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# Demonstration of 3.5 MWth Parabolic Trough with Ternary Molten Salt at the Évora Molten Salt Platform

Niklas C. Dicke[1][https://orcid.org/0000-0001-8057-0043], Mirko Meyer-Grünefeldt[1][https://orcid.org/0000-0003-4124-3482], Michael Wittmann[1], Jana Stengler[1][https://orcid.org/0000-0001-6124-8286], Pedro Horta[2][https://orcid.org/0000-0002-7679-0200], Paula Martins[2][https://orcid.org/0000-0003-1926-9993], Mehrdad Torabzadegan[3][https://orcid.org/0000-0002-8777-4222], Kai Schmitz[4], Mark Schmitz[4], Nils Gathmann[5][https://orcid.org/0000-0001-7761-9651], and Christian Stefan[5][https://orcid.org/0000-0003-1814-0872]

[1] German Aerospace Center (DLR), Institute of Solar Research, Linder Höhe, 51147 Cologne, Germany

[2] University of Évora, Renewable Energies Chair, Polo da Mitra da Universidade de Évora, Edifício Ário Lobo de Azevedo, 7000-083 Nossa Senhora da Tourega, Portugal

[3] Yara International ASA, Drammensveien 131, 0277 Oslo, Norway

[4] TSK Flagsol Engineering GmbH, Anna-Schneider-Steig 10, 50678 Köln, Germany

[5] Steinmüller Engineering GmbH, Fabrikstr. 5, 51643 Gummersbach, Germany

**Abstract.** Commercial solar thermal parabolic trough power plants use thermal oil as a heat transfer medium in the solar field. Within the framework of the “High Performance Solar 2” (HPS2) research project a molten salt parabolic trough demonstration plant was commissioned in summer 2021 in Évora, Portugal. Since then it has been operated for more than 5.500 h between 180°C and 500 °C, jointly by the University of Évora, DLR and TSK Flagsol. This article presents the main steps of cold and hot commissioning as well as experiences gained in plant operation. It has been shown that filling a preheated solar field with ternary molten salt is not critical, but its drainage can be challenging depending on the quality of the heat tracing and the solar field slope.

**Keywords:** Parabolic Through, Ternary Molten Salt, Linear System Operation

## 1. Introduction

The HPS2 research project funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), industry partners, the Portuguese Science and Technology Foundation and the Regional Operational Program Alentejo2020, is integrated in the Portuguese National Research Infrastructure on Solar Energy Concentration [1]. Within the HPS2 project, a 3.5 MWth parabolic trough plant with ternary molten salt as heat transfer fluid (HTF) has been demonstrated at the Évora Molten Salt Platform (EMSP), which could decrease levelized costs of electricity (LCOE) for parabolic through plants by about 20% [2].

**Figure 1**. Aerial view on the HPS2 demonstration plant at the EMSP.

As previously presented [3], the solar field was erected by TSK Flagsol and consists of four HelioTrough® 2.0 collectors (two solar collector assemblies (SCA) made of eight 19-m-long elements and two of ten such elements). The total aperture area is 4635 m² and the collectors have a geometric concentration factor of 31 (6.776 m aperture width and 70 mm absorber tube diameter). The collectors feature a slight inclination of 0.15% to allow the draining of the HTF through gravity. As the ground had been levelled to horizontal before the start of HPS2, the inclination was realized through ascending pedestals integrated into the slab foundations.

The high-performance steam generation system with 1.7 $MW_{th}$ was erected by Steinmüller Engineering GmbH and consists of a new once-through type steam generator system for molten salts.

The article presents the main findings of the commissioning and more than 5537 hours of operation with molten salt flow in the solar field as well as salt melting, solar field filling, and drainage operations.

## 2. Commissioning

The commissioning of the solar loop took place in two stages:

1. Cold commissioning and water run with the aim to demonstrate that the facility is ready for operation. This commissioning phase featured various sets of equipment checks as well as the commissioning of the distributed control system (DCS), and took place from June to September 2021.
2. Hot commissioning aiming to demonstrate that the facility is ready for operation at high temperatures. It included salt melting, solar field pre-heating and solar field filling, and process control optimization, which took place during October 2021.

