phme26
OSLO (NO) - 8/10 July 2026

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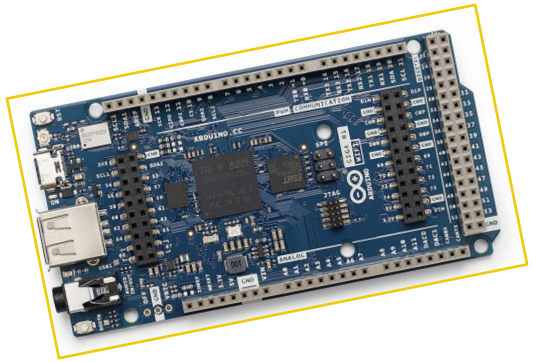
DLR

Cost-Efficient Prognostics Framework for Heliostat Drive Units

Dominik Steinberg, Stefan Nicolas Huestegge, Daniel Maldonado Quinto, Marc Röger, Benedikt Kölsch, Robert Pitz-Paal

Wednesday 8th July, 2026, Oslo

Image: ChatGPT



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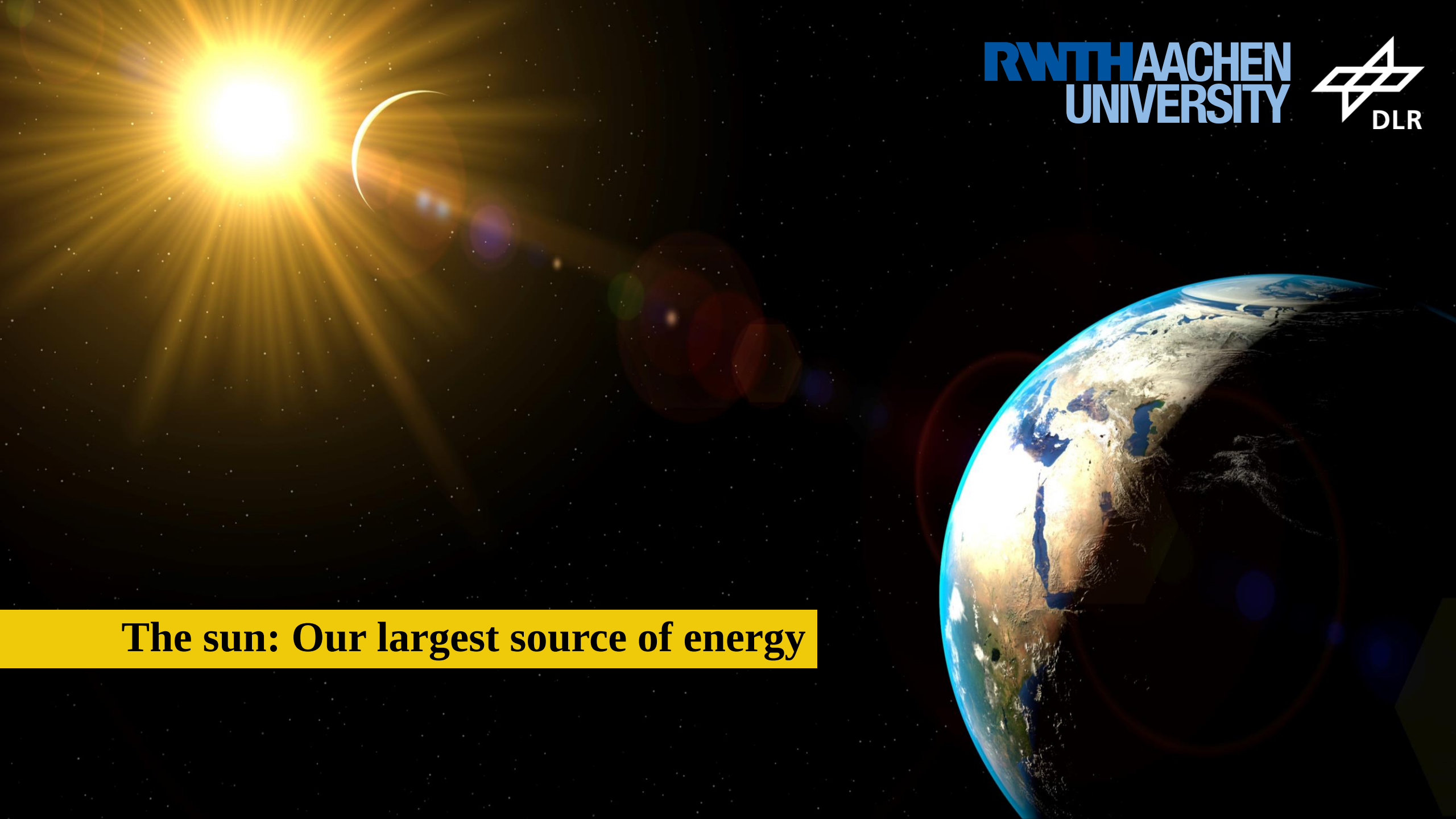
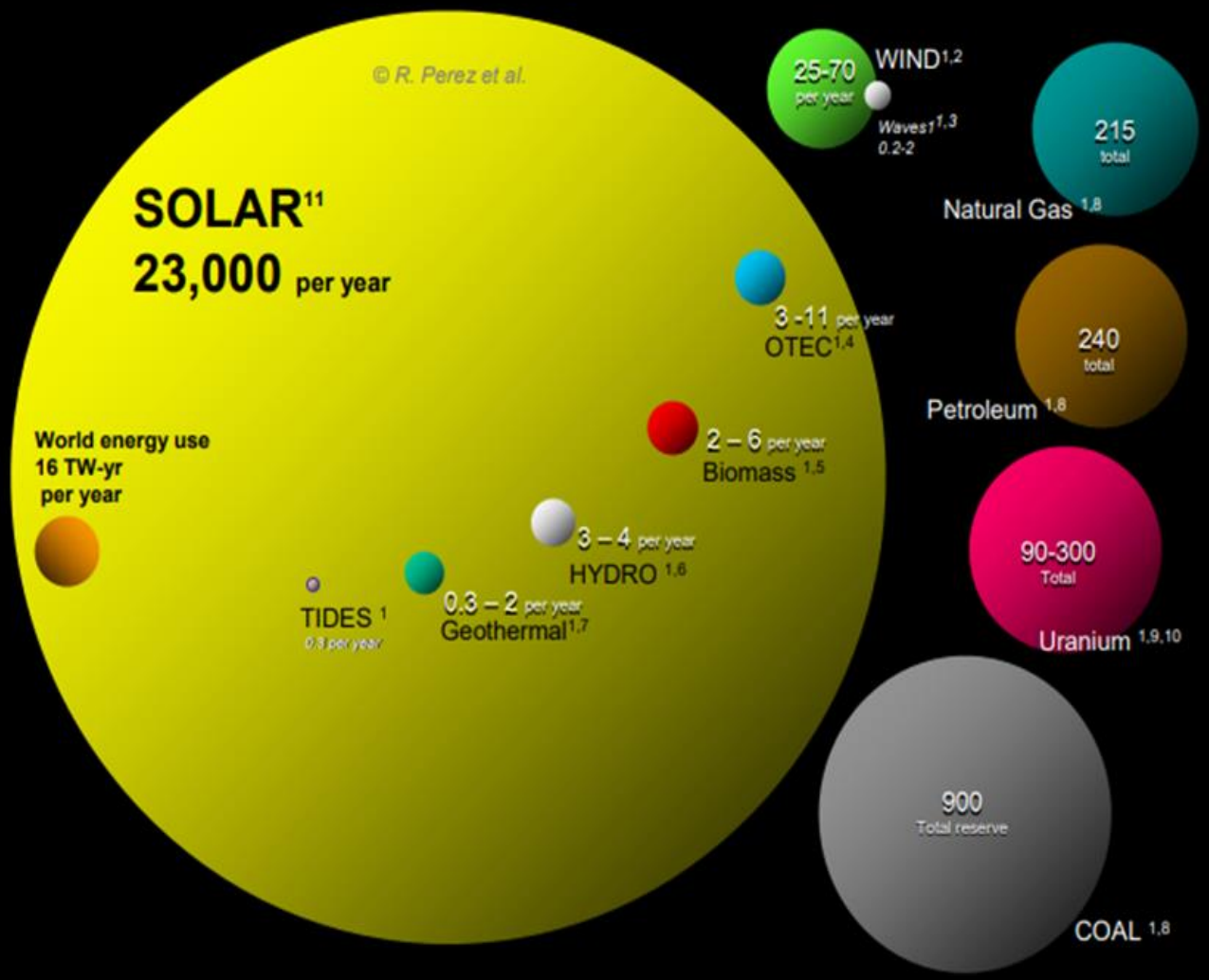


The sun: Our largest source of energy



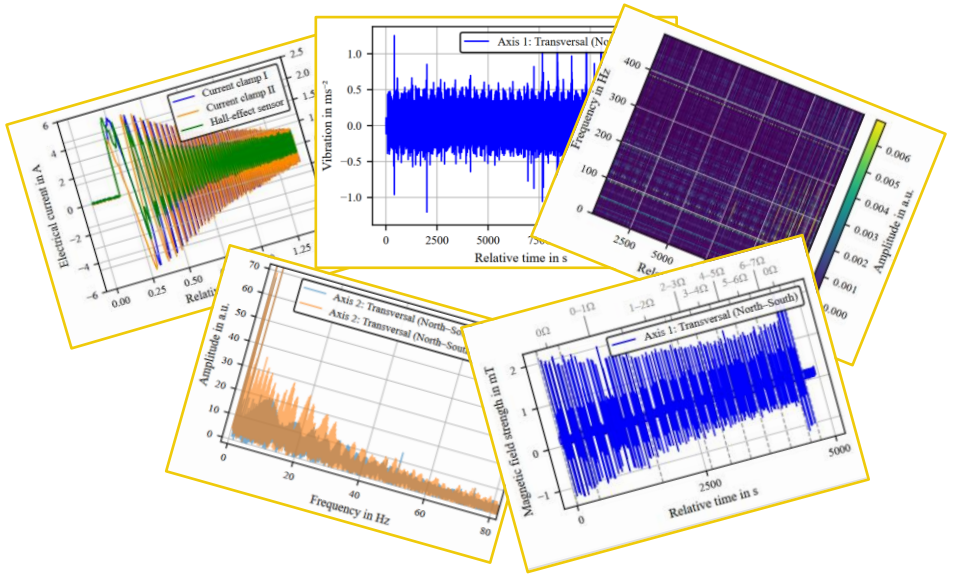
Available solar energy:

- More than 90% of renewable energy resources
- Energy for 1,000 Earths

Source: Perez et al. (2009): A fundamental look at energy reserves for the planet. The IEA SHC Programme Solar Update, Volume 50, 2009.

Agenda

1. **Research Motivation and Introduction**
2. **Background and Related Work**
3. **Methodology**
4. **Experimental Results and Discussion**
5. **Conclusion and Outlook**



(1) Research Motivation and Introduction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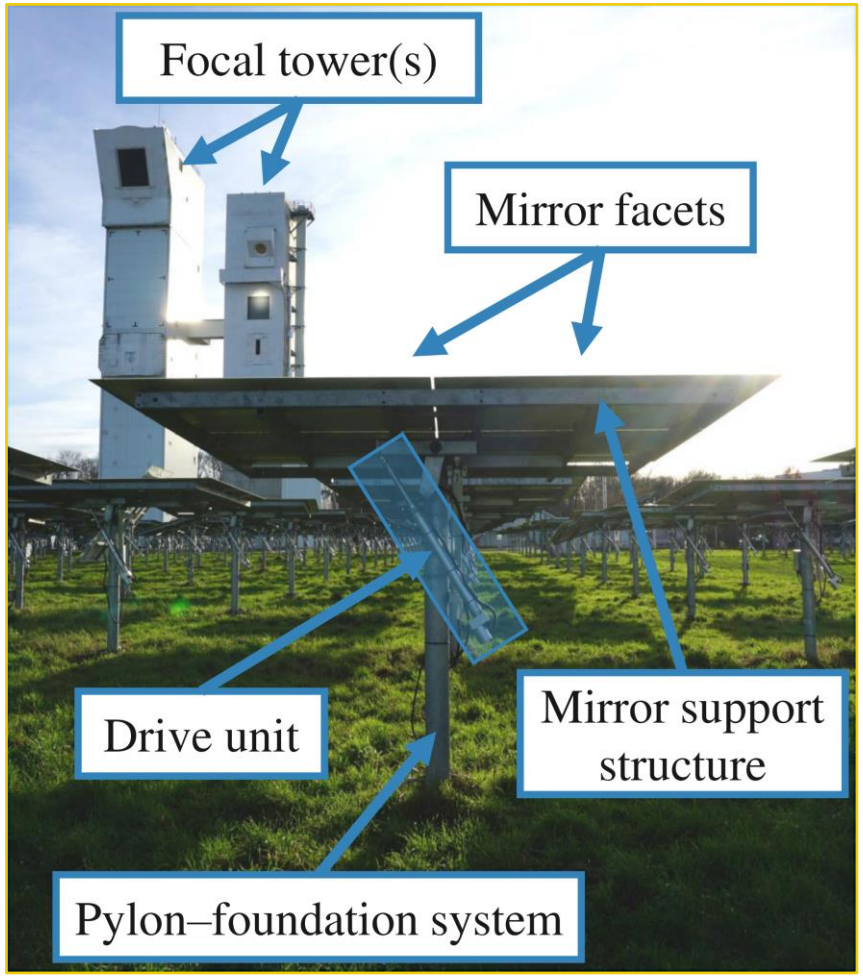
Concentrating the sunlight

