SMART CSP

HOW ARTIFICIAL INTELLIGENCE CAN SUPPORT CONCENTRATING SOLAR TECHNOLOGIES

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DLR

Outline

1. Characteristics of CSP

2. Status and Perspectives

3. Advanced methods to operate a CSP plant efficiently and autonomously
   - Airborne condition monitoring of solar collector fields
   - Data driven flux density prediction
   - Dispatch optimization of power production considering weather forecast uncertainties

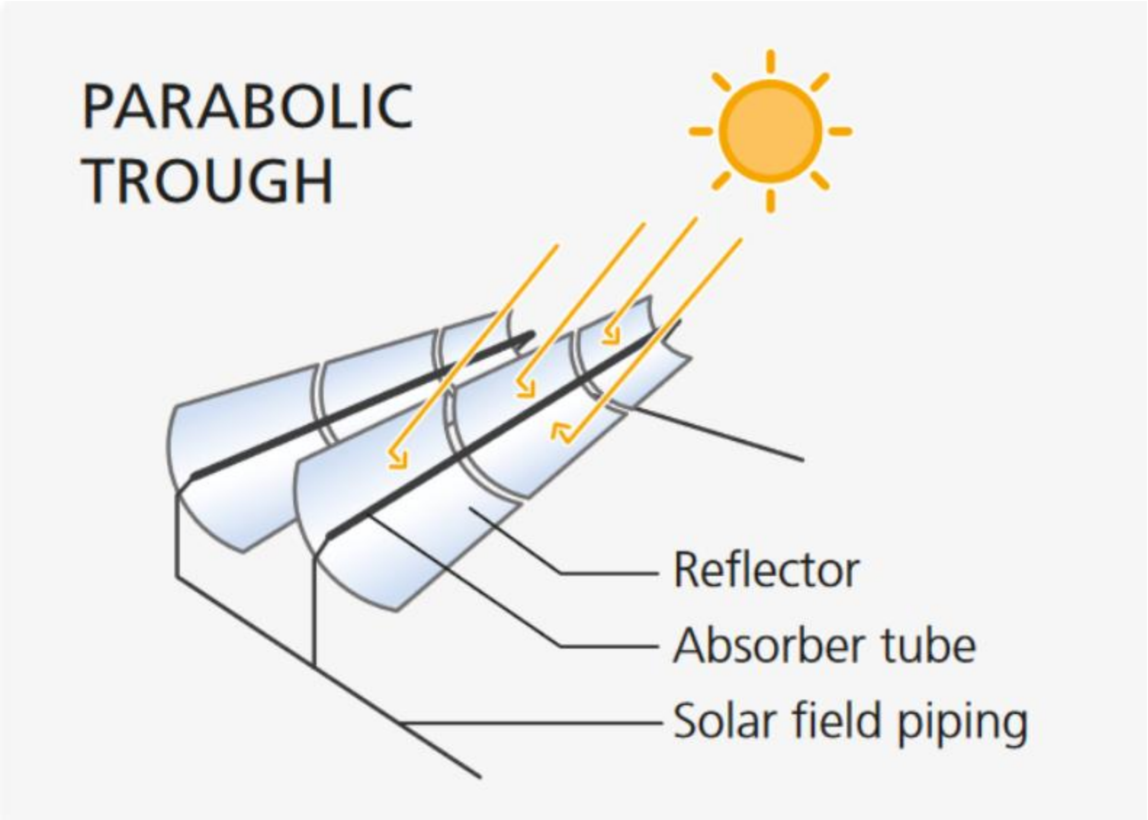
4. Conclusions

CHARATERISTICS OF CSP

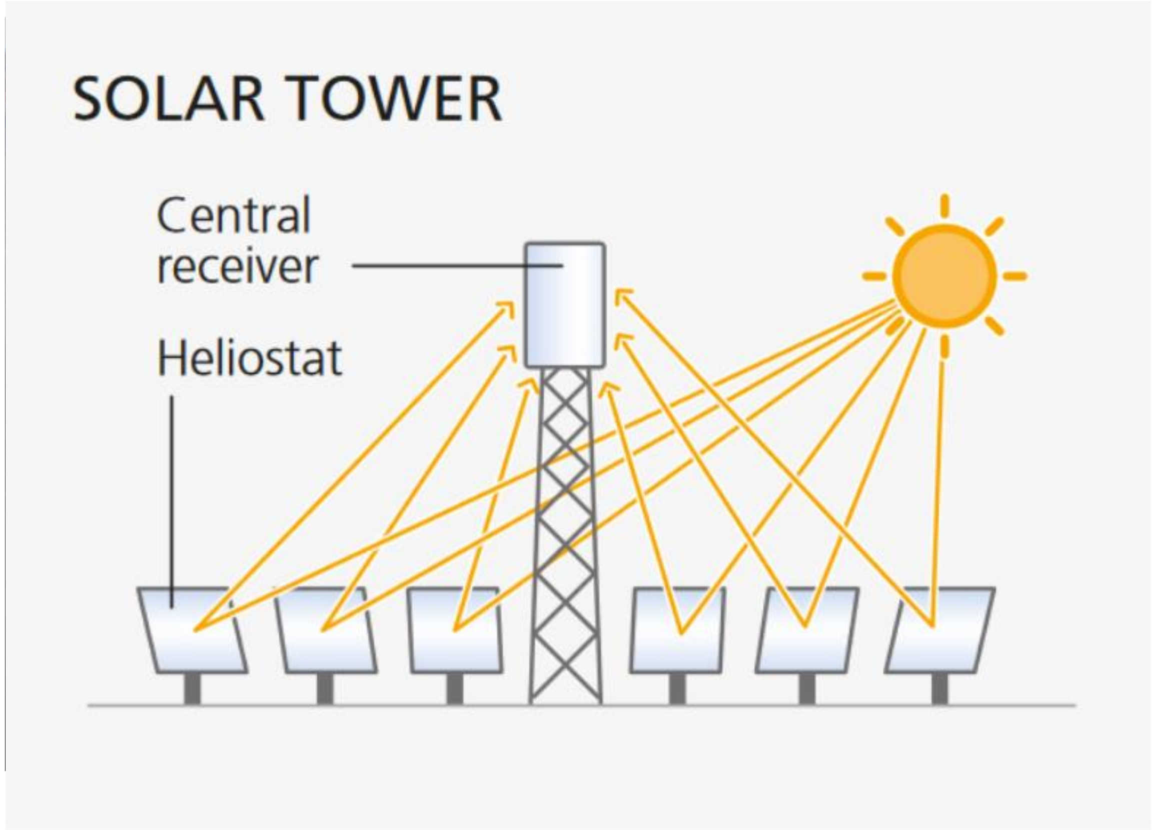
In a nutshell: How does a solar thermal power plant work?

Special mirrors focus direct sunlight and reflect it onto...

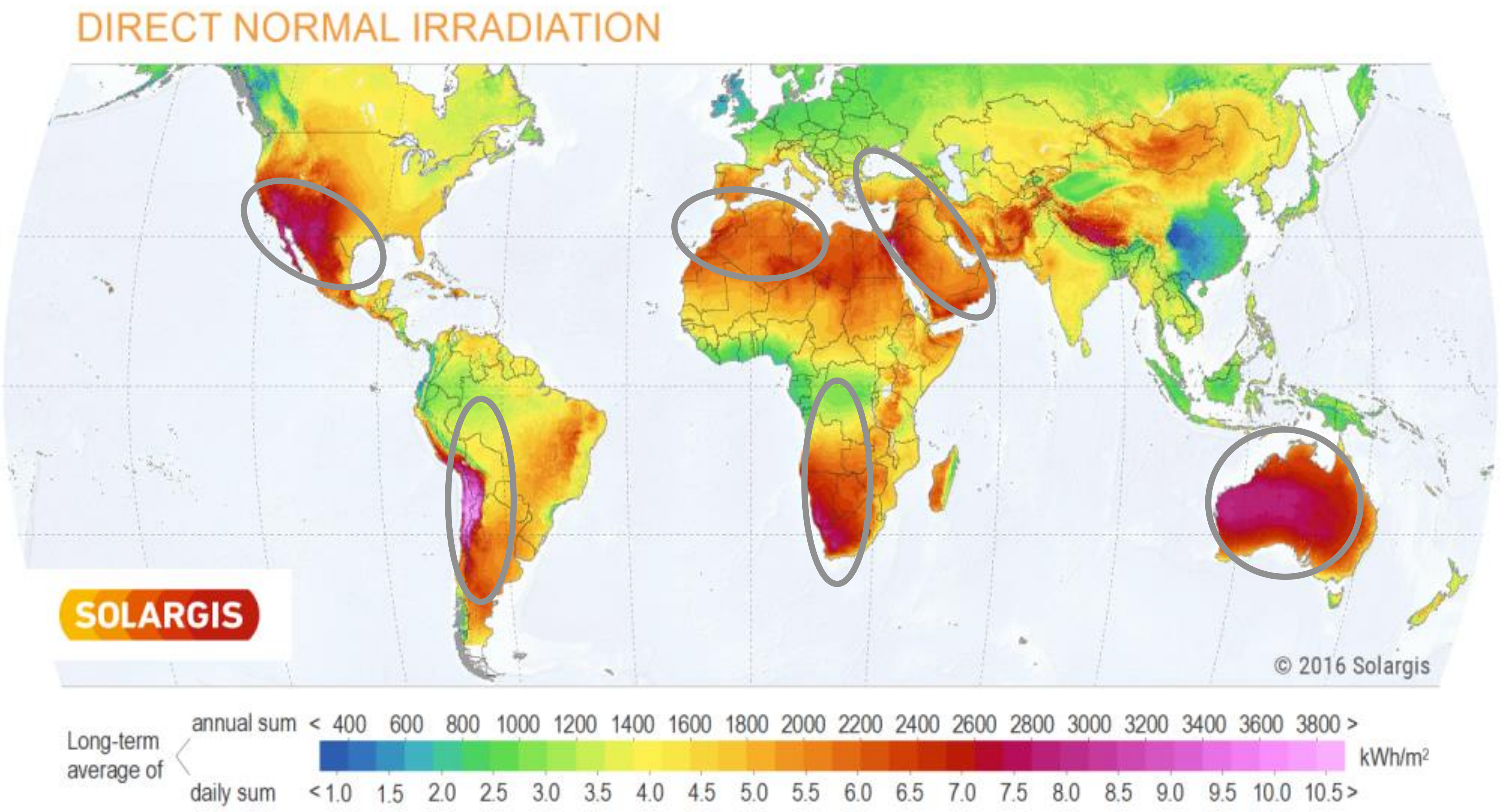
- ... a linear receiver



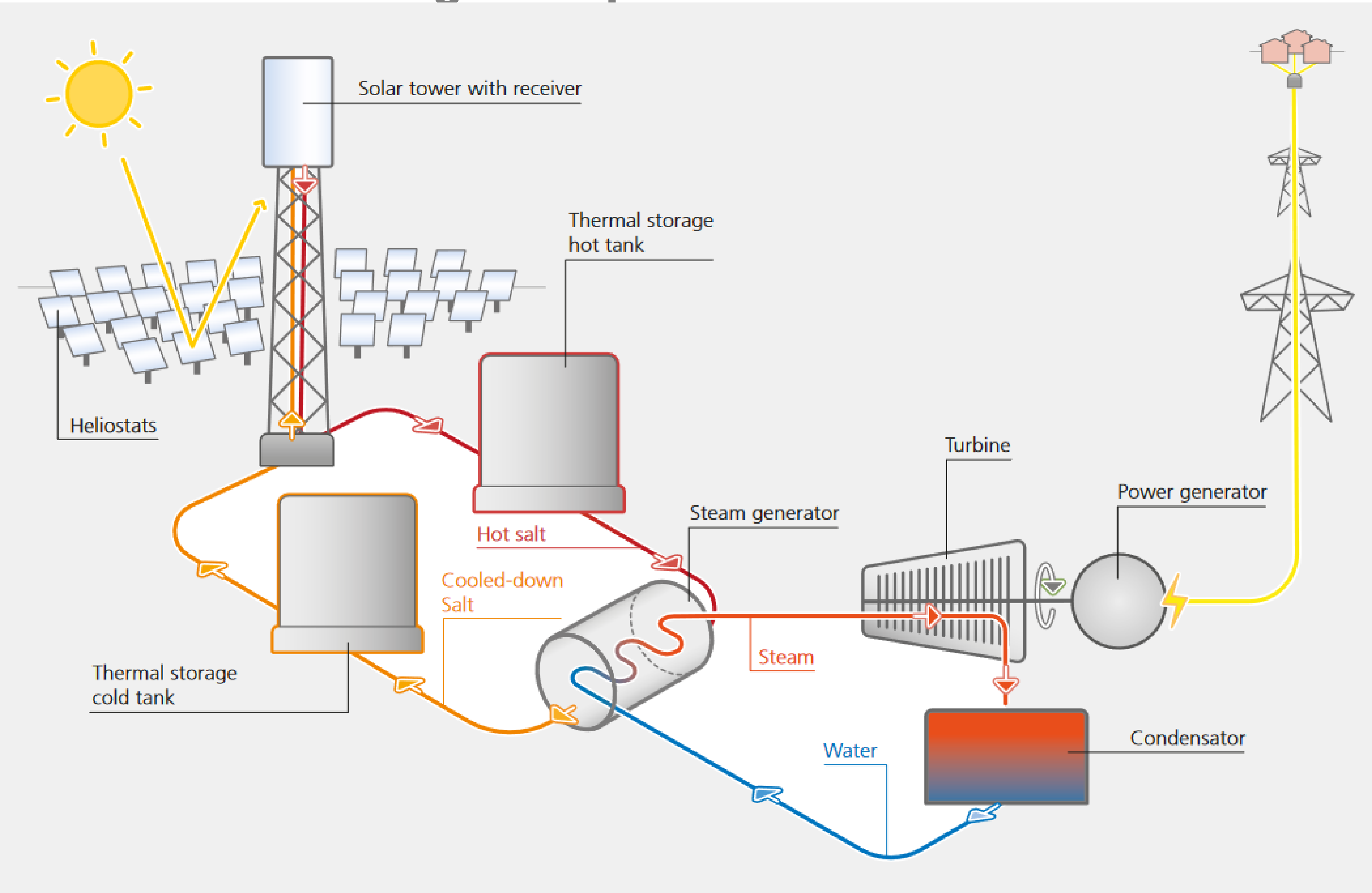
- ... a central receiver



CSP best suitable in areas with high direct normal radiation

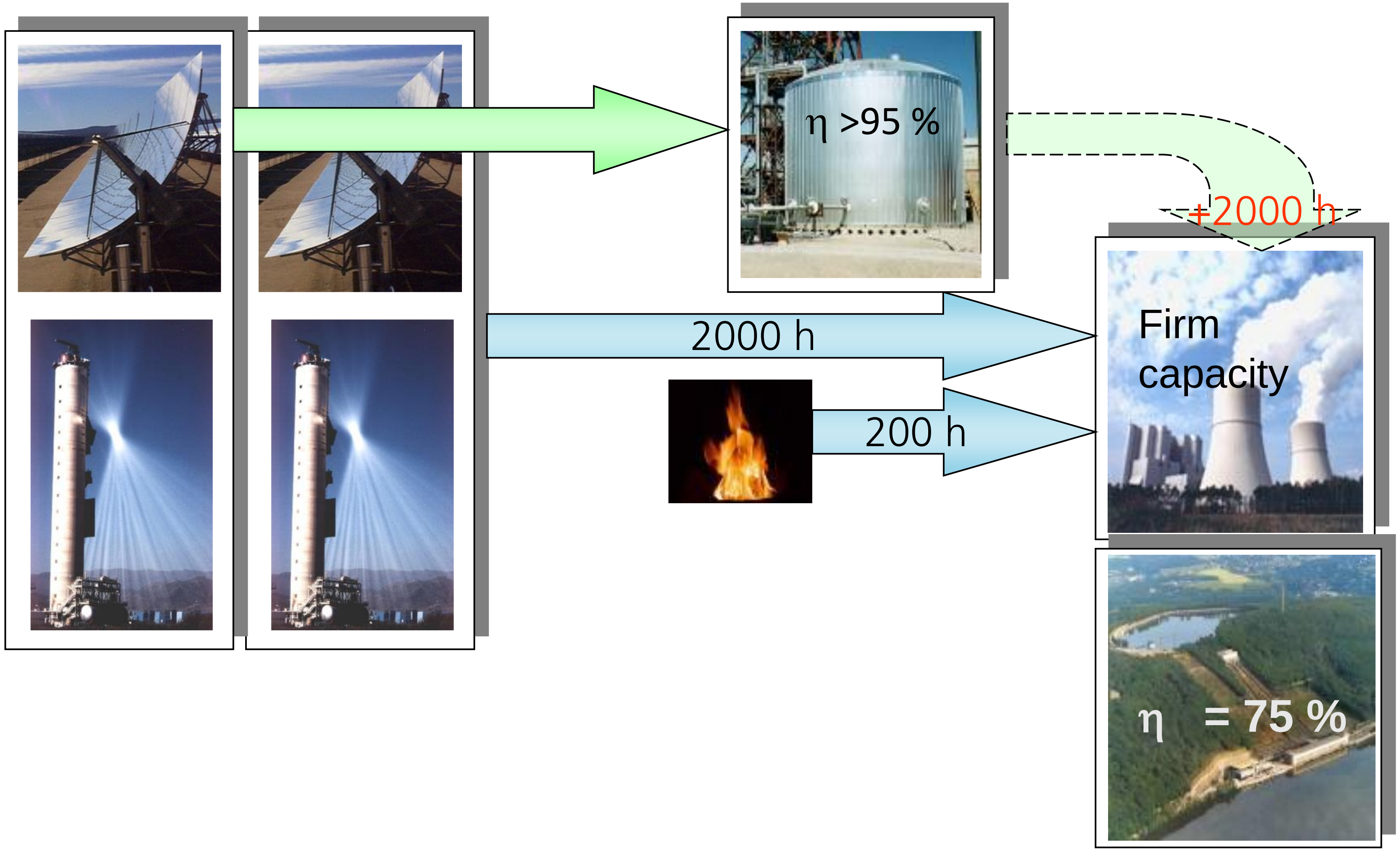


In a nutshell: From high temperatures to electric current



Thermal Storage vs. Electric Storage

CSP with thermal storage and fossil back provides reliable dispatchable power at no additional cost