## 2.1. Cold Commissioning and Water Run

### 2.1.1 Commissioning of the distributed control system

Starting from cold commissioning, the operation and maintenance (O&M) team was trained on the plant in all relevant subsystems, as well as in the DCS. The DCS software T3000, normally used in commercial power plants, is a comprehensive and fail-safe system consisting of redundant servers that integrate the subsystems as black boxes. Therefore, several programmable logic controllers (PLC) need to communicate properly and exchange relevant data via Profibus. Communication and loop checks of all DCS signals were performed by DLR's subcontractor Siemens Energy Portugal and includes:

- Network and IP address configuration and check
- Setup and test of system time and its synchronization with the subsystems
- Communication check of field instrumentation and black box systems (heat tracing and field supervisory control)
- Check of interlocks, component logics and setpoints related to the functional description
- Check of DCS functionalities and storage of data on the history server
- Adaptation of Human-Machine Interfaces and controller tuning
- Blackout and emergency case simulation and including configuration of the emergency diesel generator

The loop checks involved extensive work of the O&M team due to the brown field situation of the HPS plant from 2012 on. Numerous repair and calibration work had to be carried out on instrumentation and actuators before the loop check was concluded and water run could be started.

### 2.1.2 Solar field cold commissioning

The solar field has its separate control system consisting of a central PCS-7-based field supervisory control (FSC) and PLC-based local controllers (LOC) on the drive system of each SCA. During cold commissioning the individual SCA functionality (drive system, position measurement, temp and pressure sensors) was verified:

- Check of all IP addresses and configuration of network equipment
- Test of system wide time synchronization
- Check of data exchange between FSC and LOCs (commands to SCA, status from SCA)
- Calibration of SCA position measurement
- Verification of sun angle and incidence angle calculations
- Check of weather station data (wind speed, irradiation, ambient temp)
- Loop check for data exchange between FSC and DCS (interlocks, flow sensors, safety signals)
- Individual parametrization of HTF properties (e.g. salt density functions for mass flow / volume flow conversions)
- Verification of all defined safety functions and interlocks (e.g. automated preparation for emergency drainage)
- Setup and configuration of data archival (history server)

### 2.1.3 Water run and performance test of the salt pumps

Before the plant was filled with cool demineralized water the motor and power control center (MCC and PCC) was commissioned and all AC motor including the salt pumps were tested to shorten the duration (< 30 days) of the water run, as demineralized water could harm the bearings of the pumps. One hot salt pump showed high vibrations, because of loosen bolts and needed to be reassembled. As the system is prepared to have redundancy on the critical components, this issue was not critical to the persecution of the commissioning works. To ensure a correct functioning of the pumps according to design before filling of the system with molten salt, the pumps characteristic curves were checked and confirmed by manual pressure measurements on the pressure side of each salt pump. Subsequently, the pressure meter was removed, and the nozzle was welded. Finally, the salt piping system including the salt tanks were drained and dried.

## 2.2. Hot Commissioning

### 2.2.1 Salt melting

After the water run with demineralized water, loop checks and tank cleaning, the melting process of 95 t of the ternary salt mixture comprising 42% calcium nitrate, 43% potassium nitrate and 15% sodium nitrate named ("Yara Molten Salt") started. With a melting point of approx. 131 °C, this ternary salt mixture features a considerably lower melting temperature compared to standard Solar Salt, and therefore is of interest for process heat applications, but also for solar thermal power production at sites with medium-to-high solar irradiation such as the Iberian Peninsula. The melting of the solid components was carried out by means of a pre-melting unit especially designed for the Yara Molten Salt mixture. During the melting process, it should be noted that between 180 °C and 230 °C there may be more foam formation, due to the boiling out of the crystal water (9 wt.%). The foam formation can be controlled by adjusting the heating power and eventually the temperature gradient. Above these temperatures, the viscosity of the salt is much lower, as thermophysical analyses have shown. The foam bubbles therefore collapse quickly, so that only a thin layer of foam forms and the tank level can be reliably monitored with radar level sensors. As in comparable plants [4] with molten nitrate salts, nitrogen oxides (NOx) emissions were detected when heating the ternary salt mixture to 300 °C.

### 2.2.2 Preheating of the solar field

To preheat the pipes for salt filling, the HPS2 loop is equipped with a trace heating and an impedance heating system that is designed and installed by the project partner eltherm. Trace heating systems use mineral insulated heating cables (MI cables), while the impedance heating system uses a high current flow through the pipe wall for heating. For safety reasons, the voltage level of the impedance heating system is limited to 50 V AC. All interconnecting piping system of the HPS2 plant is equipped with trace heating including the cross-over pipe and the rotating and expansion performing assemblies (REPAs) on the north and south-side of the solar field. The receiver tubes of the solar field and the REPAs in the center of the solar field are heated by the impedance heating system.