The operational reliability of the heliostat drive units is highly important



Solar Tower research facility in Jülich, Germany

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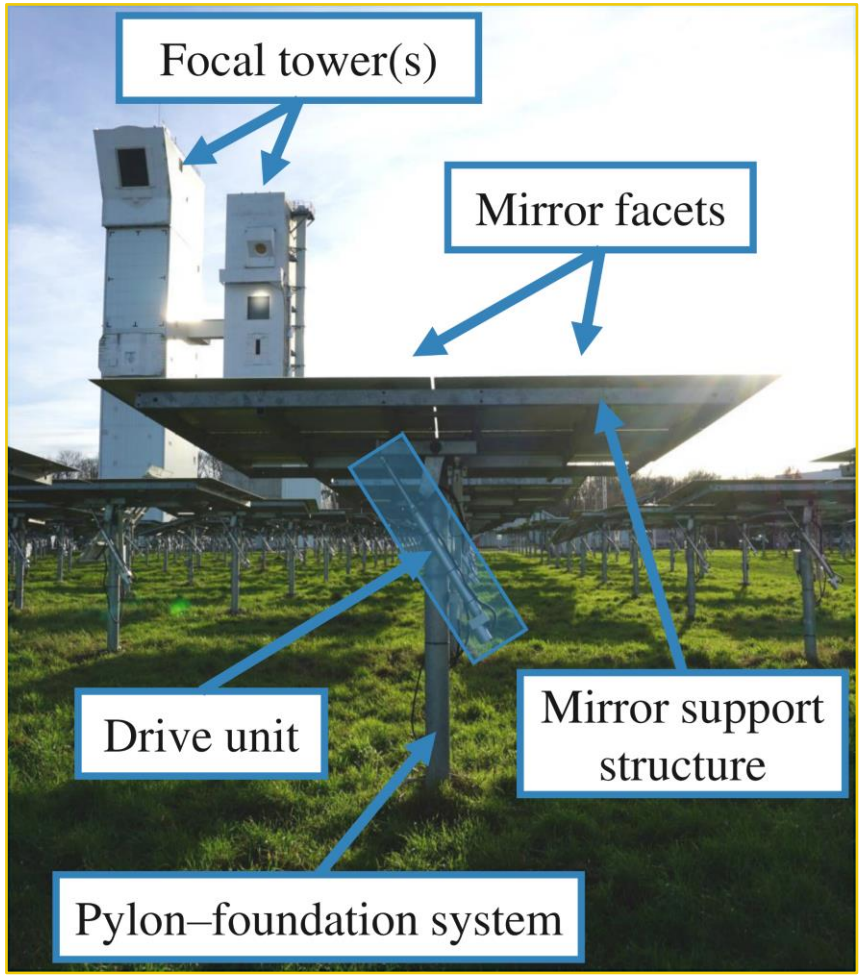


Solar Tower research facility in Jülich, Germany

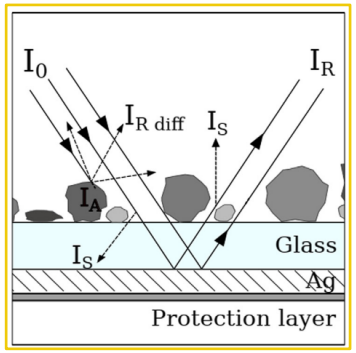
- Commercial heliostat fields with **10^3 to 10^5** heliostats, each with **two drive units**
- Failures of the drive units
  → Large maintenance efforts
  & **reduced** plant **availability**
- Misdirected solar radiation
  → operational risks & **safety risks**

(2) Background and Related Work

Review of literature: O&M of heliostat fields

Existing research:

- Optical aspects
  - Soiling



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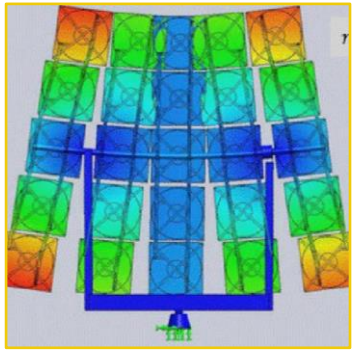

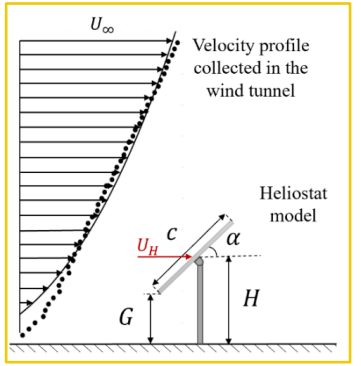

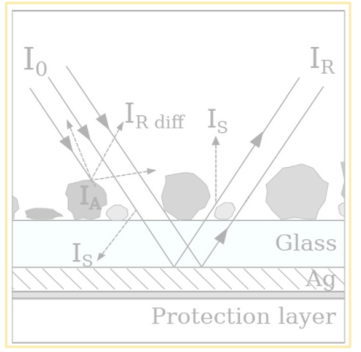

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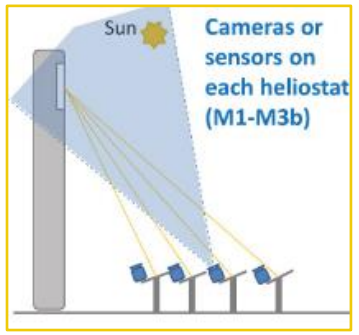
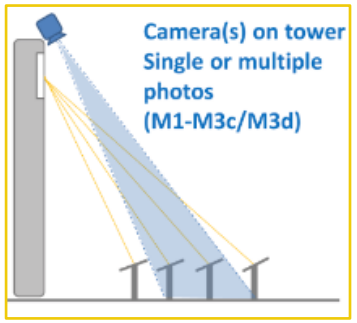
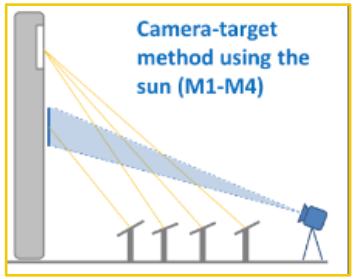
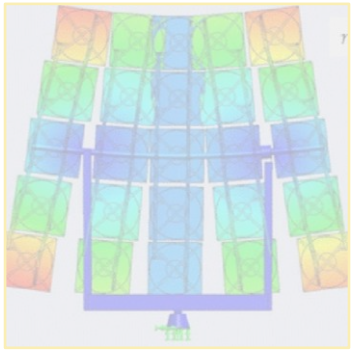
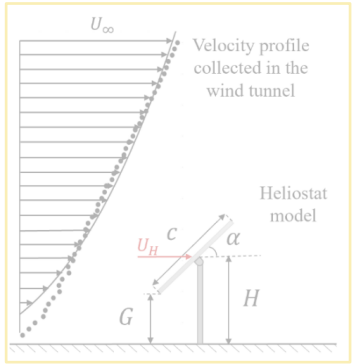
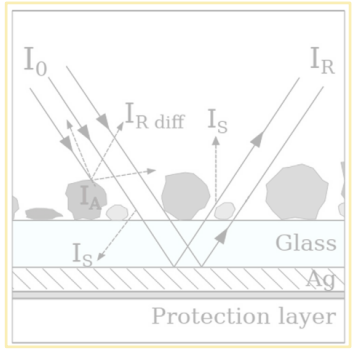










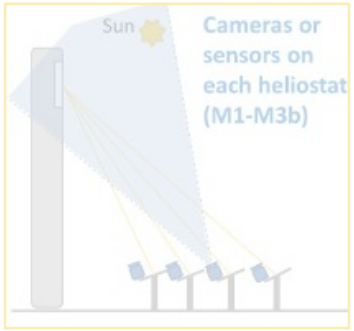


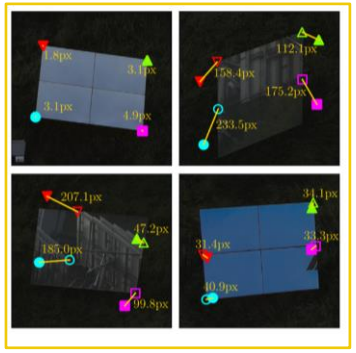
Review of literature: O&M of heliostat fields

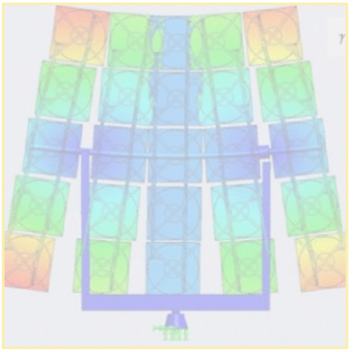
Existing research:

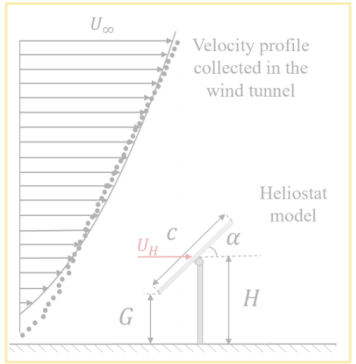
- Optical aspects
  - Soiling
- Wind-induced effects
- Calibration procedures

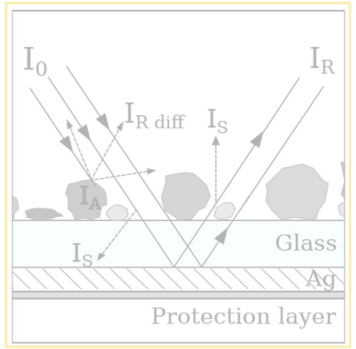
- Image-based (UAV-based) measurements











Review of literature: O&M of heliostat fields

Existing research:

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However, large **research gaps** regarding heliostat **drive units:**

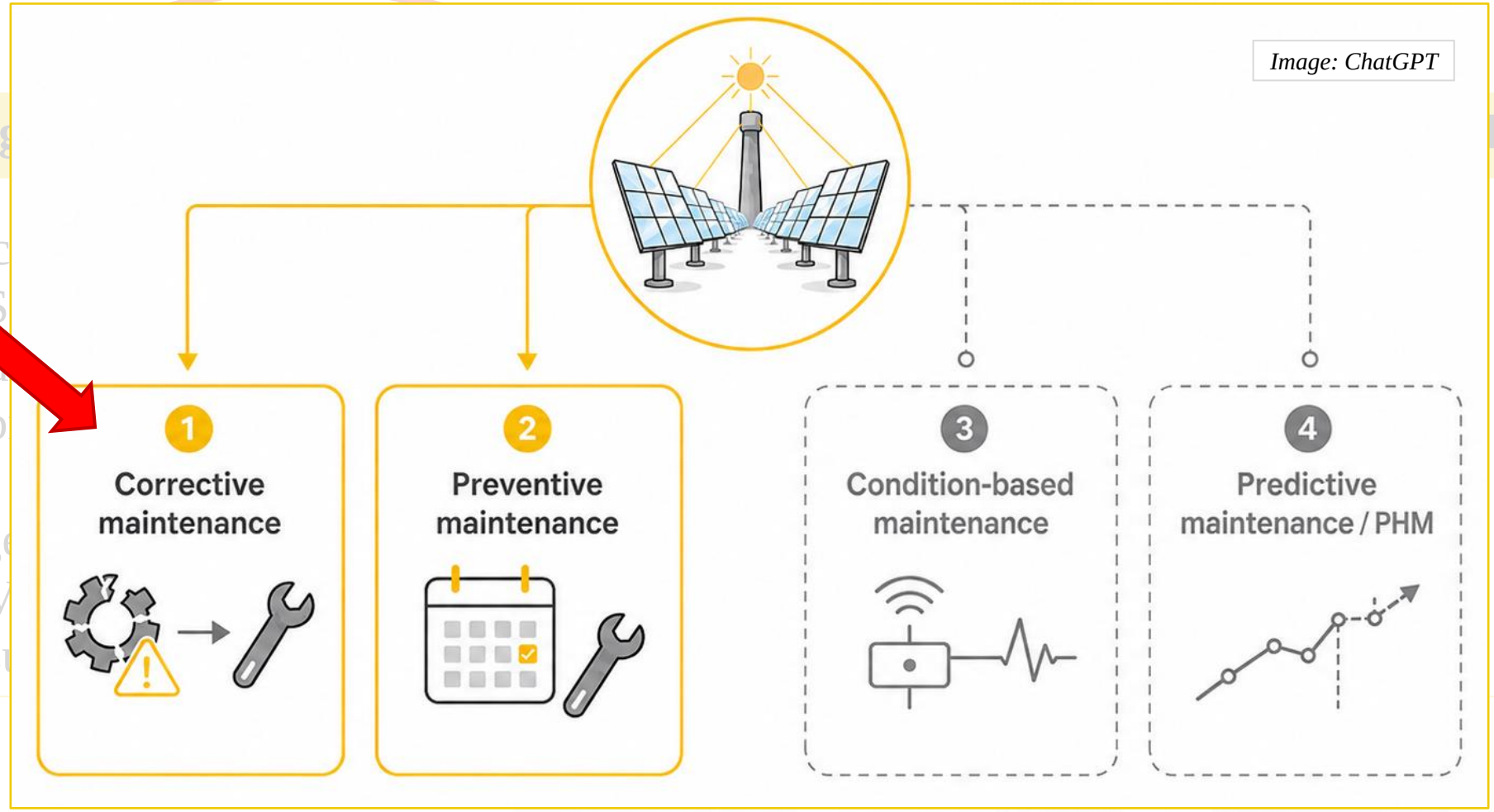
- **Operational health** up to now **unexplored**
  - **No experimental investigations**

