Graphical Abstract

Solar Energy Autopilot (SOLEA): A Holistic System Architecture for Autonomous Concentrated Solar Thermal Plants and Its Evaluation in an Operational Power Tower Facility

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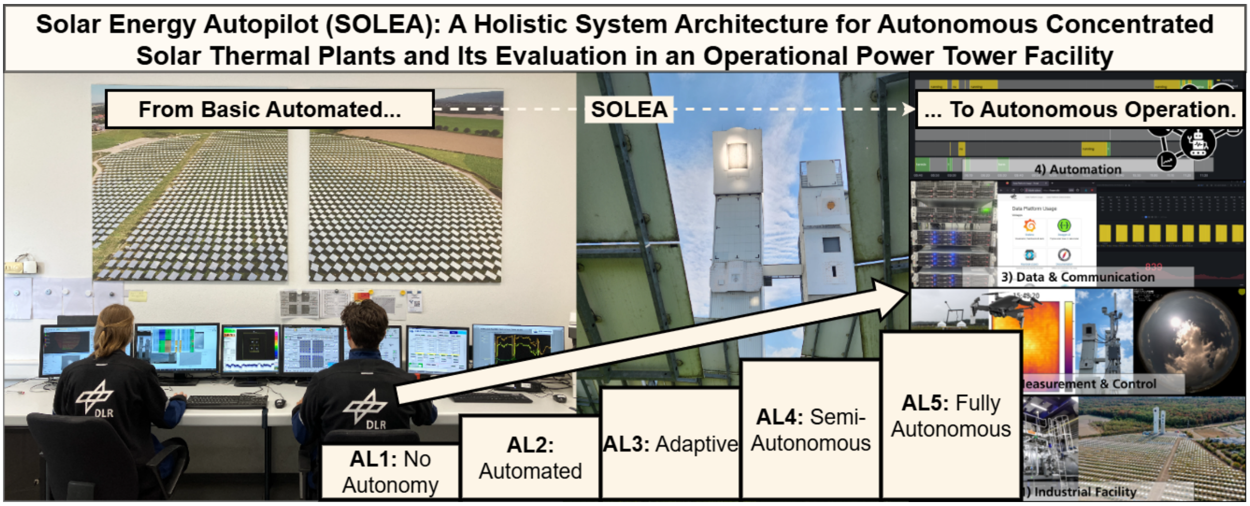

Highlights

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- Retrofit traditional automation into autonomous cyber-physical CST systems
- Holistic 4-layer architecture enabling autonomous CST plant operation
- Evaluate CST benefits and degree of autonomy from a multi-dimensional perspective
- Successful transition of an operational CST plant to a (semi-)autonomous factory
- Autonomous operation boosts CST efficiency, robustness, and cost savings

Solar Energy Autopilot (SOLEA): A Holistic System Architecture for Autonomous Concentrated Solar Thermal Plants and Its Evaluation in an Operational Power Tower Facility

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ABSTRACT

Concentrated solar thermal (CST) plants can provide dispatchable renewable energy but remain complex and costly to operate due to tightly coupled subsystems, dynamic environmental conditions, and high safety requirements. This work presents the Solar Energy Autopilot (SOLEA), a holistic four-layer architecture that transforms a traditional solar power tower plant into an autonomous cyber-physical system (CPS). The architecture integrates plant hardware and control systems, advanced optical and meteorological measurement systems, a CPS middleware platform with a standardized digital twin, and a multi-agent automation layer for operation planning and control. SOLEA is implemented and evaluated at an operational research facility, where intelligent agents autonomously plan operating days, start and shut down the plant, and regulate the receiver flux and outlet temperature under varying environmental conditions. A dual-sided evaluation quantifies benefits in terms of efficiency, robustness, and cost-related indicators and assesses the system's autonomy using a multi-dimensional maturity model. The results show substantial reductions in operational and investment costs, highly robust operation despite challenging environmental conditions, and efficiency gains in plant operation enabled by an increased autonomy level of the facility. Overall, the study demonstrates that the layered modular SOLEA architecture can effectively bridge the gap between isolated automation solutions and plant-wide autonomous CST operation and provides a reusable blueprint for advancing autonomy in future CST plants and comparable industrial environments.

1. Introduction

Concentrated solar thermal (CST) technologies can play an increasingly important role in achieving a climate-neutral energy system. Due to their ability to generate and store high-temperature heat, CST systems provide stable and dispatchable electricity generation, supporting grid stability and complementing intermittent renewable sources such as photovoltaics (PV) and wind energy [27]. Beyond electricity generation, CST plants can directly supply thermal energy for industrial and thermochemical processes with high efficiency, including hydrogen production, water purification,

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and high-temperature applications such as drying, sterilization, or distillation [42]. Despite these advantages, the global expansion of CST technology has stagnated in recent years, mainly due to the high operational complexity and associated investment, operational, and maintenance costs. An increased level of digitization and automation is considered a key strategy to address these challenges by better managing operational complexity, improving efficiency, and thus reducing the overall costs of CST technology [27].

At the same time, industry and energy sectors are undergoing a transformation toward autonomous operation. Motivated by economic and environmental incentives, autonomous systems are being developed to improve efficiency, increase robustness, and reduce production costs [17]. Advances in artificial intelligence (AI), digital twins (DTs), and industrial automation technologies have made large-scale autonomous operation technically feasible [20]. However, in the CST domain, the level of automation remains comparatively low [36]. This domain is characterized by complex subsystems, highly dynamic physical processes, and stringent requirements for reliability, latency, and safety. Such characteristics make digital transformation costly and challenging, yet also particularly promising in terms of potential impact [27]. Increasing the degree of system autonomy in CST plants can help to exploit the full potential of solar heat generation while reducing overall costs [33]. Moreover, system autonomy opens pathways for new business models and deployment scenarios. For example, in industrial process heat applications, autonomy enables heat-as-a-service concepts, in which CST plants are remotely operated by specialized providers that supply climate-neutral heat to industrial facilities as a service. In parallel, autonomous operation also improves the feasibility of CST power generation in regions such as deserts, where exceptionally high solar radiation enables large-scale electricity production, but the remote location and harsh environmental conditions make continuous on-site operation by human personnel challenging.

Despite significant progress in digitization and AI-based control, existing research focuses primarily on isolated automation tasks rather than holistic system concepts [36]. To date, no comprehensive architecture for an autonomous CST plant has been implemented and evaluated under real industrial conditions [57]. Most existing work addresses only subsystem-level automation, such as heliostat calibration [32], solar field inspection [7], or maintenance robots [22] and neglects integrated plant-wide architectures that are essential for successful digital transformation and advancement of the overall degree of system automation [36]. Furthermore, research innovations are only rarely validated in operational CST facilities, offering limited insights on the practical benefits and limitations of autonomous operation in solar thermal systems [57]. Thus, there is a clear research gap concerning both the architectural integration of autonomous operation principles to pave the way toward fully autonomous operation and the empirical assessment of their effects on efficiency, cost, and robustness in real CST instead of laboratory environments.

This article addresses this research gap by presenting a holistic architectural concept and evaluation of an autonomous CST plant in a real-world operational CST facility, referred to as the Solar Energy Autopilot (SOLEA). The work synthesizes results achieved through interdisciplinary collaboration at the German Aerospace Center (DLR), culminating in the first demonstration of fully autonomous CST plant operation at the solar power tower (SPT) facility in the German city of Jülich. The study contributes on two levels: (1) it introduces the conceptual and technical architecture of an autonomous CST plant that integrates various innovations from solar research into SOLEA, and (2) it systematically evaluates the performance of the system, exploring both benefits and current limitations of autonomous operation.

These considerations lead to the following research questions, which guide the development, implementation, and evaluation of the SOLEA architecture:

1. How can recent technological advances be synthesized into the holistic SOLEA architecture for autonomous CST plant operation?
2. What degree of autonomy is attained at the operational CST facility through the currently implemented state of the SOLEA architecture?
3. How does the current implementation of autonomous operation at the operational CST facility contribute to improvements in efficiency, robustness, and cost reduction?

The remainder of this article is structured as follows. Section 2 provides the theoretical background on system autonomy and CST plants, while Section 3 summarizes related work on autonomous systems in the CST domain. The methodology used to synthesize the overall architecture and design the evaluation is outlined in Section 4. Section 5 then presents the SOLEA architecture for an autonomous CST plant together with the results of the experimental evaluation. Finally, Sections 6, 7, and 8 discuss limitations, summarize the main findings, and indicate directions for future research.

2. Background

This section presents the theoretical foundations of system autonomy and CST technologies relevant to this study.

2.1. System Autonomy

The concept of system autonomy has received increasing attention across various technical disciplines, yet there is still no universally accepted definition or standard that precisely delineates what constitutes an autonomous system [37]. As a result, interpretations differ significantly between domains such as manufacturing, transportation, or energy systems [23, 48]. Nevertheless, from a high-level perspective, most contributions in the scientific literature commonly describe an autonomous system as one that can achieve its objectives in uncertain or changing environments with minimal or no external intervention [38, 2, 9, 10]. The term 'autonomous', derived from the notion of self-governance, implies a system's capability for independent decision-making, adaptation, and purposeful action with little or no human involvement [38, 56]. In contrast to traditional automated systems where actions follow predefined rules within stable conditions, autonomous systems must perceive, analyze, and interact with their environment, maintaining functionality even under unforeseen disturbances [20].

Autonomy is not an absolute state, but a continuum. Systems typically progress step by step from manual to increasingly autonomous operation, driven by the integration of advanced control, perception, and learning mechanisms [10, 17]. This development has led to the emergence of so-called self-x capabilities, such as self-learning, self-management, or self-adaptation, which collectively describe a system's capacity for self-governed improvement [2]. Because this evolution is gradual rather than binary, researchers have proposed numerous maturity models to describe and assess the degree of system autonomy. These models provide a structured framework to evaluate the extent to which a system has advanced along the autonomy continuum and to identify directions for further development.

Analogously to the well-known SAE taxonomy in the field of automated driving [49], several level-based maturity models categorize autonomy in industrial systems according to degrees of human involvement and system decision-making capabilities [56]. Typically, the lowest level describes fully manual operation without automation, whereas the highest level represents full autonomy, where the machine assumes complete control even under unpredictable conditions. The number of levels defined in such models varies, ranging from 4 to more than 10 levels [56] and their characterization differs due to the absence of unified standards [25]. For example, Gamer et al. [20] define the highest level of autonomy as full independence from human operators in all situations, while Dumitrescu et al. [15] consider autonomy primarily as long-term self-sufficient operation in which occasional human intervention may still be required. In contrast, Vagia et al. [56] emphasize that even highly autonomous systems may require humans to intervene when unanticipated errors occur that fall outside the system's predefined scope.

Beyond level-based models, several researchers have proposed multi-dimensional frameworks to capture the diverse aspects contributing to system autonomy. Such models expand the assessment beyond a single maturity scale by considering different dimensions, for example, autonomy in operation, planning, or maintenance [20]. Other multi-dimensional approaches evaluate different functional aspects that collectively define autonomy, such as human–machine interaction, self-x capabilities, knowledge management, or decision-making mechanisms [37]. This granular perspective is especially valuable for complex systems composed of multiple subsystems that may exhibit varying degrees of autonomy. During transitional phases from manual to fully autonomous operation, certain processes or components may already function autonomously, while others continue to rely on human interaction. Multidimensional maturity models thus support a more precise identification of autonomy gaps and targeted areas for improvement.

In summary, the concept of system autonomy remains ambiguous and lacks standardized criteria for assessment. In general, autonomous systems are characterized by their ability to pursue defined objectives independently in uncertain environments with limited human input. Progress toward autonomy typically unfolds incrementally as technological capabilities evolve, leading to increasingly sophisticated self-x properties. To capture this progression, various single- and multi-dimensional maturity models have been developed, each reflecting different interpretations of autonomy levels and system characteristics. This diversity underscores the current absence of universal definitions for autonomous systems, which hinders consistent assessment and clear communication of system autonomy levels among researchers and practitioners.

2.2. Concentrated Solar Thermal

CST technology harnesses solar radiation to generate high-temperature thermal energy, which can be used for either electricity production or direct heat consumption for industrial or thermochemical processes. A CST plant typically

Figure 1: SPT plant in the German city of Jülich operated as a CST research facility.

consists of thousands of mirrors, known as heliostats, that track the sun and concentrate sunlight onto a receiver. At the receiver, the concentrated solar radiation is absorbed and converted into thermal energy, which is subsequently used for power generation via a thermodynamic cycle or directly supplied to connected industrial facilities or thermochemical reactors for direct heat use. To ensure a stable energy supply even during periods of low or no solar irradiation, CST plants are typically equipped with thermal energy storage systems that allow stored heat to be dispatched when required [59].

Four primary CST technologies are currently in use: parabolic trough, solar power tower (SPT), linear Fresnel reflector, and dish Stirling systems. Among these, SPT technology has emerged as the leading configuration for new plant installations in recent years, accounting for the majority of global CST capacity additions [27]. SPT plants are particularly advantageous for high-temperature operation and integration with large-scale energy storage, making them an important foundation for research on next-generation solar thermal systems.

A prominent example of such a facility in Europe is the SPT plant located in Jülich, Germany (see Fig. 1). In this plant, a heliostat field concentrates sunlight onto a central receiver at the top of a tower, where solar irradiation is focused to achieve temperatures of up to 700 °C. The absorbed heat is then converted into electricity in a conventional steam cycle using a steam turbine generator [42]. The facility is being used by the German Aerospace Center (DLR) as a large-scale research infrastructure in the configuration of a real power plant, allowing experimental validation and further development of CST technologies under realistic operational conditions [13].

Despite its potential, CST still depends on further cost reductions and performance gains to remain competitive with other dispatchable renewable energy sources, such as PV combined with pumped hydro or battery storage [27, 12]. In recent years, research in the CST domain has increasingly emphasized digitization and automation as key enablers of efficiency improvements, operational flexibility, and cost reduction [27, 42, 60]. In line with the broader Industry 4.0 paradigm, technologies such as DTs, cyber-physical systems (CPS), and AI are being referenced as core elements of this digital transformation, although they are only rarely applied in operational facilities [12]. In parallel, an industry stakeholder study by Sandia National Laboratories shows that practitioners of solar thermal plants expect huge potential in automation concepts such as heliostat calibration and monitoring, closed-loop field control, real-time condition monitoring, and analytics for storage and market participation, underlining the practical relevance of advanced automation for CST operation [33]. Nevertheless, there is a substantial gap between technological potential and current practice, highlighted by several studies that describe that digitization and automation in CST are still in an early stage [57, 39].

In summary, CST offers high-temperature renewable energy with integrated thermal storage, but further cost and performance improvements are needed to remain competitive. Digitization and automation, leveraging Industry 4.0 technologies such as DT, CPS, and AI, provide promising means to enhance control, maintenance, and operational efficiency. However, current levels of digitization and automation in operational CST plants are still comparatively limited.