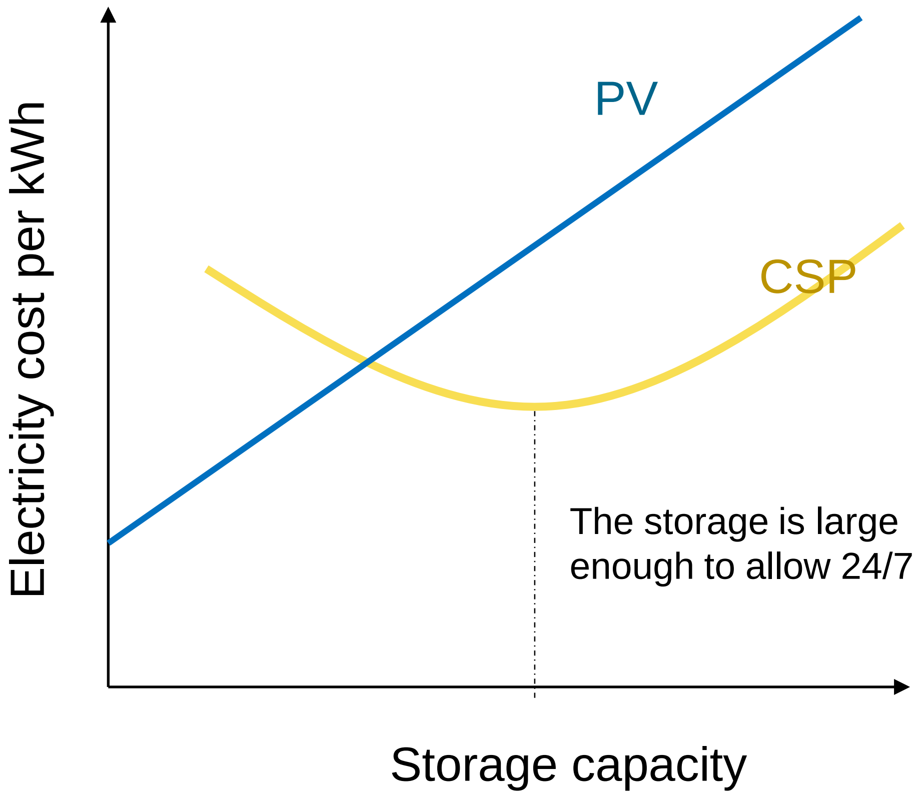


CSP / PV complement each other -
Security of supply around the clock cheaper than with oil, gas, and coal

- CSP power plants with storage deliver **cheaper** power than CSP power plants without storage

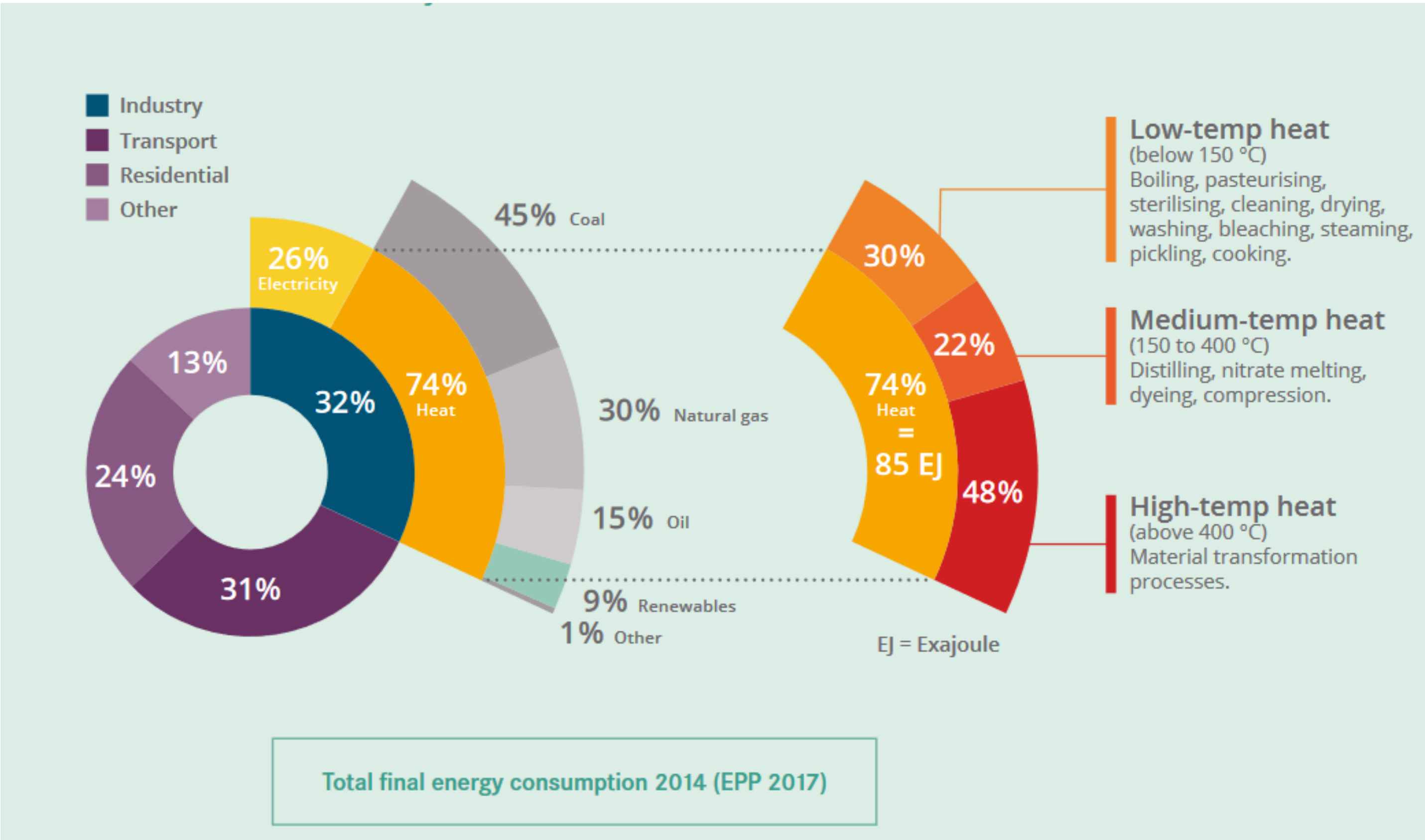
- For PV systems, a system without storage always has the **lowest electricity costs.**

- **Hybrid systems (CSP + PV)** offer the lowest cost of electricity when **electricity** is **also needed at night**

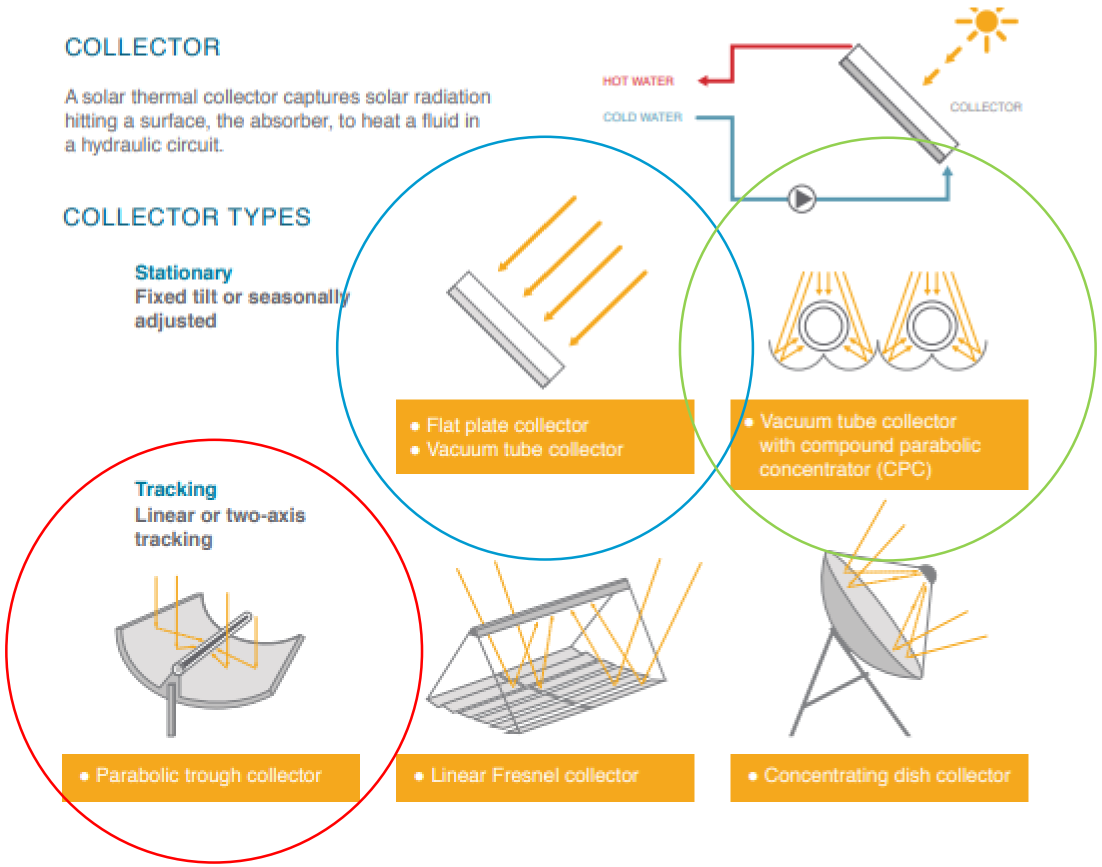


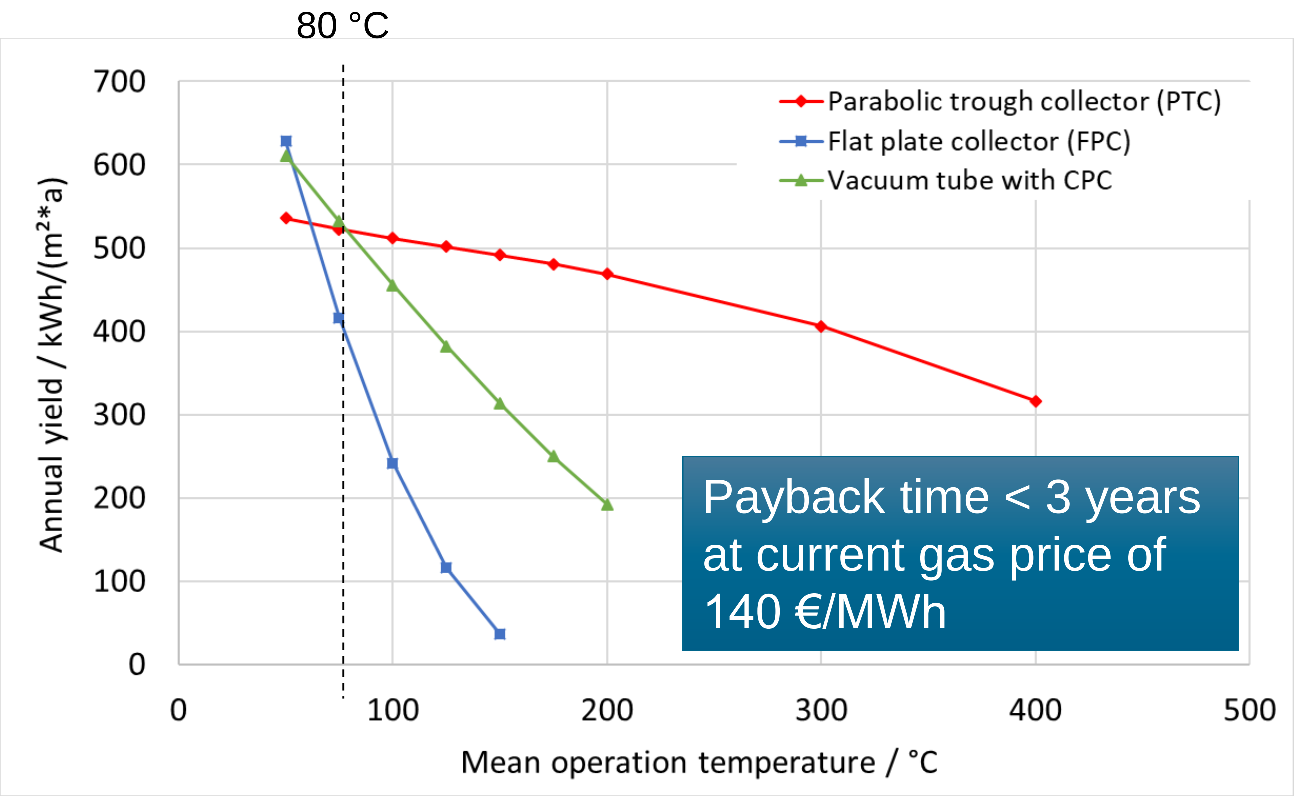
Market potential of CSP technologies for industrial process heat

- Mature technology with more than 800 MW installed worldwide
- Temperature range up to 400 °C fully commercial
- Round-the-clock operation through integrated thermal energy storage
- Low cost compared to fossil fuels
- Growing number of European companies committed to rapid deployment



Energy yield of solar collectors in Germany

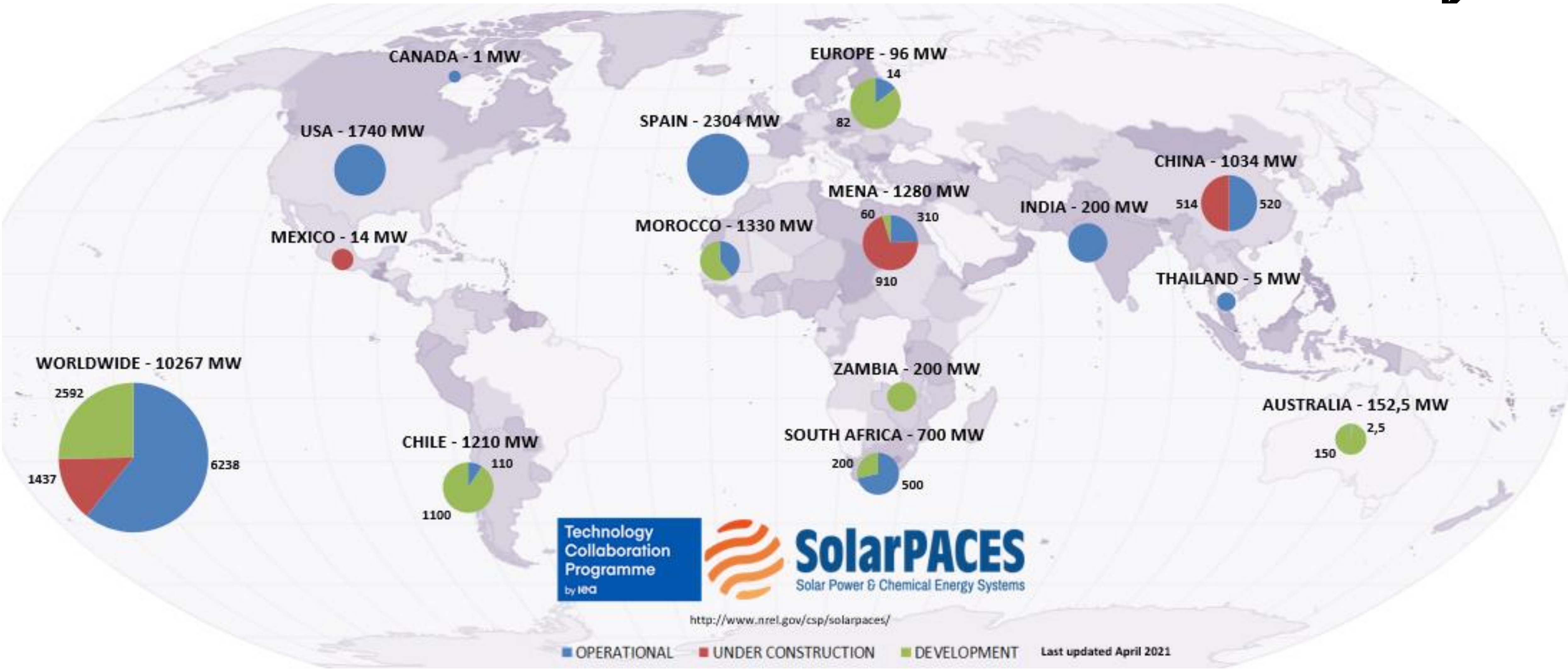




Advantages of concentrating collectors
- More yield from approx. 80 °C collector outlet temperature
- Reaches the desired storage temperature at any time of the year
- Operation also of heat networks with 130 °C flow temperature