- **No** peer-reviewed studies **on sensor-based** component **condition monitoring**
  - E.g. motors, gearboxes

- **Lack** of publicy available **time-series datasets**

Images: ChatGPT

Review of literature: O&M of heliostat fields

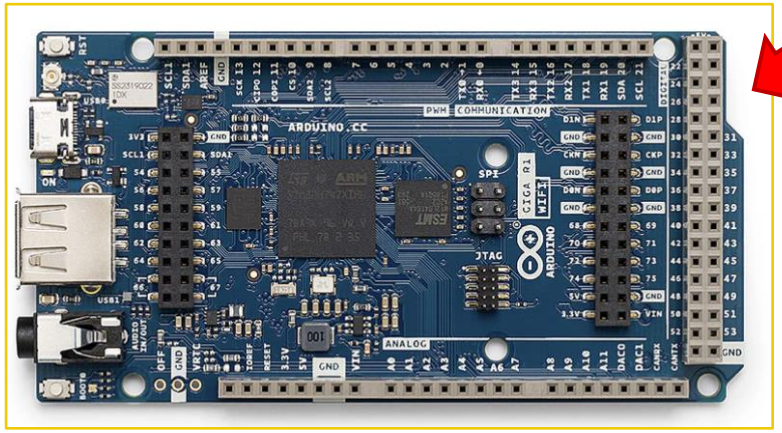


(3) Methodology

Experimental setup: Measurement concept and Data Logging

Measurement concept:

- **Cost-efficient** and non-intrusive sensing concepts
  → Low-cost **Arduino-based DAS**
- Detection of **deviations between baseline** and **actual behaviour**



Details about the
Data Acquisition and Logging Architecture:

- **Arduino GIGA** R1 WiFi (STM32H747XI microcontroller)
- Optional analogue signal conditioning stage with gain V = 11.6
- **Sampling rate** of **1 kHz**

- **Continous data stream** via USB to PC
  - Basic consistency checks of the data
  - Data storage in HDF5 format

Experimental setup at the Solar Tower research facility in Jülich

Measurement concept:

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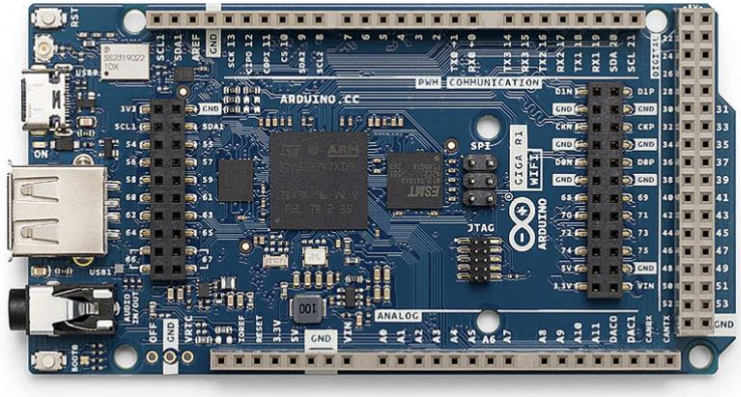
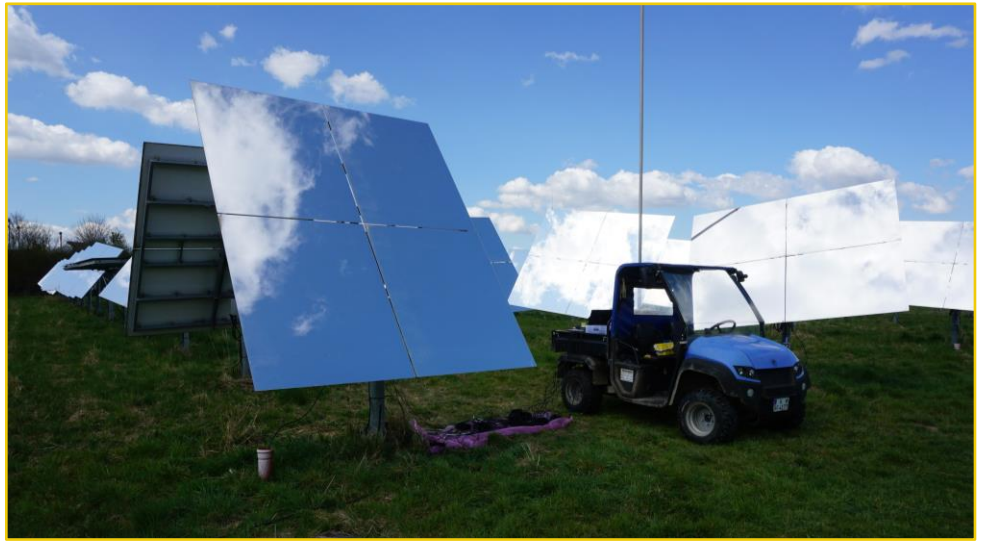
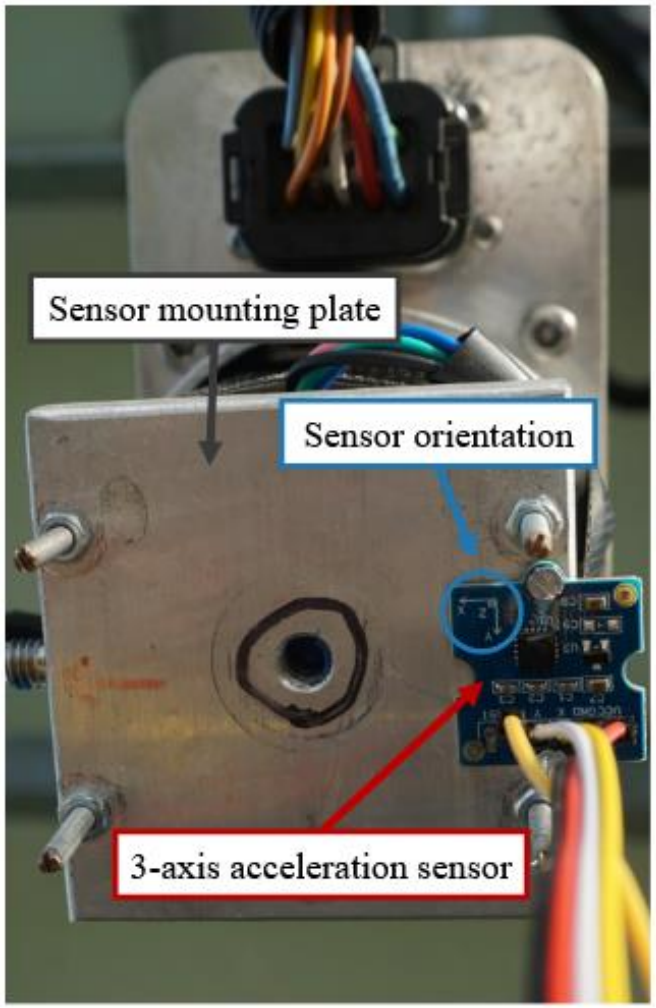


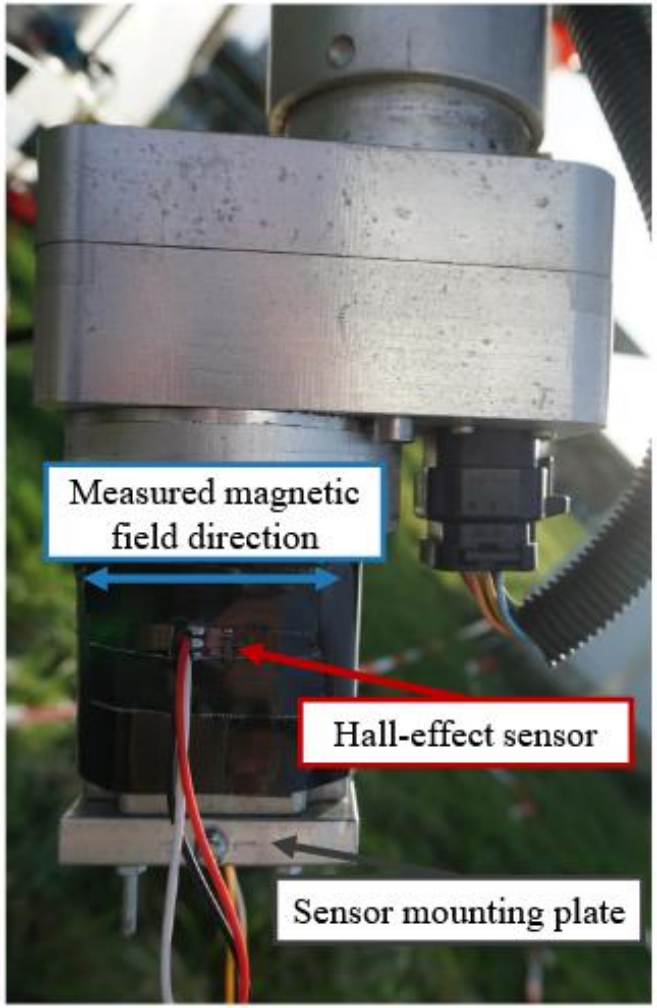


Data collection:

- July 2025 to November 2025
- Representative subset of eight heliostats
- **330 hours** of effective **measurement time**
  - Approx. **110 GB of data**

