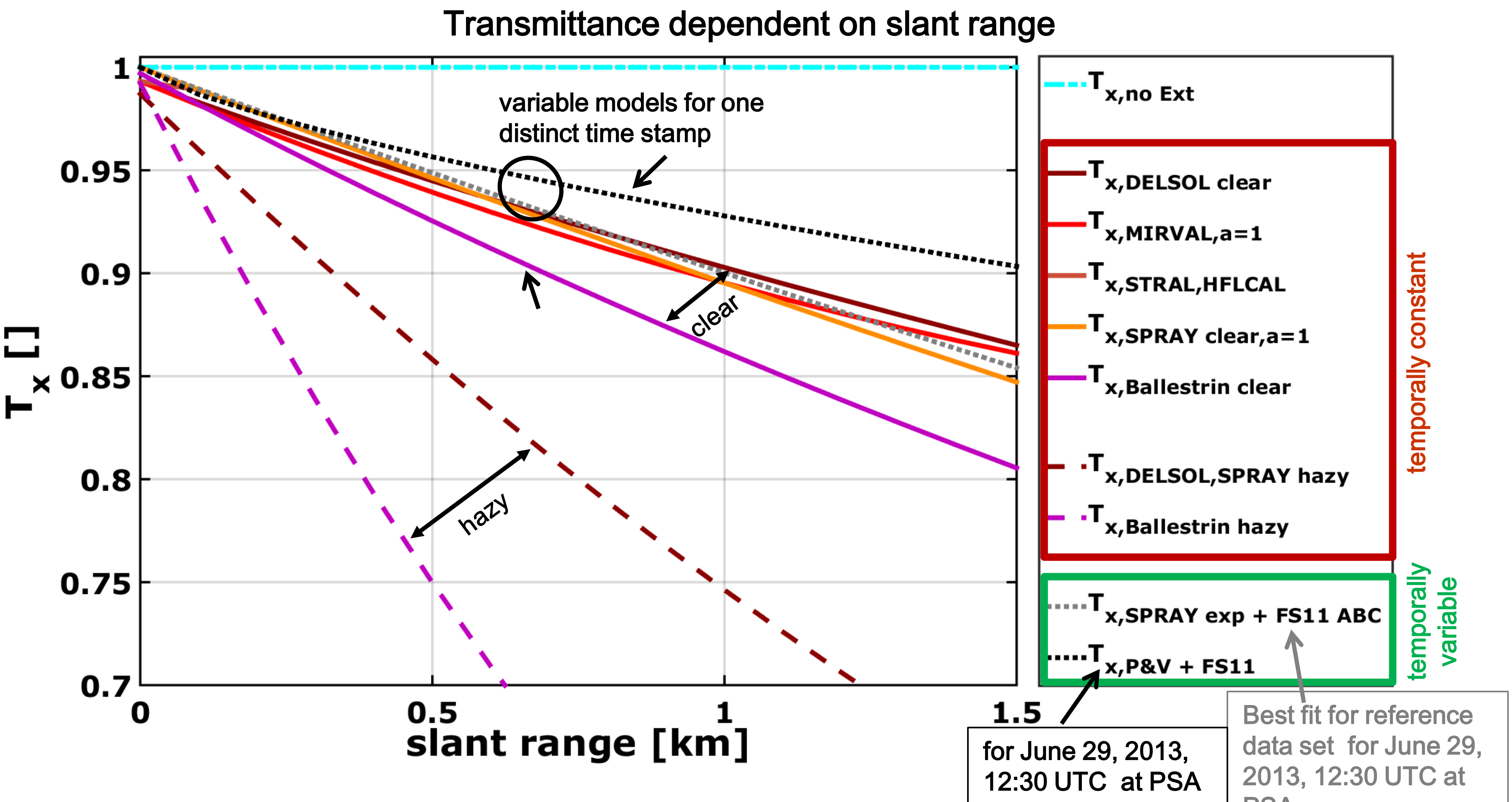
Select between clear or hazy conditions in simulation tools