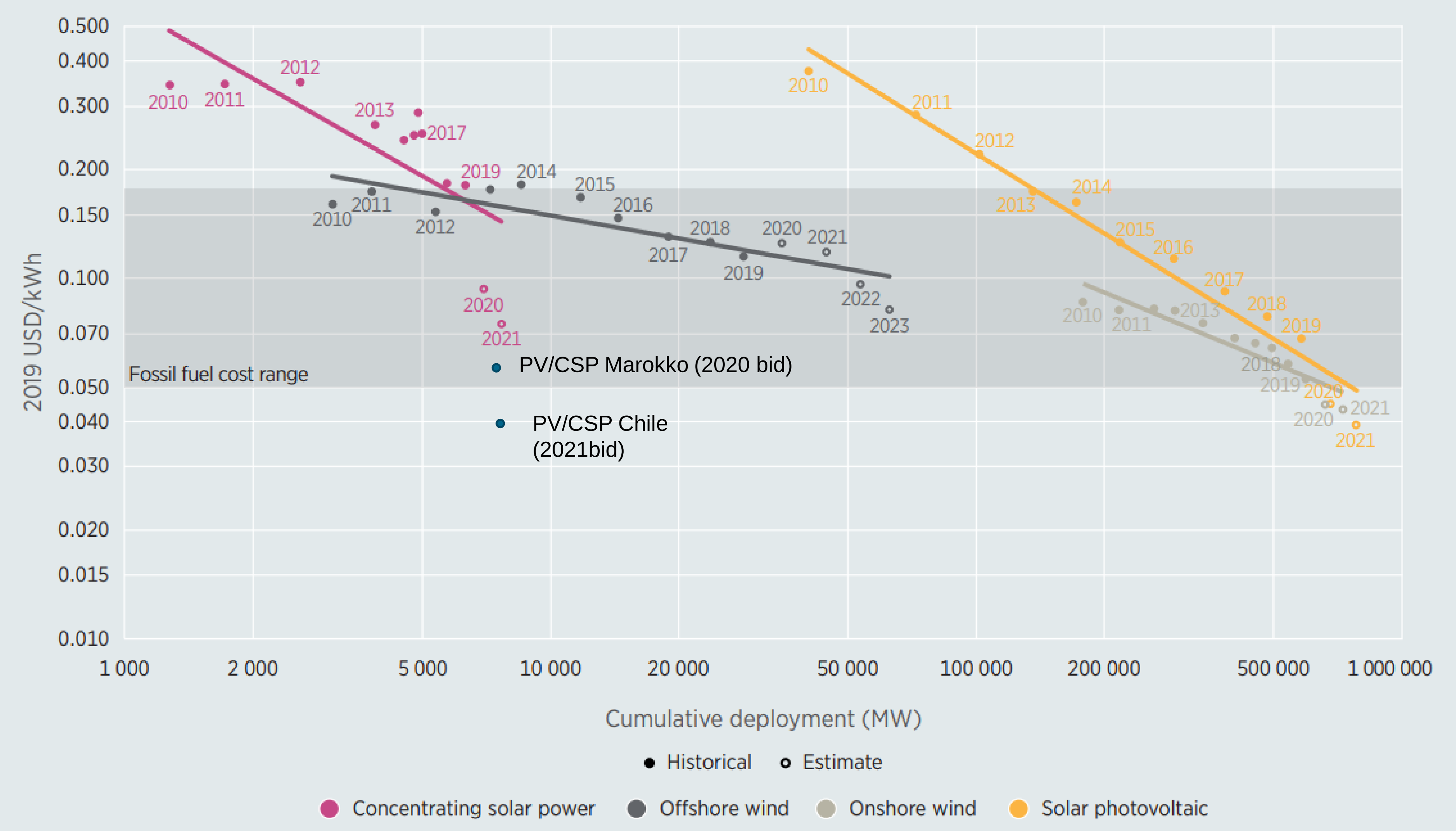
STATUS AND PERSPECTIVES

Current Market Overview CSP: 6.2 GW operational around the world



https://www.solarpaces.org/csp-technologies/csp-projects-around-the-world

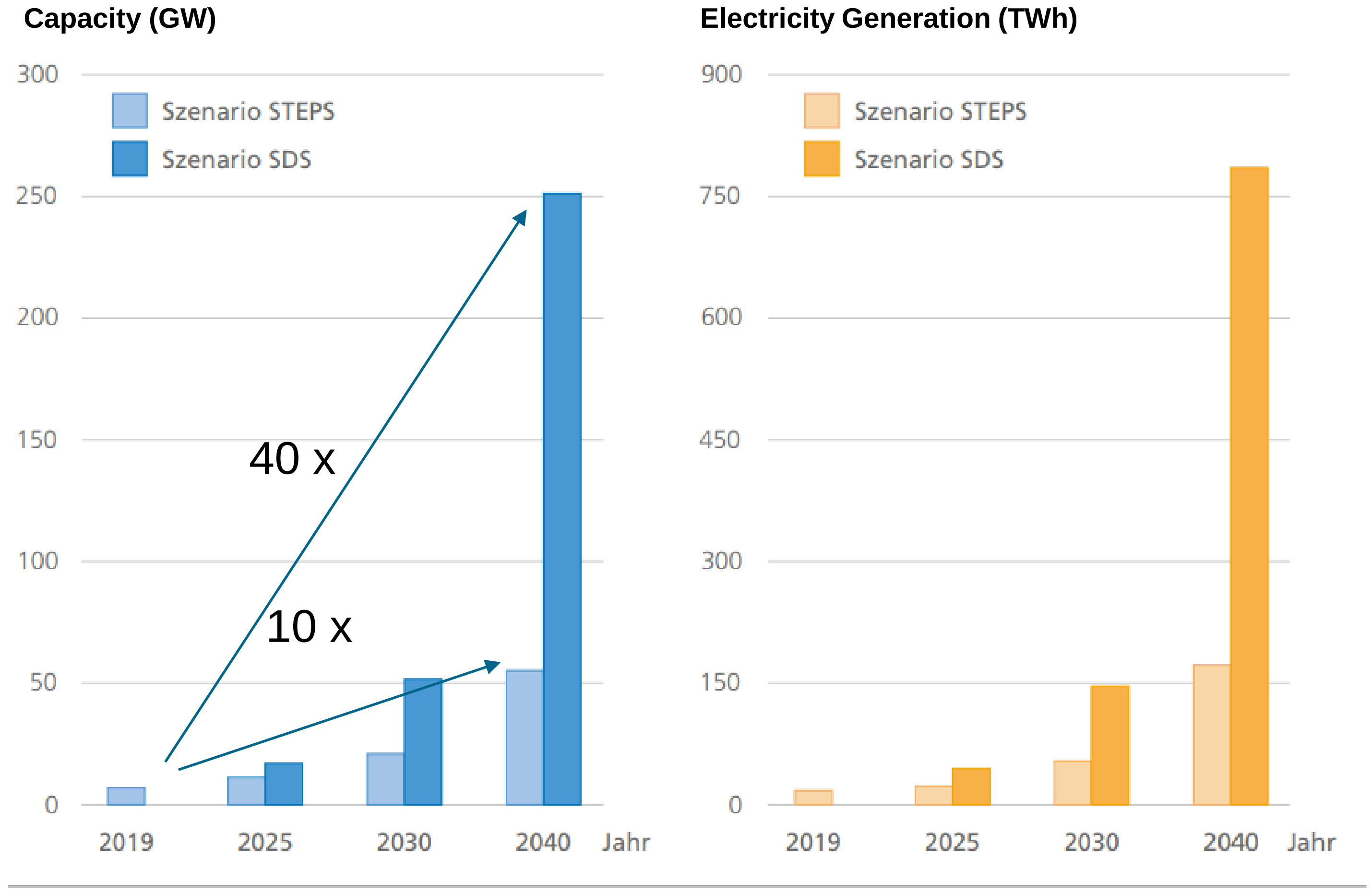
Strong cost degression in CSP at relatively low total deployment



Source: **IRENA, RENEWABLE POWER GENERATION COSTS IN 2019, Figure 1.11** The global weighted-average LCOE and Auction/PPA price learning curve trends for solar PV, CSP, onshore and offshore wind, 2010 – 2021/23

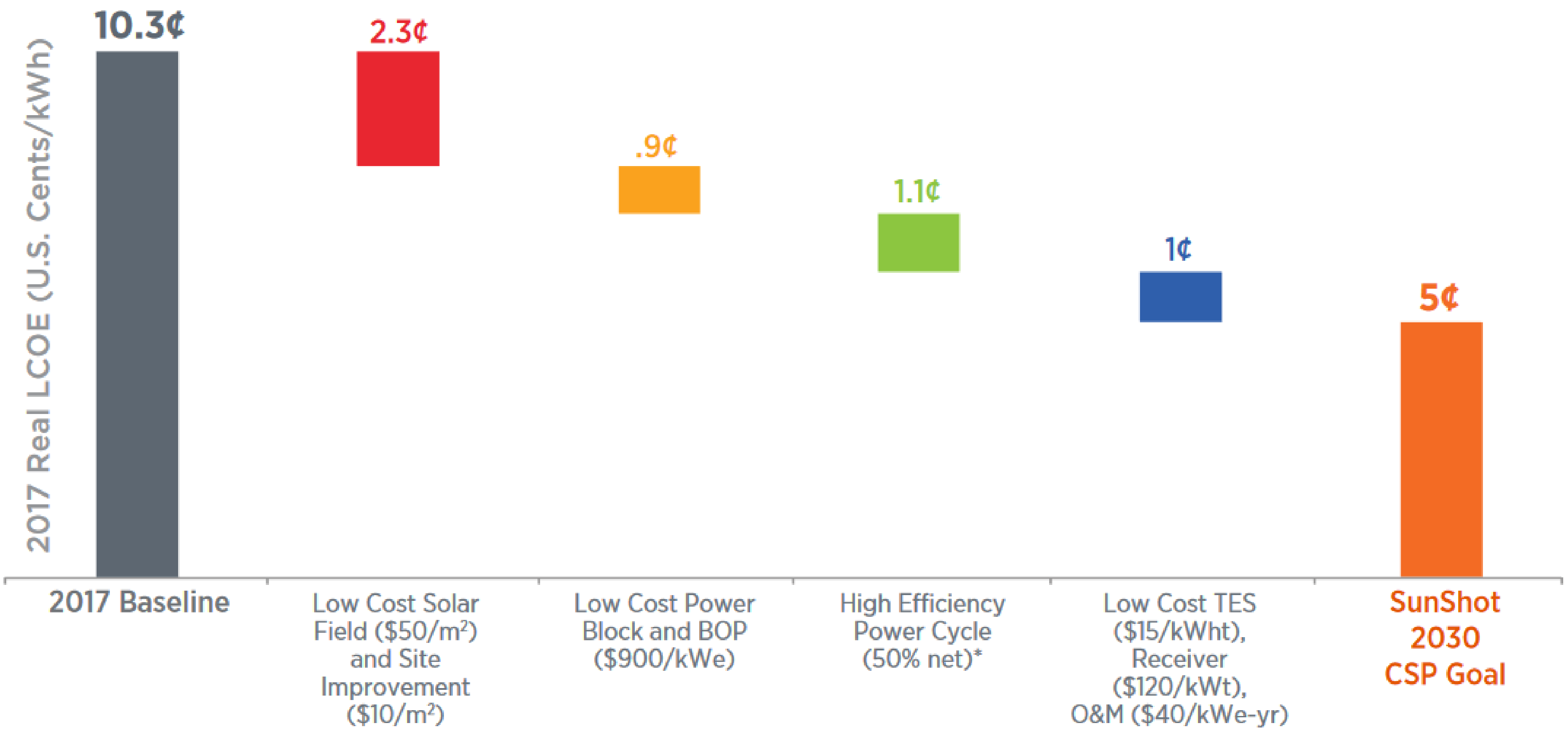
Possible CSP growth scenarios of IEA 2020-2040
(in conjunction with growing capacities of PV and Wind)

15 - 25 % annual growth rate estimated



STEPS: Stated Policies; SDS: Sustainable Development (<1,5 °C)
Source Data from IEA-WEO 2020, Table A.3

Cost reduction scenario of DOE

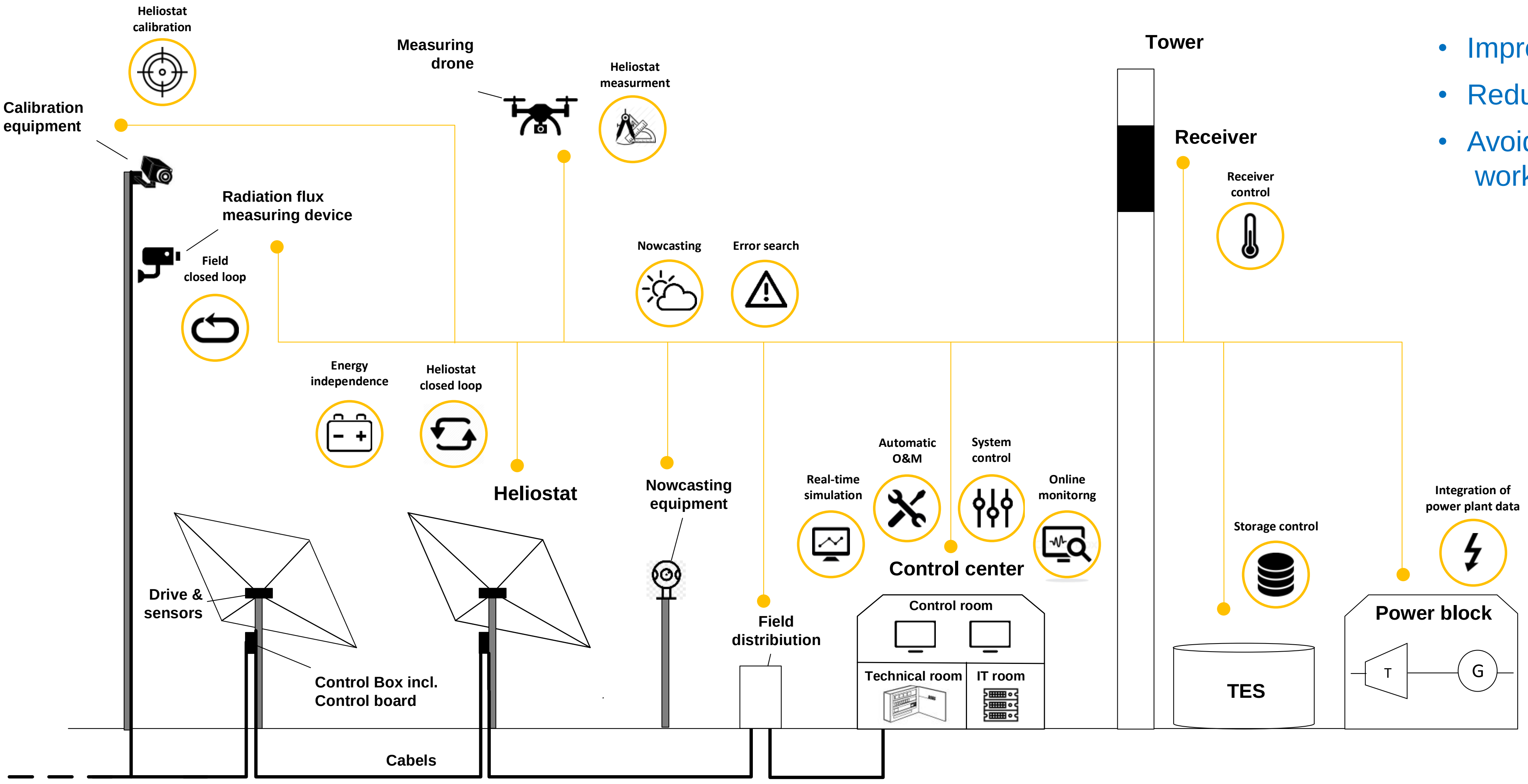


*Assumes a gross to net conversion factor of 0.9

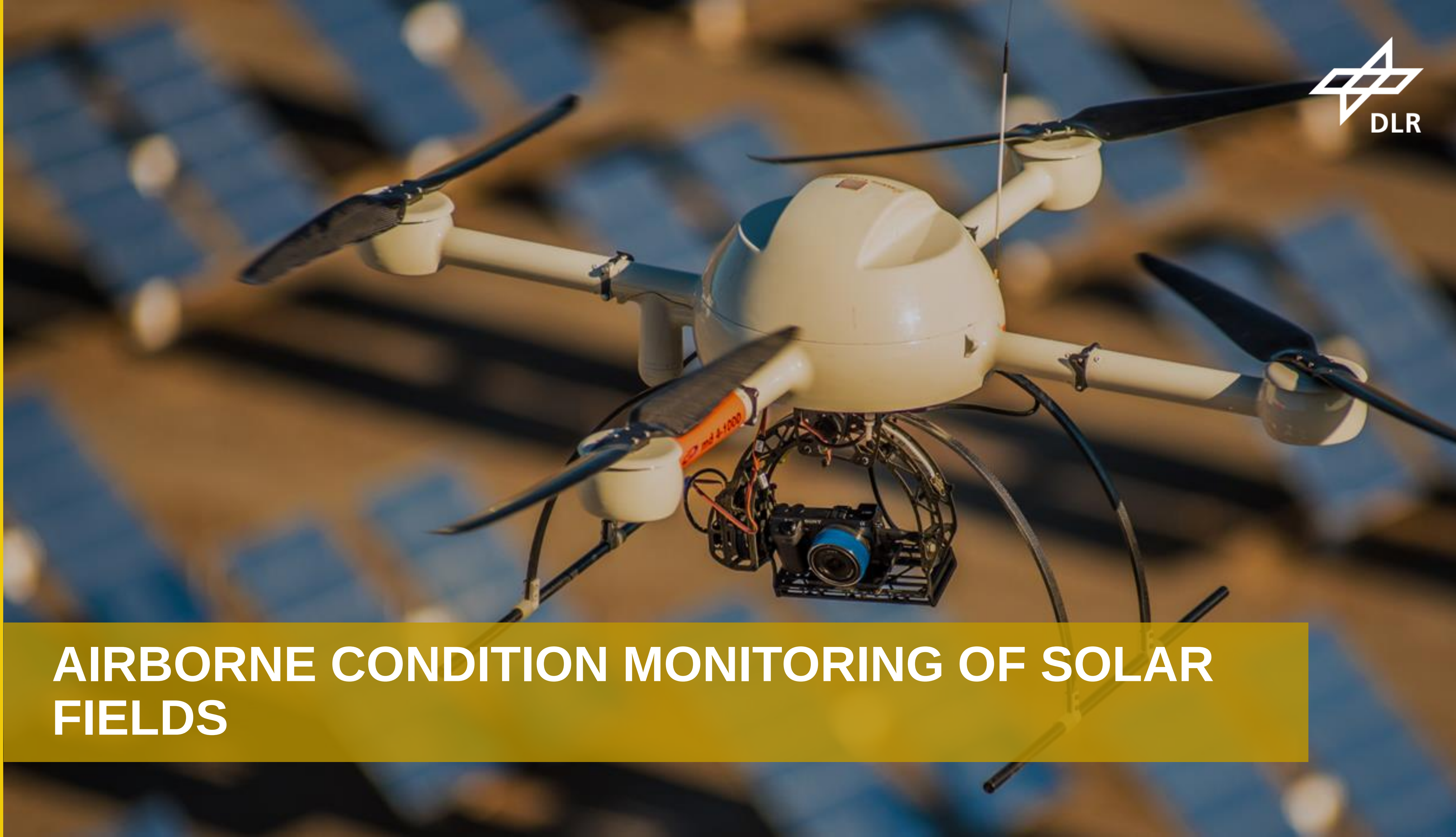
Source: DoE

ADVANCED METHODS TO OPERATE A CSP PLANT EFFICIENTLY AND AUTONOMOUSLY

Autonomous CSP Plant Control based on Artificial Intelligence



- Improved energy yield
- Reduced OPEX
- Avoidance of harsh working conditions

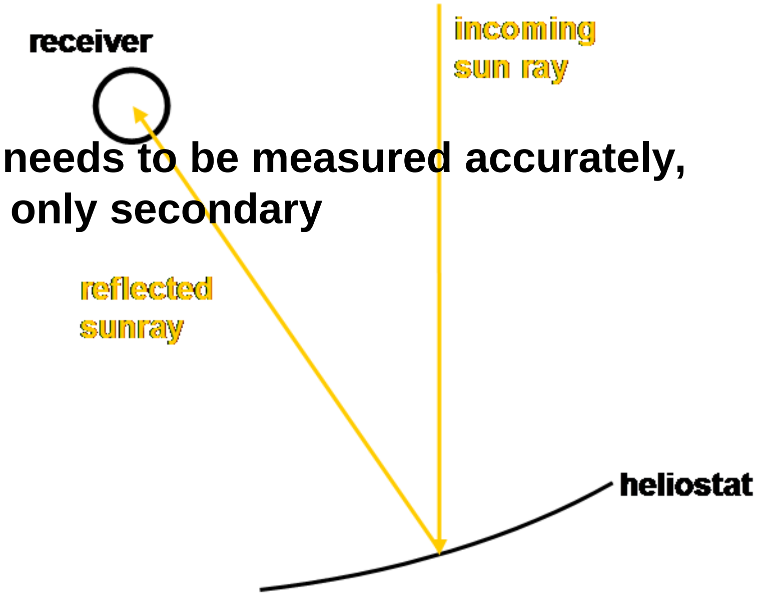


AIRBORNE CONDITION MONITORING OF SOLAR FIELDS

Introduction: Shape and Slope Deviations

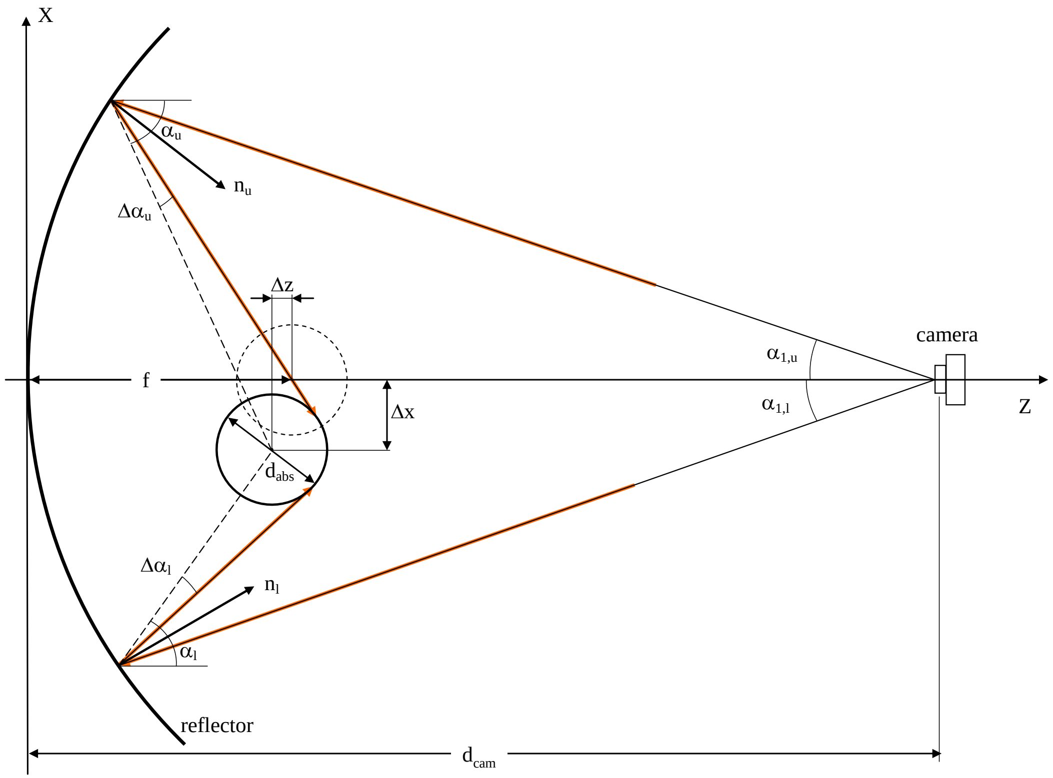
Deviations of the ideal shape of curved mirrors for CSP applications can have a significant impact on the optical efficiency and thus the performance of the power plant.