For temperature monitoring during operation, PT100 sensors with and without thermowell are installed in the solar field at the collectors' in- and outlets, and at the fixed pipe at the drive pylons. These PT100 measure the temperature of the fluid at the center of the pipes. The REPAs are equipped with surface temperature sensors for monitoring and control of the trace and impedance heating. Initially it was planned to derive the temperature of the impedance heated absorber tube from its electrical resistance. During commissioning however, it was observed that this approach is too unprecise due to leakage currents, which occur at various points of the impedance heating system. The estimated error of about 20% was considered too high to use this theoretically calculated temperature for control. Therefore, the concept was changed and the PT100 without thermowell, which feature a higher dynamic than the ones with thermowell, were used by eltherm for control of the absorber tube impedance heating.

During preheating and before filling with molten salt, the piping system is filled with air and only natural convection occurs inside the pipes. At this state, the PT100 installed in the center of the pipes do not reflect the temperatures present in the pipe walls since the losses due to heat conduction to the ambient are higher than the thermal transfer by natural convection to the measuring tip of the sensor. Therefore, temperatures measured in the solar field are much lower (by about 150 K) than the actual pipe wall temperatures. Only the surface temperature measurements of the REPAs with close contact to the wall indicated the actual preheating temperature. To overcome this problem, a hot air blower was used to apply forced convection to the temperature sensors inside the solar field and it could be observed that as soon as air is blown through the system, the measured temperatures increased significantly, reaching the expected values of up to 270 °C. Forcing convection in the pipes also helped to avoid potential cold spots and equalized the temperatures in the piping system before the first filling with molten salt. To improve temperature monitoring during preheating, surface temperatures sensors were installed in the follow-up project.

The following Figure 2 shows the effect of the air blower on the PT100 temperature measurements with (solid lines) and without (dotted line) thermowells at the drive pylons. In the morning the air blower was off and impedance heating was active in all collectors except solar collector assembly SCA1. Between 7:40 and 8:15, the hot air blower was tested to ensure air flow in the solar field and adjust temperature of heater to prevent overheating. At about 8:50, the blower was started leading to the steep increase in the temperature measurements. The temperature difference between the different sensors installations is around 20K. From sunrise until 13:00 the receivers were additionally exposed to unconcentrated sunlight. Afterwards, when the shade from the concentrators came onto the receivers, a slight decrease in temperature can be seen. In SCA1 it can be seen, that even without impedance heating, temperatures of more than 200 °C can be reached due to unconcentrated solar input. This temperature level would theoretically be sufficient to fill the collector with Yara Molten Salt without impedance heating.