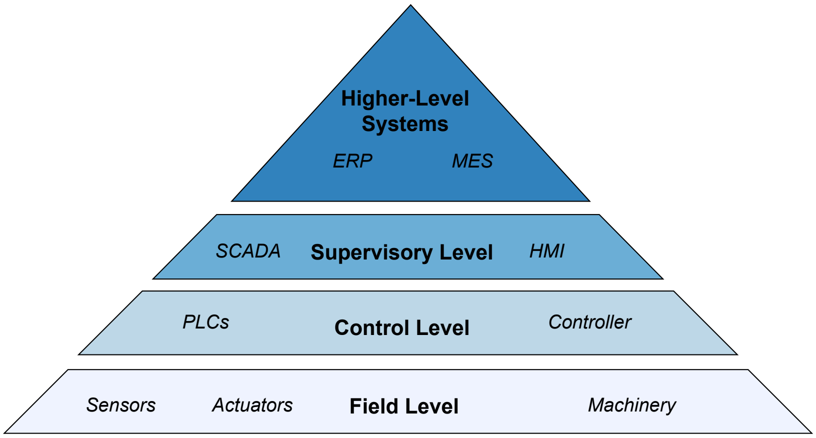

Figure 2: Schematic of the classical automation pyramid architecture of the Jülich CST plant.

3. Related Work

Research related to this study can be grouped into two main strands: holistic system architectures for CST plants that prepare the ground for increasingly autonomous operation, and experiences with autonomous operation of systems and subsystems in real-world CST facilities.

First, only a limited number of studies propose holistic, plant-scale system architectures for CST automation [12, 57, 35]. Most existing work applies recent digital technologies to specific problems such as automated mass-flow control, hardware design of CST systems or subsystems, localized prediction of direct normal irradiance (DNI) in the heliostat field, and forecasting of thermal energy at the receiver [36], without addressing their integration into a coherent architecture for autonomous plant operation [39]. In contrast, the SOLEA concept outlines a modular, end-to-end architecture that spans field devices, middleware, and plant-level automation services and combines real-time plant data, data-driven models, and advanced analytics for planning, monitoring, and control, thus paving the way toward more intelligent and autonomous CST plants.

Second, practical implementations and field demonstrations of autonomous CST systems or subsystems also remain scarce, limiting industrial experience with real-world integration and operation of autonomous functions [39]. Several patents and design studies propose autonomous heliostat concepts that integrate local power supply, embedded control, and wireless communication to reduce field-level infrastructure and supervisory effort [5, 40]. In addition, robotic solutions such as Heliogen's ICARUS system automate heliostat installation, inspection, cleaning, and maintenance tasks in large solar fields, with the goal of reducing labor costs and improving availability [22]. These approaches advance subsystem-level autonomy of the heliostat field, but they typically operate as specialized, loosely coupled subsystems and do not address coordinated, plant-wide autonomy that jointly optimizes receiver, storage, and power-block operation.

In summary, while CST technology offers substantial potential for renewable energy generation, the digital transformation of the field is still in its infancy. Further advances are needed to fully exploit the potential of CST technology. Holistic architectural concepts that close existing automation and digitization gaps and explicitly target coordinated, plant-scale autonomy are still largely missing, which motivates the SOLEA architecture and its experimental validation in an operational CST facility.

4. Methodology

This study makes two main contributions: (1) the development of a comprehensive architecture for an autonomous CST plant and (2) its empirical evaluation with respect to both system autonomy and the associated benefits for the CST domain. The following subsections detail the methodology for each contribution.

4.1. Architecture

The CST plant in the German city of Jülich provides the technological and operational foundation for this study. Constructed in 2009, the facility was originally designed according to the classical automation pyramid architecture (see Fig. 2), a paradigm that is still widely adopted in industrial sectors, including solar thermal plants [12]. This hierarchical structure is organized into three primary control levels representing the Industry 3.0 paradigm. At the field level, sensors, actuators, and physical devices continuously monitor plant components and execute low-level operational commands. The control level hosts programmable logic controllers (PLCs) that acquire data from field devices and execute predefined control algorithms. The supervisory level comprises supervisory control and data acquisition (SCADA) systems, as well as specialized industrial software applications, which allow centralized monitoring and control via human–machine interfaces (HMIs) in a plant control room [4].

In this baseline configuration, the degree of autonomy is minimal. Plant operators manually plan and control operations, handling both the heliostat field and the remaining plant components for power generation in response to real-time environmental conditions. Although certain safety systems such as a protection PLC for monitoring receiver temperature thresholds, automated plant shutdown in case of excessive wind, or automated calibration procedures provide limited automation capabilities, all critical plant operations including start-up, aim point and process control, and shutdown require active human decision-making and control. Operators rely on continuous observation of measurement systems, including cloud camera, DNI sensors, and wind-speed meters, to optimize performance within safe operational limits to prevent equipment damage or unplanned shutdowns. This makes operating a CST plant a demanding task, where efficiency heavily depends on personnel skills, and continuous manual efforts drive up operational costs.

Building on this reference architecture, DLR pursued a long-term research initiative spanning seven years to evolve the classical hierarchical structure toward autonomous operation. The project integrated a series of innovations across multiple subdomains of solar research, each contributing specific functionalities required for optimized autonomous system behavior. Individual research groups advanced technologies in areas such as flux density measurement, intelligent process automation, big data management, and DNI prediction modeling. The cumulative results of these subprojects were integrated into a holistic system architecture, termed the SOLEA, which serves as the main contribution of this article and provides the structural framework into which the individual research innovations are embedded. The SOLEA concept extends traditional automation by incorporating intelligent decision-making, adaptive control, and advanced coordination mechanisms, and defines the conceptual and technical architecture for autonomous CST plant operation (see Section 5.1). From a methodological perspective, the SOLEA architecture has been derived in an iterative design process that combined requirements analysis, expert workshops, and the integration of prior research prototypes from a holistic system architecture perspective. The design objectives were to increase the degree of autonomy, optimize operational complexity and improve efficiency, robustness and costs by systematically leveraging recent research innovations. The resulting architecture has been implemented at the Jülich SPT plant and evaluated in field experiments as described in the next subsection.

In summary, the Jülich CST plant initially has a low level of autonomy based on the classical automation pyramid architecture, requiring manual planning and control of all critical operations. The SOLEA concept builds on this baseline by integrating multiple research innovations into a holistic autonomous system architecture that was subsequently designed, implemented and evaluated at the Jülich SPT plant.

4.2. Evaluation

The second objective is to systematically quantify the effects of the architecture and implementation of the autonomous CST plant. The evaluation methodology follows a dual-sided approach, assessing both (1) the benefits of autonomy for CST operation and (2) the degree of system autonomy achieved by the currently implemented version of the SOLEA. Through this twofold evaluation strategy, the study provides both quantitative and qualitative evidence of how system autonomy contributes to technological progress in the CST domain and highlights areas where further research is necessary to advance toward full autonomous operation.

To quantify the impact of system autonomy on CST performance, an extensive experimental evaluation was conducted at the Jülich facility during the third quarter of 2025. Over a total of 30 hours of operation over 5 operating days, the autonomous CST plant was tested under real-world conditions encompassing three weather categories — clear sky, sunny, and cloudy — and multiple target receiver temperature setpoints ranging from 300 °C to 550 °C depending on environmental conditions. Fig. 10 in the appendix provides an overview of the details of the test days, their duration, and the challenging environmental dynamics in the experiments.

ID	Name	Description	Metric	Unit	Study Goal
M1	Availability	Fraction of time SOLEA software services and infrastructure are operational and ready to execute control tasks without failure during autonomous plant operation	SOLEA uptime / autonomous operation time	Percent	Robustness
M2	Forced Outage Rate	Fraction of unplanned outage hours of the physical plant caused by automated shutdowns during autonomous operation relative to total autonomous operation hours	Forced outage time / autonomous operation time	Percent	Robustness
M3	Focal Spot Recognition	Relative mean pixel deviation between the focal spot extracted by the UNet-based optical measurement service and its ground truth	Relative mean pixel deviation according to [30]	Percent	Robustness
M4	Manual Effort Reduction	Time savings in human operation effort due to autonomous planning and control compared to the manual baseline scenario	Saved manual operation time / baseline manual operation time	Percent	Costs
M5	Autonomous operation time	Proportion of autonomous to manual operation on an operating day, indicating the extent to which plant operation can be performed without human intervention	Autonomous operation time / daily operation time	Percent	Costs
M6	Operational Profit Gains	Increase in daily operating profit achieved by optimized operation planning of the operation management agent compared to manual reference control strategies	Profit (optimized operation plan) / profit (reference strategy)	Percent	Costs
M7	Investment costs	Reduction in communication infrastructure investment costs by using a wireless 5G-based field communication system instead of a conventional wired solution	CAPEX (wireless) / CAPEX (wired)	Percent	Costs
M8	UAV Coarse Calibration Accuracy	Average tracking accuracy of heliostat target aim points achieved by real-time UAV-based coarse calibration and tracking outlier correction during operation	Mean tracking error	mrad	Efficiency
M9	UAV Fine Calibration Accuracy	Average tracking accuracy of heliostat target aim points achieved by UAV-based fine calibration during field commissioning	Mean tracking error	mrad	Efficiency
M10	Real-time Data	Improvement in operational efficiency enabled by real-time data via the CPS middleware platform	Latency	ms	Efficiency

Table 1
Key figures summarizing the benefits of autonomous CST plant operation for cost, efficiency and robustness.

The first part of the evaluation focuses on three primary performance dimensions that reflect the key advantages expected from system autonomy: efficiency, robustness, and cost. For each dimension, a set of quantitative metrics was defined at both component and system level, as summarized in Table 1 and further detailed in Section 5.2.1. During experiments at the Jülich SPT plant, these metrics were measured and recorded values were compared against the baseline scenario and state-of-the-art CST control practices. In general, the metrics draw on two types of evidence: (i)

Level	Level Name	Level Description
AL1	Factory without Autonomy	The systems rely on operator actions and decisions, and general systems are not connected together or have any centralized control other than the operator.
AL2	Basic Automated Factory	The inclusion of centralized control in connected systems allows for improved levels of automation and some context-aware features. Human operators are still needed to intervene for many tasks.
AL3	Adaptable Factory	Introduces self-adaptable behaviors and predictive features to meet unpredictable events. Human operators receive suggestions for optimized activities, but the main system tasks are still under human control, either directly or via a centralized control system. Collected data is continuously monitored and automatically shared between all connected systems.
AL4	Semi-Autonomous Factory	The system defines its own course of action based on high levels of context-awareness, within established boundaries. Human operators work cooperatively with the system. Even if the system is able to analyze its environment for "business as usual" execution, system goals and the response to major disturbances are still monitored by humans.
AL5	Fully Autonomous Factory	The system is fully self-adaptable to uncertain or unforeseen inputs, enabled by advanced self-learning capabilities. The system is able to choose the best option to meet common goals for connected manufacturing systems without human intervention, even in the face of new and unforeseen challenges.

Table 2
Five-level model of Mo et al. [37] to describe and characterize the degree of system autonomy.

measurements collected during the 30-hour experimental campaign with fully autonomous operation under varied weather conditions and (ii) dedicated experiments and data sets from previous and subsequent campaigns at the same facility, in which individual SOLEA building blocks were evaluated in isolation against reference concepts. The 30-hour campaign mainly serves to validate plant-wide autonomous operation and to quantify integrated performance effects, while the additional experiments provide more focused assessments of specific components such as flux prediction, operation planning, or wireless communication. Rather than reassessing each underlying method separately, the evaluation uses quantitative results from original studies to show how the SOLEA building blocks provide benefits in specific task domains and, taken together, translate into improvements in overall plant performance.

The second part of the evaluation assesses the autonomy level of the CST plant using a multi-dimensional framework from recent literature [37]. The framework of Mo et al. enables a structured assessment of autonomy across different functional areas, including (1) data management, (2) process automation, (3) human interactions, (4) system infrastructure, (5) self-x capabilities, and (6) measurement performance. The underlying assumption is that higher maturity of individual features such as structured and integrated data, predictive optimization, or collaborative human–machine interaction enables higher system-level autonomy. Thus, each feature is graded on a discrete maturity scale and then related to one of five autonomous levels (AL), starting with a factory without autonomy at the first level up to fully autonomous factory at the highest level (see Table 2). In the end the results for each feature are synthesized into an overall autonomy level for the entire system. Both the initial classical automation architecture of the plant and the SOLEA implementation of the autonomous CST concept were evaluated according to this model. The results allow a comparative analysis of achieved autonomy levels, identification of gaps, and discussion of future improvement potential.

Overall, this evaluation quantifies autonomous CST's operational advantages in effectiveness, robustness, and cost efficiency across varied real-world conditions at Jülich and assesses its system autonomy level through a multi-dimensional framework. The experimental results in an operational CST facility provide concrete evidence of technological advancements over baseline practices while identifying targeted gaps for future development toward full autonomy. These findings establish a robust foundation for advancing autonomous concepts in CST systems and comparable industrial facilities that still rely on conventional Industry 3.0 automation paradigms.

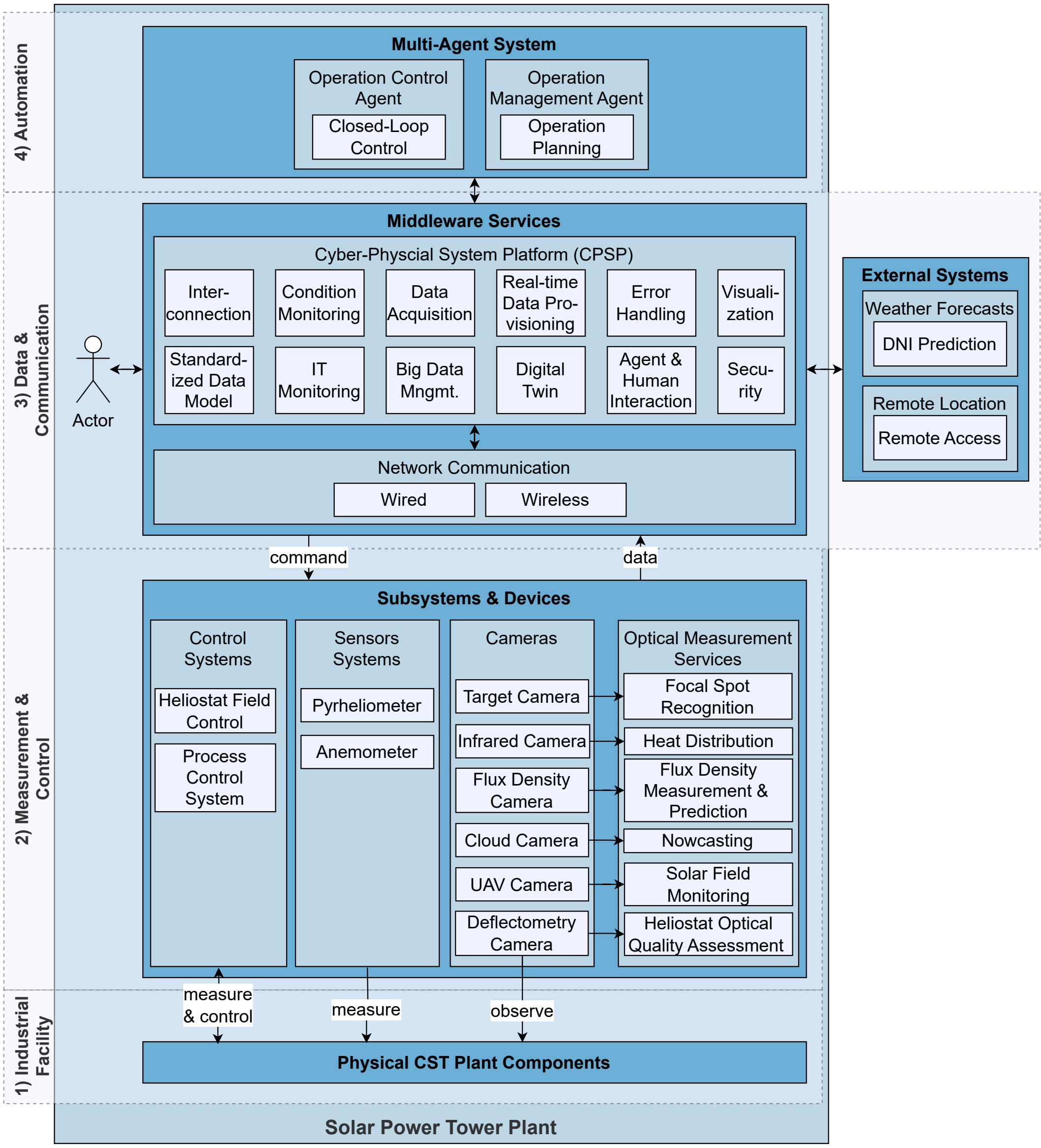

Figure 3: Four-layer architecture of the autonomous CST plant, comprising (1) industrial facility, (2) measurement and control, (3) data and communication, and (4) automation layers.