Critical measure is slope deviation, not shape deviation:

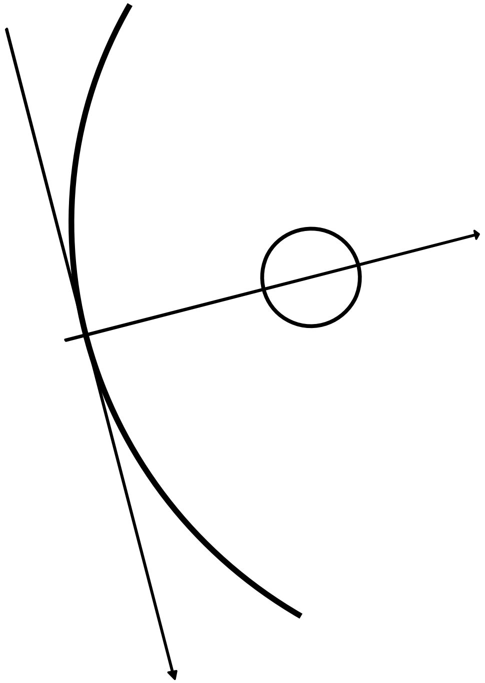


-> slope needs to be measured accurately, shape is only secondary

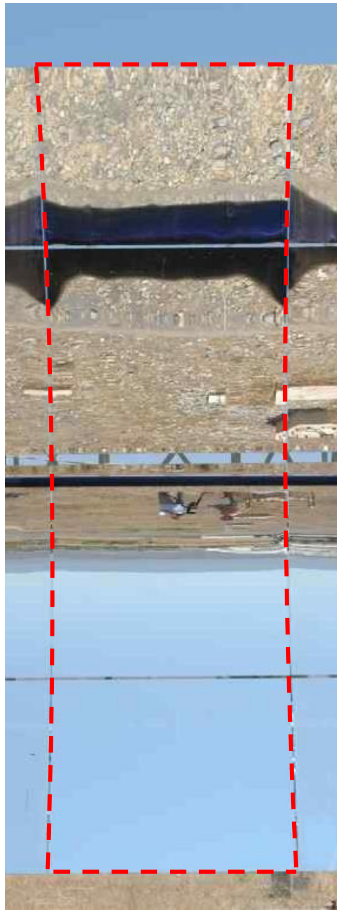
TARMES (Trough Absorber Reflection Measurement System): Basic idea and set-up of measurement system



Measurement:
Turning of collector with camera at close distance (~17 m)

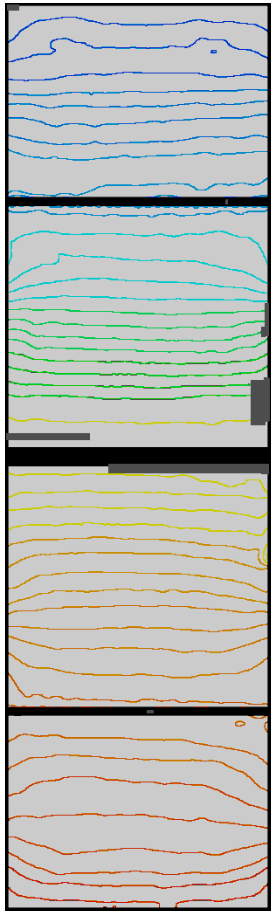


Evaluation

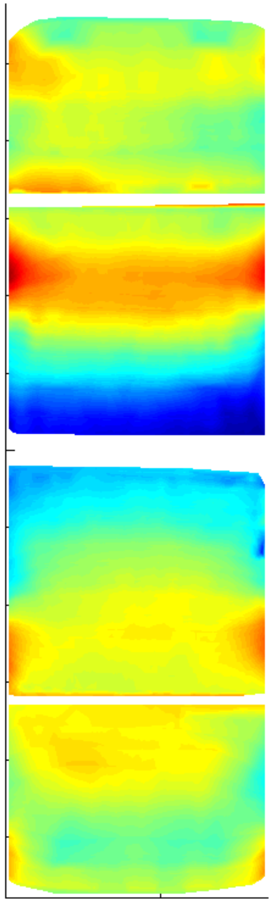


- *Correction of lens distortion*
- *Image rectification*

- *Image treatment*
- *Edge detection*



- *Input of geometrical set-up*
- *Calculation of slope errors*

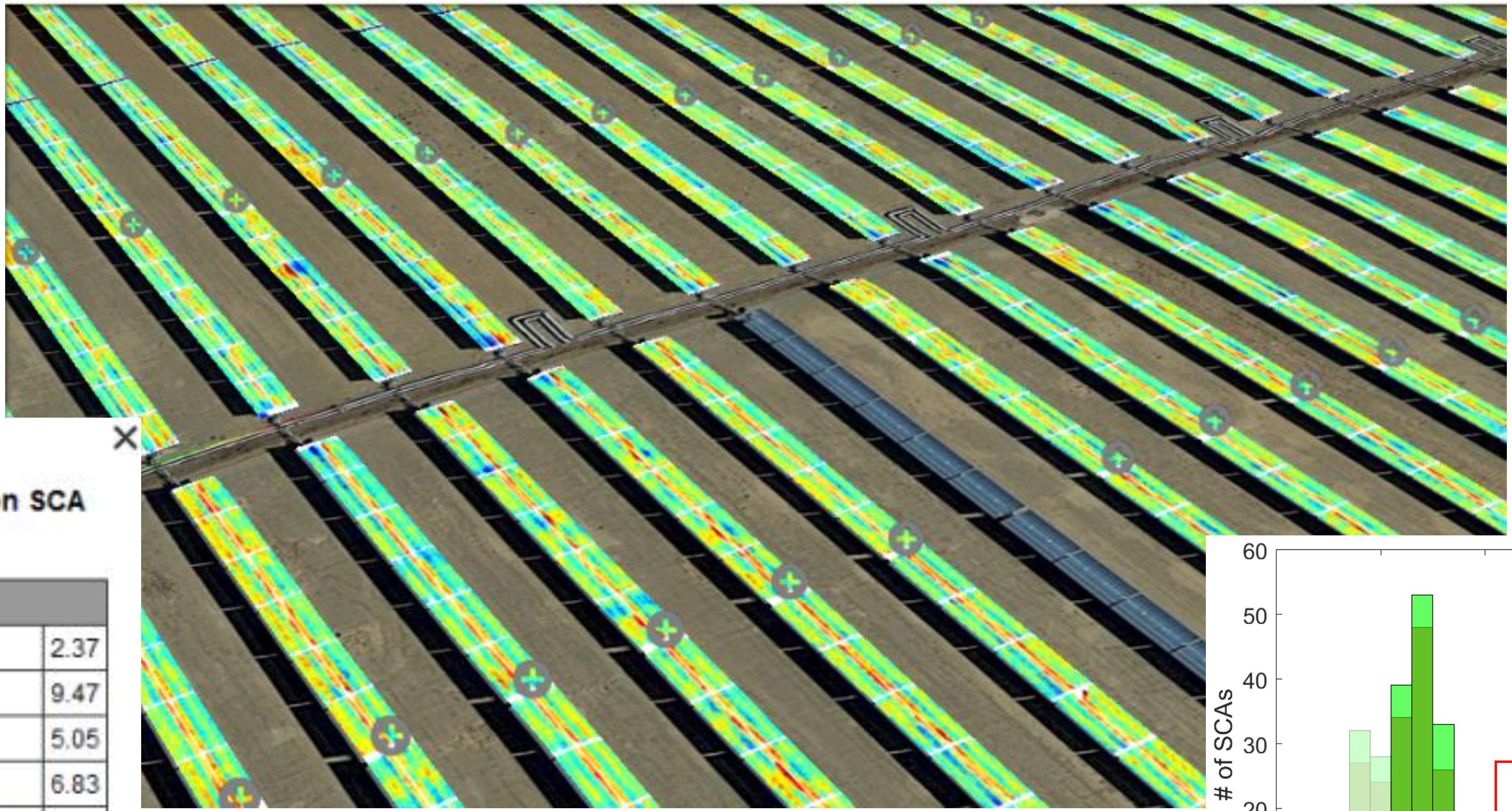


Example 1 Parabolic Trough Shape Accuracy
QFly Data Acquisition

Example 1 Parabolic Trough Shape Accuracy

QFly Results: Solar Field

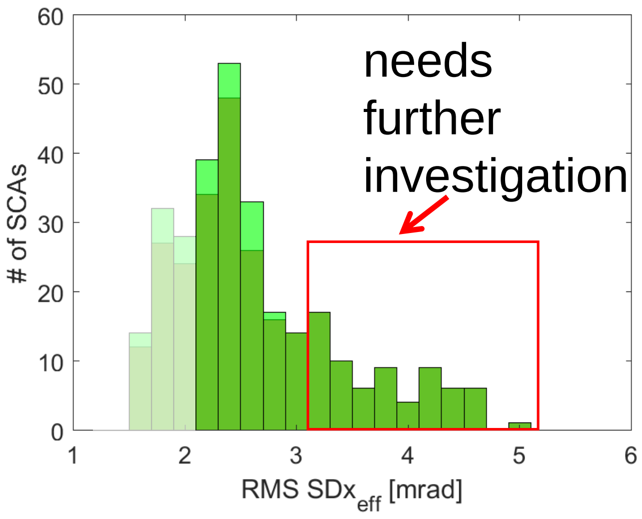
Slope Deviation *SDx,eff* for the whole collector (SCA) in mrad



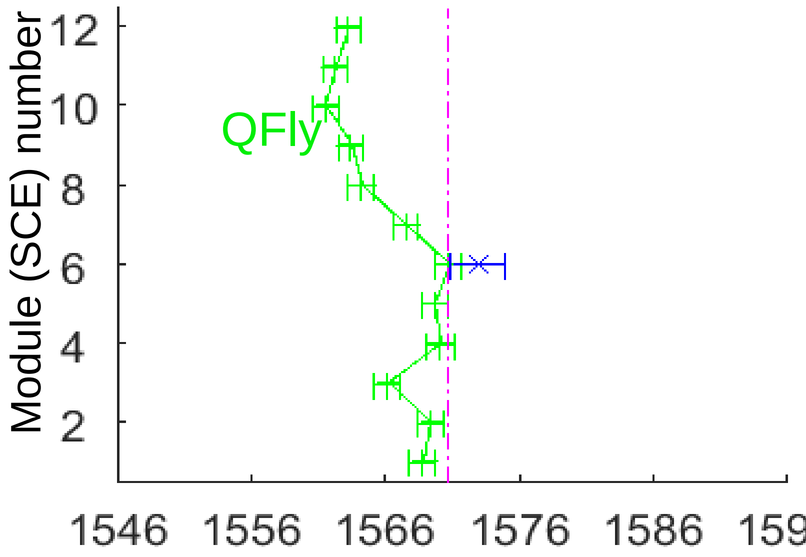
Additional Information on SCA 22

Additional Information	
RMS_SDx	2.37
RMS_FDx	9.47
dtrack_SurveyMinusLOC	5.05
dtrack_SurveyMinusTarget	6.83
dtrack_RMSWithinSCArel2Drive	1.65

Directions: To here - From here

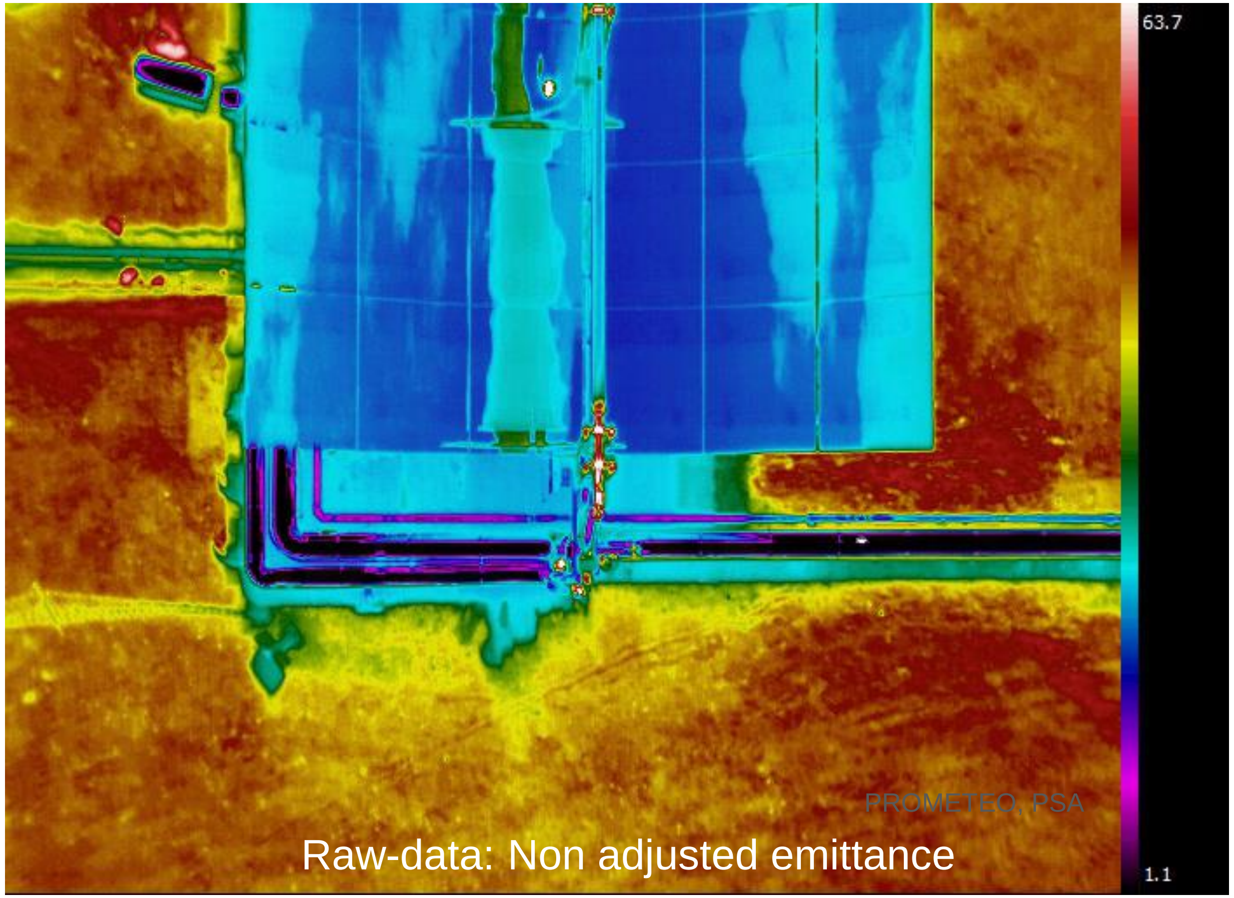


Example 2 Parabolic Trough Torsion/Tracking
QFly Results: Collector (SCA)



Example 2 Parabolic Trough HCE Quality Screening

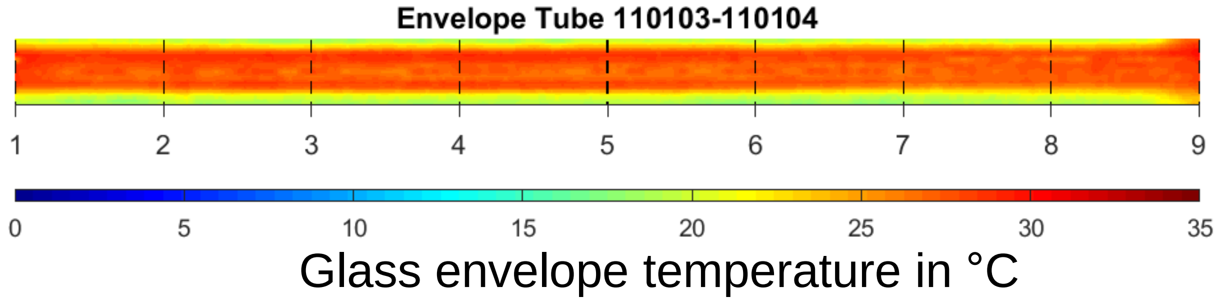
- Measurement of glass envelope temperature by IR camera
- Measurement accuracy ~2 K



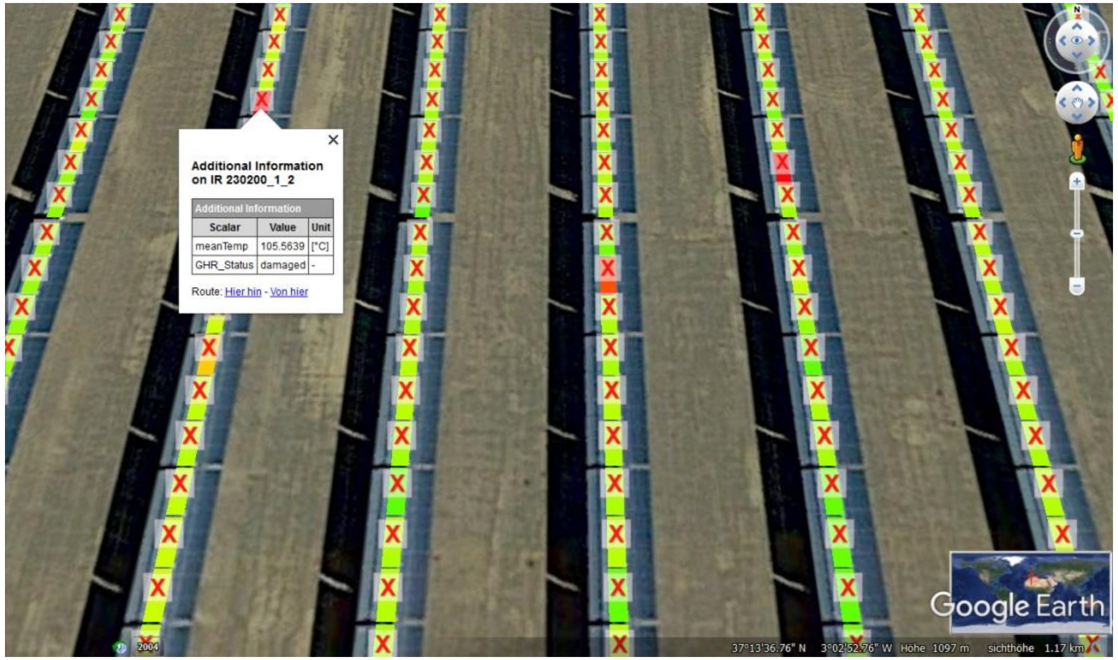
Example 3 Parabolic Trough HCE Quality Screening