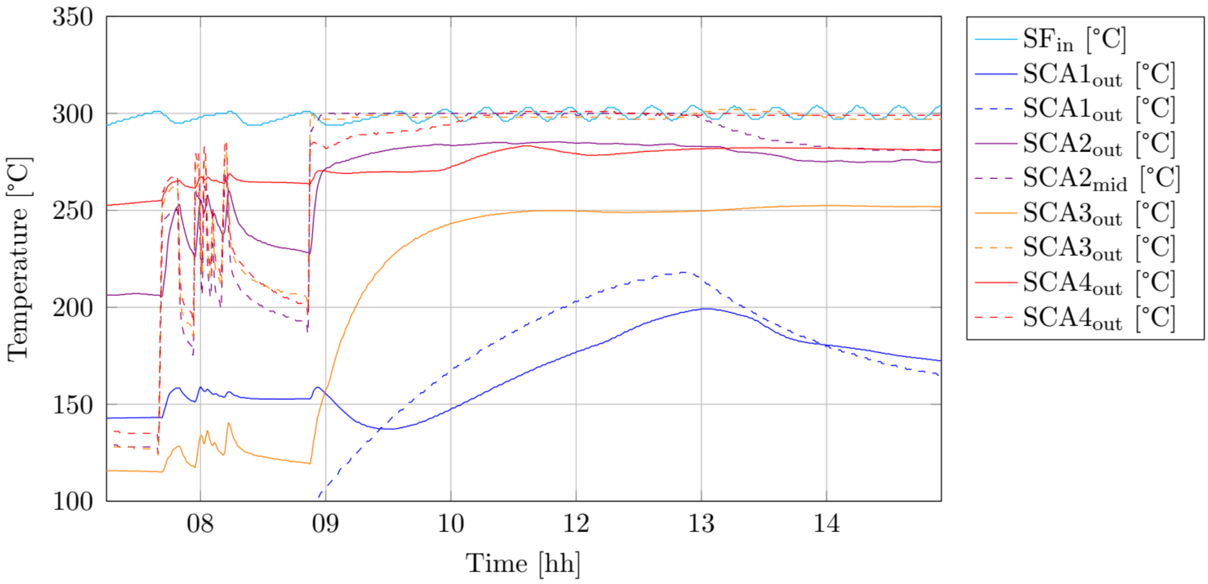


**Figure 2.** Pre-heating of the solar field (SF) with and without hot air forced convection.

### 2.2.3 Solar field filling and hot commissioning

One crucial aspect during the filling process is to avoid too large temperature gradients over the circumference of the receiver tubes, which could lead to bending and contact of the absorbers with the glass envelopes. In extreme cases, temperature gradients over the circumference can even lead to breakage of the glass tubes. One advantage of a molten salt system with trace and impedance heating is the fact that both the salt temperature and the temperature of the empty tube can be adjusted to the same temperature level before filling, eliminating the risk of problems due to temperature gradients.

On October 19th, 2021, the demo loop was filled with a mass flow of 10.8 kg/s (75% pump speed) within approx. 15 minutes without any technical issues. It was decided to use a relatively high mass flow during filling in order to avoid bending of the receivers due to temperature gradients over the circumference. During this first filling process it could also be demonstrated that venting at the cross over pipe valve is not necessary during filling as all air is pushed out of the piping system. Salt spillage from venting is therefore no issue and can be avoided. The receivers (Rioglass PTR 70) were monitored with cameras during filling, no deformations were detected.

### 2.2.4 Steam generation system

The steam generation system was erected by Steinmüller Engineering GmbH and consists of a new 1.7 $MW_{th}$ once-through type steam generator system for molten salts to enable highly dynamic operation and facilitate frequent load changes. However, during the hot commissioning of the steam generation system the feedwater pump broke down and could not be repaired or replaced during the runtime of the project. Therefore, the steam generation system, which also serves as heat sink for the plant, could not be fully commissioned and tested. The replacement of the pump and commissioning and testing of the steam generation system is planned for the follow-up project MSOpera (founded by German Ministry BMWK, 03EE5028B).

In commercial plants, centrifugal pumps have usually proven to be a reliable pump type for feedwater pumping. Due to the low mass flow at the test plant, a plunger pump was used here instead. During hot commissioning the increasing temperature and pressure lead to evaporation of the lubrication water leakage flow through the annual gap of the plungers and their packings and destroyed the plunger coating and the packings (Figure 3).

**Figure 3**. Damaged coating from plunger of the feed water pump.

## 3. Solar Operation

From initial filling in October 2021, the HPS2 solar field has been successfully operated for over 5.500h. Within the operation time, experience on the operation procedures and strategies (start-up, normal operation, freezing prevention, drainage, emergency stops) were acquired. The operation of the HPS2 loop also served testing purposes for performance tests, heat loss tests, corrosion tests, salt degradation tests and receiver preheating tests. Evaluation of the performance tests data is still ongoing and will be published separately as well as the analysis of the corrosion samples. The analysis of the ternary salt samples, which were taken regularly during the operating period, were discussed within the MSOpera project [5].

### 3.1 Main operation sequences

The daily operation begins with a startup sequence in the morning. The process description including process flow diagrams has been published in [3]. Here, the mass flow in the solar field is increased, the collectors are sent to track mode, and salt is circulated into the cold salt tank until the target outlet temperature is reached. The switch over to the hot tank is done when the solar field outlet temperature approaches the hot tank setpoint by 20 K. This is followed by normal operation mode or test operation, where the collectors are focused and the nominal conditions are settled. If the maximum temperature at the solar field outlet is exceeded, it is possible to increase the mass flow or to apply a dumping factor to the collectors as in a commercial system. In the evening, the shut-down sequence transfers the plant into the convective anti-freeze mode. A salt mass flow of about 2 kg/s is pumped through the solar field to prevent freeze events. Salt is circulated into the cold tank and mixed with salt from the hot tank to compensate for the heat losses of the solar field. If any temperature falls below the lower process temperature (270°C nominal), the electric anti-freeze mode in this section or equipment is activated and the required temperature is maintained with electric heaters and the heat tracing systems.