The same selected condition is used for the whole simulation time series

State of the art: Extinction in Simulation Tools



State of the art: Extinction in Simulation Tools



→ Temporally constant models do not present diurnal, monthly or annual variations

→ Although T_{1km} = 0.9 is suitable for PSA, this might not be the case for other site

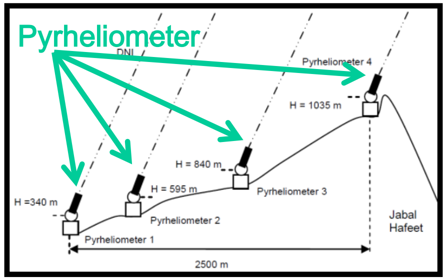
Existing methods to determine extinction from literature

Swaihan experiment of Tahboub et al. (2012, 2013):

Several pyrheliometer in different distances to a heliostat → Output: extinction coefficient

Jebel Hafeet experiment of Tahboub et al. (2012, 2013):

Several pyrheliometer located at different elevations at Jebel Hafeet Mountain → Output: extinction height profile



Digital camera approach of Ballestrín et al. (2015):

Based on images of white target from different distances. Different brightness of target → Output: extinction coefficient

Simulation approach of Elias et al. (2015):

Based on aerosol optical depth and boundary layer height data provided by AERONET and ECMWF → Output: extinction coefficient

→ not validated

or not applicable to generate long time series

or under development

Further validated methods to determine extinction

Pitman & Vant-Hull model (1982):

- Scatter coefficient measurements necessary (e.g. from scattero- or transmissometer)
  Output: transmittance for several x
- Assumption: scatter coefficient at 550nm represents solar spectrum perfectly
  → Source for scatter coefficient has to be chosen carefully (most instruments measure almost monochromatically)
  → diurnal spectral variations of solar spectrum are not considered

libRadtran

Scatterometer approach of Hanrieder et al. (2015):

- Absorption and broadband correction (ABC) of Vaisala FS11 scatterometer data (β_{875nm})
  → Output: broadband transmittance for several x
- Homogeneous extinction height profile up to tower height (according experiments at PSA conducted)
- Absolute uncertainty for T_{1km} = 0.9: ~ 0.04 (10 min. resolution), ~0.02 (for yearly averages)
- Low maintenance demand → suitable sensor for remote sites
- Resource assessment → selection of CSP technology + design tower plants (mirror no. + position…)

Further validated methods to determine extinction

Transmissometer approach of Hanrieder et al. (2015):

- ABC for Optec LPV4 transmissometer data (β_{532nm}) → Output: broadband transmittance for several x
- Absolute uncertainty for T_{1km} = 0.9: ~ 0.07 (10 min. resolution). ~0.05 (for yearly averages)
- Measurements along slant path possible, higher accuracy for larger operation paths
- Much smaller ABC correction than for the scatterometer
- High maintenance demand → complicates application on remote sites and resource assessment
- But: Suitable sensor during plant operation → aim point + defocusing dependent on extinction

DNI based model of Sengupta & Wagner (2011, 2012) and Hanrieder et al. (2016):

- DLR & NREL cooperation to enhance version of Sengupta & Wagner (2011, 2012)
- DNI, temperature, pressure, rel. humidity, site elevation based model → Output: broadband extinction coefficient
- Compare clear sky DNI measurement with modelled DNI for aerosol free atmosphere + assumption about aerosol height profile
- Measurements usually available at prospective CSP sites → interesting for resource assessment
- Validation at hazy site has to be performed, so far only at PSA
- Estimated absolute uncertainty for T_{1km} = 0.9: ~ 0.04 (1 minutes temporal resolution)