QFly Results: Collector (SCA)

- Measurement of glass envelope temperature by IR camera
- Measurement accuracy ~2 K

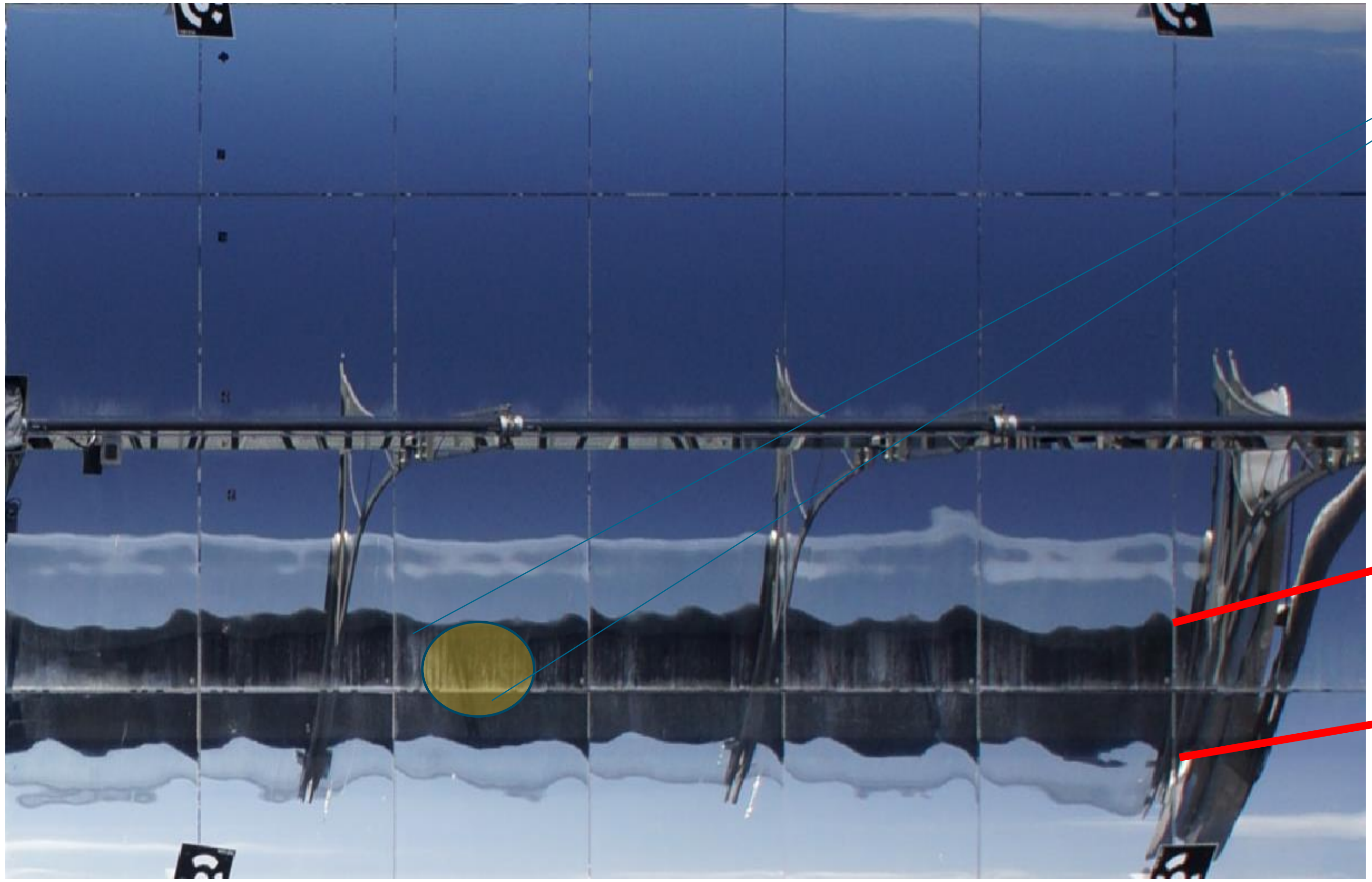


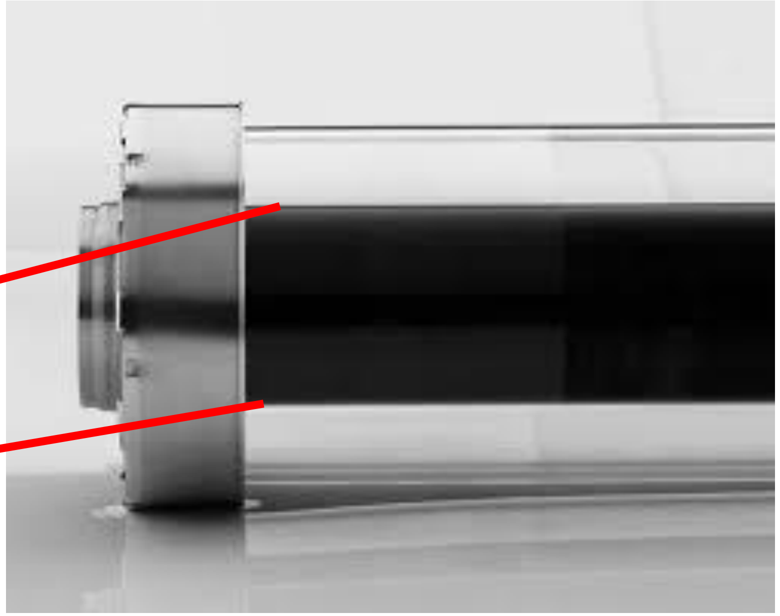
- Automatic evaluation for glass temperature
- Automatic location of receivers in solar field and reporting
- Also applicable to other piping



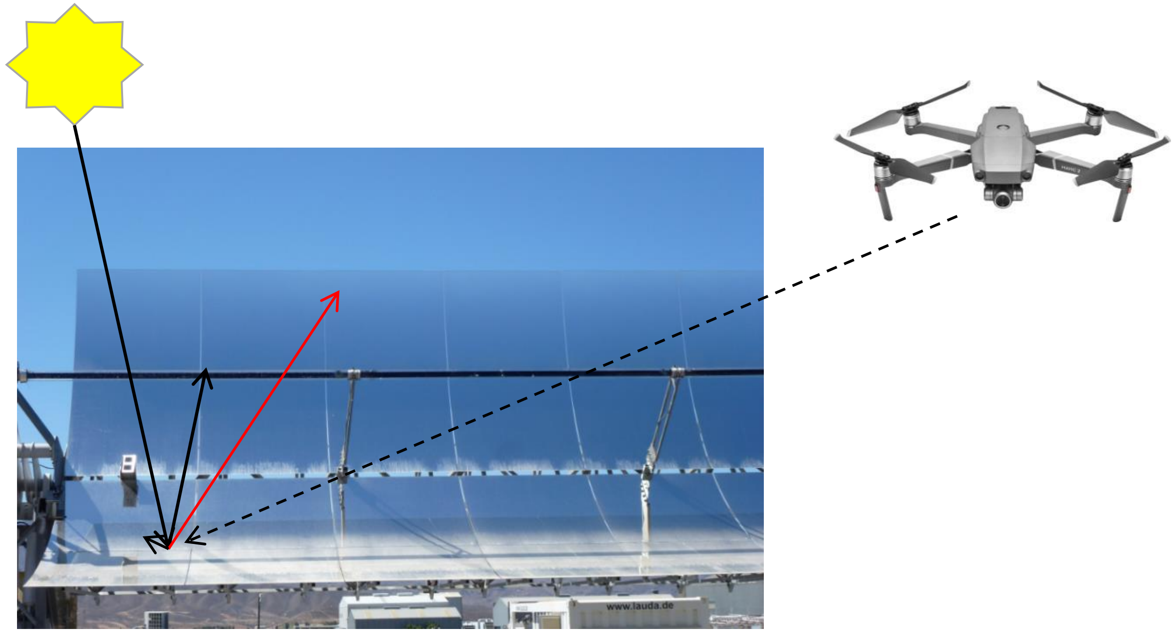
Example 4 Soiling Maps

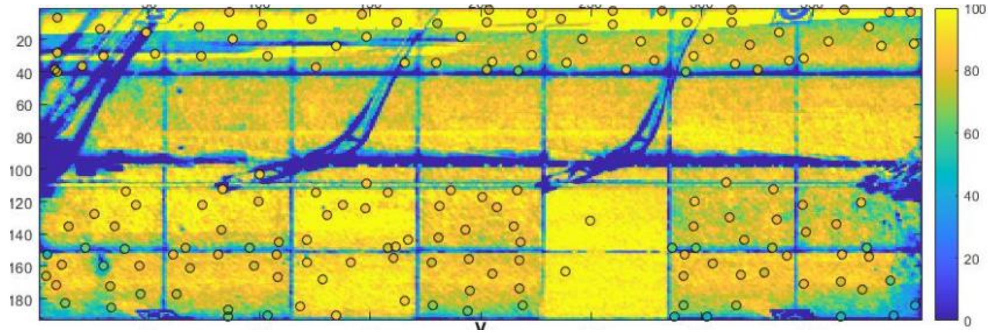
Soiled regions are brighter

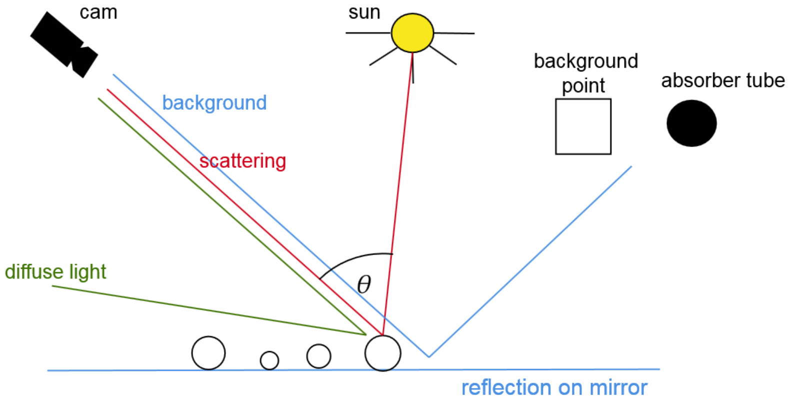


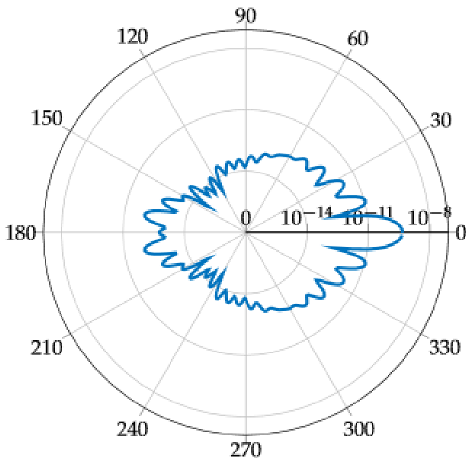


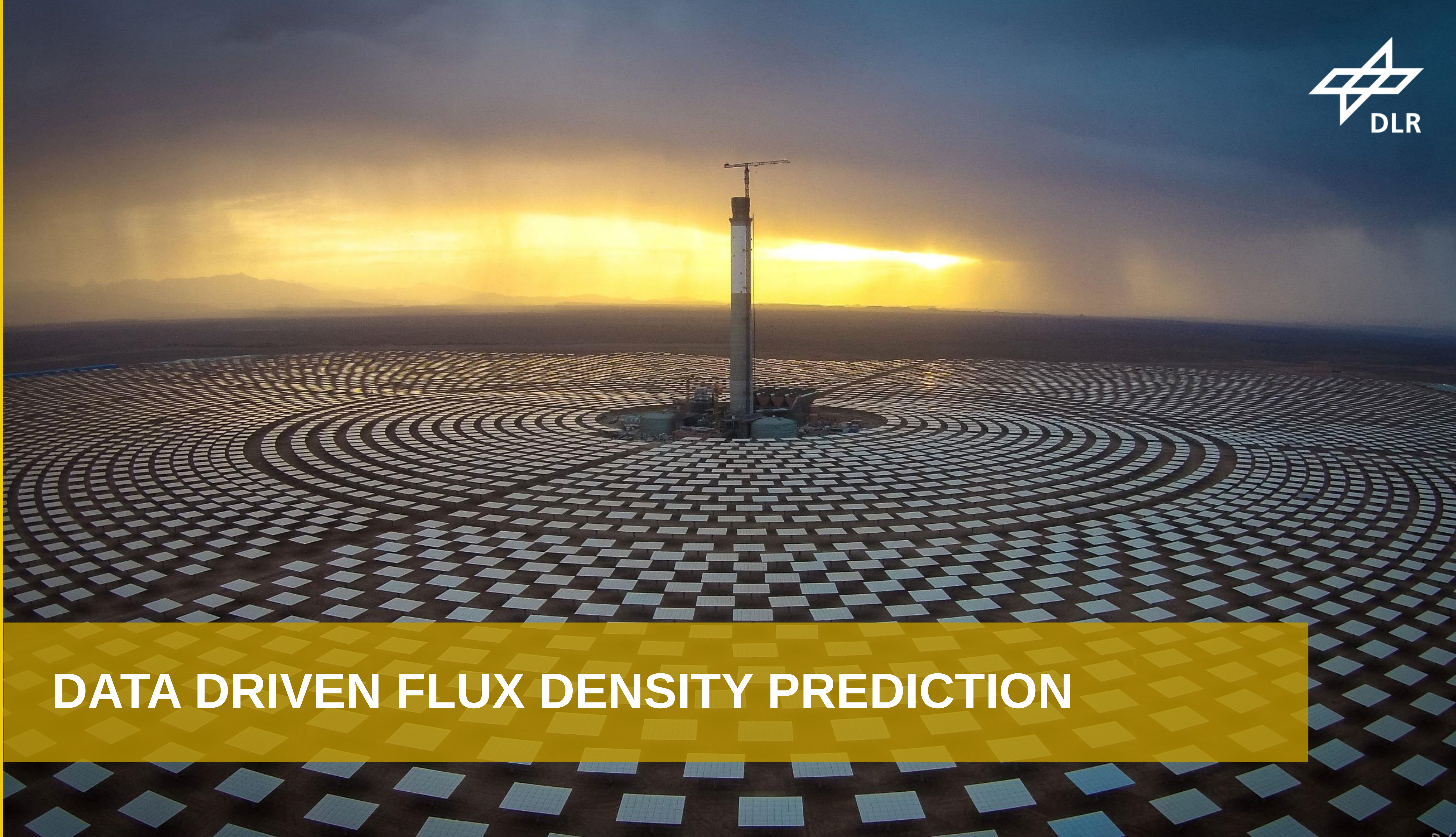
Creating soiling maps







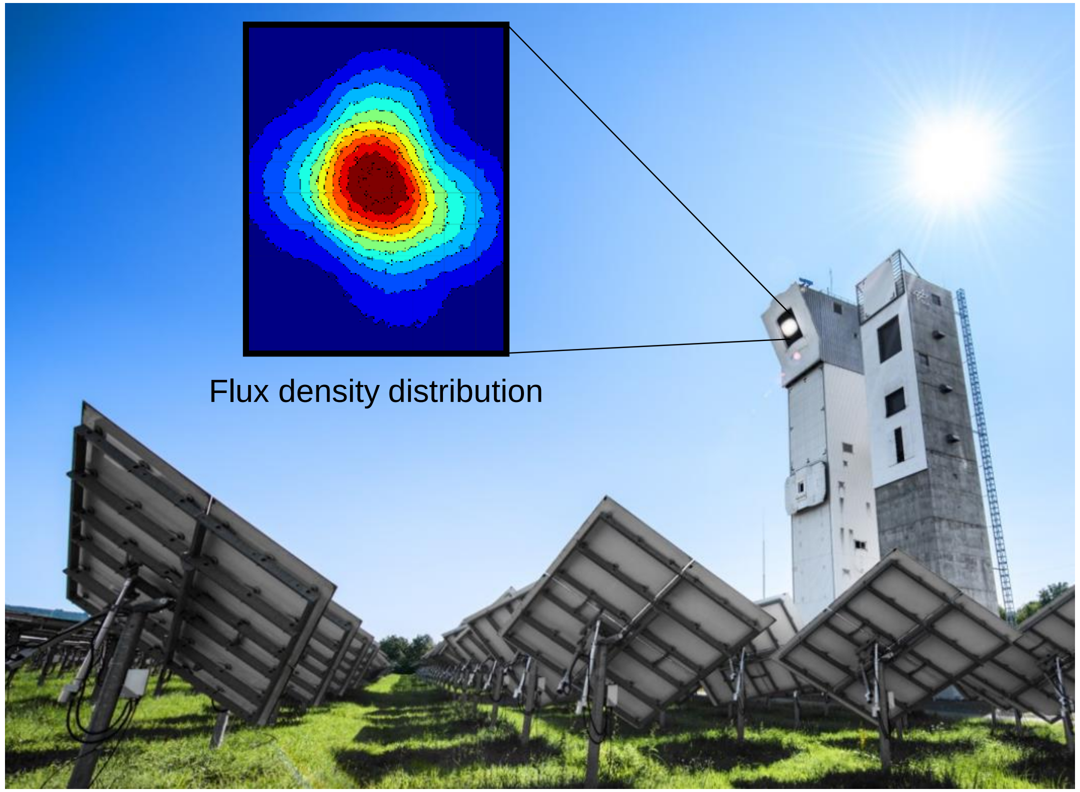




DATA DRIVEN FLUX DENSITY PREDICTION

Motivation - flux density distribution

- The flux density distribution on the receiver is the power distribution caused by the concentration of the solar radiation
- This flux density should maintain requirements for materials and homogeneity



Therefore a more precise knowledge of the flux density allows

- a more efficient control
- longer durability of the components

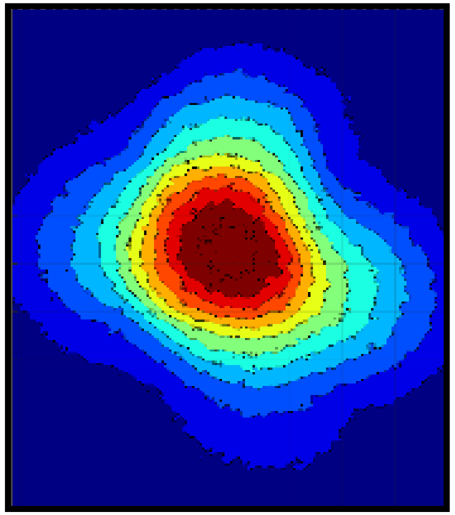
Flux spot of a single heliostat

- The flux density consists of the superposition of the focal spots of the individual heliostats of the field