5. Results

This section details the results, beginning with the autonomous CST architecture and continuing with the dual-sided evaluation outcomes.

5.1. Architecture

The SOLEA concept is implemented as a four-layer architecture that spans from the physical plant to intelligent automation agents (see Fig. 3). While some layers and subsystems are built on state-of-the-art technologies, additional innovative infrastructure and software solutions have been integrated as the foundation for autonomous plant operation.

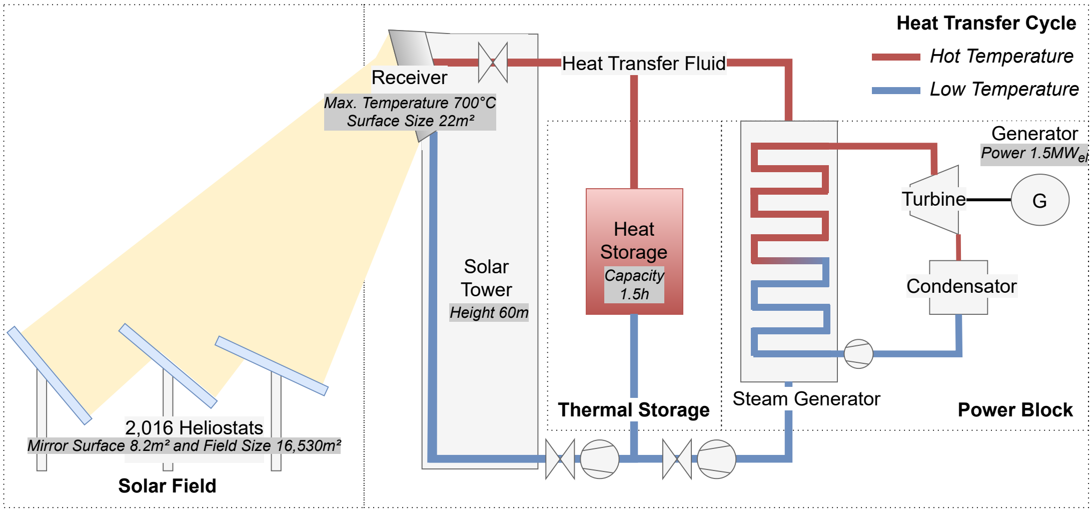

Figure 4: Schematic of the physical components and electricity-generation process of the Jülich CST plant (Layer 1).

The following subsections detail each layer of the SOLEA architecture, comprising (1) industrial facility, (2) measurement and control systems, (3) data and communication, and (4) automation.

5.1.1. Industrial Facility

The industrial facility layer encompasses all physical system components of the CST plant, including the heliostat field, receiver, thermal storage, and power block as described in Section 2.2. This layer provides the physical basis for autonomous operation on which higher levels of measurement, control, data, communication, and automation services are built.

As shown in Fig. 4, the Jülich facility features 2,016 dual-axis heliostats, each with a mirror surface of 8.2 m^2, forming a heliostat field spanning 16,530 m^2. Furthermore, the plant is made up of an open volumetric air receiver at the top of the solar tower with a surface size of 22 m^2 that can heat air up to 700 °C, a packed bed heat storage made of ceramic bricks with a with a capacity of 1.5 hours of operation and a common steam turbine generator for the thermodynamic conversion of heat into electrical energy with a power output of 1.5 MW. Compared with commercial CST tower plants for electricity production, which can employ from a few thousand to more than 100,000 heliostats, exceeding 100 MW of electrical output, and use thermal storage to enable 24-h power generation [54], the setup in Jülich is a small-scale facility that demonstrates real-world CST plants at a relevant size for research purposes [21].

While the downstream components behind the receiver follow established power plant technology, significant research and development activities focus on improving the CST-specific subsystems, particularly the solar field, receiver technologies, and heat storage system. Compared to the initial hardware setup which has been build in 2009, several optimizations have been applied at the solar field of the SPT plant in Jülich. Thereby, heliostats have been retrofitted with optimized linear actuators, modified kinematics, and four mirror facets instead of a single one to improve optical quality, tracking accuracy and robustness of the heliostat design. Results from [21] show that these changes improved the optical performance of the heliostat focal spots and their tracking accuracy from about 5 mrad to less than 2 mrad average pointing error comparing the deviation of the center of the sunreflection at the target area to the desired aim point. Furthermore, the return air system of the main receiver was upgraded with nozzle boxes at the sides and bottom of the absorber area to rise the return air ratio and reduce pump losses of the air blowers due to lower differential pressures in the system. The remaining components installed at the SPT plant in Jülich rely on the hardware installed in 2009 and have not been substantially modified. Nevertheless, considerable research progress has been achieved on diverse CST hardware improvements, which are outlined in Section 8 as an outlook on how optimized hardware in the industrial facility layer can further enhance plant operation.

In summary, the industrial facility layer comprises the physical assets of the CST plant, including the heliostat field, receiver, thermal storage, and power block. The Jülich facility operates as a small-scale research platform that demonstrates commercial CST plants and enables the ongoing development of solar field, receiver, and storage

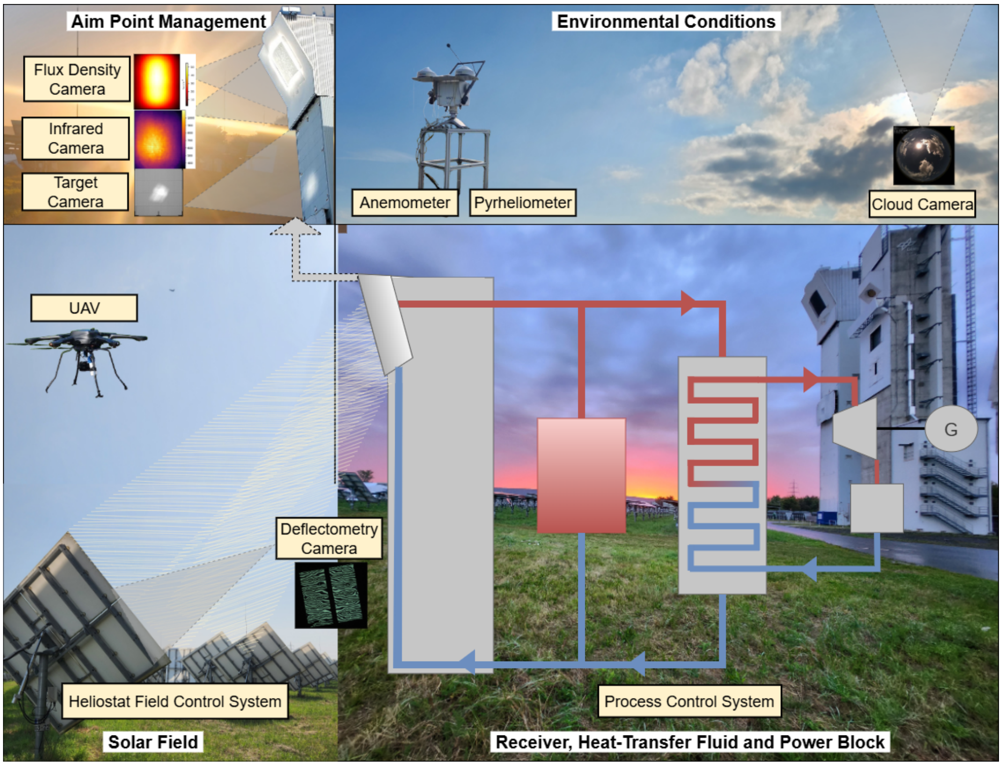

Figure 5: Overview of measurement and control systems at the Jülich CST plant (Layer 2).

technologies under real operating conditions. For this study, the receiver and heliostat field have been retrofitted to improve optical and thermal performance, while the heat storage and power block correspond to the original 2009 configuration.

5.1.2. Measurement and Control Systems

The measurement and control systems layer includes all control and measurement systems required to monitor the environment and CST plant components and regulate the heat generation process accordingly. As illustrated in Fig. 3 these can be logically grouped into (1) control systems, (2) sensor systems, (3) cameras, and (4) optical measurement services that derive information from camera footage. Fig. 5 gives an overview of the measurement and control systems that are installed at the Jülich SPT plant.

First, two main control systems are used in the Jülich facility following industrial state-of-the-art approaches: a dedicated heliostat field control system and an industrial SCADA-based process control system for the receiver, heat transfer cycle and power block. The latter is realized using a conventional Siemens process control system. The heliostat field is controlled by the HeliOS software, a modular control system developed by DLR, which moves the mirrors in the field and executes basic automation functions such as updating heliostat motor positions with the sun's motion and performing continuous heliostat calibration using the state-of-the-art camera-target method [21].

In the baseline scenario both control systems provide a human machine interface (HMI) which allows the operator to control the heliostat field and the thermal-conversion-process according to the phase of operation and possibly changing environmental conditions. In the baseline scenario, all processes in the plant, besides some basic automation procedures described above, are manually controlled by the operator. This encompasses starting the plant components, controlling the thermal conversion process to provide stable heat despite environmental dynamics, and shutting down the plant at the end of the operating day, as well as planning of basic decisions for optimized operation such as defining the operation schedule, setting target parameters for process control, and choosing an operating strategy with respect to storage loading and heat generation for subsequent electricity production.

As part of the autonomous CST plant initiative, the heliostat control software has been further developed to support reliable monitoring and control of heliostat fields by higher-level software services over a ZeroMQ-based interface for automated control. Furthermore, an additional optical measurement service has been integrated into the control software to improve the accuracy of the camera-target calibration procedure through intelligent focal spot recognition, as described later in this chapter when discussing optical measurement services installed in Jülich.

Second, the plant is equipped with several sensor systems for both meteorological and process condition monitoring. Meteorological monitoring is provided in particular by sensors measuring DNI and wind speed to enable regulation of plant operation according to target temperatures and ensure adherence to safety constraints, such as initiating shutdowns under excessive wind conditions. The DNI is continuously recorded using Kipp & Zonen SOLYS sun trackers equipped with CHP1 pyrheliometers, which are classified as first-class instruments with an expected measurement uncertainty of about 2% for hourly totals under typical operating conditions [28]. Wind speed is measured with Thies Clima First Class cup anemometers, which provide both frequency and analog output with a specified measurement uncertainty below 2% in the range 0.3–50 m/s [1]. Multiple weather-related sensor stations are distributed across the solar field and on top of the solar tower to provide spatially resolved environmental data. In addition, the control systems for the solar field and the CST plant supply up-to-date process information through standardized interfaces, including set points of mechanical subsystems, temperature measurements, and possible component alerts.

Third, optical measurement systems play a crucial role in the CST domain, capturing information beyond the capabilities of conventional sensors, such as the spatial distribution of solar flux on the receiver, cloud-induced shading of the solar field, and heliostat tracking accuracy. At the Jülich SPT facility, five types of camera systems are deployed for these purposes. The first is a calibration camera, used for improved heliostat alignment and calibration procedures based on the camera-target method. The second and third cameras are a flux-density and an infrared camera, which capture images of the receiver surface to determine the energy and heat distribution for heliostat aim-point optimization. The fourth is a deflectometry camera, which captures the reflection of stripe patterns projected onto heliostats for surface slope and optical quality determination. The fifth is an all-sky imager (ASI) that monitors cloud movements to predict local variations in DNI, enabling proactive heliostat focusing or de-focusing for smoother temperature transitions, material protection, and stable thermal operation. This supports safe and efficient management of solar flux and heat distribution by maximizing thermal input, compensating for environmental fluctuations, and preventing hot spots that could reduce receiver lifetime.

Fourth, as part of the autonomous plant initiative, several optical measurement services have been implemented at the Jülich SPT facility to analyze camera footage and extract actionable information. Heliostat mirror and concentrator shapes can be measured by deflectometry using the automated QDec system [55, 11]. The deflectometry camera captures reflected stripe pattern distortions from a field projector to generate high-resolution surface slope maps, enabling fully automated optical quality assessment of large heliostat fields in one night. These measurements serve as a ground-truth baseline for other SOLEA building blocks and beyond, including optical performance assessment in the industrial facility layer (see Section 5.1.1), training deep learning models for heliostat surface prediction [32], and validating intelligent services such as UNet-based focal spot recognition [30]. Next, HeliOS utilizes calibration camera images and an optical measurement service to calibrate heliostats using the camera-target method as described above. The optical measurement service implements the just referenced UNet-based beam characterization of Kuhl et al. [30], which separates the focal spot from the background while compensating for varying irradiation, target irregularities, and non-uniform reflectivity. This enables a robust and precise identification of focal spot shape and centroid for automated heliostat calibration.

Other optical measurement services are used to monitor heat and energy distribution on the receiver based on the infrared and flux density camera. To determine the temperature distribution on the receiver, a long-wave (7.5–14 μm) infrared camera with a 60 mm telephoto lens is used and parametrized with environment-, receiver-, and measurement-specific information such as average humidity and outside temperature, receiver emissivity, and camera–receiver distance. Subsequent digital signal processing converts camera signals into surface temperature maps by accounting for emissivity, reflectance, and atmospheric transmittance similar to the method described in Weber et al. [58], with the difference that receiver emissivity has been determined in a dedicated calibration campaign at the Cologne high-flux solar furnace [41]. To evaluate flux density distributions from camera images, SOLEA uses the patented optical scan method of Offergeld et al. [45, 46]. This method measures the solar radiation that is directly reflected on the receiver surface by first characterizing the direction-dependent reflection behavior for 16 heliostat groups. Each flux-density image is then evaluated together with the experiment-specific irradiation state of these clusters. The fractional intensity of each cluster is computed using the STRAL ray-tracing software [6] and used to weight the static reflection behavior of the corresponding field group. This enables live flux-density measurements without time-consuming cluster-defocus images, because simulated tracking errors replace real tracking errors that would otherwise be derived from differential images [44]. For receivers equipped with radiometers, the average radiometer signal is used to calibrate the gray-value image, already corrected for reflection and intensity, into a local flux-density map using 32 correction matrices. In the case of the SPT Jülich receiver, a specific camera-calibration series links receiver images to STRAL-simulated power, and regression slopes at several times of day are used to determine the experiment-specific calibration factor. Because the captured reflection properties remain stable over long periods of operation, new scans and evaluations are needed only after several years or major receiver modifications.