→Application at remote sites possible, adaption to site elevation necessary

Effect of atmospheric extinction on plant yield

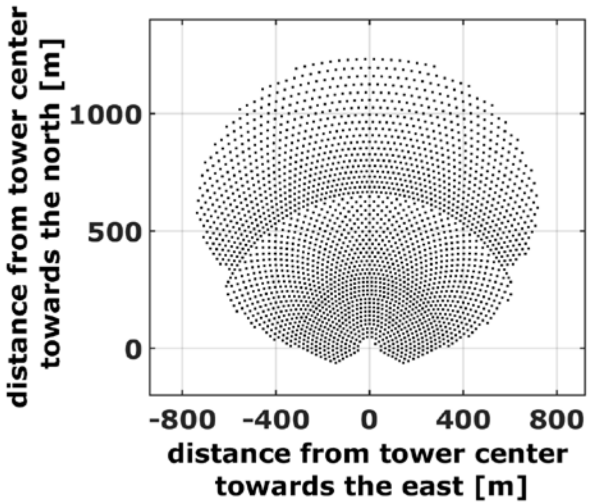
Annual plant yield simulations

Ray-tracing simulations with SPRAY May 2013-May 2014

Input of on-site DNI measurements

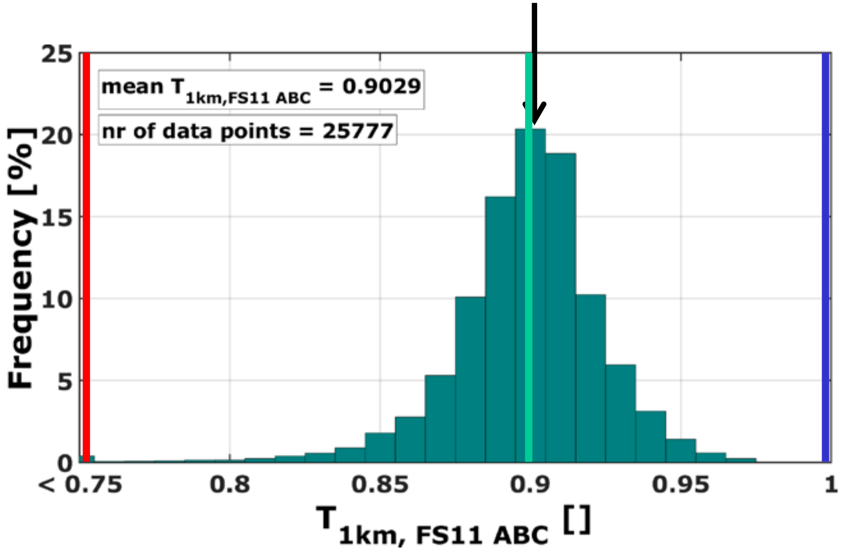
Exemplary plant at PSA:

- north-orientated heliostat field
- cavity receiver, molten salt as heat transfer fluid
- 162 MW_{th}, 27 MW_{el} design power



Four simulations with different extinction assumptions:

1. exponential model of SPRAY: $T_x = e^{-\beta_{ext} \cdot x}$ using atmospheric extinction time series of PSA (scatterometer approach of Hanrieder et al. (2015))
2. atmospheric extinction neglected
3. standard clear model of SPRAY
4. standard hazy model of DELSOL