In the first months of 2022, the temperatures in the plant were successively increased from 350 °C to up to 500 °C hot tank (HT) temperature, depending on the weather as reaching the highest temperatures requires several hours of high DNI. The strong temperature fluctuation and oscillation is explained to the lack of a heat sink since the steam generator system is currently out of operation. With the convective anti-freeze mode the solar field is kept warm during the night and with the increasing DNI, the start-up sequence is initiated. The temperatures rise and when it reaches the switch-over temperature of in this case 495 °C, the salt will no longer be circulated back to the cold tank, but fills the hot salt tank. The switch-over temperature is defined as the solar field outlet temperature -20 K. After the switch-over procedure the normal operation starts and the hot tank is heated up. As there is no heat sink available the cold tank temperature increases already during start-up and the hot tank is heated up until 9:30 consequently, the possible temperature increase in the solar field becomes smaller especially for the SCA1. As a result, minimum dumping of SCA1 was set to 100% and the remaining three collectors have to dump also up to 100% of the irradiation.

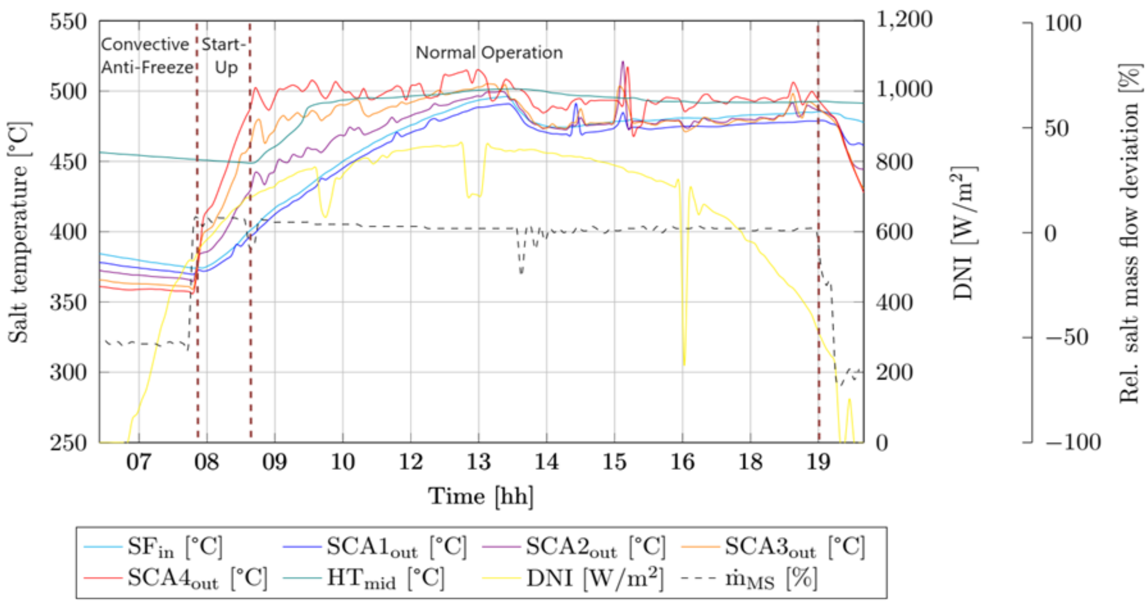


**Figure 4**. Measurements of DNI, relative salt mass flow, collector (SCA)- and hot tank temperatures with "Yara Molten Salt" on April 30th 2022 @ HPS2 test loop.

## 3.2 Handling of drainage operation and prevention of freezing events

During periods of bad weather or maintenance, the system can be drained as all piping has been designed with a slope towards the drainage tank (2% for most interconnecting piping and 0.15% for the collectors and absorber tubes). In molten salt systems the drainage procedure entails the highest risk of freezing to the plant. Due to the low and decreasing flow velocities, the salt may crystalize even at small cold spots, which are uncritical in normal operation. Additionally, salt rests remain at sinks in the pipework, which in the case of the HPS2 plant occurred in the flexible metal hoses of the REPAs. To avoid the sagging of the REPA hoses, additional supports were installed within the course of the project, supporting the metal hoses horizontally in the drainage position of 0°. During the HPS2 project it could be demonstrated that the solar field and interconnecting piping system can be drained completely by gravity within about 45 minutes. During the first drainage procedure however, a salt plug had formed at one cold spot on the drainage line of the outlet of the solar field. The plug formation occurred due to missing heat tracing of a 400 mm long, vertical pipe segment at the top of the drainage tank at a scope interface. Although the mechanically connected tank was heated to up to 400 °C, the salt mixture crystalized in this short pipe segment due to the low heat conductivity of stainless steel and the low flow velocities during drainage. The cold spot was eliminated by the installation of additional heat tracing at this pipe segment and following drainage sequences were performed successfully.