To monitor cloud-induced shading of the solar field and its effects on available DNI, a nowcasting system ingests real-time ASI images and concurrent DNI measurements to generate short-term irradiance nowcasts up to 20 min ahead using a transformer-based deep learning model. This model follows the approach of Fabel et al. [18], which learns spatio-temporal cloud patterns from image sequences and irradiance history. The approach demonstrates a positive skill score throughout the entire horizon and outperforms state-of-the-art physics-based methods, enabling proactive control strategies that maintain target temperatures under rapidly changing cloud conditions.

In addition to stationary optical sensors, unmanned aerial vehicles (UAVs) provide a flexible and scalable option for field-level monitoring and calibration. Equipped with high-precision cameras and connected via wireless networks such as the 5G campus infrastructure (see Section 5.1.3), UAV-based optical measurement services have been tested at the Jülich SPT facility. Two main application areas have been demonstrated: (1) heliostat coarse and fine calibration, which can accelerate commissioning by enabling group-wise rather than sequential adjustments and reduce setup times for large-scale plants from several months to only a few days [26]; and (2) heliostat field monitoring during operation, for example, to detect mirror defects, soiling, or abnormal heliostat orientations, thereby reducing costly and time-consuming manual inspections of large heliostat fields [8]. In this context, purely data-driven deep-learning models trained on synthetic data detect heliostats and mirror edges and classify their condition, providing a baseline for both use cases [7]. Built on this deep learning approach, the Airborne Real-Time Solar Concentrator Orientation Estimation Calibration (ARTSCORE-C) enables real-time coarse calibration and orientation estimation with dynamic flight-path adjustment to rapidly identify outliers and abnormal heliostat orientations in large-scale solar fields [50]. When heliostat outliers are detected, ARTSCORE-C can be combined with subsequent fine-grained calibration methods, such as the HeliOS camera-target method or the UAV-based HelioPoint fine calibration [29], to achieve tracking accuracy below 1 mrad for efficient operation [8]. This approach was developed using a high-fidelity simulation environment that models UAV dynamics, sensor behavior, and communication links, enabling safe and cost-effective development and testing without extensive field campaigns [51]. Overall, UAV-based optical measurement systems are a promising complement to faster calibration procedures and automated, adaptive, scalable condition monitoring of large heliostat fields.

In summary, the measurement and control layer comprises the conventional control systems, distributed meteorological and process sensors, multiple camera systems, and a suite of optical measurement services that together provide the data foundation for CST plant operation and monitoring. In the baseline configuration, these systems mainly support manual operation via HMIs with only basic automation, whereas the autonomous CST concept extends them with standardized ZeroMQ-based interfaces for higher-level automated control, intelligent camera-target calibration based on focal spot recognition, infrared- and flux-based services for real-time heat and flux density monitoring, transformer-based nowcasting using all-sky images and DNI measurements, and UAV-based services for heliostat calibration and condition monitoring of the solar field.

5.1.3. *Data and Communication*

The data and communication layer forms the backbone of the autonomous CST architecture by providing middleware services. Its purpose is to seamlessly interconnect heterogeneous measurement and control systems with higher-level automation services and data analysis applications.

Basically, communication between plant components and the middleware is established via wired Ethernet connections and wireless LAN (WLAN) as state-of-the-art methodology. Additionally, an experimental 5G campus network has been installed at the Jülich solar tower to potentially reduce costs and to demonstrate the integration of heliostat communication with other (mobile) network participants such as camera-carrying UAVs, mobile operators with hand-held data devices, meteo data measurement stations or autonomous robots, as described by Schwarzbözl et al. [52]. They developed a concept for wirelessly operated heliostats with respect to both data and power and validated their concept in a large test campaign in 2024. Selected heliostats were retrofitted with PV/battery power

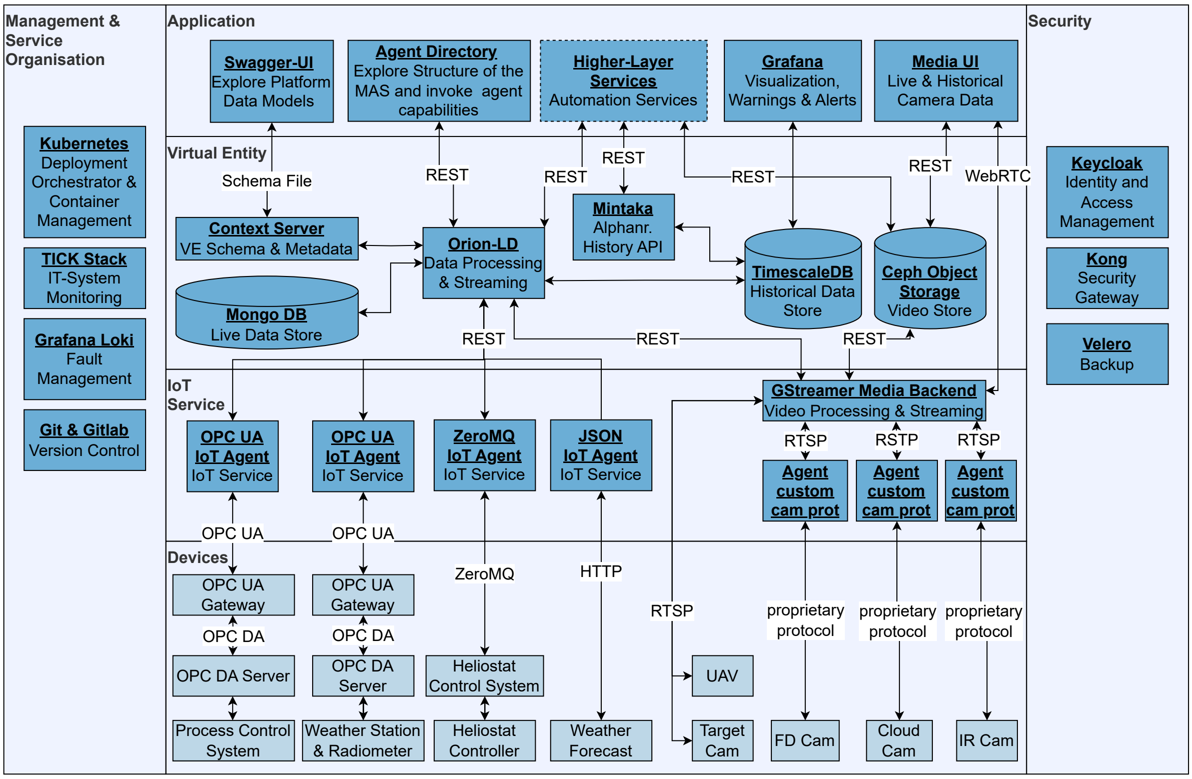

Figure 6: CPS middleware platform that interconnects systems, manages heterogeneous data sources and provides core services for data-driven and automated operation (Layer 3).

supply and 5G modules and integrated into a local private 5G network that was interconnected with the heliostat control system. In addition to heliostats, further devices such as a calibration camera, a tablet, a drone, and a weather station were integrated into the 5G network to investigate whether 5G can provide an alternative reliable and real-time communication platform for CST plants.

On top of this communication infrastructure, a CPS middleware platform has been introduced to integrate heterogeneous devices, consolidate data management, and provide basic services for plant automation, as illustrated in Fig. 6. The platform connects to all relevant measurement and control systems, continuously collects their data and stores them in a standardized DT of the plant as a baseline for advanced automation and transparent condition monitoring [35]. Compared to the baseline scenario, which uses manufacturer-specific control systems with limited automation processes and distributed data that are individually managed in data silos, the DT infrastructure consolidates data, enriches it with metadata, and provides uniform machine-readable and graphical interfaces for monitoring and controlling plant components by higher-level automation services and human operators. Services for higher-level automation software include, but are not limited to, application programming interfaces (APIs) for live and historical alphanumerical data access, streaming services to access camera footage, or infrastructure monitoring services. Human operators profit from services that support visualization dashboards, alerting capabilities based on flexible condition monitoring rules, and rich metadata, which improve the understandability of system structures. In general, the CPS middleware platform is supposed to transform the traditional hierarchical automation pyramid into a decentralized, data-centric CPS which acts as a bridge between distributed and heterogeneous measurement and control systems, human operators, and higher-level automation services.

Technically, the CPS middleware platform follows a microservice architecture that decomposes the overall functionality into loosely coupled services. This design enables a modular and extensible platform that can be flexibly deployed on-premise, in cloud environments, or as a hybrid deployment model. The services are containerized and deployed on a Kubernetes-orchestrated server cluster currently consisting of five nodes, which provides high availability, horizontal scalability, and optimized performance through replication, load balancing, and automatic rescheduling in case of node or container failures. As a result, the middleware platform can reliably handle industrial big data workloads originating from real-time measurement and control systems.

To enable transparent monitoring of agent-based process execution and seamless collaboration between agents and between agents and humans for end-to-end process automation, the CPS middleware platform extends the DT of the CST plant beyond a virtual representation of physical components by also modeling software assets as described in the study of Miadowicz et al. [34]. Thereby, the capabilities, skills, interfaces, and runtime states of all agents in the automation layer are virtually represented in a standardized DT and are exposed by the CPS middleware platform via machine-readable interfaces for agents and graphical interfaces for operators to smoothly interconnect agents and humans. On this basis, agents and humans can monitor agent-based process execution and either discover and directly invoke agent capabilities in a peer-to-peer manner or collaborate indirectly through event-driven patterns, where data persisted in the DT automatically triggers agent actions on specific conditions based on subscription mechanisms, or alerting mechanisms proactively inform human operators when interventions are required. Supporting these interaction patterns, the CPS middleware layer enables flexible composition and reconfiguration of automation services, reduces integration effort when introducing new agents or changing processes, and strengthens transparency of agent-based process execution in the CST plant.

The initial CST plant relies on sensible classical automation systems that lack up-to-date security concepts, so that the plant is operated in an offline environment which is not connected with the internet. Compared to the baseline scenario, the CPS middleware platform provides rich security concepts and up-to-date open-source software components that allow to integrate the middleware layer with the internet. The security mechanisms include, but are not limited to, an identity provider and API gateway which provide capabilities for centralized authentication, authorization, rate-limiting, and audit logging. Employing an orchestrated and containerized deployment of the microservice architecture, this approach allows to isolate the services and provide secured access to the infrastructure to ensure confidentiality, availability, and integrity of data and functions. The enhanced security mechanisms, allow the consumption of online sources and remote access to data and services for monitoring and control. As part of the study, publicly available forecast data from national meteorological services have been integrated into the DT as a baseline for optimized operation planning by intelligent agents from the automation layer.

Together, the communication infrastructure and the CPS middleware platform establish a cohesive data and communication backbone that virtualizes the CST plant, standardizes access to process and context data, and exposes rich services to agents and human operators. This architecture replaces isolated, vendor-specific control systems with a unified cyber-physical platform that supports flexible automation, transparent agent-based process execution, and secure integration of external data sources such as weather forecasts as well as remote access, thereby providing the technical basis for advanced autonomous operation of the CST plant.

5.1.4. Automation

The automation layer is responsible for automating power plant processes and coordinating intelligent decision-making across the CST plant. It is structured as a multi-agent system (MAS) in which dedicated software agents assume responsibility for specific tasks and cooperate with each other and with human operators to operate the plant safely and efficiently. Thereby, the agent-based automation operates at a supervisory level and interacts with existing SCADA and PLC control loops via setpoints and commands, without replacing the local control algorithms of individual subsystems. The automation layer is supported by the data and communication layer, which provides live data from measurement systems and unified access to control systems. Additionally, the CPS middleware platform virtually represents the MAS to allow transparent monitoring of agent-based process execution and flexible collaboration among agents and humans (see Section 5.1.3).

In the current implementation of the SOLEA, two automation agents are deployed. The operation management agent uses weather forecasts, real-time meteorological measurements, current plant states, and electricity market prices to parameterize a simplified CST plant model. Its objective is to compute a cost-optimized operating schedule specifying start and stop times, strategic decisions regarding power generation versus storage charging, and target operating parameters. The agent supports two modes of use: in manual mode, it acts as a recommendation system that provides data-driven operation plans to the operator via the CPS middleware platform; in autonomous mode, it directly triggers the execution of the optimized schedule by actively delegating tasks to the operation control agent.

The operation control agent acts as a supervisory control layer that orchestrates multiple plant actuators to robustly achieve desired heat transfer fluid (HTF) operating conditions under fluctuating environmental conditions. Target operating points for receiver outlet temperature and HTF mass flow are provided by the operation management agent, while the operation control agent itself executes the autonomous control actions. To this end, it manipulates three main actuators: (1) HTF mass flow rate, (2) solar power delivered to the receiver via the number of focused heliostats, and (3) the aim point distribution on the receiver surface. Measured data from meteorological sensors, plant instrumentation, and optical systems are continuously processed in a state-machine-based supervisory layer that determines the current plant state and the appropriate control actions. The state machine covers the main phases of CST operation, including heat-up, stabilization, nominal operation, and transient operation during disturbances such as cloud passages, and switches between them based on receiver outlet temperature and other process indicators. For thermal control, the agent uses an adaptive receiver performance map that models the relationship between incident solar power, HTF mass flow, and receiver outlet temperature and is continuously re-calibrated during operation. The solar power input is adjusted by focusing or defocusing heliostats, while the HTF mass flow is regulated by a subordinate controller to keep the outlet temperature within the desired range. For optical control, a machine-learning-based model characterizes the focal spot of each heliostat as a function of mirror deformation, sun position, and actuator and axis geometry [31]. Based on this model, the agent periodically optimizes the aim point distribution to obtain a smooth, efficient flux profile that minimizes spillage losses and avoids local hotspots, thereby improving receiver efficiency and protecting components.

Fig. 7 shows the composition and interaction of the two agents throughout an autonomous operation day. The operation management agent periodically generates an optimized operation plan and invokes the capabilities of the operation control agent to execute it. In particular, it calls the 'Adapt Target Parameter' capability to set the desired target temperature and mass flow according to the current environmental conditions. Furthermore, it invokes the 'Start Operation' capability when the optimized start time is reached, prompting the operation control agent to start the plant and operate it using the configured target parameters. When the optimized stop time is reached, the operation management agent triggers the 'Stop Operation' capability so that the operation control agent gradually cools down the components and shuts down the plant. Throughout agent-based process execution, both agents continuously update their virtual representations in the DT, enabling other agents and human operators to transparently monitor operation via machine-readable API or the visualization services of the CPS middleware platform. If an error occurs during agent-based process execution, it is likewise reflected in the DT, and human operators or other agents are proactively alerted so that they get automatically notified in case intervention is necessary. Fig. 11, 12, 13, and 14 in the appendix illustrate example agent-monitoring dashboards and alerting mechanisms used in the SOLEA.