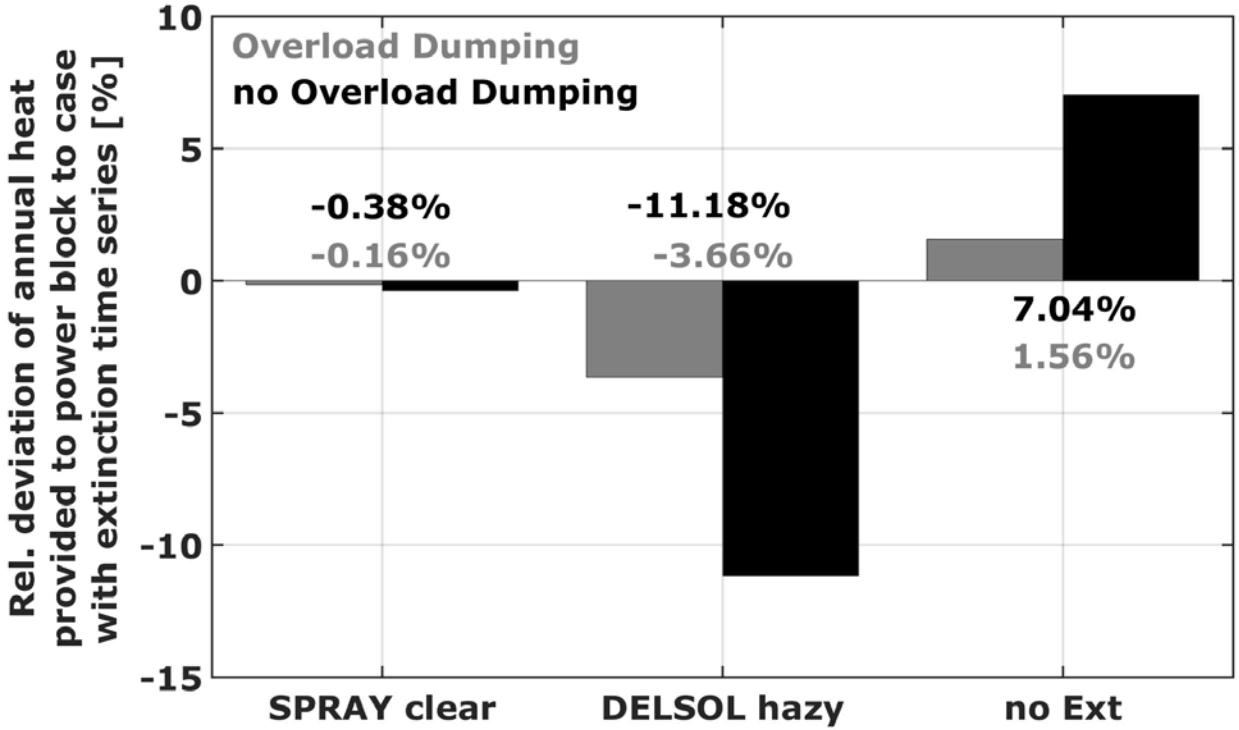


Effect of atmospheric extinction on plant yield

Results of simulations

Operation strategy. Overload dumping, if:

1. net thermal power at receiver exceeds more than 15% of receiver design power
2. storage capacity of 12 hours is exceeded



Conclusions for PSA:

1. Overload dumping has to be considered when examining the effect of extinction
2. Standard hazy model → significant underestimations of the annual plant yield
3. Standard clear model only

   ~ sufficiently accurate in the **annual mean**

   Annual variations in extinction not covered (hazy summer, clear winter)

→ On-site extinction time series important for yield calculations and plant optimization

DLR

Conclusion and future research needs

- **At hazy sites**, annual plant yield loss due to extinction can account for several percent.

- Several methods and experiments to determine extinction have been investigated, **four are validated.**

- **Recommendation for tower plant projects:** Consideration of extinction time series instead of standard model equations during plant optimization and yield analysis.
  - **To identify a clear site**, the model approach of Hanrieder et al. (2016) based on DNI measurements could be sufficient.
  - For a **detailed examination** of extinction **especially at possibly hazy sites**, the scatterometer and transmissometer approaches of Hanrieder et al. (2015) can be applied

  → Only scatterometers recommended for remote sites with non-daily maintenance

  → Correction for spectral errors required, especially for scatterometers

DLR

Conclusion and future research needs

- **Further research needs** for resource assessment:
  - Geographical maps of extinction (time series and long-term averages)
    → Measurements at several locations for validation
  - Further investigation of extinction height profiles at other sites than PSA

→Global extinction data sets will reduce CSP yield uncertainty

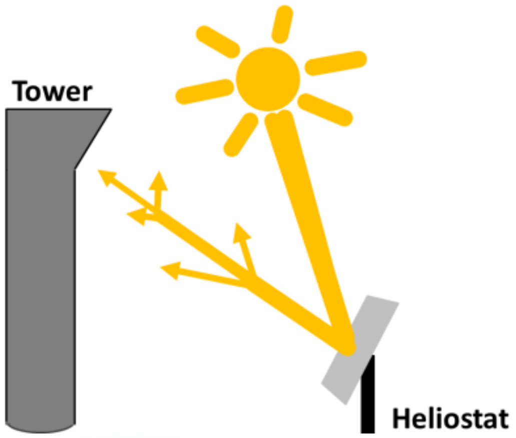
→ lower risk margins and optimal site specific plant layouts

→ lower costs of tower plant projects !