The system is operated in three shifts 24/7 as long as salt is circulated in the solar field. If the solar field is drained, three shift operation is not required anymore, since the salt tanks can only freeze after many hours or days, and the tank heaters proved to be reliable. To reduce the operating personnel, further plant automation is currently being planned and implemented in the follow-up project MSOpera.

## 4. Lessons Learned and Conclusions

During hot commissioning, electrical isolation parts in the collector were found to be defect. A root course analysis showed that deficiencies in the assembly process led to the failures of the parts. In future generations of the solar collector, more robust and easier to install solutions for the electrical isolation will be implemented. Additionally, it was found that the electrical installation of the impedance heating system required some effort. Also, the temperature measurement of empty pipes and of the REPA system is challenging, but can be handled in a way to ensure safe operation. The operational experience shows a high potential for innovative solar-only preheating strategies to reduce hardware expense on trace heating systems.

The filling of the solar collector loop proved to be unproblematic. Neither bending of the heat collecting elements (HCEs) nor plugging of any piping was encountered. Even at high mass flows for filling no noise or vibrations could be detected. It can be concluded that the mass flow for filling the solar field can be high as this reduces the filling time and consequently the risk for freezing and avoids critical circumferential temperature gradients.

Although the HPS2 facility was originally designed for binary solar salt, the use of ternary molten salt as combined HTF and storage material was tested successfully for the first time in a scalable size for CSP applications. In the regular daily operation of the solar field (warm-up, heat production, freeze-protection) no operational issues were encountered. It can be expected that the operation of commercial power plants will run smoothly, as the large storage capacity of such systems will provide a safe source of heat for freeze protection, and the inertia of such systems will be positive for the operation of molten salt solar fields.

Due to the supercooling effect, the ternary molten salt used in the experimental campaign solidifies at lower temperatures than its melting point. This phenomenon was observed at the end of operation time with Yara Molten Salt when the temperature in the hot tank was below 100 °C in the hot tank, in the salt mixture was still in liquid phase. However, from the experimental experience with the HSP2 facility, it is concluded that the drainage procedure is one of the critical processes in molten salt parabolic trough systems. It is essential to avoid cold spots in all lines to be drained. Especially those areas of the solar collector loop which are drained last need to be properly insulated and heat traced as the drainage process is driven by gravity. Due to the particularly flat site at the EMSP, the solar field has a very low inclination, and drainage takes about 45 minutes. The last trickles of salt in the pipes can accumulate into solid salt plugs at cold spots, which should also be considered in the collector alignment. When the system is in a hot state, it is recommendable to scan piping network with an infrared camera and spot for hot areas which can form cold spots during drainage. Draining of the solar field should be further investigated. Especially the impact of a different salt mixture with reduced viscosity (solar salt) should be analyzed.

## Data Availability Statement

Raw data were generated at Évora Molten Salt Platfom. Derived data supporting the findings of this study are available from the corresponding author N.C. Dicke or J. Stengler on request.

## Author contributions

**N.C. Dicke:** Conceptualization, Data curation, Validation, Investigation, Visualization, Writing - original draft, Writing - review & editing. **M. Meyer-Grünefeldt:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, **M. Wittmann:** Supervision, Writing - review & editing, **J. Stengler:** Supervision, Conceptualization, Writing - review & editing, **P. Horta:** Writing - review & editing, **P. Martins:** Writing - review & editing, **M. Torabzadegan:** Investigation, Writing - review & editing, **K. Schmitz:** Investigation, Writing - review & editing, **M. Schmitz:** Supervision, Investigation, Writing - review & editing, **N. Gathmann:** Conceptualization, Investigation, Writing - review & editing, **C. Stefan:** Conceptualization, Investigation, Writing - original draft

## Competing interests

The authors declare no competing interests.

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