Currently, the operation management and operation control agent provide capabilities for autonomous planning of operating days and control of the CST plant. The modular and flexible MAS design in the automation layer allows additional agents to be integrated with little effort, extending the SOLEA concept to further use cases such as automated handling of unexpected shutdowns or maintenance tasks. Based on the DT approach, each agent registers itself with the DT during deployment or redeployment and continuously updates its runtime data so that the virtual representation remains synchronized with the actual system state. Once registered, new agents can invoke the capabilities of other agents and can themselves be discovered and used by both other agents and human operators to execute tasks. Although the first two agents were interconnected in a peer-to-peer manner for the experiments, an alternative integration using event-driven patterns from the CPS middleware platform is also possible. In this case, subscriptions are configured on data streams, and occurring events automatically trigger notifications that invoke specific agent capabilities. For example, the operation management agent could alternatively store the operation plan in the CPS middleware platform, and subscription mechanisms could then automatically invoke the capabilities of the operation control agent instead of invoking the capabilities directly as described in [34].

In summary, the automation layer of the autonomous CST architecture enables intelligent process control and decision-making through a modular MAS. The operation management and operation control agents collaborate to autonomously operate the heat generation process while optimizing plant performance. The management agent generates optimized operation schedules and invokes the capabilities of the operation control agent to start up, operate, and shut down the plant over an entire operation day. The control agent executes these capabilities by processing diverse sensor inputs and adjusting heliostat and plant systems to meet heat generation targets. Owing to its flexible, agent-based architecture, the automation layer can be extended with additional agents for tasks such as maintenance or fault handling, enhancing the system's adaptability and autonomy beyond its current state.

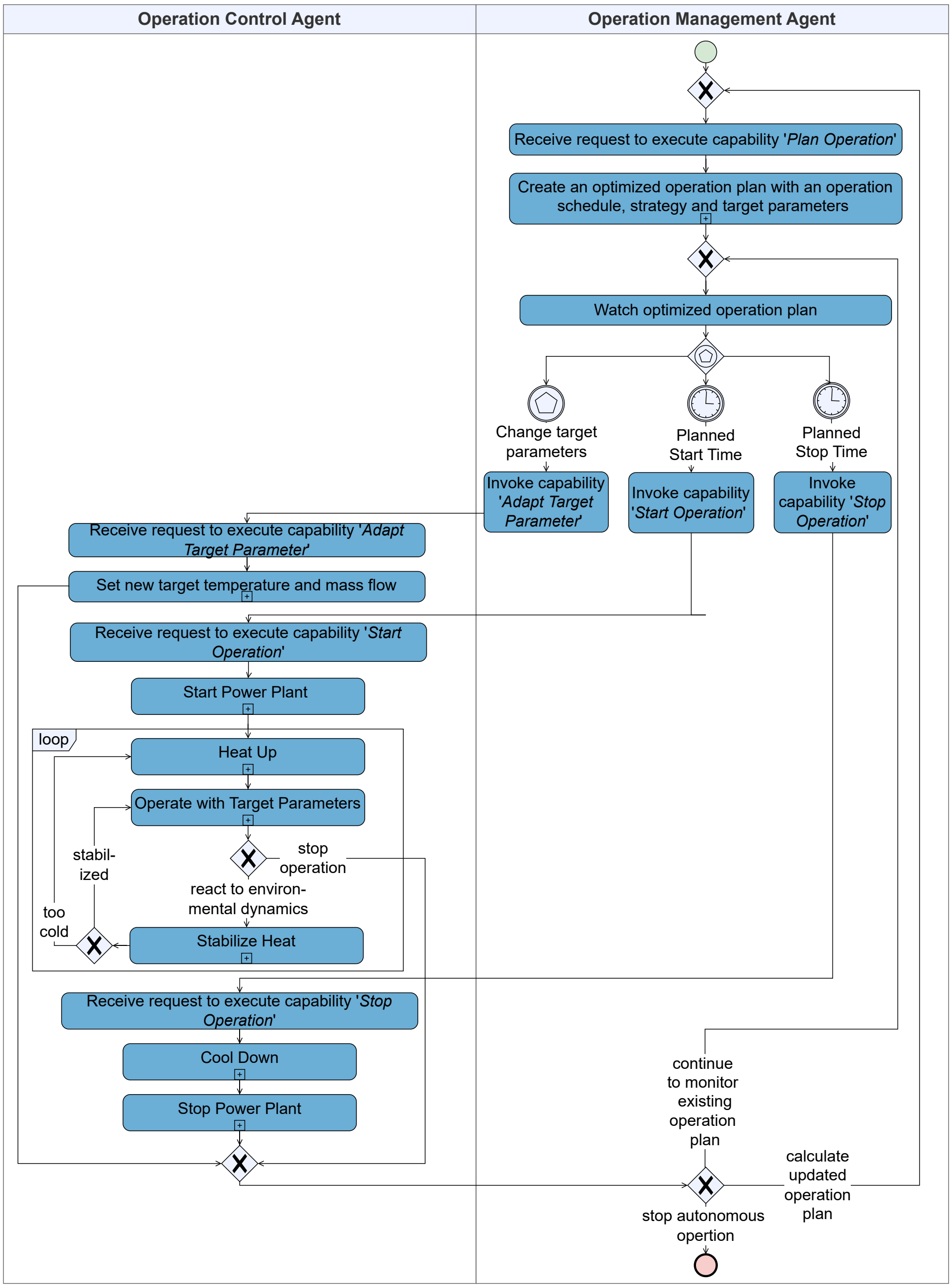

Figure 7: Composition of automation agents for operation planning and control (Layer 4).

5.2. Evaluation

This chapter presents the evaluation of the autonomous CST concept along two complementary perspectives. First, Subsection 5.2.1 quantitatively assesses how autonomous operation affects key performance dimensions of CST plant operation under real operating conditions. Second, subsection 5.2.2 analyzes the autonomy level achieved by the implemented architecture using a structured autonomy maturity framework, identifying strengths, limitations, and remaining gaps toward fully autonomous CST plant operation.

5.2.1. Benefits for CST operation

As outlined in the methodology Section 4, the first part of the evaluation is concerned with assessing the advantages of autonomous operation for the CST domain. In this context, the effects of autonomous operation on robustness, costs, and efficiency are studied from a quantitative perspective based on the metrics summarized in Table 1 and a comparison to state-of-the-art methods or common benchmarks from the recent literature.

First, the robustness of SOLEA is assessed to evaluate the reliability of autonomous plant operation. To quantify robustness, three metrics were used. The first two metrics were measured during the 30-hour autonomous-operation campaign, while the third metric is based on a separate evaluation of the optical measurement service at the Jülich SPT plant. The first metric assesses the time-based availability of software and infrastructure components, defined as the fraction of the test period during which these systems were operational and ready to execute control tasks without failure (M1). The second metric quantifies the forced-outage rate as a standard reliability indicator used for conventional and renewable power plants [24] (M2). It is defined as the fraction of unplanned outage hours relative to total operating hours. At the SPT plant in Jülich automated shutdowns are triggered by low-level safety services due to exceeding safety limits in certain components in the autonomous heat generation process. Accordingly, we counted and measured the time spent in unplanned outages of the physical plant that were caused by operation errors of SOLEA during the campaign. The third metric quantifies the robustness of focal-spot recognition for heliostat calibration based on the camera-target method (M3). To measure the robustness of the method, a pixel deviation measure has been used which assesses the relative mean pixel deviation between the focal spot extracted by the UNet-based optical measurement service and its ground truth [30].

During the 30-hour test period, physical plant components, measurement and control systems, middleware components, and software agents remained fully available without notable crashes or network communication errors, resulting in a availability of 100% during the observation window. In particular, the CPS middleware platform which plays a critical role by providing real-time measurement data as the basis for intelligent, agent-based operation demonstrated high reliability and performance. Through containerization and orchestration, the platform services have been replicated and load balanced on five servers to ensure low-latency and high-availability under varying and during operation extreme high workloads. In addition, automated health checks and error-handling procedures were implemented so that individual services are automatically restarted in case of a failure, guaranteeing continuous data and service availability for higher-level automation services.

Regarding the second metric, only one unplanned shutdown occurred during the early stage of the test phase. It was triggered by an excessive heating rate that caused the receiver's temperature gradient to exceed its defined safety limit. Analyzing and resolving the error has currently to be done manually by a human and lasted approximately 10 minutes until the system could be operated again by the agents. After adjusting control parameters of the operation control agent, no further unplanned shutdowns occurred, even under challenging environmental conditions with frequent cloud cover and fluctuating solar irradiance (see Appendix Fig. 10). Over 30 hours of operation, 0.17 hours of forced outage correspond to a forced outage rate of about 0.56%.

In comparison, long-term statistics for utility thermal plants and large wind or PV plants compiled in international studies and databases such as NERC's Generating Availability Data System (GADS) typically show time-based availabilities in the 90–98% range, with forced-outage factors of only a few percent under IEEE 762-style reporting. For concentrating solar power plants, however, detailed forced-outage and availability statistics are rarely published in the open literature, and most public reports focus on design studies or annual energy yields rather than standardized reliability indices. Against this background, the observed 100% availability of the software and infrastructure and a forced-outage rate of approximately 0.56% during the test period indicate a high level of robustness and operational stability for the SOLEA after initial parameter tuning. Nevertheless, the test duration was limited to 30 hours, so longer-term operation may reveal additional software or infrastructure issues that are not captured in this short-term evaluation (see Section 6).

With respect to the third metric, the incorporation of a UNet architecture into the heliostat calibration process addresses key limitations of conventional camera-target methods by explicitly accounting for background irradiation, target surface irregularities, and spatially varying reflectivity, thereby improving focal spot recognition. A quantitative evaluation revealed a relative mean pixel deviation of about 1.5% compared to the ground truth, indicating a significantly more robust basis for heliostat calibration [30]. To the best of our knowledge, no comparable focal-spot recognition methods in the heliostat calibration literature report image-level performance in terms of relative mean pixel deviation. Existing approaches based on the camera-target method typically evaluate their quality indirectly via tracking or pointing errors in mrad, flux-prediction accuracy, or generic segmentation metrics such as precision and recall, rather than quantifying pixel-wise deviations between predicted and reference focal-spot images. Consequently, the reported 1.5% mean pixel deviation of the UNet-based method provides a more explicit and fine-grained benchmark for focal-spot recognition accuracy than is commonly available in related work.

The second goal is the reduction of costs, which is measured based on four metrics that quantify the reduction of manual effort (M4), the fraction of autonomous operation time (M5), profit gains achieved through optimized operation planning (M6), and reduced investment costs enabled by the wireless communication infrastructure (M7). Metrics M4 and M5 are derived from the 30-hour autonomous-operation campaign, whereas M6 and M7 are based on dedicated studies of the operation management agent and the wireless 5G communication network at the Jülich SPT plant. The reduction of manual effort is quantified in working hours saved during an eight-hour operation day, while the fraction of autonomous operation time is expressed as the ratio of manual to autonomous operation efforts, indicating the extent to which plant operation can be performed without human intervention. The operational profit-gains metric is defined as the relative increase in daily electricity revenue, computed by integrating turbine power multiplied by the time-dependent electricity price over the operating day, for an optimized operation plan generated by the operation management agent compared to a manual reference control strategy. Both strategies were validated over two consecutive operating days for different weather scenarios, using weather and plant data recorded during the autonomous-operation campaign at the Jülich SPT plant. The manual reference control strategy neither uses day-ahead market prices nor weather forecasts for subsequent days. Therefore, the reference strategy aims to operate the turbine at its maximum operating point at all times for clear-sky days; surplus radiation is stored whenever possible and later used to extend plant operation. For cloudy days with only short periods of moderate irradiance, the reference strategy does not charge the thermal storage; instead, the turbine is operated purely solar, and its power output directly follows the instantaneous solar input. The fourth metric, communication-infrastructure investment costs, is defined as the relative reduction in capital expenditures that can be achieved by deploying a wireless 5G-based communication infrastructure in the solar field instead of a conventional wired solution requiring expensive earth works and cable costs.

In the baseline scenario, the operation team conducts a daily planning meeting of about 30 minutes to review the weather forecast, define the daily operation strategy, and assign responsibilities for plant operation. During operation, two operators are responsible for starting the plant, heating up the receiver by gradually focusing heliostats, and controlling the solar field and process parameters to maintain stable operation despite changing environmental conditions. They also continuously monitor sensor data and optical measurements, optimize heliostat aim points for uniform heat distribution, adapt the mass flow to hold the process temperature, and adjust the operational mode between direct generation and storage loading as conditions change. At the end of the day, the plant is either shut down or continues operation using thermal energy from the heat storage. Overall, this corresponds to 16 hours of manual operation time, as two operators are required throughout an eight-hour working day.

In case of the SOLEA, these tasks are largely automated. The operation management agent autonomously performs daily planning to generate an optimized operation plan. This plan is executed by the operation control agent, which starts, operates, and shuts down the plant based on real-time data. In this scenario, the human operator mainly assumes a passive supervisory role, being alerted only in case of anomalies or when manual intervention is required. Hence, the required manual operation time is reduced to less than 8 hours per day, as one operator only needs to be available on demand and can parallelize other duties, such as maintenance. This corresponds to a reduction of at least 50% in required staffing resources for standard operation days. Regarding the autonomous operation time metric, nearly all operational tasks are carried out autonomously. Exceptions include strategic changes in operation modes such as switching from thermal storage loading to direct electricity production, which are currently only recommended by the planning agent but must be manually configured by the operator. Additionally, human intervention is necessary to handle unexpected error situations, such as unplanned shutdowns triggered by exceeding predefined threshold values, which the system cannot yet resolve independently. Consequently, the autonomous operation time reaches up to 100% under ideal conditions and only decreases marginally when manual reconfiguration is required to change the operation mode or when human intervention is needed for error handling. During the experimental period, one unplanned shutdown occurred over 30 hours of operation, which was resolved within 10 minutes, after which the system continued to operate continuously without storage usage. Under these conditions, the fraction of autonomous operation time achieved during the test period was approximately 99%. However, this value could decrease slightly if more frequent changes in the operating strategy or additional unplanned shutdowns occur.