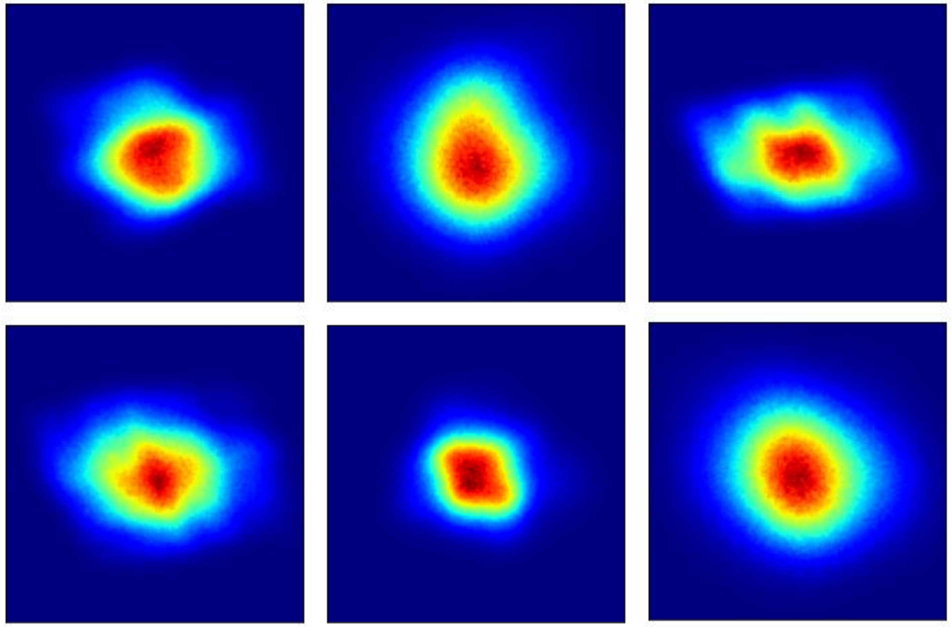
- The focal spots can have different sizes and shapes and vary with the position of the sun

➢ We want to predict the focal spots of the individual heliostats at any sun position

Flux density distribution

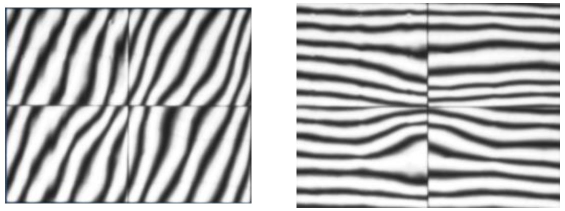


Focal spots of individual heliostats

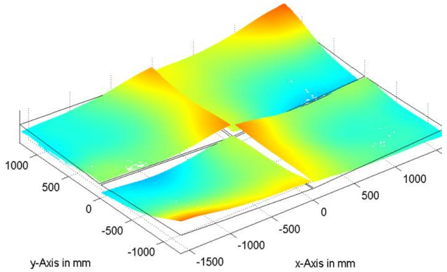


…

State of the art: Stripe deflectrometry

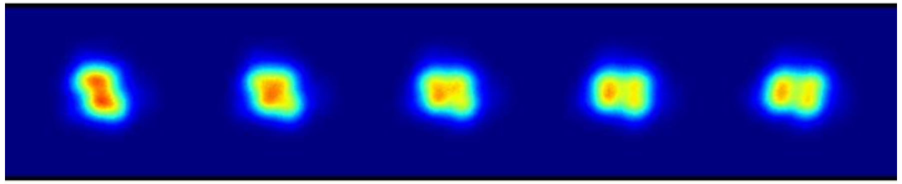


Pictures of heliostat from stripe deflectrometry measurement



calculate surface deformations

Predictions



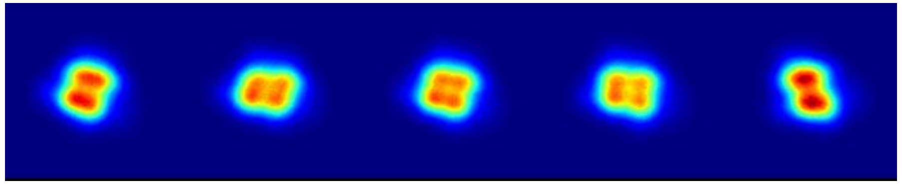
Sun position $\vec{s}$

Use surface within a raytracer to get flux predictions

[Automated high resolution measurement of heliostat slope errors, *Ulmer et al.*]

Idea: Use existing data to improve flux predictions

Measured train data: Flux $\boldsymbol{X}(\vec{s})$

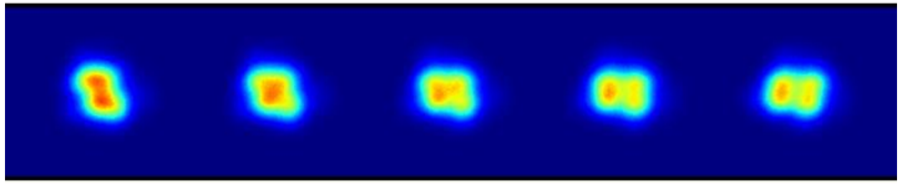


Measured data from target of single heliostats during calibration process

heliostat model

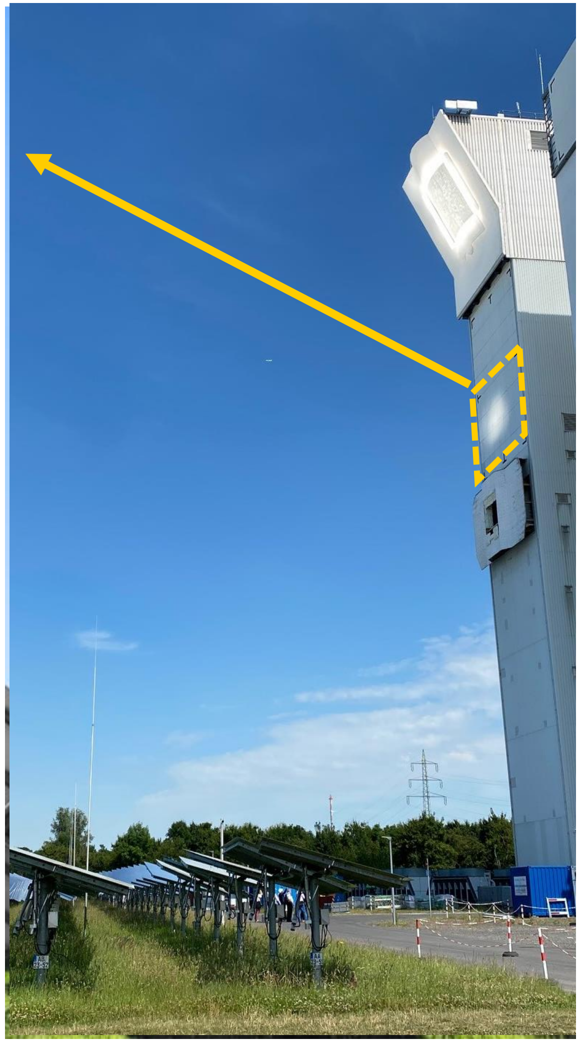
Use data to train a heliostat model

Predictions



Sun position $\vec{s}$

Use trained model to predict any future flux density distribution



Physical vs. data driven heliostat model

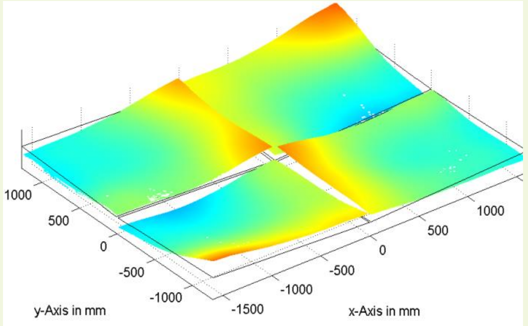
heliostat space

flux space

Different heliostats

Physical heliostat models

- Size
- Position
- Surface deformations
- Canting
- …



parameter fitting

simulation

a physical heliostat model can be fitted to the data and then used to calculate future fluxes

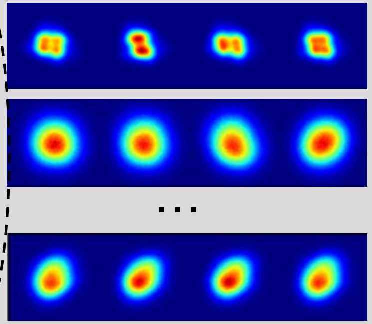
Train data

h_1

h_2

…

h_i



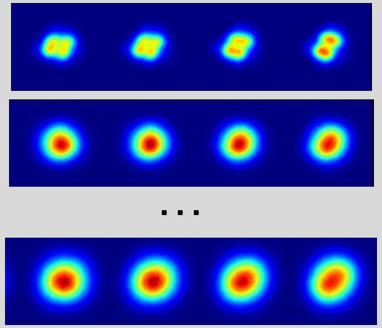
Predictions

h_1

h_2

…

h_i



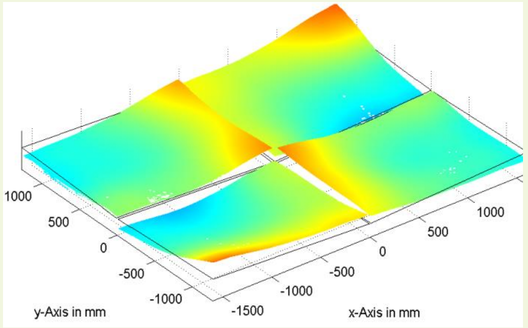
Physical vs. data driven heliostat model

heliostat space

flux space

Physical heliostat models

- Size
- Position
- Surface deformations
- Canting
- …



parameter fitting

Non-unique mapping, underdetermination

Information level

Model assumptions/simplifications

simulation

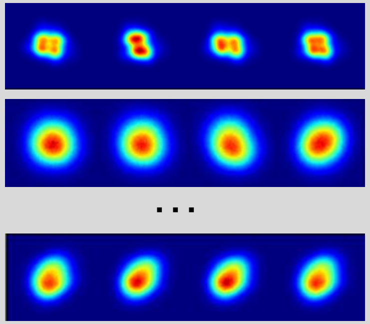
Train data

h_1

h_2

…

h_i



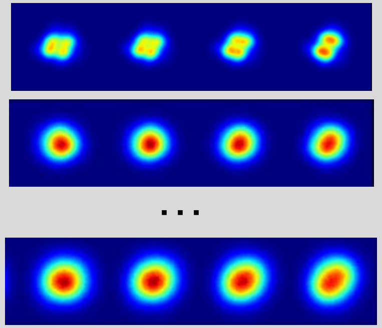
Predictions

h_1

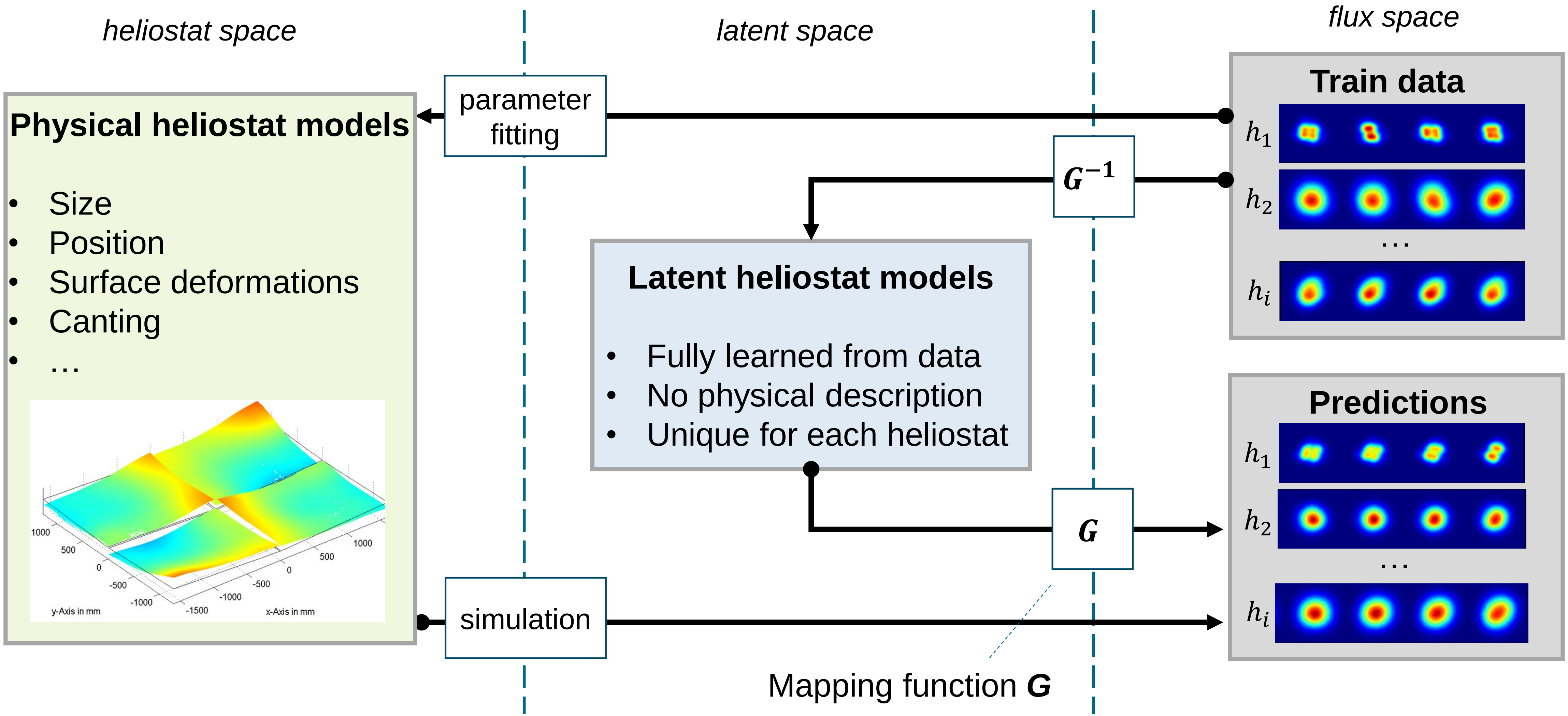
h_2

…

h_i

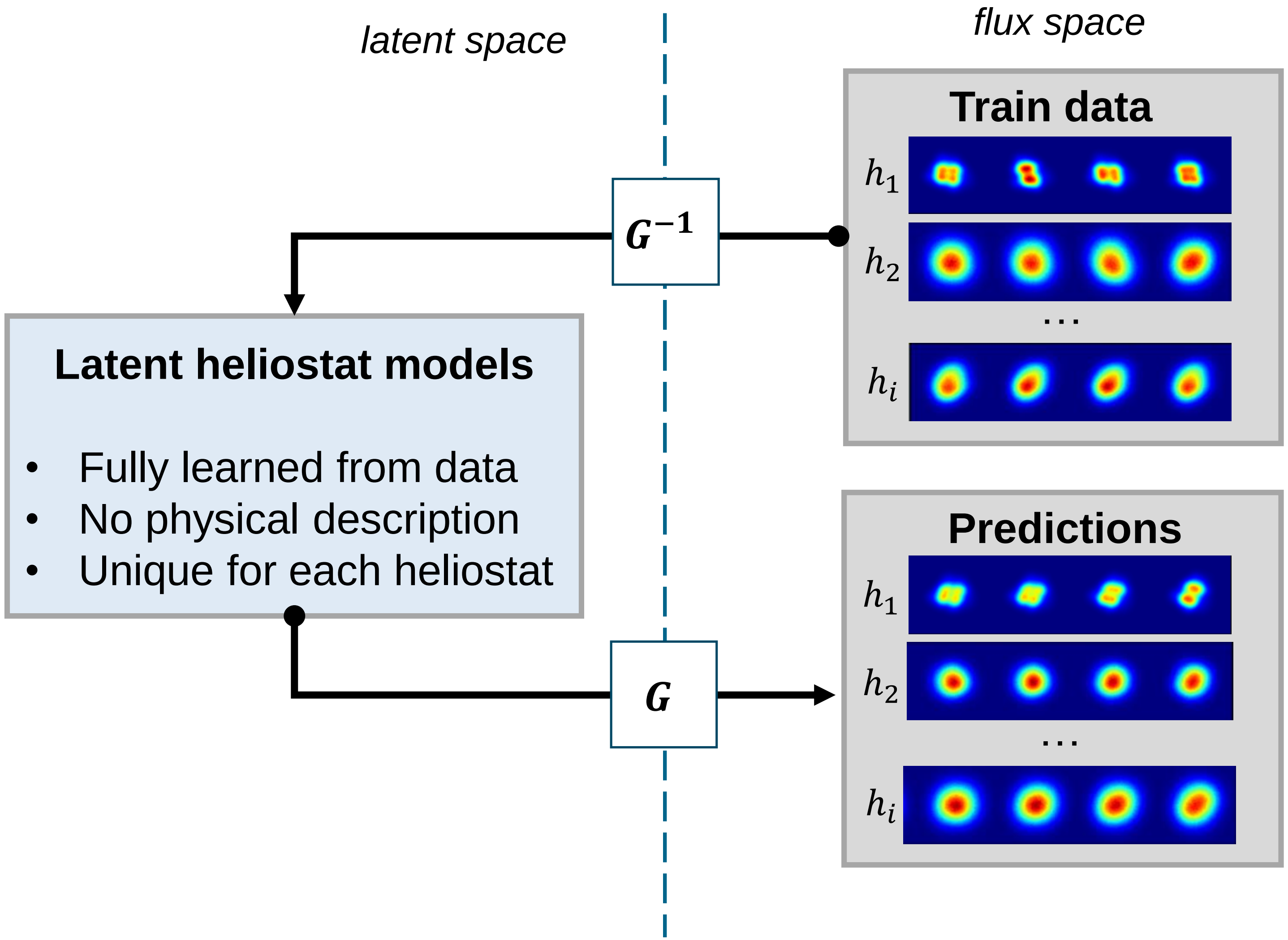


Physical vs. data driven heliostat model

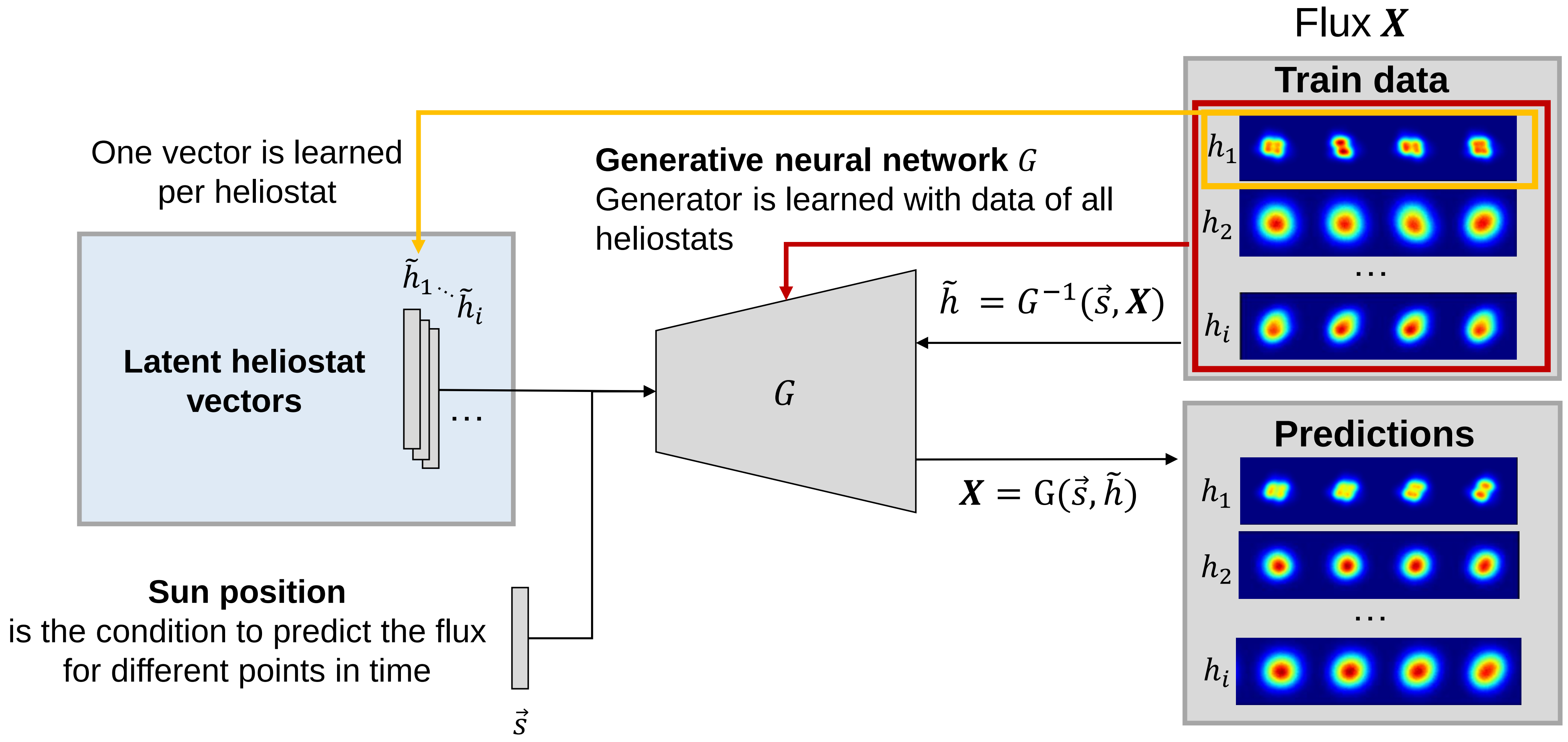


Physical vs. data driven heliostat model

- Instead of a physical model a unique abstract latent model for each heliostat is learned
- without the physical regularization, there is less information lost when mapping to the heliostat model
- The mapping function ***G*** is also learned from the data
- Because both ***G*** and the latent models are learned form data, we are able to find a more suitable representation for the flux space