Sensor selection, mounting and field instrumentation





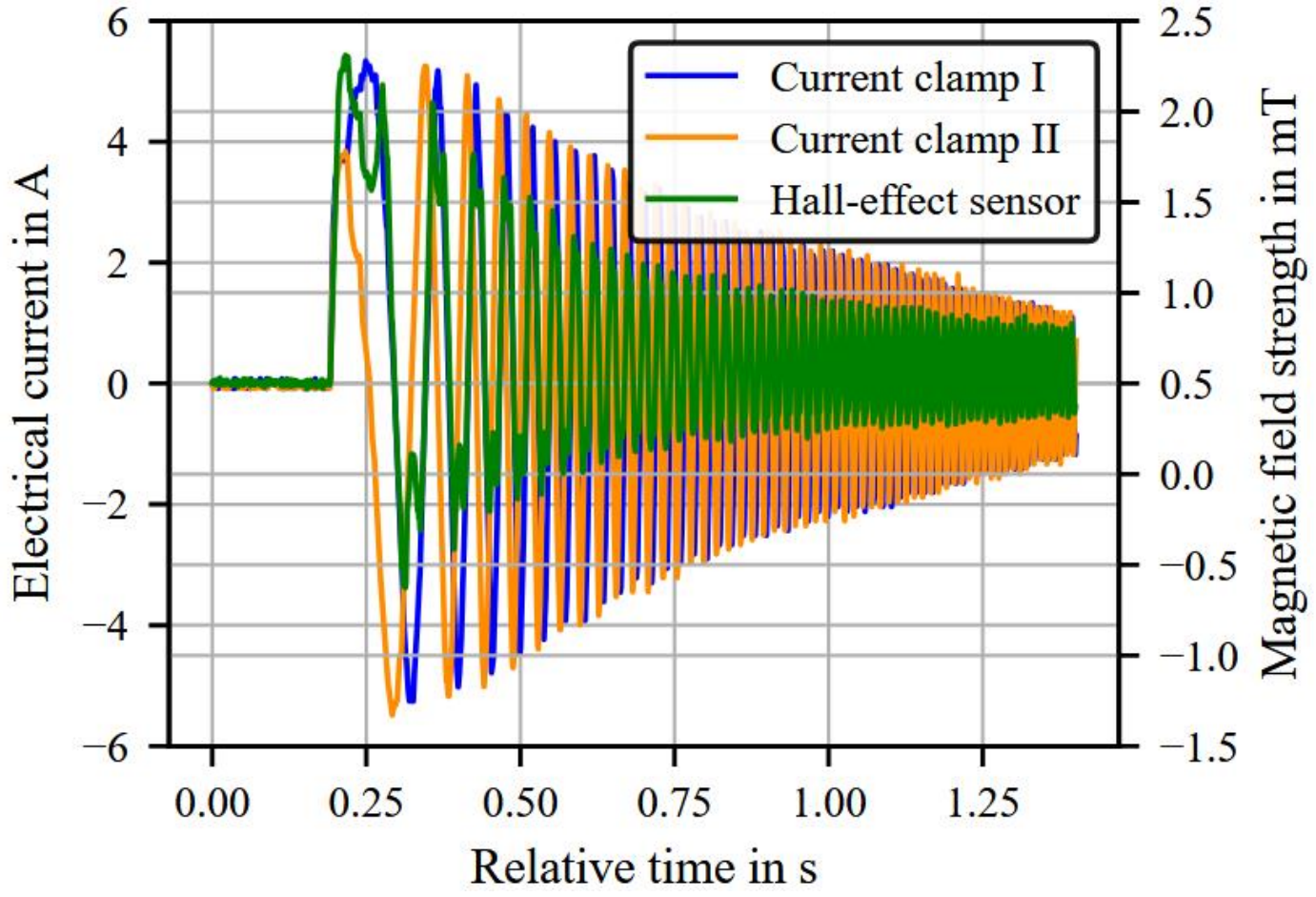
Sensor Selection

- We want to measure:
  - Vibrational responses
  - Electromagnetical response
- MEMS-based (3-axis) **accelerometer**
- **Hall-effect** sensor (1-axis)

→ Four sensor channels per heliostat axis (eight channels per heliostat)

(4) Experimental Results

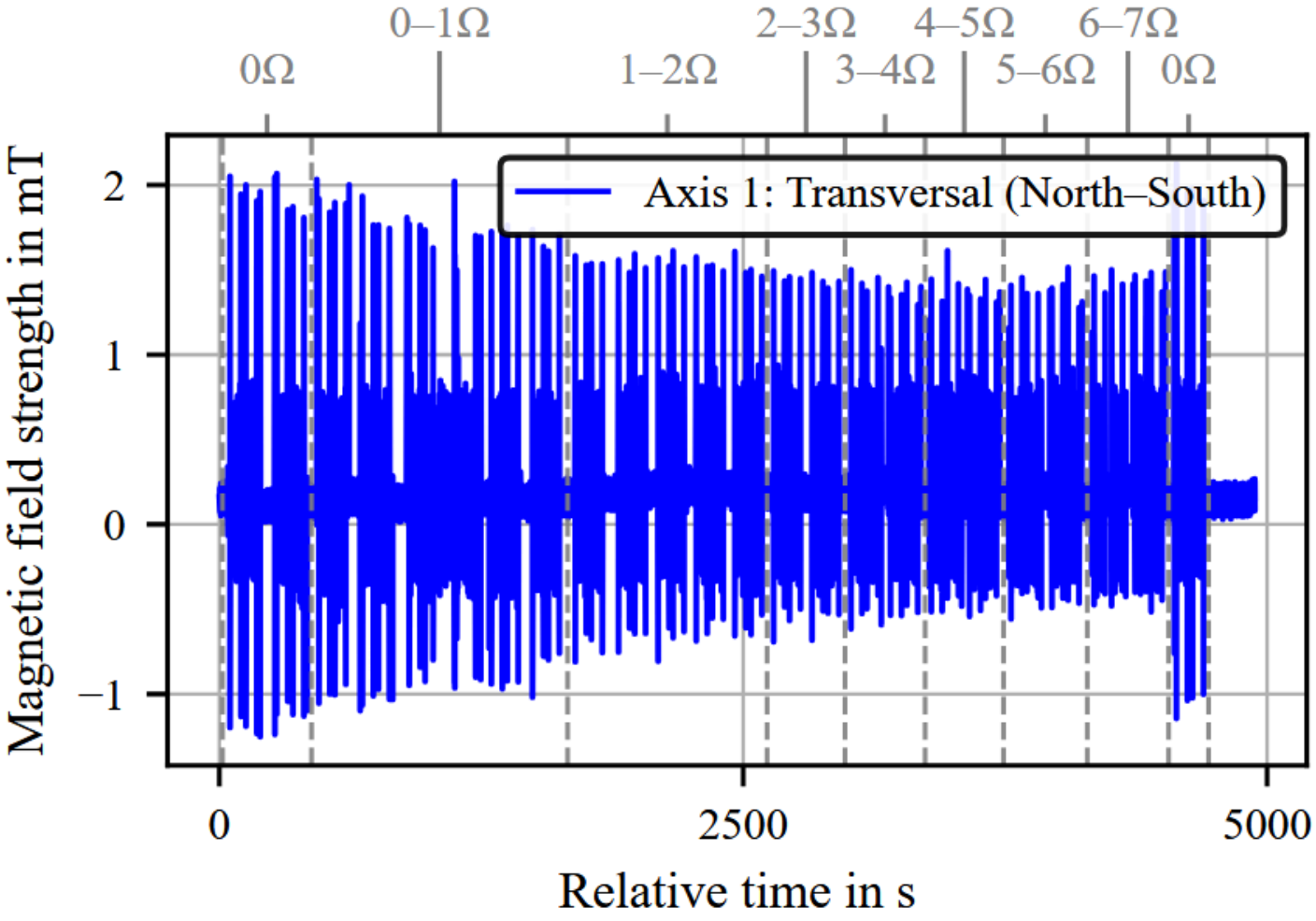
Comparison of Conventional Industrial-Grade Sensors and Cost-Efficient Arduino-Based Sensors



Observations:

- **Qualitative comparison** shows **strong correspondence**
  - Measured current signals and magnetic field signal
- Hall-effect sensor offers **similar insights/** comparable information as current clamps
  → **Low-cost alternative**

Sensitivity Analysis: Controlled Variations of the Motor Phase Resistance



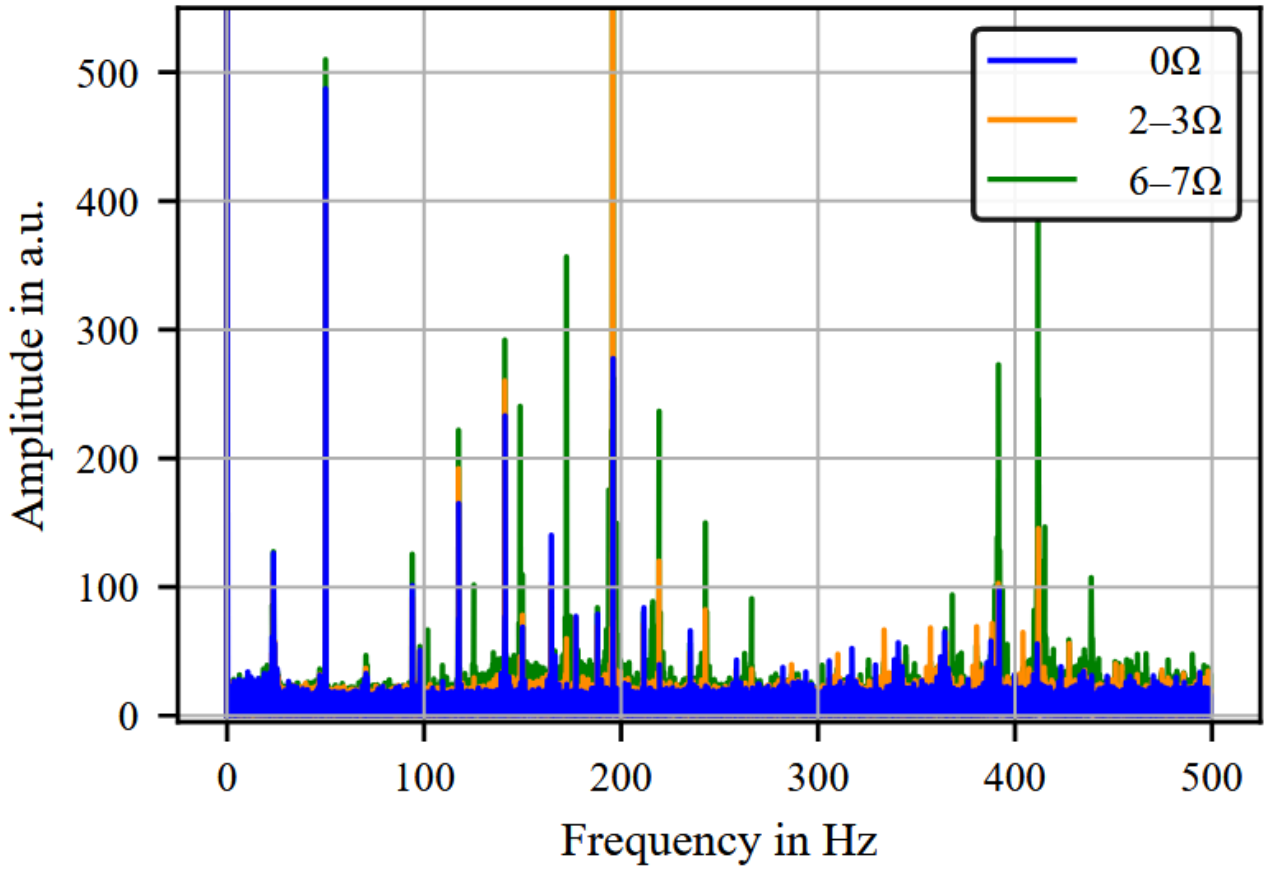
Ideas:

- Intentionally **modify electrical** operating **conditions** of the motor
- External resistor R is inserted in series with one of the motor coil pairs
- Variation in R → variation in current → **Variation** in **magnetic field**

Observations:

- Reduction of magnetic field amplitude
  - Ohm's law ($U = R \cdot I$)
  - $R \geq 3\Omega$: Reduction $\sim \frac{1}{3}$
- Even small changes in electrical properties of the drive units → Clearly detectable changes in magnetic field signatures

Sensitivity Analysis: Controlled Variations of the Motor Phase Resistance

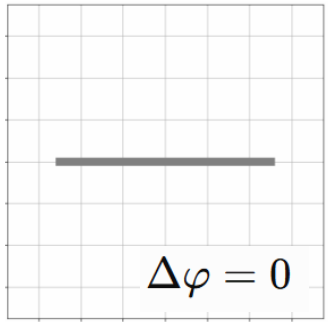


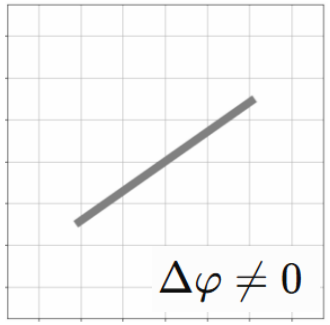
Observations:

- **With higher R-values,** several **vibration peaks** become **significantly increased** compared with baseline condition
  - f ~ 400Hz: Amplitude increase by 2 to 4
- **Setup** is not only **very sensitive to magnetic field** changes but **also** to **vibration** changes

$$i_1(t) = \hat{I}\cos(\omega t)$$

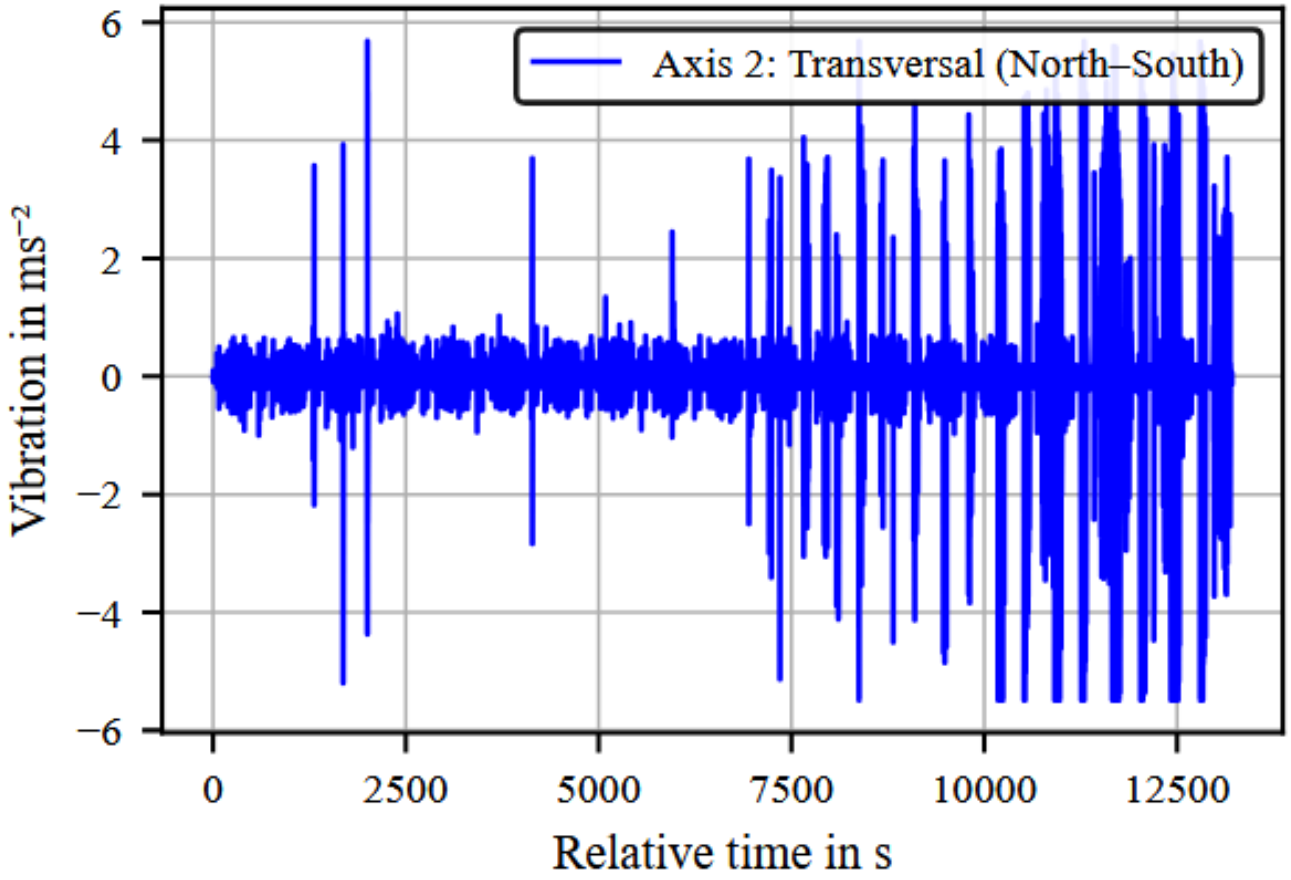
$$i_2(t) = \hat{I}\sin(\omega t + \Delta\varphi)$$





Demonstration of the Prognostics Framework: Early Ageing and Anomaly Detection

Heliostat (ID: 12023)
- Normal operating conditions



Observations:

- Measurement data with **clear deviations** from typical, **characteristic signal patterns**
  → Anomalous ageing-related behaviour
- $t \geq 7{,}500\text{s}$: increasingly pronounced outliers/ anomalous peaks reaching amplitudes of nearly 6m/s^2 (= **ten times nominal vibration** level)
- **Wind** and other **external influences** (e.g. ambient temperature, global field disturbances) were found **not** to significantly **affect** the measurements.

→ **Early warning system** for this heliostat
→ Targeted inspection by O&M personnel

(5) Conclusion and Outlook

Conclusion and Outlook

Current **heliostat field O&M** focuses mainly on **soiling, wind**-induced effects and **calibration** procedures
→ Research gap regarding **heliostat drive units**: **no peer-reviewed studies** (no experiments)

Development of a **cost-efficient prognostics framework** and experimental **validation**
→ Successful application to heliostats at the Solar Tower research facility in Jülich

Identification and analysis of **real-world operational anomalies** from the measurement data
→ Lowering barriers to scalable PHM through cost-efficient monitoring

Conclusion

Systematic **long-term field validation**, advanced **data analytics**, and data-driven **predictive modelling**

Ongoing measurement campaign: Controlled **accelerated ageing/ deliberate stress experiments**
→ Generating **fault and degradation data on demand** - beyond naturally occurring failures

Outlook

Thank you very much!

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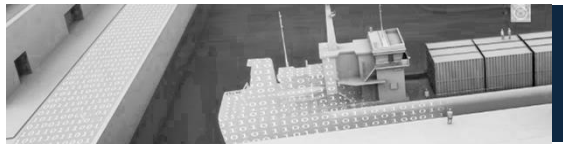
Paper

Contact me ☺

BACKUP Slides

DLR - Research Organisation + Space Agency + Project Management Agencies

Aeronautics	Aerospace	Energy	Transport
			



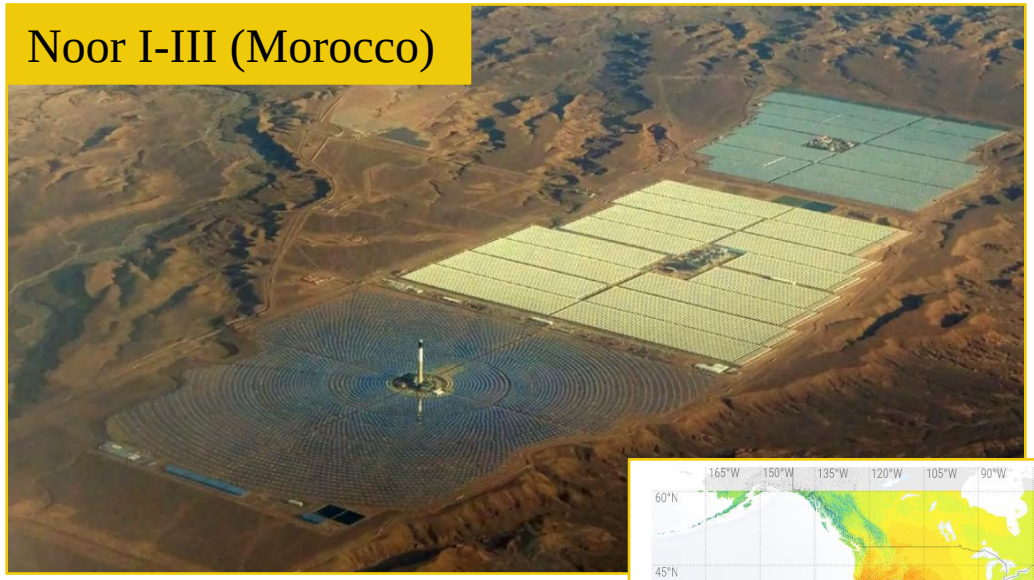
Security
security research (civil & defense)

Digitalisation
Quantum technologies & system modelling

- Largest European research organisation for engineering and aerospace
- Close cooperation with research, economy and industry actors
- Institutionally funded by Federal Ministry for Economic Affairs and Climate Action, additionally by Federal Ministry of Defence, project funding by many others (e. g. Federal Ministry of Education and Research)

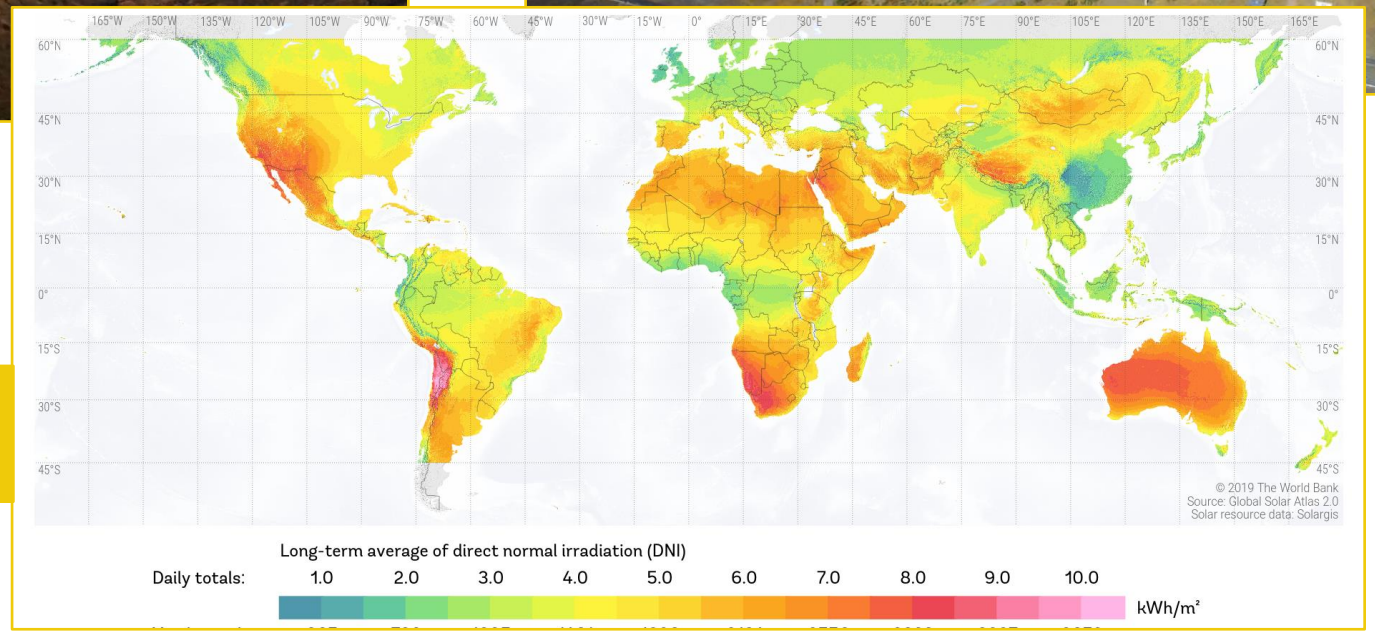
Examples of Concentrated Solar Power (CSP) tower plants

Noor I-III (Morocco)

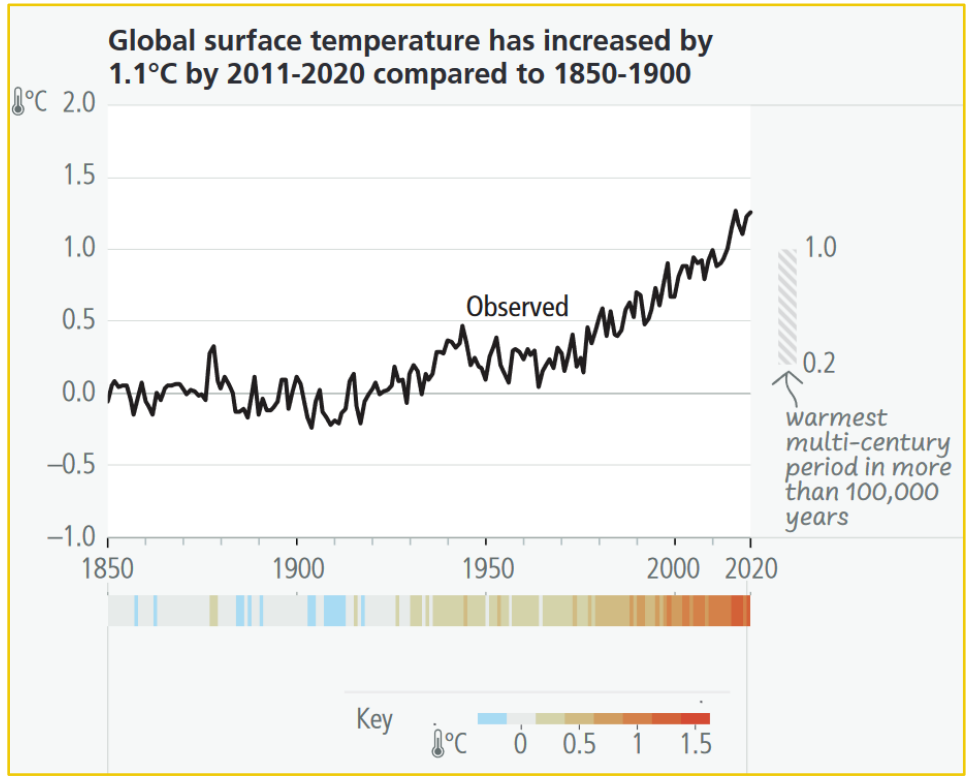


PSA, CIEMAT (Spain)