In addition to the cost advantages of the overall system, the metrics M6 and M7 assess SOLEA cost optimizations due to optimized operation planning and the wireless communication infrastructure. For the profit-gain metric, the operation management agent uses early irradiance to charge the thermal storage and systematically shifts electricity production into high-price periods at clear-sky conditions while operating the turbine near its efficiency maximum, leading to an observed revenue increase of about 4.9% compared to the reference strategy, with only a marginal increase in total generated electricity. On cloudy days, the manual strategy operates the turbine purely solar with no storage charging, whereas the agent primarily charges the storage on the first day and then discharges it in the evening of the second day, resulting in about 46% higher revenue and roughly 14% more generated electricity than the reference in the simulation study. While the underlying planning model includes simplified economic penalties for starts and stops, it does not yet capture all dynamic and part-load constraints of the real turbine, so these results should be interpreted as indicative potential rather than exact operational performance. Fig. 15 and 16 in the appendix illustrate the differences of the control strategies graphically. Regarding communication infrastructure costs, 5G-based wireless field communication has proven to be a performant, reliable, and cost-efficient alternative to wired networking throughout the field. The main investment-cost savings are expected to come from reduced hardware requirements for the communication infrastructure and the avoidance of extensive trenching and cable installation. Comparative CAPEX analyses between wired and wireless designs estimate savings of approximately 15–30% for communication infrastructure hardware alone, excluding the additional cost reductions achieved by eliminating expensive excavation work for cabling [53].

With respect to system efficiency, individual hardware and software additions at all four layers collectively contribute to an improved performance of the overall system. For each building block different measurements for efficiency can be found that are discussed in the related articles that study individual subproblems. Based on our holistic architecture concept, we have been able to integrate all research innovations into a common system and profit from efficiency improvements in each area at plant level. We summarize the efficiency gains from selected related studies to point out improvements on each system layer.

At the measurement and control system layer, reliable and accurate measurement and control systems are essential as the baseline for autonomous operation. In our system setup, we used several commercial control and measurement systems described in Section 5.1 that operated reliably and within their specified uncertainties when cleaned and maintained regularly. Innovations that have been introduced can be found especially in the field of optical measurement services with respect to focal spot recognition, flux density measurement, nowcasting, and UAV-based solar field monitoring and calibration. Quantitative improvements have been measured for UAV-based technologies in two tasks. First, heliostat field fine calibration during commissioning using the HelioPoint method achieves a tracking accuracy better than 0.3 mrad for entire heliostat fields [29] (M9), enabling rapid initial fine tuning to ensure high optical quality before the plant enters regular operation. Second, during operation, heliostat tracking outlier recognition and coarse orientation calibration in heliostat fields can be performed in real-time with dynamic flight planning using ARTSCORE-C. This measurement system flexibly identifies field areas of interest and recalibrate heliostats with low latency and an average angular RMSE of approximately 3.6 mrad [50] (M8), providing the basis for subsequent fine calibration steps such as the camera-target method where required. For the other optical measurement services, no quantitative performance figures are available yet, but systematic evaluations are planned to assess the effectiveness and accuracy contributions of each individual service in future work.

The CPS middleware platform is a central component of the SOLEA architecture, as it supplies higher-level automation services with unified access to measurement and control data, as well as up-to-date information on virtual assets represented in the DT, including the MAS itself. The availability of real-time data for all connected data sources and their corresponding virtual representations is therefore critical, because automation agents plan and operate the CST plant based on this information, and increased latency can directly lead to operational issues in autonomous operation. In addition, real-time access to consolidated plant data and DT information also supports data-driven situational awareness and decision-making by human operators. Miadowicz et al. assessed the performance of the CPS middleware platform and reported stable behavior under varying workloads, with an average latency for live data of about 40 ms [34, 35] (M10), which is significantly below the commonly accepted 100 ms threshold for real-time monitoring and control in many industrial process settings [16].

In the automation layer especially, the operation control agent improves operational efficiency based on differentiable aim-point control. The agent considers individual heliostat characteristics and uses machine learning to determine target aim points for an evenly distributed and optimized flux-density distribution every 20 s. Although a dedicated quantitative assessment is still ongoing, the optimized aim-point strategy has provided a smooth and efficient flux profile that minimizes spillage losses and avoids local hotspots, thereby improving receiver efficiency and protecting components. In addition, the operation control agent has proven to be able to reliably react to environmental dynamics with a short reaction time, resulting in improved efficiency and robustness of the heat-generation process compared to

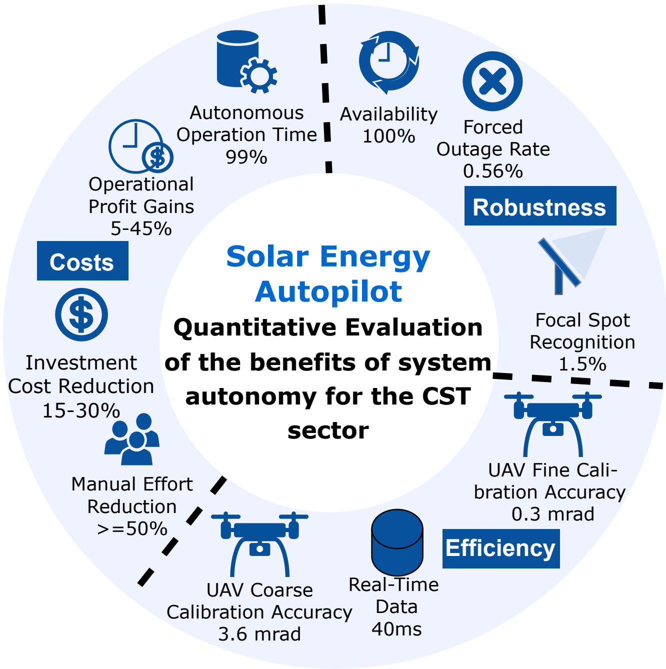

Figure 8: Infographic that summarizes benefits of the SOLEA for the CST domain with respect to costs, efficiency, and robustness.

manual operation. In this way, the plant was operated at receiver outlet temperatures above 500 °C without unplanned downtime, even under highly fluctuating DNI caused by cloud passages. It should also be noted that the operation control agent effectively required only about 50% of the heliostat field to achieve and maintain these high temperatures, highlighting the improved efficiency of autonomous control and optimized aim-point strategies.

In summary, autonomous operation based on the SOLEA architecture improves robustness, costs, and efficiency in a mutually reinforcing way as illustrated in Fig. 8. Robustness benefits arise from highly available middleware and automation services, low forced-outage rates during autonomous operation, and a more reliable basis for heliostat calibration through advanced focal spot recognition. Cost reductions are achieved by substantially lowering the manual operation effort, increasing the fraction of autonomous operation time in the day-to-day plant operation, improving operational profit through optimized schedules, and enabling lower-CAPEX communication infrastructures via wireless 5G field networking. Efficiency gains are contributed by multiple building blocks across all four layers of the architecture, including more accurate UAV-based coarse and fine heliostat calibration, improved optical measurement services, reliable real-time data provisioning by the CPS middleware platform, and data-driven aim-point and process control that maintains high receiver temperatures and stable operation under dynamic irradiance conditions. Together, these results illustrate that a holistic autonomous CST architecture like SOLEA can leverage advances at component level into system-level improvements in performance, economics, and reliability that go beyond what is typically achievable with isolated single-task automation solutions and conventionally operated CST plants.

5.2.2. Degree of Autonomy

This subsection assesses how SOLEA changes the degree of autonomy of CST plant operation compared to manual operation in the original baseline system setup. The evaluation follows the multi-dimensional maturity model for autonomous manufacturing systems introduced in Section 4.2, which links feature-level maturity in six functional categories to system-wide autonomy levels from AL1 (no autonomy) to AL5 (fully autonomous factory). The goal is to determine the overall degree of autonomy of the SOLEA relative to the initial baseline scenario, to understand how far the SOLEA concept progresses towards an autonomous factory and which dimensions still rely on manual effort and human decision-making. In the following, each functional category of the five-level maturity model is described and assessed for both the baseline system and the SOLEA implementation.

In the category of data, information, and knowledge, the baseline system provides largely unstructured data, data processing is limited to raw data collection within the respective subsystems, and data integration follows a traditional information pyramid architecture in which data is managed in isolation in each subsystem. Accordingly, knowledge management is restricted to low-level representations within individual subsystems, and interoperability is confined to physical connectivity and compatible equipment, so that the baseline reaches an overall maturity level of approximately 1.6 out of 5 in this category. With SOLEA, data becomes structured and consolidated through a CPS middleware platform, which enables real-time data analysis at middleware and higher automation layers. All systems are integrated around a DT of physical and software assets that supports autonomous control based on standardized data models and interfaces, ensuring a high level of interoperability. At present, knowledge management is limited to explicit knowledge design and systematic analysis of historical data, and interoperability remains at the level of knowledge and information interoperability without formal certification, resulting in an overall maturity of around 4.3 out of 5 in this category.

With respect to the process-related features, the baseline system exhibits only partial synchronization and optimization capabilities. Material and logistic synchronization exists between some processes, but physical synchronization is limited, and optimization is based on data collected at individual stations rather than for the whole production system, so that decisions remain largely local. Reliability is limited to the detection of critical failures that lead to unplanned shutdowns, without automated recovery mechanisms or predictive routines, placing the process category at a moderate overall maturity of 2/5. In the SOLEA scenario, synchronization reaches the highest level, as the system autonomously decides when to start, stop, and adjust processes based on an optimized operation plan and live measurement and control data. Optimization is fully embedded, with the system continuously optimizing itself without human intervention, and reliability is enhanced through error detection, redundancy, and recovery routines for critical software components. Hardware issues are currently only identified and reported to human operators for resolution, which limits full recoverability, but overall the SOLEA raises the process category to an overall maturity of approximately 4.7/5.

Interactions between humans, machines, and devices remain limited in the baseline scenario. The system runs predefined programs without awareness of the broader production context or the situation of the human operator. Safety reaches a medium level with intrinsic built-in safety rules, but these still require worker involvement in the definition and management of rules. Human interaction is characterized by individual access points for each control and measurement system, manual programming by uploading instructions, and basic human-in-the-loop control with low integration, resulting in an overall maturity of about 1.6/5 in the interactions category. SOLEA significantly improves interactions through higher context-awareness and richer human–system collaboration. The system can identify current content and context at the system level, enabled by graph-based data structures that represent actual data as well as meta-data about the data source and its role in the overall plant. However, the operator is not yet integrated into the consolidated data model, so that the context in which the human interacts with the system cannot be taken into account by the current SOLEA implementation. Safety is handled by flexible and adaptive rules that can be created dynamically for all consolidated data in the CPS middleware platform, using graphical and machine-readable interfaces of the alerting service to allow safe operation. Human interaction in operation reaches the highest maturity, with flexible task-oriented collaborations coordinated via the DT of the MAS, and programming and control advance to intermediate-to-high levels through the use of intelligent learning techniques and full integration of operators in decision and control processes when desired, yielding an overall interaction maturity of about 4.7/5.

In the infrastructure category, connectivity in the baseline system is implemented as a centralized production network with some integration at the production-system level. Industrial control is partially automated at the production system level, without extended, connected control across locations and with limited capabilities restricted to heliostat calibration, sun tracking, and hard-coded safety rules. Cybersecurity is at a minimum compliance level, with limited monitoring built into some subsystems and an offline environment without a connection to the internet, resulting in an overall maturity of roughly 1.8/5 in this category. Under SOLEA, the infrastructure is upgraded to a decentralized and interconnected factory, where production elements can communicate more directly and robustly. Industrial control is implemented as an intelligent connected control layer throughout the factory, and cybersecurity is strengthened with authentication, authorization, rate limiting, and audit logs. Building on this cybersecurity stack, SOLEA can predict possible attack vectors and report them to responsible humans, approaching but not yet reaching fully autonomous intrusion detection and response; overall, this results in a high infrastructure maturity of approximately 4.3/5.

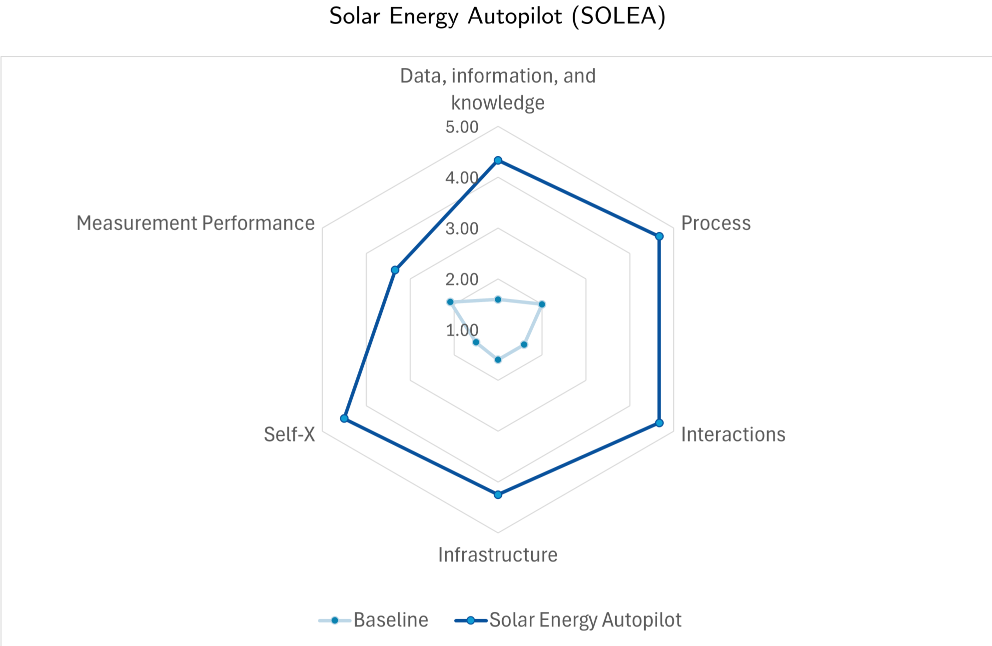

Figure 9: Multi-dimensional evaluation of the degree of autonomy of the baseline scenario and of the SOLEA.

The baseline system shows almost no self-X behavior. There is no self-organization or self-protection, and self-control and self-monitoring are limited to basic, static functions, so that the system largely depends on humans for configuration, recovery, and protection, keeping this category at a very low maturity of about 1.5/5. By contrast, SOLEA is strongly characterized by self-X capabilities. The automation layer self-organizes based on the DT and flexible task-oriented collaborations between agents and between agents and humans. In addition, the system controls itself autonomously during normal operation without human intervention, and self-monitoring is fully implemented so that the system identifies issues and reports them to agents or humans for correction. Self-protection is implemented at a basic level through an identity provider and API gateway that provide authentication, authorization, audit logging, rate limiting, and limited self-healing at the middleware layer. In the future, audit logs can be automatically analyzed to implement more advanced self-protection capabilities into the system. Overall, the SOLEA raises the maturity in this category to about 4.5/5.

In the baseline, measurement performance is strongly constrained by manual intervention and limited adaptation. Accuracy depends on human calibration and parameter updates as conditions change, and repeatability is only achieved after operators manually adjust settings. Changing conditions are not detected automatically, so sensitivity remains low, and there are no mechanisms to handle drifting or varying measurement quality, which reduces stability. Moreover, certainty is restricted to taking measurements during operation without identifying or compensating for sources of uncertainty. Taken together, these limitations result in an overall maturity score of about 2.1/5 for measurement performance. With SOLEA, measurement performance supports a slightly higher degree of autonomy. Accuracy improves through automatic detection of low precision and poor sensitivity in pyrheliometers and anemometers by comparing measurements from different devices and notifying maintenance personnel when cleaning or recalibration is required. However, the system does not yet autonomously adapt measurement settings or increase sensitivity without human intervention. Stability nevertheless increases because unusual measurements can be detected proactively and addressed in a targeted way, leading to a higher maturity of about 3.2/5 in this category.