Data driven heliostat model and generator

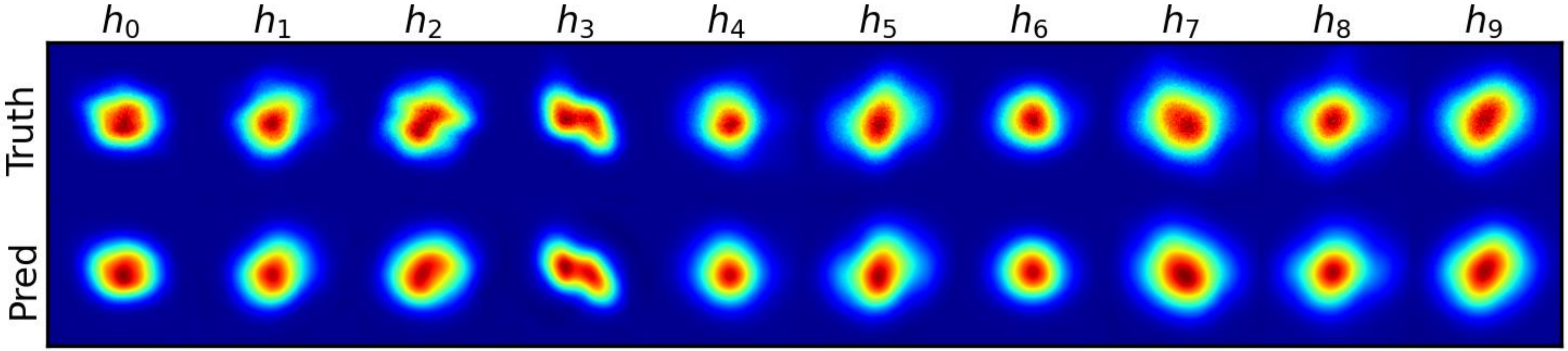


- Generator learns generalizing flux prediciton for all heliostats
  - ➢ Heliostats profit from each others data
- ➢ Heliostat specific features get extractet to latent vector

Results:
Predictions for new unseen sun positions for different heliostats

Model is able to

- extract heliostat specific features to latent vector
- predict flux for unseen future sun positions



Predicted flux by model (lower row) compared to groundtruth (upper row) for different heliostats h_i

Accuracy of flux predictions as a function of distance

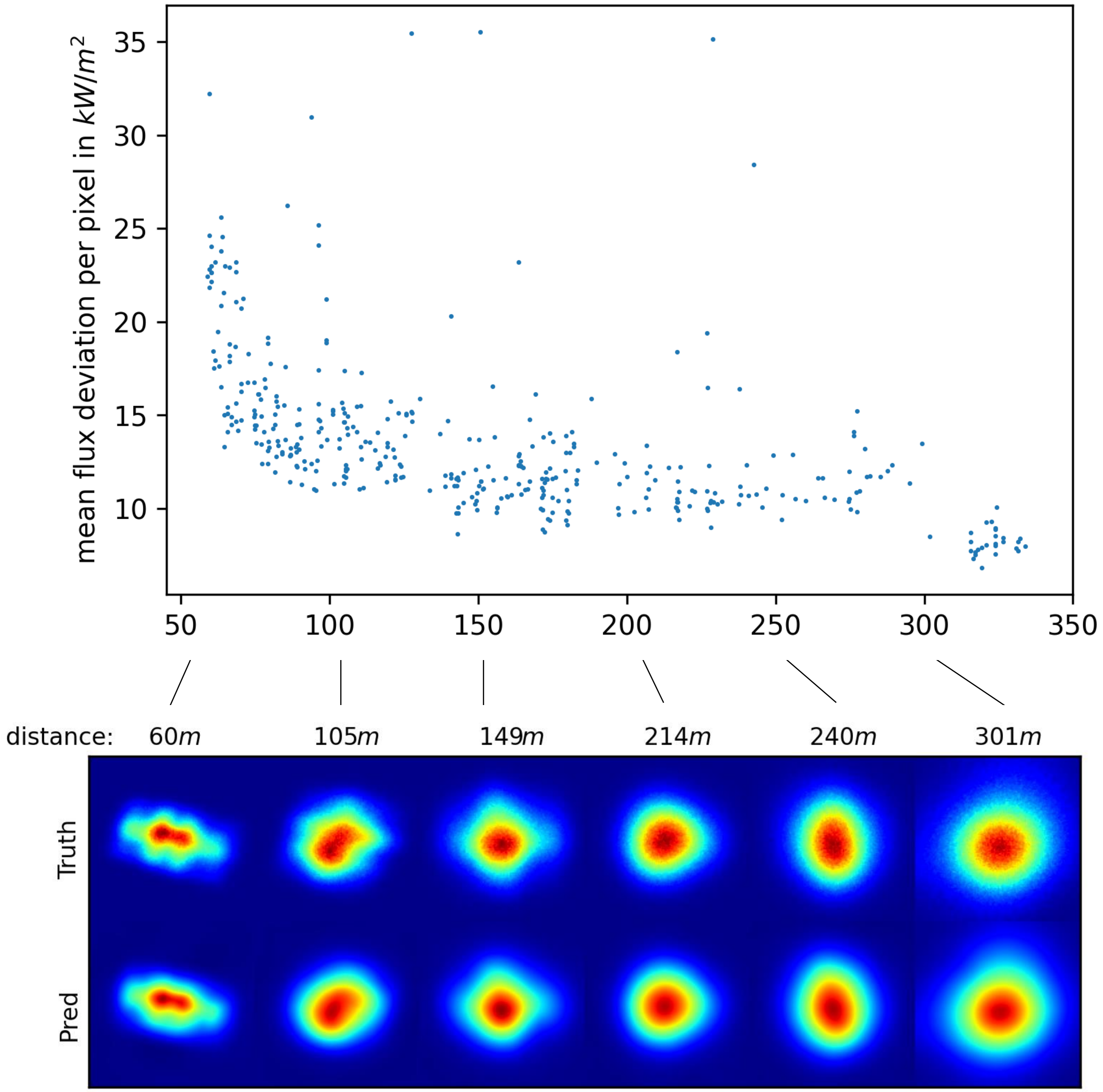
- Further distances lead to less information about the heliostat in the flux density

➢ the model is able to correctly predict the flux density for these heliostats

➢ Error ~5 %

➢ The error becomes smaller even for increasing distance

➢ which is due to the fact that those focal spots are easier to predict and better conditioned for pixelwise loss

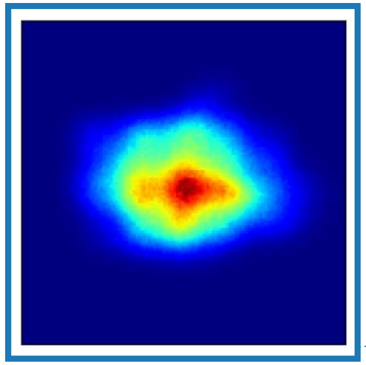


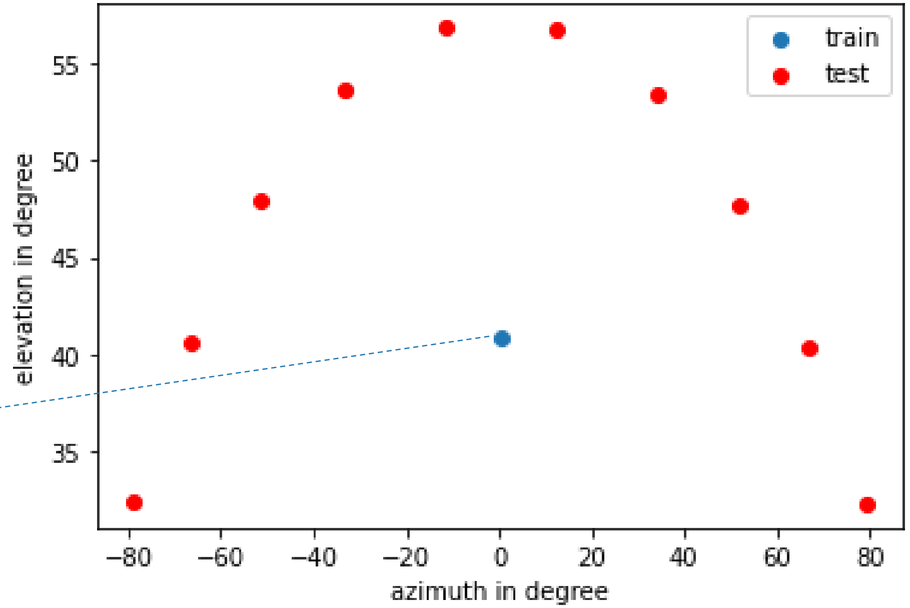
Predictions of heliostat vector trained with 1 picture

- Even from 1 training picture the model is able to predict other focal spots with different shapes

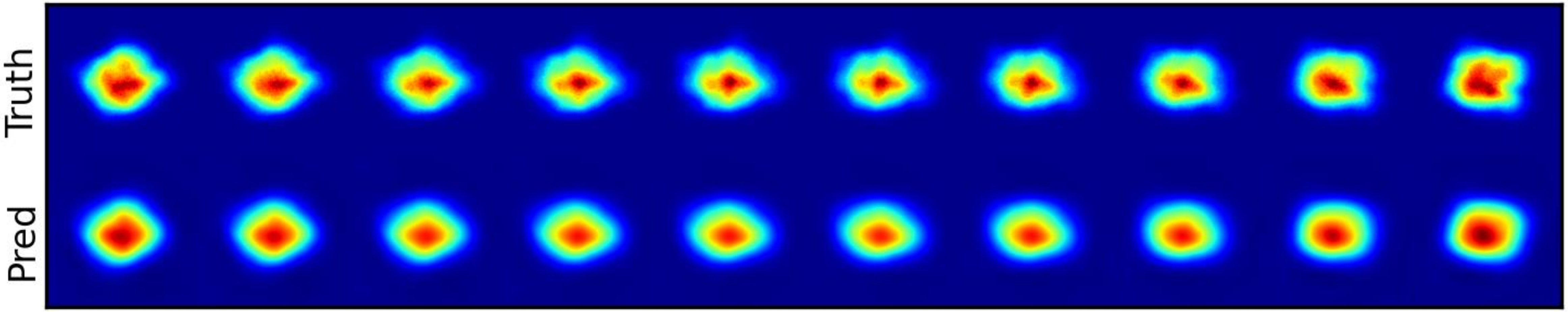
➢ Generator is able to transfer knowledge between heliostats

Training picture



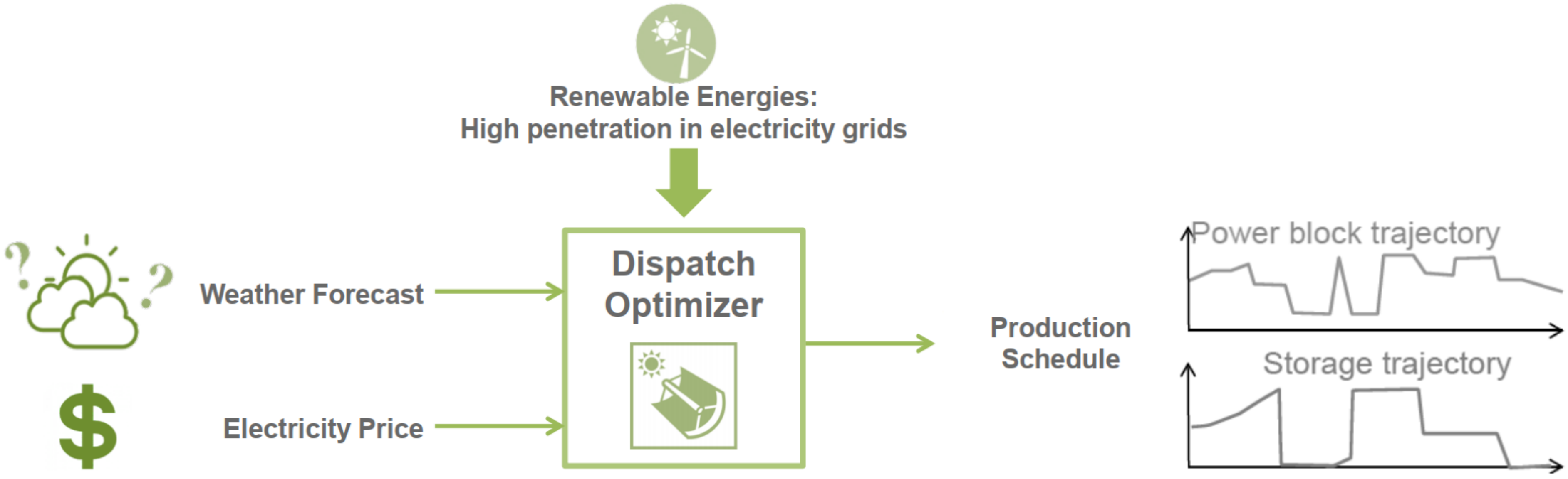


Predictions



DISPATCH OPTIMIZATION OF POWER PRODUCTION CONSIDERING WEATHER FORECAST UNCERTAINTIES

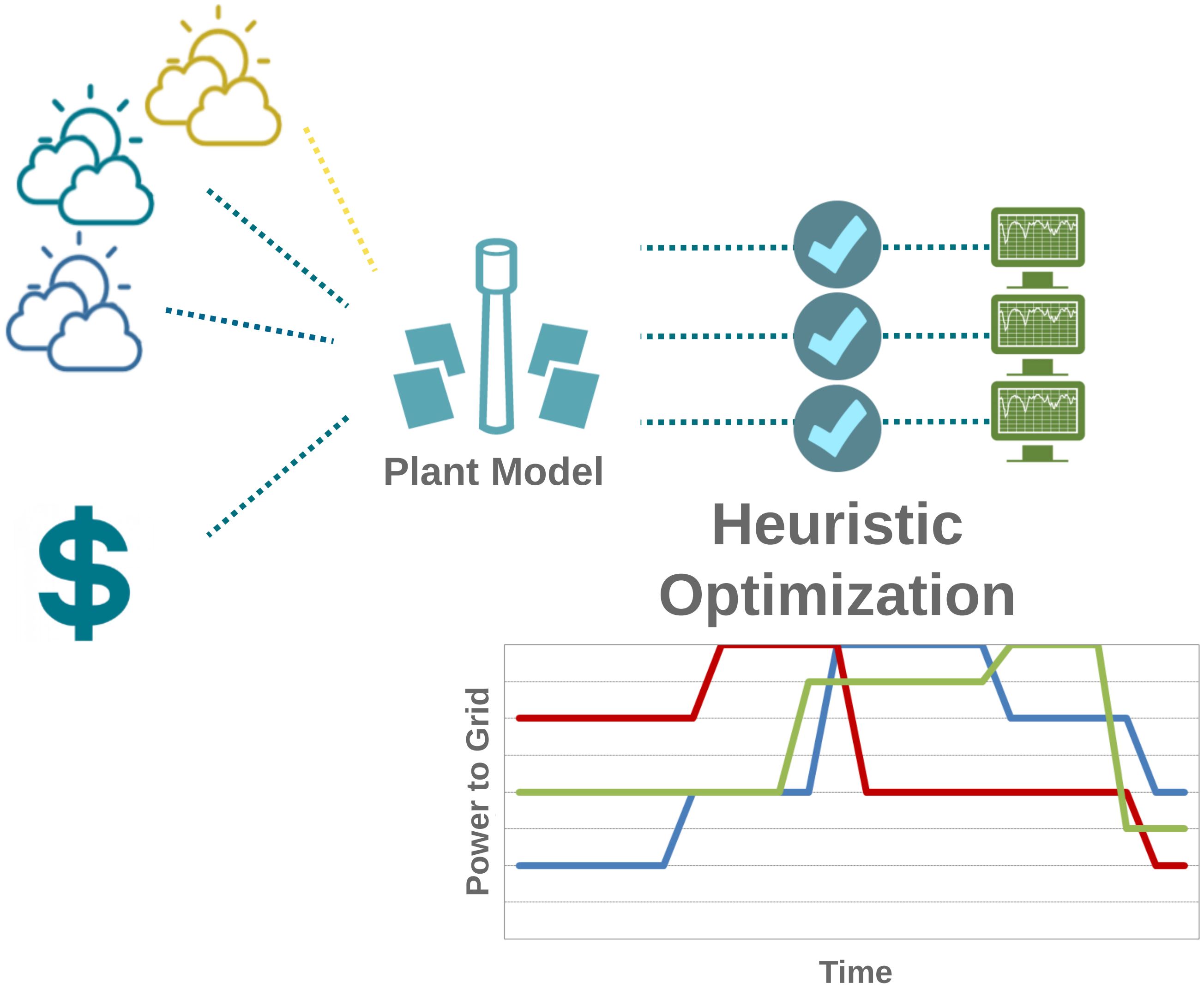
How to operate a CSP power plant?