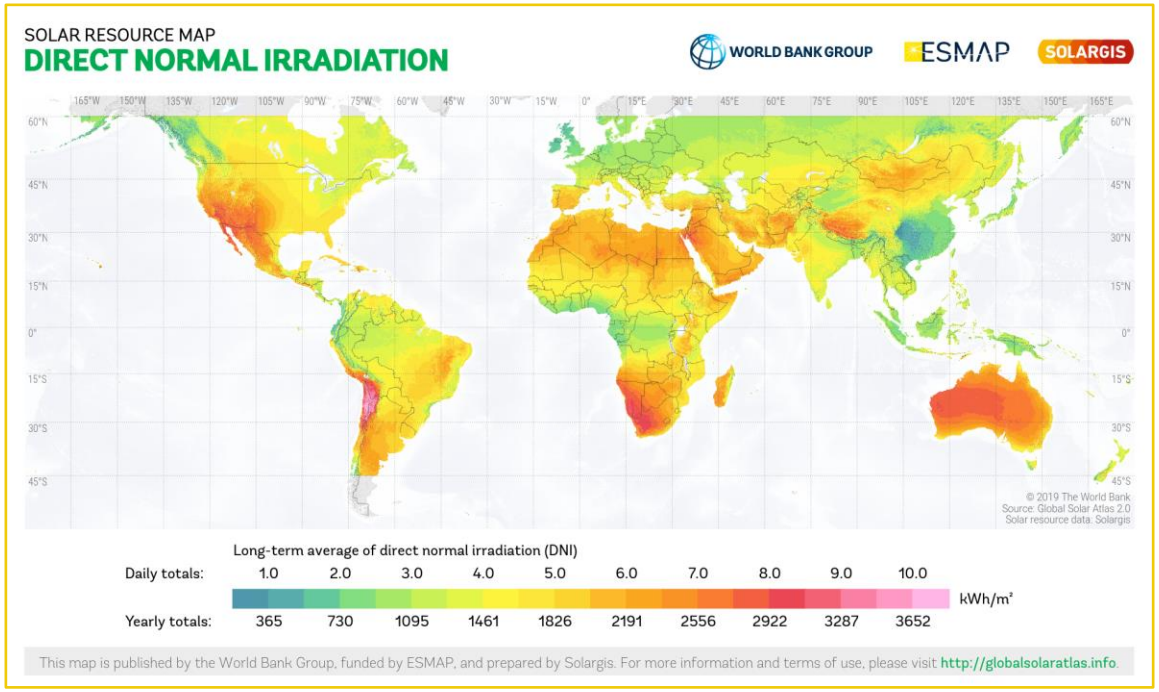
Direct normal irradiation (DNI)



„Humans are responsible for global warming“



Climate Change 2023 Synthesis Report [1]



Norway: ~800 $\frac{kWh}{m^2a}$

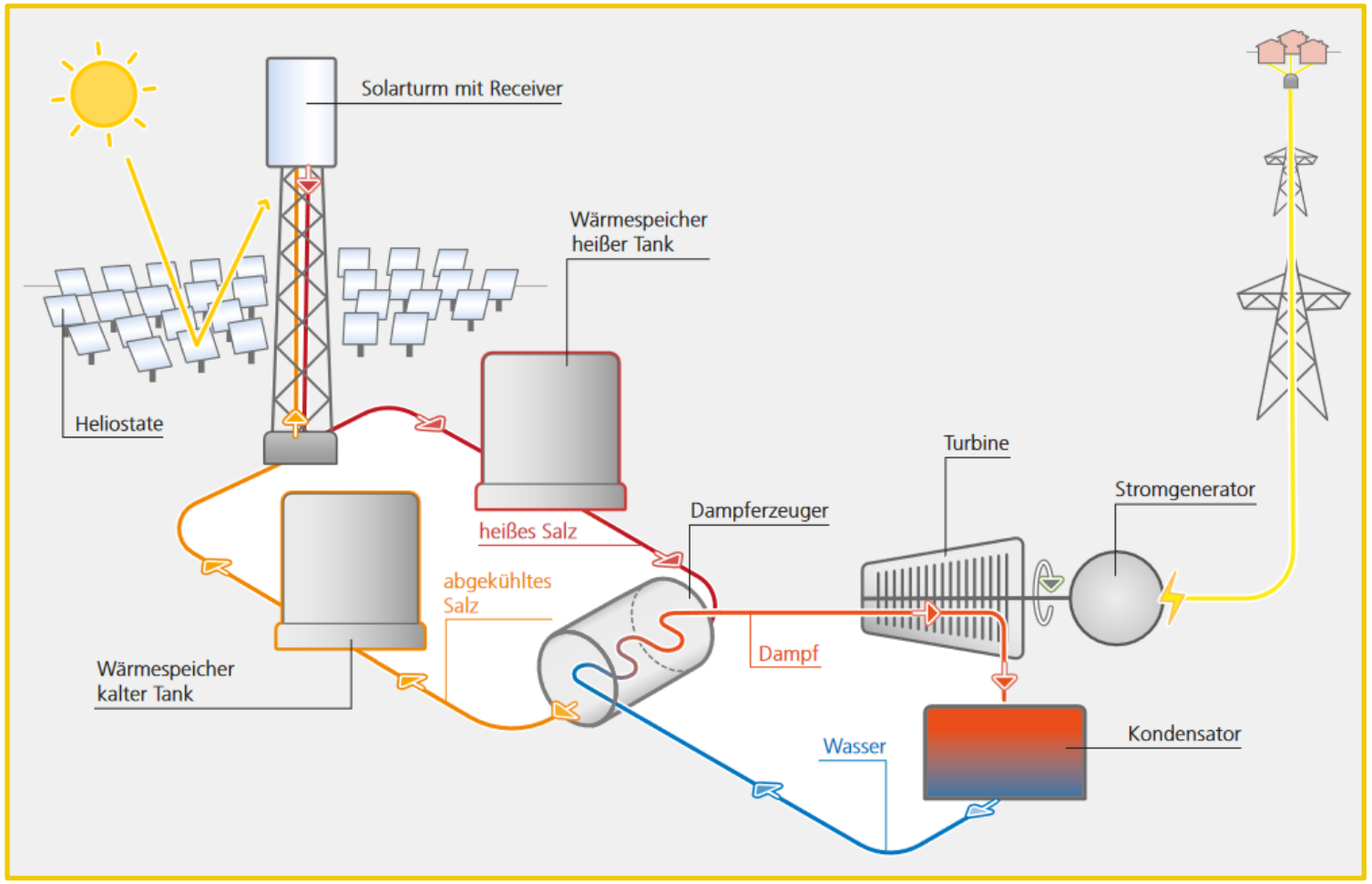
Germany: ~1,100 $\frac{kWh}{m^2a}$

Sahara: ~2,200 $\frac{kWh}{m^2a}$

≈ 500 €
when charging electrical car

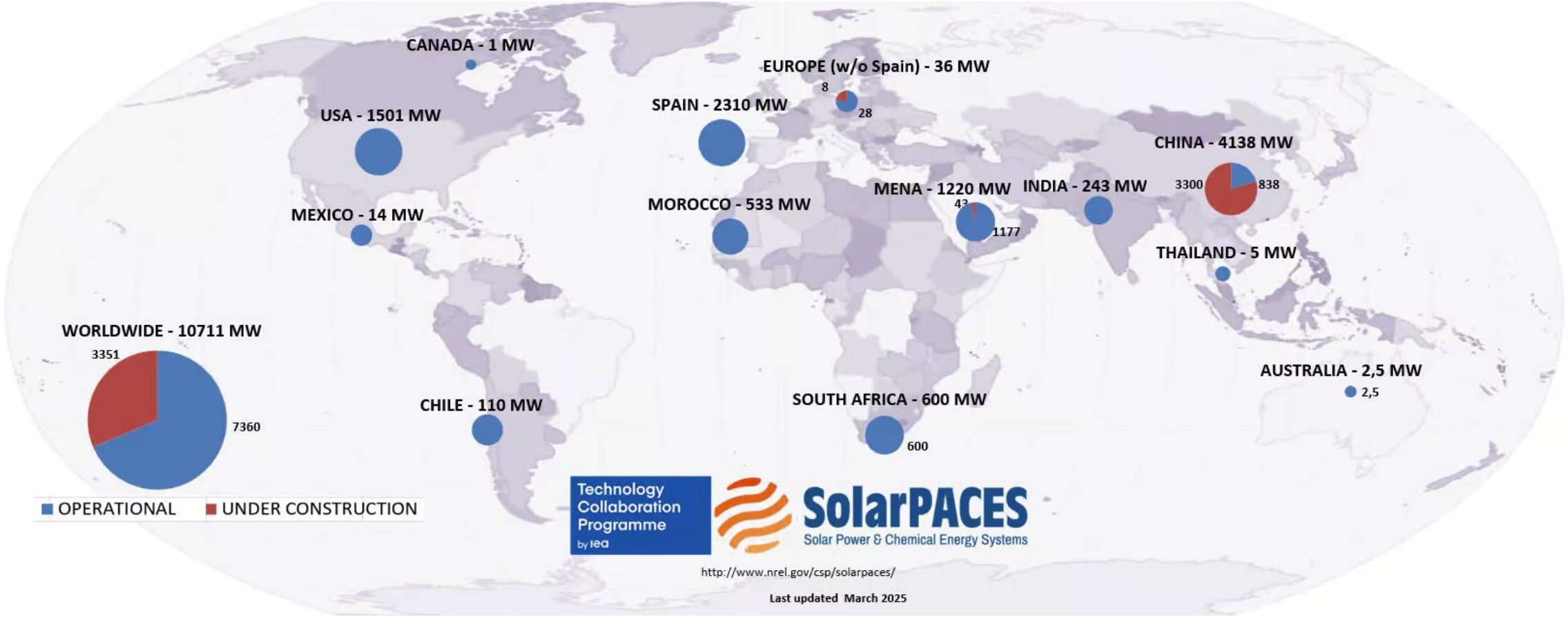
[1] https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

How does a CSP tower plant work?



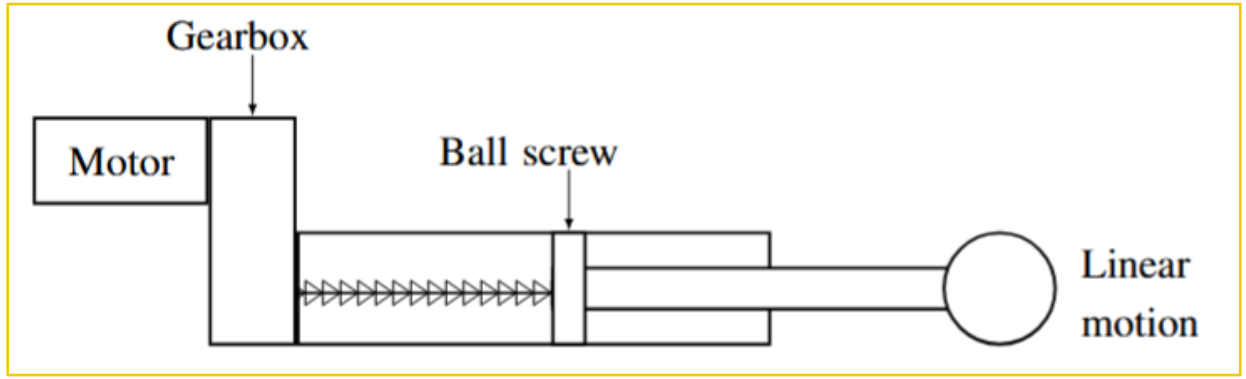
For more details [2]:

CSP Projects around the world

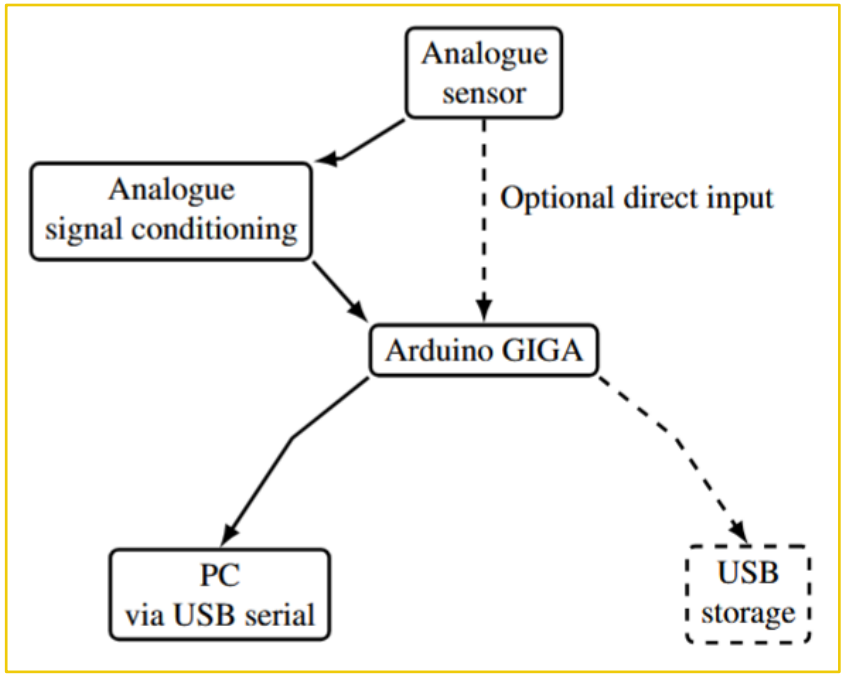


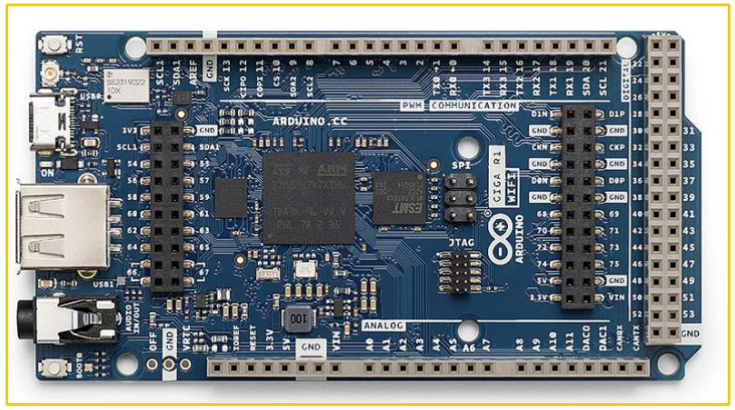
Source: https://www.solarpaces.org/worldwide-csp/csp-projects-around-the-world/

Experimental setup at the Solar Tower research facility in Jülich



Drive units convert rotational motion of the electric motor into linear motion via a gearbox and a ball-screw mechanism.