To summarize, the SOLEA substantially increases the maturity of autonomy-enabling features across all six categories compared to the baseline, with particularly strong improvements in process, interactions, infrastructure, and self-X capabilities, and more moderate gains in measurement performance. The baseline system remains in the lower maturity range with category scores between roughly 1.5/5 and 2.1/5 and an overall average of about 1.8/5. The SOLEA consistently achieves values between about 3.2/5 and 4.7/5 with an overall average of roughly 4.1/5, indicating a transition from a basic automated factory towards a semi-autonomous factory with features approaching full autonomy. The overall effect of these changes is illustrated in Figure 9, which presents a spider web diagram of the maturity scores for the baseline and SOLEA system and makes the relative progress in each functional category immediately visible.

6. Discussion

The evaluation of SOLEA at the Jülich SPT plant demonstrates that a holistic autonomous CST architecture can be implemented and operated under real plant conditions and that autonomous operation is beneficial for the CST domain. However, several threats to internal and external validity with respects to the results of the study must be considered which are discussed in this Section.

Internally, the quantitative assessment of the benefits of autonomous operation in the CST domain is based on a relatively short test period of 30 hours, so rare events, long-term degradation effects, and planned downtime due to maintenance are not fully captured. The present study should therefore be regarded as a first step toward quantifying the effects of system autonomy for CST at an operational facility. Extended campaigns over different seasons and operating conditions are needed to obtain more robust long-term estimates and to study system-wide and component-specific impacts on efficiency, costs, and robustness. In addition, the cost analysis focuses on operational benefits such as reduced manual effort, increased profit per operating day, and potential savings in communication infrastructure, while the investment, integration, and maintenance costs of the additional hardware and software services have not yet been systematically compared against these gains. Future work should incorporate full life-cycle cost analyzes to complement the operational perspective in the long-term evaluation.

With regard to external validity, the quantitative results were obtained for a specific SPT research facility with a particular configuration of receiver, storage, and power block, as well as specific market and weather conditions. As such, the numerical values reported for availability, forced-outage rate, autonomous operation hours, and revenue gains cannot be directly generalized to other CST technologies (e.g., parabolic trough or linear Fresnel), commercial plants with different operating strategies, or other similar industrial environments. Instead, the results should be interpreted as evidence that an integrated autonomous operation concept like SOLEA can yield substantial benefits under realistic conditions, while the exact magnitude of these benefits will depend on plant design, operating context, and local markets. Carefully designed follow-up studies at different CST facilities are required to assess the transferability of the findings and to refine the quantitative results within a multi-case study setting.

Furthermore, the autonomy assessment through the multi-dimensional maturity model likewise introduces methodological limitations. Large, heterogeneous systems such as CST plants cannot be assigned a single autonomy level without abstraction, because different subsystems simultaneously exhibit different degrees of autonomy. The autonomy evaluation in this study demonstrates that autonomy is achieved unevenly across dimensions in the case of the CST plant: data, process, infrastructure, interaction, and self-X capabilities reach high maturity, whereas measurement performance and autonomous fault recovery still lag behind, limiting fully independent operation in unforeseen situations. On the one hand, the challenging evaluation of system autonomy in the CST plant highlights the value of multi-dimensional maturity models which allow a fine-grained assessment of the degree of autonomy in complex systems with varying degrees of autonomy. On the other hand, it also emphasizes the challenge to determine the degree of autonomy for the entire system. Additionally, the lack of standardization on the concept of system autonomy described in Section 2.1, further complicates the categorization of systems as autonomous or not. In this context, different maturity models proposed by the recent literature might lead to another categorization of the degree of autonomy of the CST plant as we infer based on the five-level maturity model. Nevertheless, we transparently communicate the difficult categorization of a system as autonomous or not and have intentionally chosen a multi-dimensional maturity model to systematically access the degree of autonomy despite its inhomogeneous autonomy levels at different functional dimensions.

Furthermore, the multi-dimensional maturity model relies on qualitative judgments that may be affected by evaluator subjectivity. To mitigate this, the evaluation followed a structured procedure in which at least two researchers independently rated each functional dimension based on predefined criteria and resolved discrepancies through discussion, but subjective bias cannot be entirely eliminated.

In summary, the study demonstrates the feasibility and benefits of an autonomous CST plant architecture in a real-world setting, but the results are subject to limitations regarding observation duration, cost coverage, autonomy assessment methodology, and generalizability beyond the specific SPT facility. These limitations were taken into account through careful research design choices, such as the use of a multi-metric evaluation, a multi-dimensional autonomy model, and discussions among experts to compensate subjective bias by the evaluators. Additionally, we outline clear directions for future work, including long-term evaluation, full life-cycle cost analyzes, and replication at other CST plants in a subsequent multi-case study.

7. Conclusion

This work introduced the SOLEA, a holistic four-layer architecture that transforms a conventional SPT plant into an autonomous CPS and evaluated its performance under real operating conditions at the Jülich SPT plant. Building on recent advances in measurement, communication and information technologies, SOLEA demonstrates how existing CST plants can be retrofitted and gradually evolved toward higher degrees of autonomy.

Regarding the first research question, the study shows that recent technological advances can be synthesized into a coherent architecture for autonomous CST plant operation by structuring the system into four layers that span physical plant components, field devices, middleware, and plant-level automation services. The measurement and control layer integrates advanced sensing and control systems, the data and communication layer provides wireless network communication capabilities and a CPS middleware platform to consolidate and give access to heterogeneous plant data, and the multi-agent automation layer implements autonomous planning and control agents to autonomously perform daily operation. Together with targeted hardware retrofits, this layered concept yields a modular and reusable blueprint that can be adapted to other CST facilities and comparable industrial systems to improve the overall level of plant automation.

Addressing the second research question, the autonomy assessment with a multi-dimensional maturity model reveals that the currently implemented SOLEA state achieves a high degree of autonomy in several functional areas of the Jülich SPT plant. Data management, process control, infrastructure, interaction, and self-X capabilities reach advanced maturity levels, enabling the agents to autonomously plan operating days, start up and shut down the plant, and regulate receiver flux and outlet temperature under varying environmental conditions. At the same time, the evaluation highlights that measurement performance and autonomous fault recovery remain less mature, so occasional human intervention is still required.

With respect to the third research question, the dual-sided evaluation provides quantitative evidence that the current implementation of the SOLEA contributes positively to efficiency, robustness, and cost-related indicators. The autonomous system maintained high availability and a low forced-outage rate during the 30-hour test period despite challenging weather conditions, demonstrating robust plant operation. Operational costs were reduced by substantially lowering manual operation time and staff effort, improving daily revenues through optimized operation planning, and enabling lower capital expenditures for field communication through wireless 5G networking. Efficiency gains were achieved by combining improved optical measurement and calibration, including UAV-based coarse and fine heliostat calibration, with reliable real-time data provisioning and data driven aim point and process control, resulting in stable high temperature operation under dynamic irradiance.

Taken together, these results provide the first empirical demonstration that a layered, modular autonomy architecture like SOLEA can bridge the gap between isolated automation solutions and plant-wide autonomous CST operation. The study thus delivers a scientific contribution on two levels: conceptually, it offers a generalizable architectural pattern for evolving complex industrial energy systems toward autonomy, and empirically, it quantifies the technological and operational benefits that autonomous operation can unlock in a real CST plant. In this way, SOLEA can serve as a foundation for a new generation of autonomous CST plants that combine high operational flexibility with reduced complexity and costs, thereby strengthening the role of solar thermal energy in a world-wide, climate-neutral, digitally enabled energy system.

8. Outlook

The SOLEA concept and its implementation at the Jülich SPT plant show that autonomous CST operation is technically feasible and can deliver measurable benefits for efficiency, robustness, and operational costs. At the same time, autonomy remains a continuum, and there is substantial potential to further enhance all four layers of the architecture with respect to performance, cost, and robustness by incorporating ongoing research innovations. Thanks to the modular design, individual building blocks from physical hardware to measurement and control systems, middleware services, and automation agents can be flexibly replaced or extended, allowing a stepwise progression toward improved operation and higher autonomy levels without disrupting the overall system.

On the industrial facility layer, future work will focus on advancing heliostats, receiver, and storage technologies to lower investment costs and improve efficiency on hardware level. Improved heliostat designs and control concepts can further increase pointing accuracy, robustness, and cost efficiency [19], while innovations in receiver and thermal storage design may enable more flexible operating envelopes and tighter integration with autonomous control strategies. On the measurement and control layer, ongoing research on AI- and physics-based flux density prediction [14, 47], advanced heliostat characterization [32], improved nowcasting predictions to adequately assess the prediction of ramp events [43], and UAV-based heliostat monitoring, soiling detection, and calibration can be integrated to reduce calibration effort, improve measurement and prediction accuracy, and extend the SOLEA capabilities to additional inspection and maintenance tasks. In particular, future UAV developments include an ARTSCORE-C-based real-time fine-calibration procedure (ARTSCORE-F) and geometry-transfer extensions of deep-learning heliostat and mirror-edge detection to additional heliostat geometries [3, 8, 50].

On the data and communication layer, future development targets include enhanced data-quality management, automated interoperability validation, and more advanced self-protection mechanisms based on systematic analysis of security logs and anomaly patterns. These capabilities would allow the CPS middleware to not only integrate heterogeneous systems but also to continuously assess and improve the reliability and security of the data and services on which autonomous agents depend. Finally, on the automation layer, new agents can be introduced for predictive maintenance, fault diagnosis and recovery, manufacturing and commissioning support, and lifecycle optimization, extending autonomy beyond daily operation into the full lifecycle of CST plants.

Beyond the Jülich facility, the SOLEA architecture provides a transferable blueprint for progressively upgrading existing CST plants and future solar thermal infrastructures toward higher autonomy levels. While the findings are based on a specific SPT research facility and a limited test period, they indicate that system autonomy is a promising lever to enhance the competitiveness of CST technology and motivate further research on long-term operation, life-cycle costs, and the transfer of the SOLEA concept to other plants and application domains. Applying and adapting SOLEA in diverse plant configurations, market environments, and industrial process-heat applications will be crucial to validate its generality and refine design patterns for autonomous energy systems.

CRediT authorship contribution statement

I. Miadowicz: Writing – original draft, Writing - review and editing, Conceptualization, Methodology, Software, Investigation, Validation, Data curation, Visualization, Supervision, Project Administration. **M. Kuhl:** Writing – review and editing, Investigation, Software, Validation, Data curation. **D. Maldonado Quinto:** Writing – review & editing, Investigation, Validation, Resources, Project administration, Funding acquisition, Supervision. **N. Dürr:** Investigation, Software, Validation, Data Curation, Visualization, Writing – review & editing. **P. Schwarzbözl:** Writing – review & editing, Investigation, Resources, Funding acquisition, Supervision. **M. Sibum:** Writing – review & editing, Software, Data Curation, Validation, Investigation. **V. Rasing:** Writing – review & editing, Software. **B. Nouri:** Writing – review & editing, Investigation, Software. **E. Saez Martinez:** Investigation, Software. **A. Schnerring:** Writing – review & editing, Investigation, Software, Validation, Data Curation. **R. Broda:** Writing – review & editing, Investigation, Software, Validation, Data Curation. **B. Schlögl-Knothe:** Writing – review & editing, Software. **S. Wilbert:** Supervision, Funding acquisition. **M. Röger:** Writing – review & editing, Supervision, Funding acquisition, Validation. **F. Göhring:** Writing – review & editing, Supervision, Funding acquisition, Resources. **K. Wieghardt:** Supervision, Funding acquisition. **R. Pitz-Paal:** Supervision, Funding acquisition. **M. Felderer:** Supervision.

A. Appendix

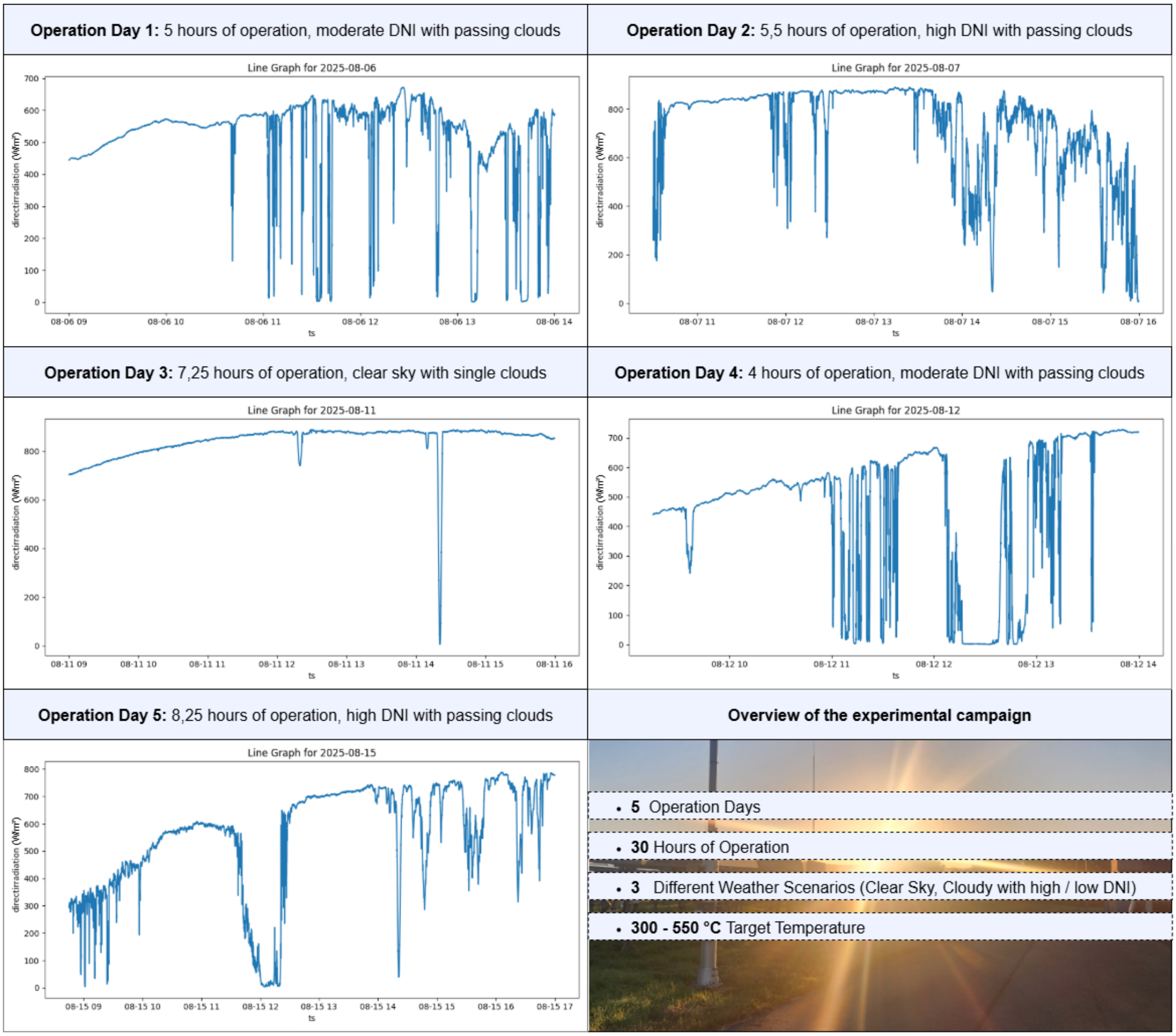

Figure 10: Overview on the experimental campaign and its weather conditions for the evaluation of SOLEA.