Thank you for your attention!

For questions and more details please contact:

Natalie.Hanrieder@dlr.de



DLR

References

- Ballestrín, J., R. Monterreal, M. Carra, J. Fernández-Reche, J. Barbero, and A. Marzo (2015). “Measurement of Solar Extinction in Tower Plants with Digital Cameras.” In: SolarPACES. Capetown, South Africa.
- Belhomme B., R. Pitz-Paal, P. Schwarzbözl and S. Ulmer (2009), “A New Fast Ray Tracing Tool for High-Precision Simulation of Heliostat Fields.” In: Journal of Solar Energy Engineering 131.
- Blanco, M., A. Mutuberria, P. Garcia, R. Gastesi, and V. Martin (2009). “Preliminary validation of Tonatiuh.” In: SolarPACES. Berlin, Germany.
- Buck R. (2011), “Solar Power Raytracing Tool SPRAY.” Manual.
- Cardemil, J., A. Starke, V. Scariot, I. Grams, and S. Colle (2013). “Evaluating solar radiation attenuation models to assess the effects of climate and geographical location on the heliostat field efficiency in Brazil.” In: SolarPACES.
- Dersch J., P. Schwarzbözl and R. Richert (2011). “Annual Yield Analysis of Solar Tower Power Plants With GREENIUS.” In: Journal of Solar Energy Engineering 133, p. 9.
- DIN-ISO (2012). “ISO 28902-1 2012 Air quality - Environmental meteorology - Part 1: Ground-based remote sensing of visual range by lidar.”
- Elias, T., D. Ramon, L. Dubus, C. Bourdil, E. Cuevas-Agulló, T. Zaidouni, and P. Formenti (2015). “Poster presentation: Aerosols attenuating the solar radiation collected by solar tower plants: the horizontal pathway at surface level.” In: SolarPACES. Capetown, South Africa.
- Gertig, C., A. Delgado, C. Hidalgo, and R. Ron (2013). “SoFiA - A novel simulation tool for Central Receiver Systems.” In: SolarPACES. Las Vegas, USA.
- Griggs, D., D. Jones, M. Ouldridge, and W. Sparks (1989). “Instruments and Observing Methods. Report No. 41. The first WMO Intercomparison of Visibility Measurements.” Final Report. Tech. rep. World Meteorological Organization.
- Gueymard, C. (2012). “Letter to the Editor: Visibility, aerosol conditions, and irradiance attenuation close to the ground - Comments on "Solar radiation attenuation in solar tower plants" by J. Ballestrín and A. Marzo, Solar Energy (2012).” In: Solar Energy 86, pp. 1667–1668.

References

- Hanrieder N., M. Sengupta, Y. Xie, S. Wilbert and R. Pitz-Paal (2016), “Modelling Beam Attenuation in Solar Tower Plants Using Common DNI Measurements.” In: Solar Energy 129, 244-255.
- Hanrieder N., S. Wilbert, R. Pitz-Paal, C. Emde, J. Gasteiger, B. Mayer and J. Polo (2015), “Atmospheric extinction in solar tower plants: absorption and broadband correction for MOR measurements.” In: Atmospheric Measurement Techniques 8, pp. 1–14.
- Hottel, H. (1976). “A simple model for estimating the transmittance of direct solar radiation through clear atmospheres.” In: Solar Energy 18, p. 6.
- IRENA (2016), “The Power to Change: Solar and Wind Cost Reduction Potential to 2025”
- J. Ballestrín and A. Marzo (2012), “Solar radiation attenuation in solar tower plants.” In Solar Energy no 86, pp. 388–392.
- Kistler B. (1986), “A User’s Manual for DELSOL3: A Computer Code for Calculating.”
- Koschmieder, H. (1924). “Theorie der horizontalen Sichtweite.” In: Beiträge zur Physik der freien Atmosphäre 12, 171, pp. 33–53, 171–181.
- Leary, P. and J. Hankins (1979). “A user’s guide for MIRVAL - A computer code for comparing design of heliostat-receiver optics for central receiver solar power plants.” Manual.
- Liedke, P., M. Puppe, and S. Giuliano (2015). “QatDLR - AP 3 Pre-Feasibility-Studie, Machbarkeitsstudie zu hocheffizienten hybriden Solarturmkraftwerken.“ Tech. rep.
- Mayer, B. and A. Kylling (2005). “Technical note: The libRadtran software package for radiative transfer calculations - description and example of use.” In: Atmospheric Chemistry and Physics 5, pp. 1855–1877.
- Mustafa, M., S. Abdelhady, and A. Elweteedy (2012). “Analytical Study of an Innovated Solar Power Tower (PS10) in Aswan.” In: International Journal of Energy Engineering 2.6, pp. 273–278.
- Ortega, J., J. Burgaleta, and F. Tellez (2008). “Central receiver system solar power plant using molten salt as heat transfer fluid.” In: Journal of Solar Energy Engineering 130.2, p. 24501.