Analogue sensor **signals**

- routed directly to **Arduino microcontroller**
- or **optional** trough analogue **signal conditioning** stage

- subsequent transmission to the **measurement computer**
- or, alternatively, to **USB storage**

Characteristics of the Recorded Operational Data Using Analogue Signal Conditioning

Movement	a)	b)	c)	d)	e)	f)	g)	h)	i)
Axis 1	↑	↓	↑	↓	–	↑	–	↓	–
Axis 2	↓	↑	↑	↓	↓	–	↑	–	↓

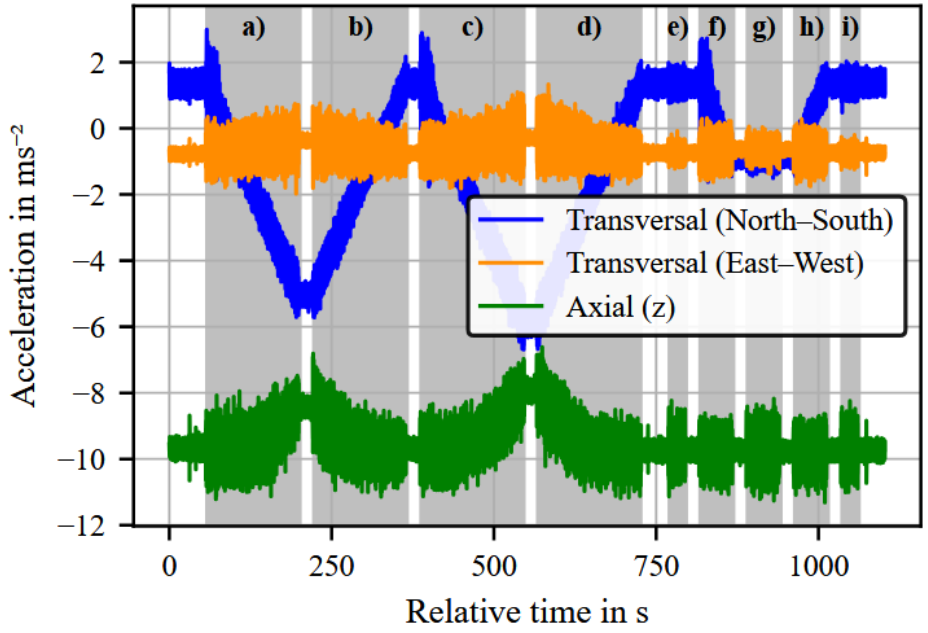


Figure 5. Raw 3-axis accelerometer signals measured at Axis 1 during the nine-step movement sequence defined in Table 1. The shaded grey regions indicate the individual movement intervals. It should be noted that the signals include the gravitational acceleration g, which leads to comparatively large acceleration amplitudes.

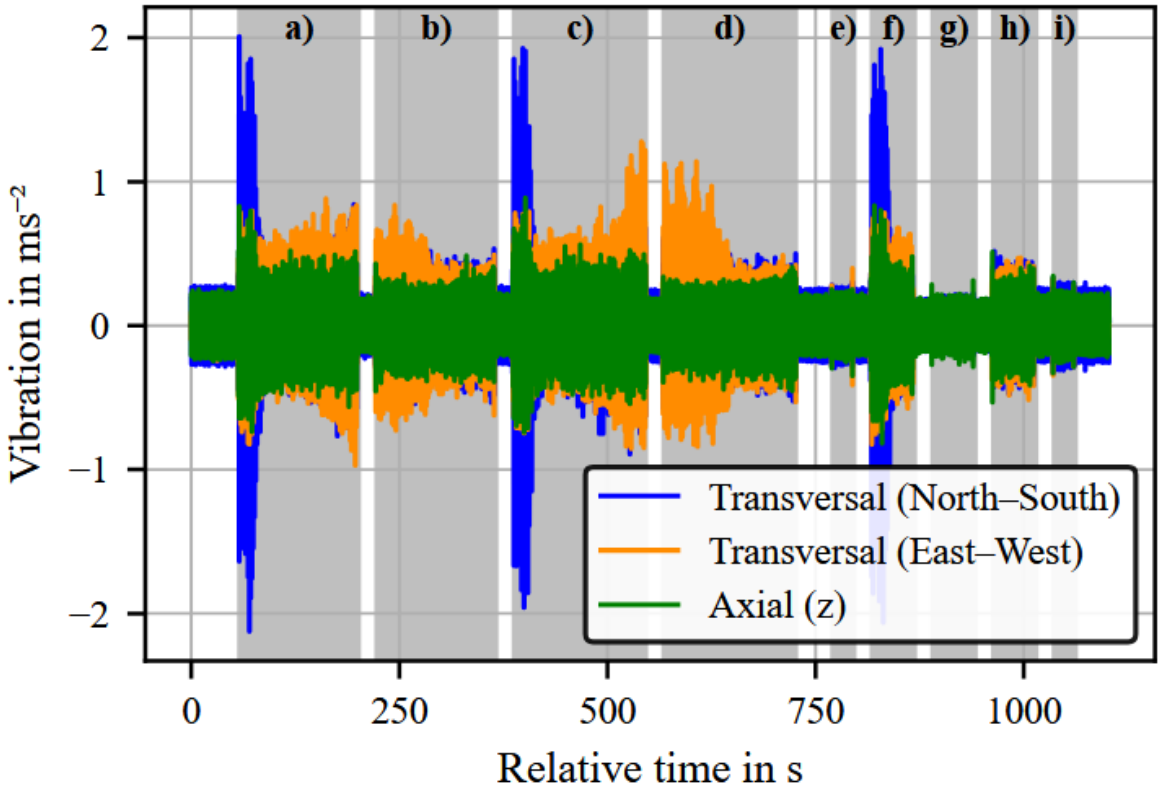
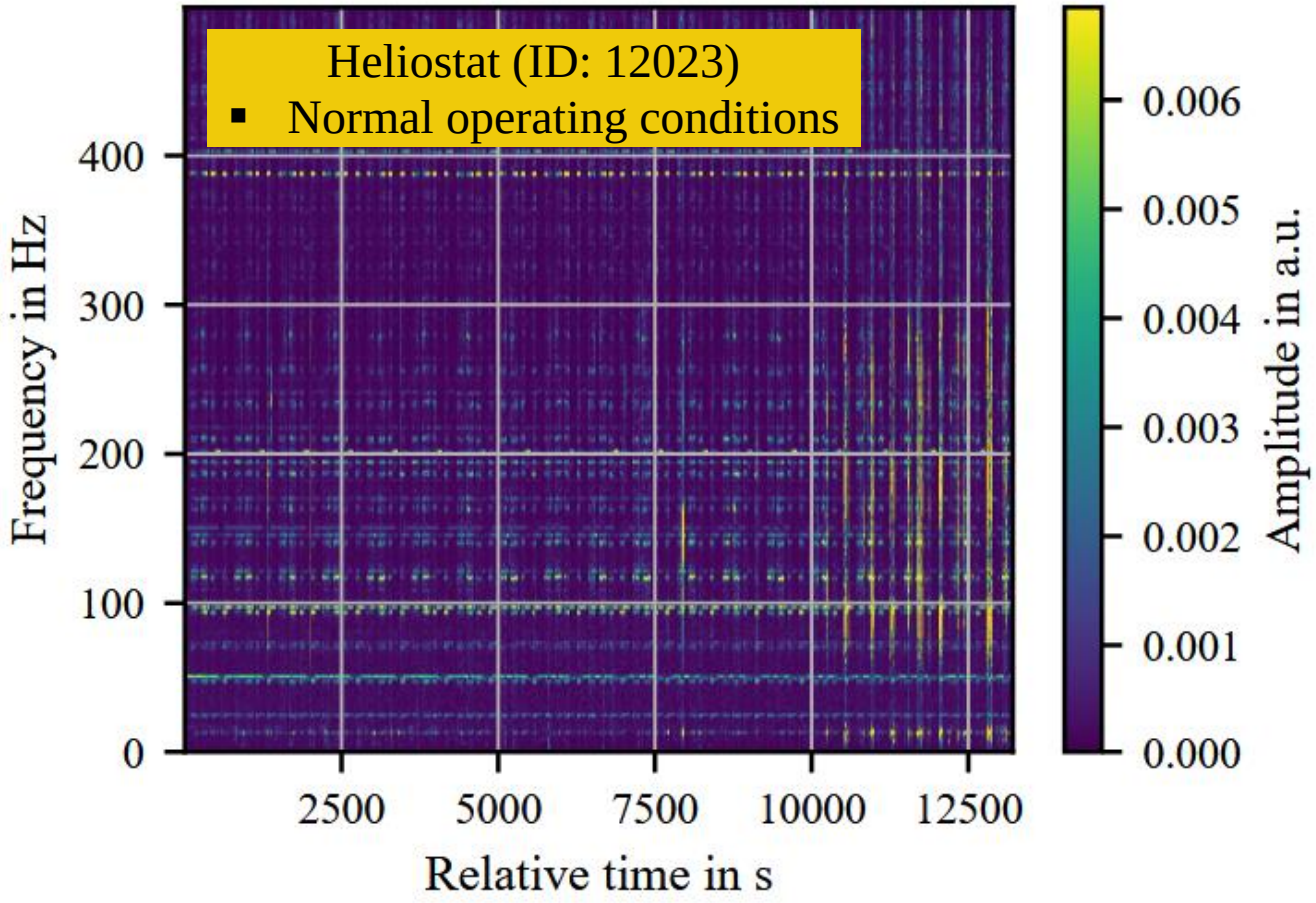


Figure 6. 3-axis vibration signals measured at Axis 1 during the nine-step movement sequence defined in Table 1 including the analogue signal conditioning. The gravitational acceleration component g is removed by the conditioning stage; therefore, the y-axis shows the resulting *vibration* signal.

Demonstration of the Prognostics Framework: Early Ageing and Anomaly Detection



Observations:

- Measurement data with **clear deviations** from typical, **characteristic signal patterns**
  → Anomalous ageing-related behaviour
- $t \geq 7{,}500\text{s}$: increasingly pronounced outliers/ anomalous peaks reaching amplitudes of nearly 6m/s^2 (= **ten times nominal vibration** level)
- **Wind** and other **external influences** (e.g. ambient temperature, global field disturbances) were found **not** to significantly **affect** the measurements.