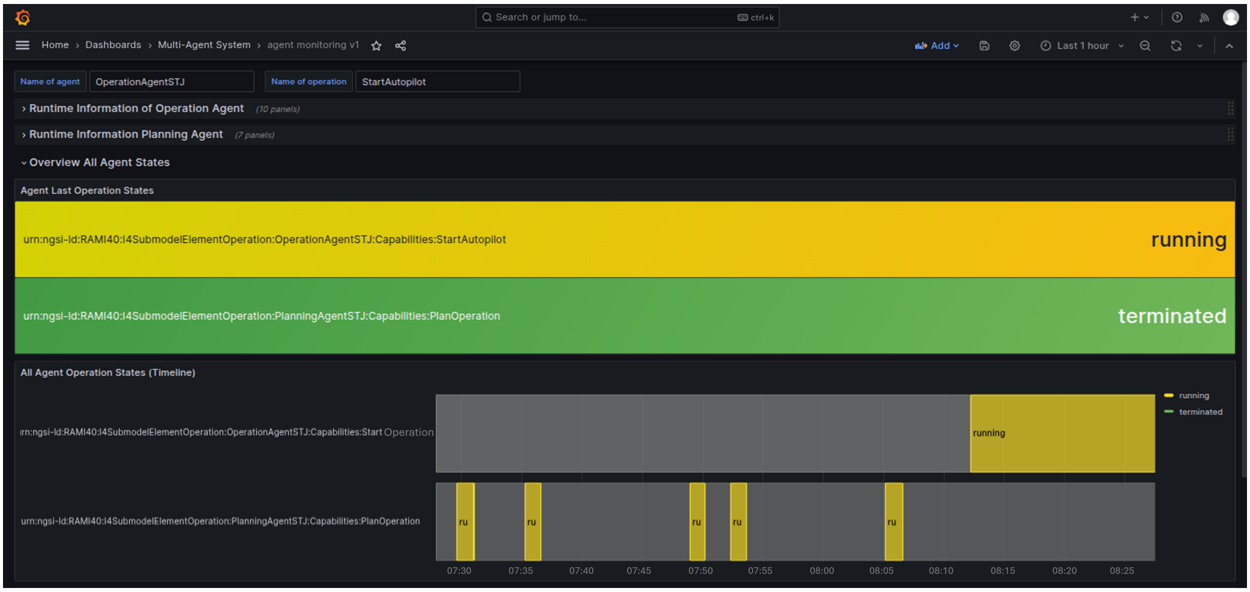

Figure 11: Dashboard to monitor of agent-based process execution and learn about the current state of each agent in the MAS.

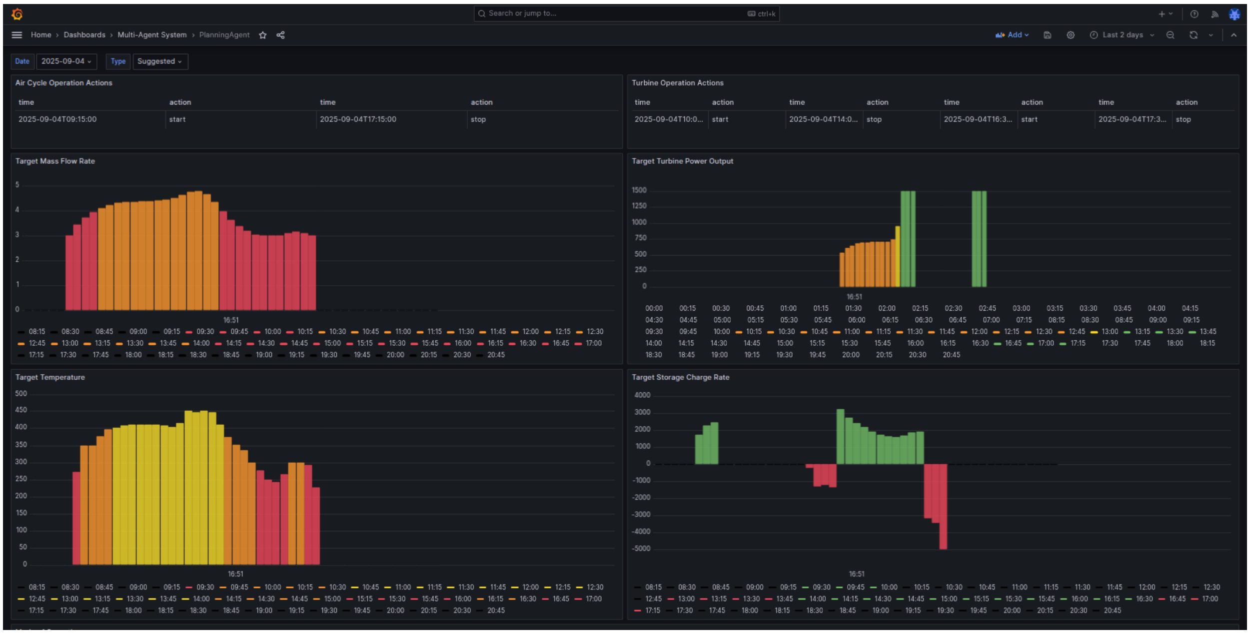

Figure 12: Dashboard to monitor the optimized operation plan created by the operation management agent.

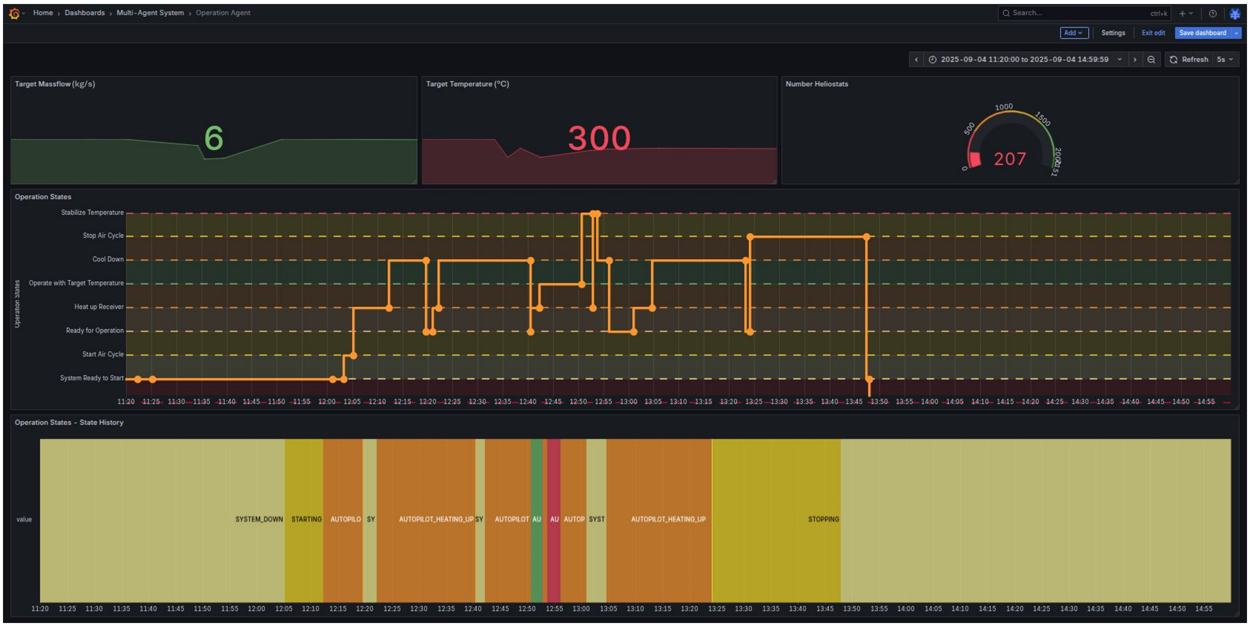

Figure 13: Dashboard to monitor the current operation state of the operation control agent.

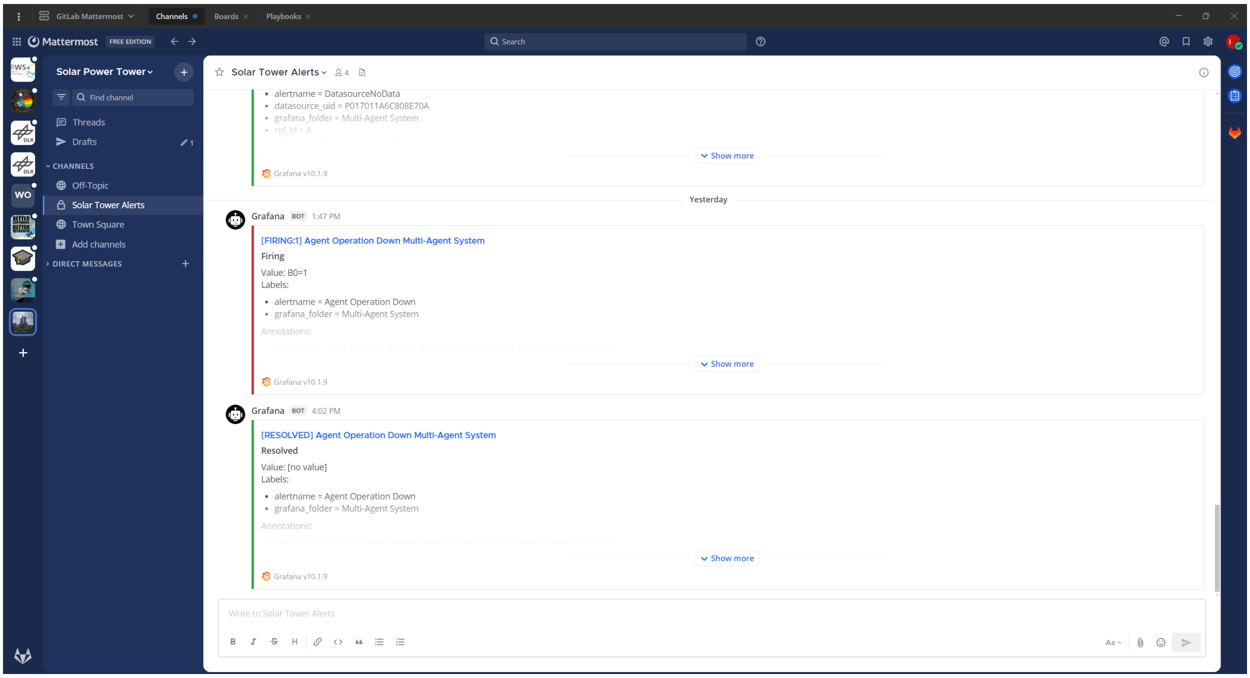

Figure 14: Alerting interface to receive notifications on certain events of the CST plant via Mattermost.

Figure 15: Comparison of optimized operation plan from the operation management agent against manual reference strategy on two subsequent sunny days. Q_Receiver: Thermal power absorbed at the receiver based on measured DNI; Q_load: Charging power of the thermal storage; Q_discharge: Discharging power of the thermal storage; P_Turbine: Electric power output of the turbine; Price: Time-dependent electricity price on the energy market

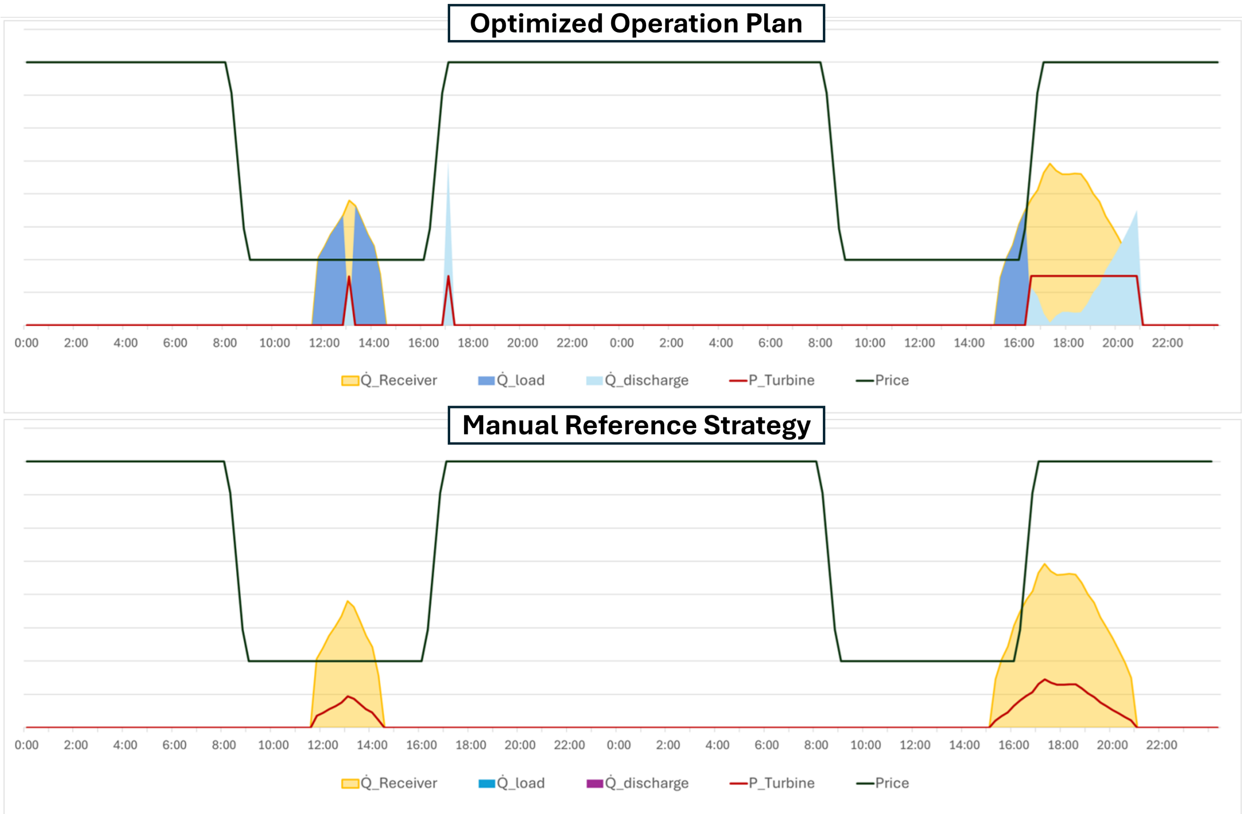

Figure 16: Comparison of optimized operation plan from the operation management agent against manual reference strategy on two subsequent cloudy days. Q_Receiver: Thermal power absorbed at the receiver based on measured DNI; Q_load: Charging power of the thermal storage; Q_discharge: Discharging power of the thermal storage; P_Turbine: Electric power output of the turbine; Price: Time-dependent electricity price on the energy market

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