References

- Pitman C. and L. Vant-Hull (1982), “Atmospheric transmission model for a solar beam propagating between a heliostat and a receiver.” In: ASES Progress in Solar Energy, pp. 1247–1251.
- Pitz-Paal, R., J. Dersch, and B. Milow (2005). „European Concentrated Solar Thermal Road-Mapping (ECOSTAR): roadmap document.” Tech. rep.
- Polo J., J. Ballestrín, E. Carra (2016), “Sensitivity study for modelling atmospheric attenuation of solar radiation with radiative transfer models and the impact in solar tower plant production”, In: Solar Energy 134, 219-227.
- Sánchez, M. and M. Romero (2006). “Methodology for generation of heliostat field layout in central receiver systems based on yearly normalized energy surfaces.” In: Solar Energy 80, pp. 861–874.
- Schmitz, M. (2007). „Systematischer Vergleich von solarthermischen Turmreflektor und- Turmreceiversystemen.“ PhD thesis. RWTH Aachen, DLR.
- Schwarzbözl P., M. Schmitz and R. Pitz-Paal (2009). “Visual HFLCAL - A software tool for layout and optimization of heliostat fields.” In: SolarPACES. Berlin, Germany.
- Sengupta, M. and M. Wagner (2011). “Impact of aerosols on atmospheric attenuation loss in central receiver systems.” In: SolarPACES. Granada, Spain.
- Sengupta, M. and M. Wagner (2012). “Estimating atmospheric attenuation in central receiver systems.” In: Proceedings of the ASME 2012 6th International Conference on Energy Sustainability. San Diego, CA, USA.
- Sengupta, M. and M. Wagner (2012a). “Atmospheric attenuation in central receiver systems from DNI measurements.” In: SolarPACES. Marrakech, Morocco.
- Tahboub, Z., A. Al Abaidli, F. Luque, I. Salbidegoitia, O. Farges, Z. Hassar, A. Oumbe, N. Geuder, and O. Goebel (2012). “Solar beam attenuation experiments -Abu Dhabi.” In: SolarPACES. Marrakech, Morocco.
- Tahboub, Z., A. Oumbe, Z. Hassar, and A. Obaidli (2013). “Modeling of Irradiance Attenuation from a Heliostat to the Receiver of a Solar Central Tower.” In: SolarPACES. Las Vegas, USA.

DLR

References

- Vittitoe, C. and F. Biggs (1978). “Terrestrial Propagation Loss.” In: Amer. Sec. ISES meeting, Denver, August 1978, Sandia release.
- Weinrebe, G. (2000). „Technische ökologische und ökonomische Analyse von solarthermischen Turmkraftwerken.“ PhD thesis. Universität Aachen.
- Wilbert, S. (2014). “Determination of Circumsolar Radiation and its Effect on Concentrating Solar Power.” PhD thesis. RWTH Aachen, DLR.
- Zhang, H., Z. Wang, X. Wei, and Z. Lu (2012). “Design of Heliostats Field for the Scale of 1MW Solar Power Tower Plant.” In: Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific. Shanghai.