→ **Early warning system** for this heliostat
→ Targeted inspection by O&M personnel

Demonstration of the Prognostics Framework: Early Ageing and Anomaly Detection

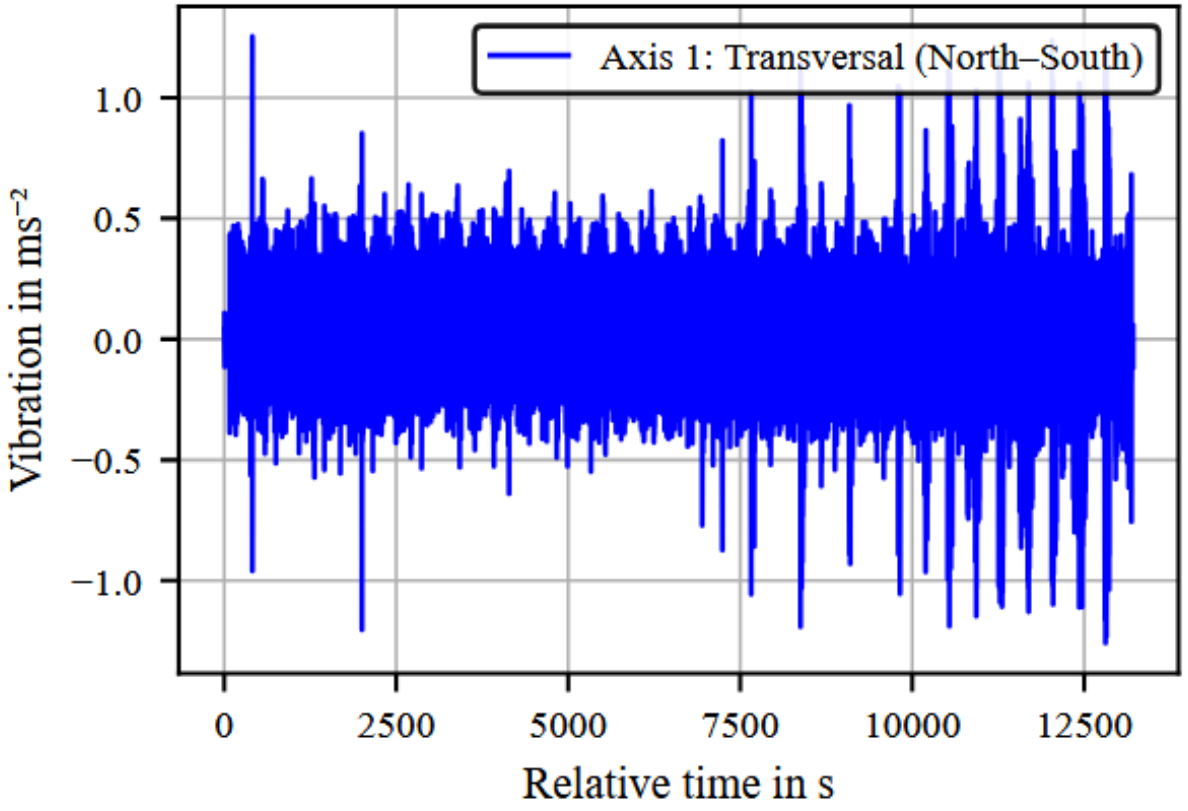


Figure 10. Measured vibration signal of Axis 1 obtained using analogue signal conditioning during the measurement period.

Demonstration of the Prognostics Framework: Early Ageing and Anomaly Detection

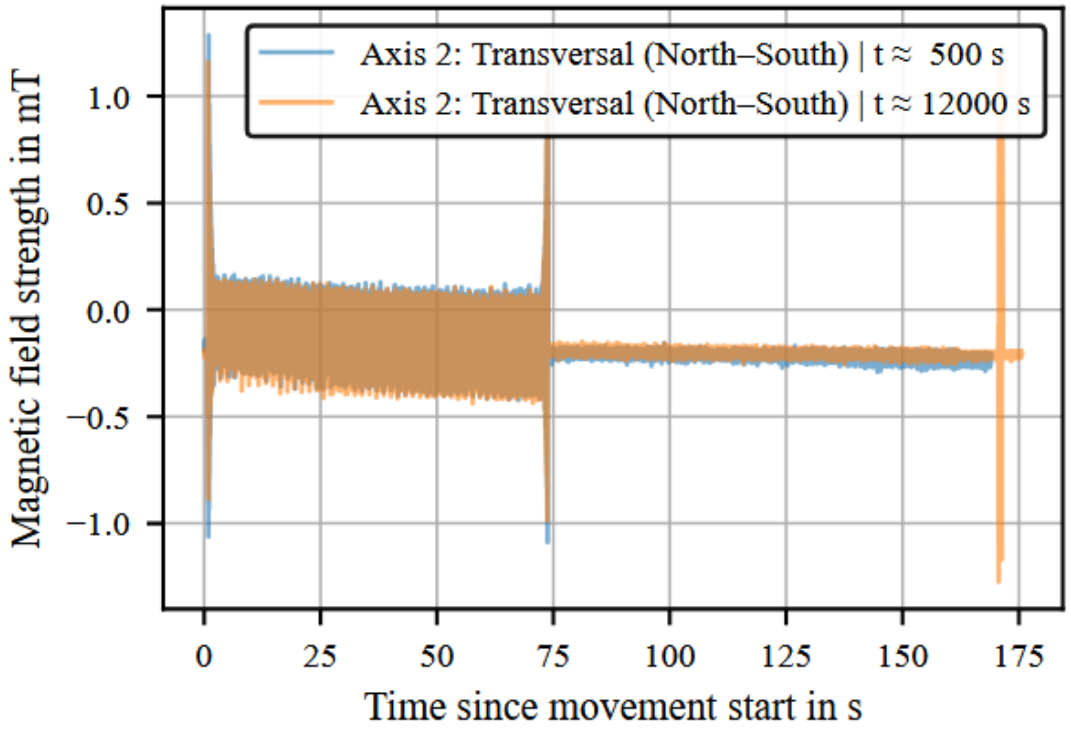


Figure 13. Time-domain comparison of early-stage and late-stage measurements obtained using analogue signal conditioning. It should be noted that the x-axis shows the time since movement start. (I.e. measurements were recorded at different points in time, but both segments are aligned to start at $t = 0\,\mathrm{s}$.).

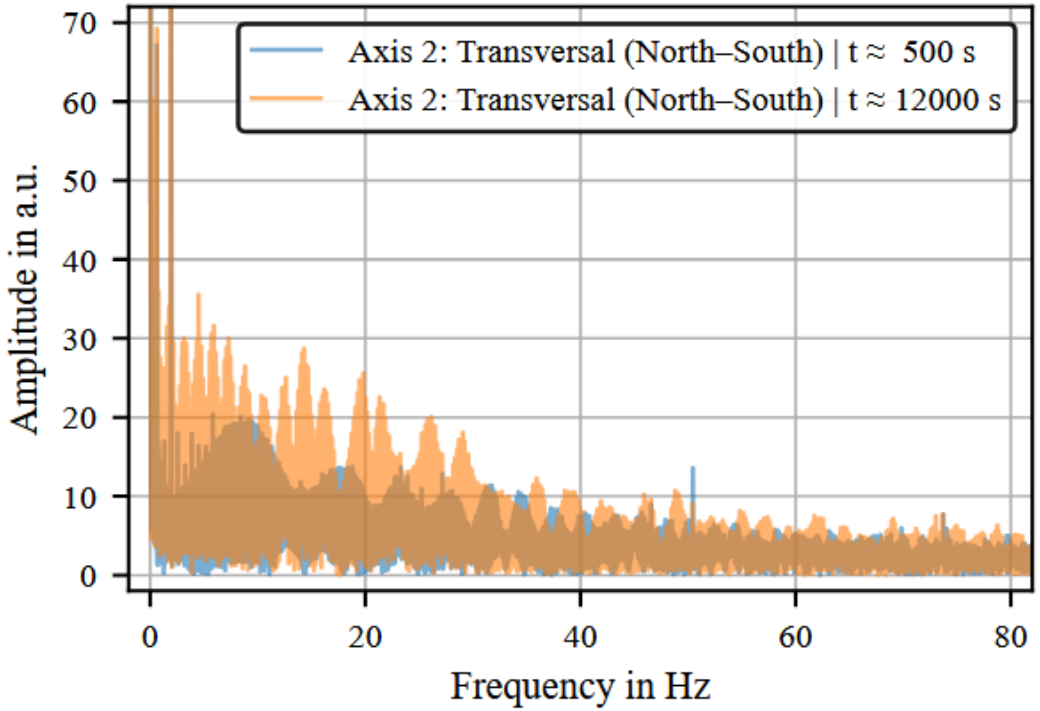


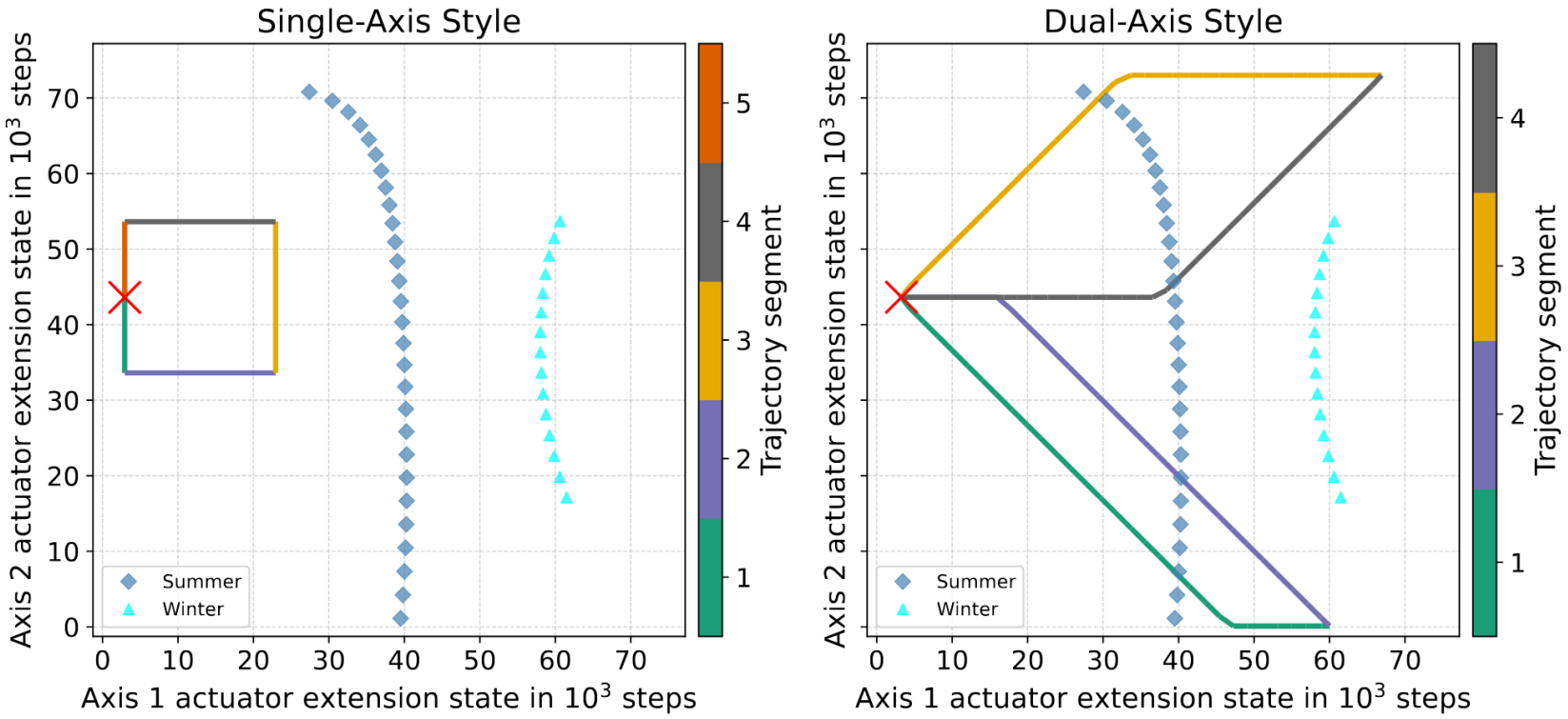
Figure 14. FFT-based comparison of early-stage and late-stage measurements shown in Fig. 13.

HelioKinet: Automated Heliostat Movement Framework

Project-Scope: Heliostat drive units
⇒ **Measuring** operational data (e.g. vibration/ current) **only possible** during active **heliostat movement**

Automated heliostat movement patterns:

- **Phase space** representation of different movement patterns



Credit Authorship Contribution Statement

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Stefan Huestegge: Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Visualisation.

Daniel Maldonado: Supervision, Resources, Funding acquisition.

Marc Röger: Supervision, Funding acquisition.

Benedikt Kölsch: Supervision, Funding acquisition.

Robert Pitz-Paal: Supervision, Funding acquisition.

\+ Preparation of the slides

Imprint

Topic: **Cost-Efficient Prognostics Framework for Heliostat Drive Units**
Presentation at the phme26

Date: July 8, 2026

Author: Dominik Steinberg

Institute: Institute of Solar Research

Credits: DLR, Author, Supervisor, References

SOLARIZE

Federal Ministry for Economic Affairs and Climate Action

Ministerium für Wirtschaft, Industrie, Klimaschutz und Energie des Landes Nordrhein-Westfalen

phme26
OSLO (NO) - 8/10 July 2026