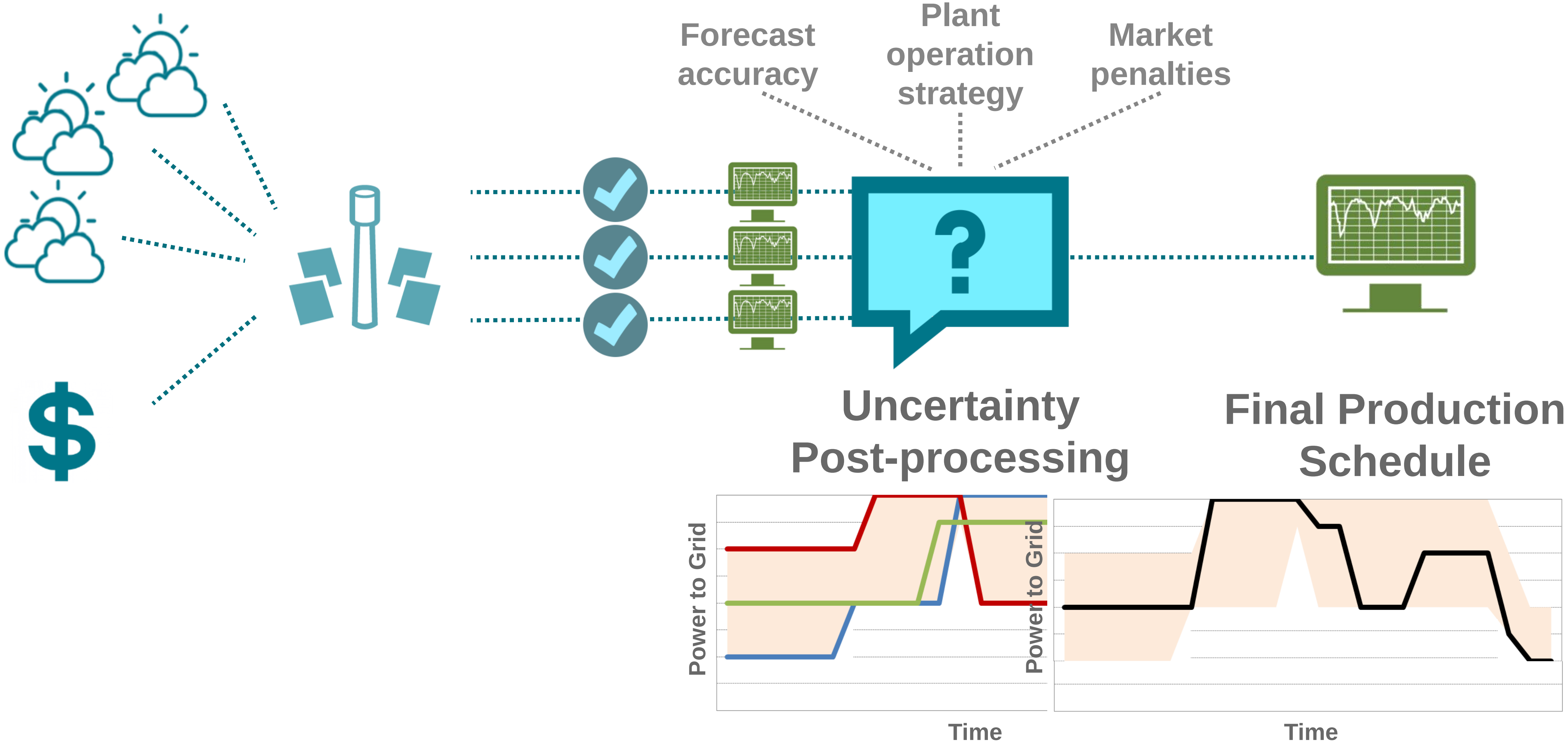
dispatch optimization algorithm that derives a plant operation schedule for the upcoming 48 hours

Goal : Include weather forecast uncertainty to find best schedule

CSP Probabilistic Scheduling
The Dispatch Optimizer Tool



CSP Probabilistic Scheduling
The Dispatch Optimizer Tool



Machine learning uncertainty post-processing

Why?

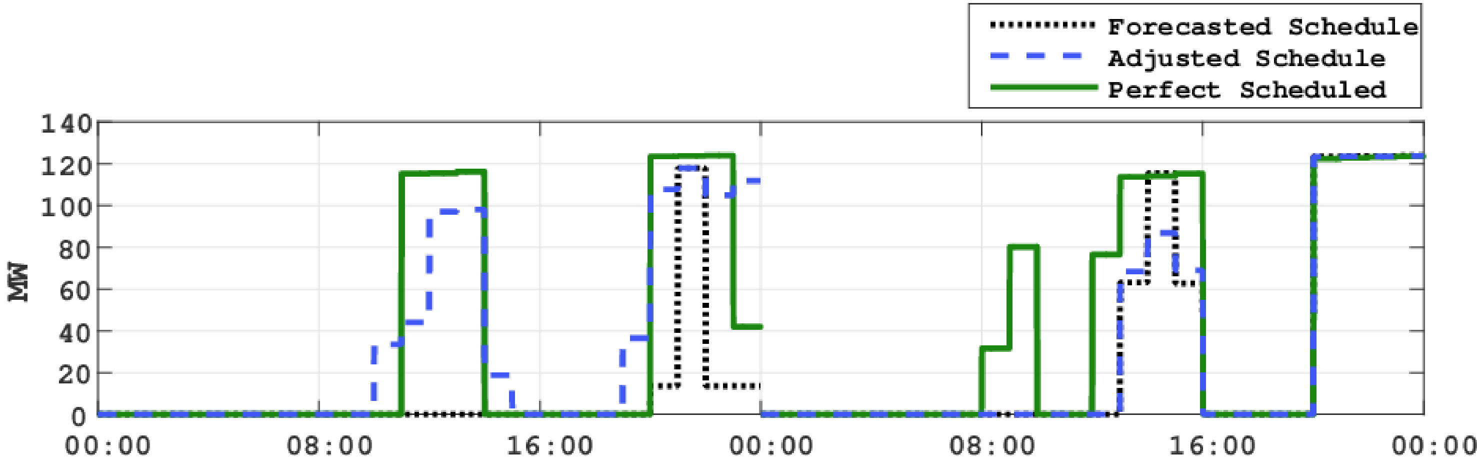
- Use of one or more possible schedule forecasts
- Use of historical data
- Use of several parameters related to the uncertainties

How?

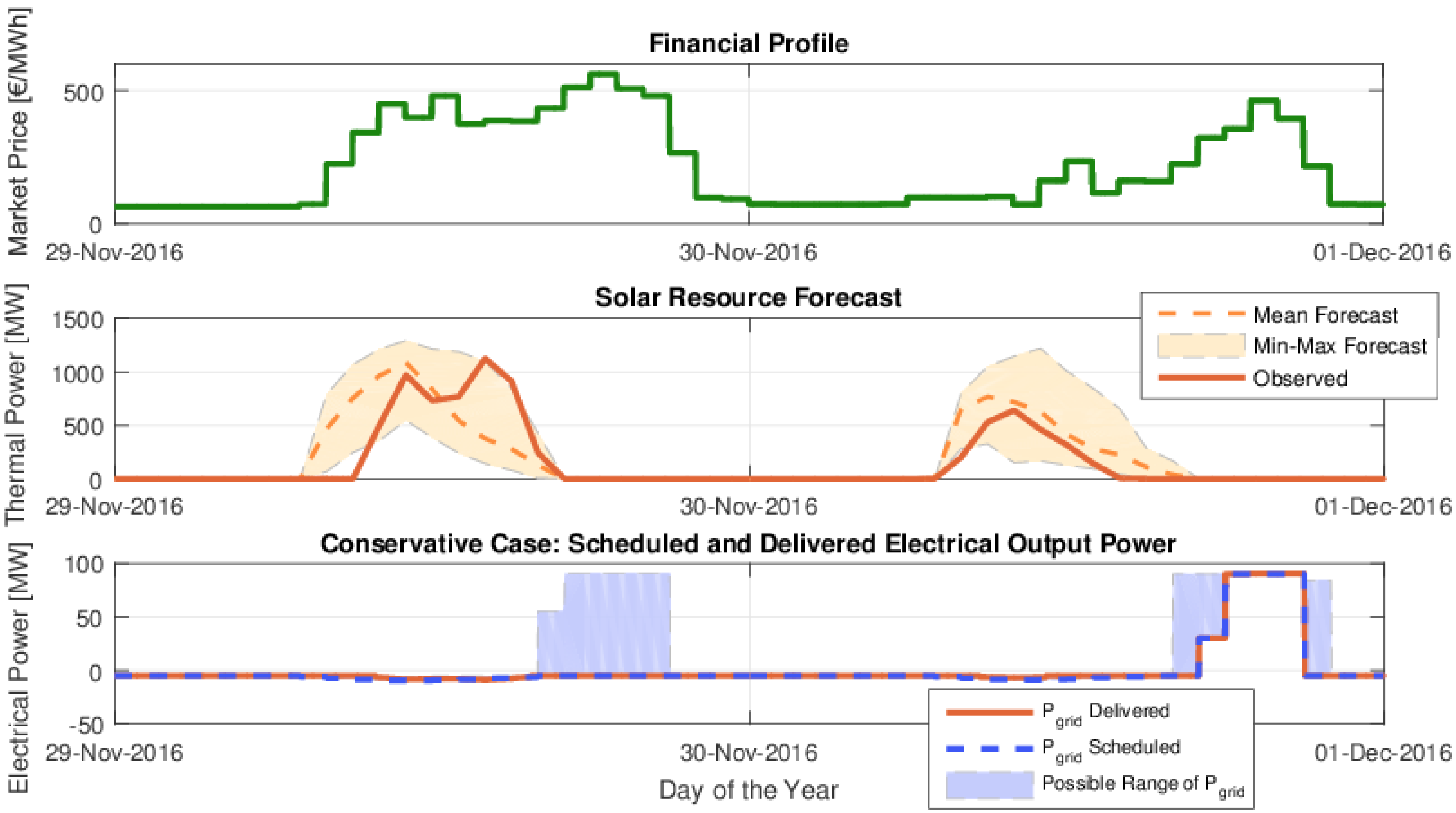
- Fuzzy Decision Tree approach

Results?

- Easy-to-understand
- Fast
- Improves the schedule quality?



CSP Probabilistic Scheduling
Simulation Results



Price Input

Probabilistic Forecast

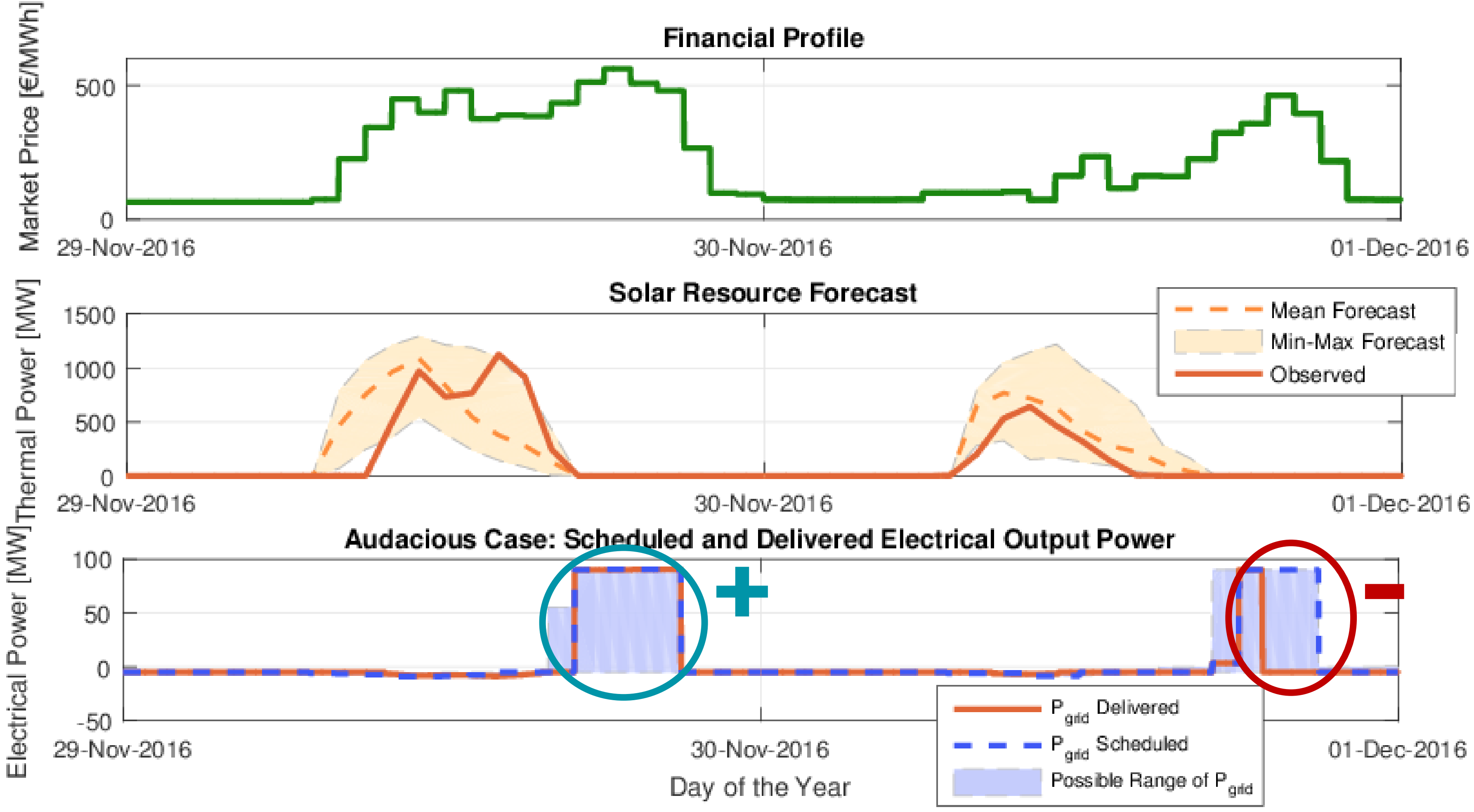
Output

Conservative Strategy $

Change in
Scheduling Strategy

Conservative → **Audacious**

CSP Probabilistic Scheduling
Simulation Results



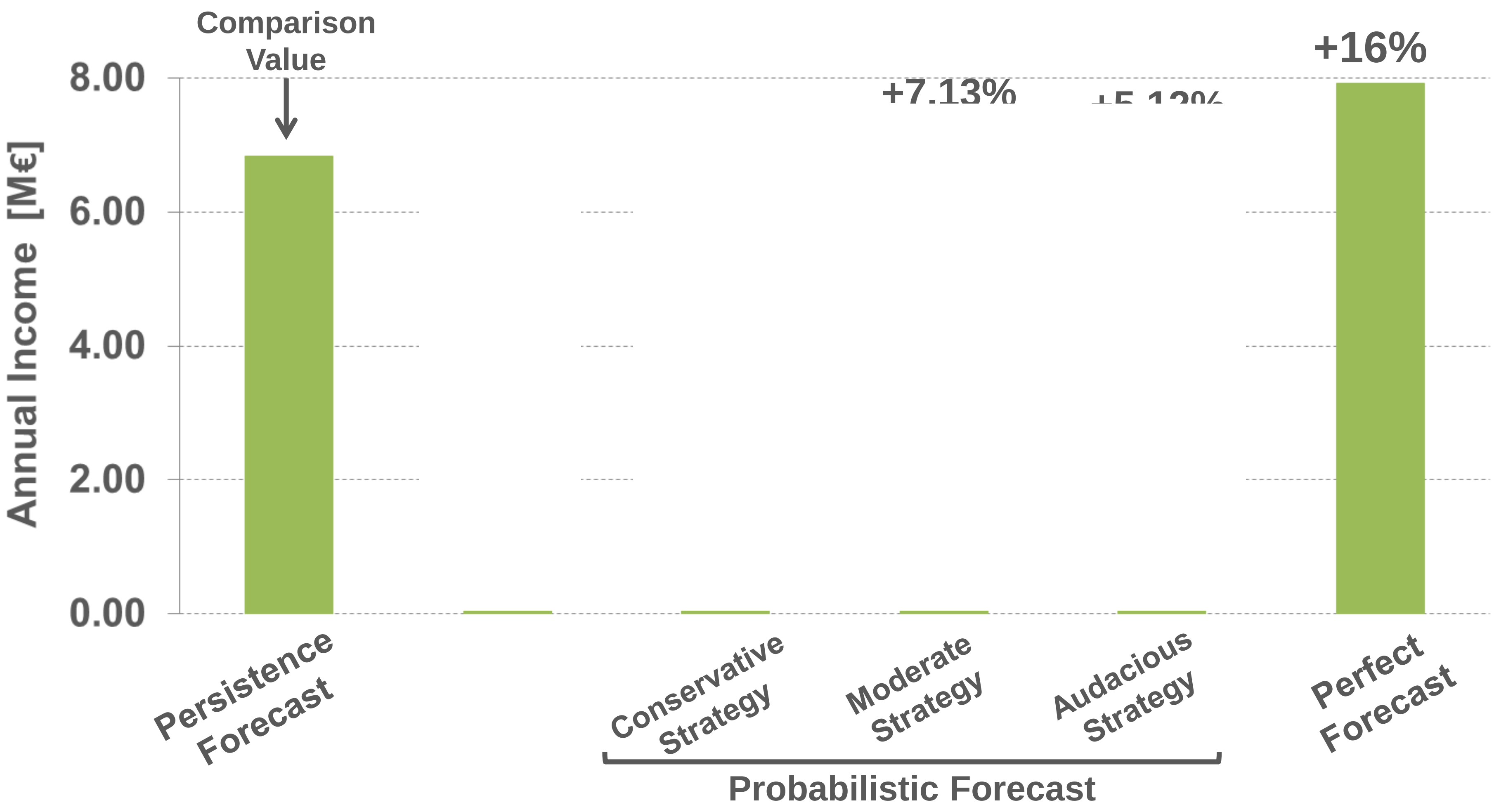
Price Input

Probabilistic Forecast

Output

Audacious Strategy

CSP Probabilistic Scheduling
Value of Forecast and Uncertainty Treatment



Summary

- CSP is a mature technology that complements PV electricity to enable reliable electricity supply around the clock.
- process heat supply @T>100°C.
- Cost reduction until 2030
  - < 5 $cents/kWh for dispatchable electricity
  - < 3 $cents/kWh for 24/7 PV/CSP hybrids
  - < 1$Cent/kWh for process heat
- Smart CSP is one key for cost reduction due to
  - performance increase
  - lifetime increase
  - maintenance cost reduction
- DLR is operating a full scale CSP power plant in Germany to develop, implement and prove the smart technology approaches in real scale to transfer it to the market.

Spin-off History

Spin-off		Business Case	Impact
2007	cspservices	Optimizing Solar Field Performance and maximizing plant lifetime	500 successful projects, resulting in a contribution to more than 90% of all installed CSP solar fields worldwide
2011	SOWARLA®	Solar Water Treatment Plants	Demonstrated successfully at DLR Lampoldshausen, project for ESA in Kourou under preparation
2016	HELIOKON	Software, network and hardware: »Custom-designed mechatronic systems for sustainable technologies«	New heliostat design and control
2017	HELIOHEAT	Commercialization of Centrec® particle receiver technology developed by DLR	24/7 Low cost electricity and process heat based on high temperature technology
2019	LUMOVIEW	We automate building analyses through a measurement that takes only 2seconds per room	Energy efficient refurbishment of buildings worldwide
2020	Volateq	Fully automated condition monitoring of CSP and PV plants - Get actionable analytics for your solar field based on a digital twin	Improve performance and increase profitability of solar power plants
2022	ExoMatter	Digital materials research and development for fast & sustainable materials development	Speed-up the search for new materials, especially for chemical industry