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Analysis and Simulation of CSP and Hybridized Systems

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ACWA Power's CSP Performance Assessment

An Online Simulation Platform for ACWA Power's CSP Plants

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Abstract. A CSP Plant and in particular the solar field has hundreds of thousands of components and the corresponding process parameters. This needs to be monitored and evaluated every day to make sure that the plant is working efficiently. A performance assessment with a production simulation is done daily where the expected and actual power production are compared. Such evaluation is usually done with the plant performance model and the necessary data is compiled in calculation programs like Excel. The work is repetitive, time consuming and human errors may easily occur. Typically, the evaluations are done from different parties with deviating results and conclusions. ACWA Power has developed an online simulation platform to automatize the data processing to increase the data reliability and reduce the time effort. The application has been implemented in the Noor Energy 1 hybrid solar plant in Dubai and shall be presented in this paper.

Keywords: Performance Assessment, Online Platform, Noor Energy 1, Concentrating Solar Power (CSP), ACWA Power, Renewable Energy, Solar Energy, Performance Model

1 Glossary

Explanation of abbreviations used in this document:

Abbreviation	Explanation
ACWA	The Saudi Arabian company ACWA Power being developer, investor and operator of power generation and desalinated water plants.
NOMAC	Operation & Maintenance company, a fully owned subsidiary of ACWA Power which operates and maintains the ACWA Power assets.
NE1	Noor Energy 1, hybrid solar power plant in Dubai, and part of the Mohammed bin Rashid Al Maktoum Solar Park.
CT	Central Tower concentrated solar plant
PT	Parabolic Trough concentrated solar plant
PV	Photovoltaic solar plant
HTF	Heat Transfer Fluid, used to deliver the energy captured from the receivers of the solar field to the Power Block
TES	Thermal Energy Storage, used to store the thermal energy from the solar field during sunny hours and deliver to the Power Block during

the night or cloudy conditions.

2 Introduction

Since 2016, ACWA Power, in collaboration with its operation and maintenance company NOMAC, has been overseeing the operation of three CSP plants in Morocco and one parabolic trough CSP plant in South Africa. These plants rely on daily, monthly, and yearly production reports to continually monitor, analyze, and optimize their operation and performance. These comprehensive reports encompass the following key aspects:

- Weather and production forecast for the following day,
- Production summaries for the day, month, and year,
- Expected production calculation according to contractual performance models and Acwa Power's performance model,
- Key Performance Indicators comparing the actual process parameters with the design or expected values,
- Availability tracker of the critical components and systems,
- Loss analysis tools,
- Graphs, statistics, and calculations

The tools have been continuously improved and partially automated and are the main data basis for production evaluations and gap analysis which then initiative plant or operation improvements. The purpose of the new CSP Online Platform is to use the existing tools for the Noor Energy 1 project in the highest automated way to which the designated users are having access according to their needs.

3 Noor Energy 1 Hybrid Concentrated Solar Power Plant in Dubai

The Noor Energy 1 (NE1) hybrid project in Dubai with 950 MW_e net capacity is the largest CSP project in the world, delivering electrical energy at a price of 7.3 US cents per kWh, being the worldwide lowest price of its kind. The project is built on an area of 63 km^2 and consists of

- three 200 MW parabolic trough plants,
- one 100 MW central solar tower and
- two photovoltaic plants of total 250 MW

Each of the four CSP plants (PT1-3, CT) has its photovoltaic plant (PV_{aux}) to cover the auxiliary power consumption, in addition to the production photovoltaic plants PV1 on the east and west side of CT and PV2 on the east side of PT3. The CSP plants are allowed to produce from April to October 24 hours per day while from November to March production is only allowed between 16h and 10h of the next day.

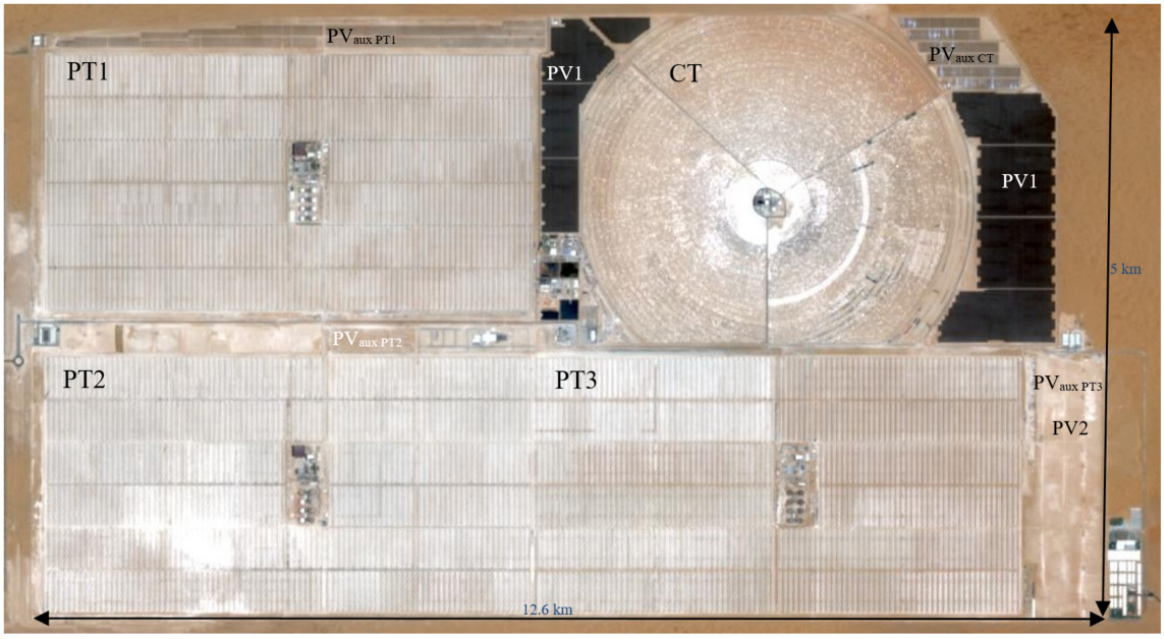


Figure 1. *Aerial view of the Noor Energy 1 hybrid solar project in Dubai (United Arab Emirates)*

Each of the three identical Parabolic Trough plants consist of:

- a solar field with 530 loops of 4 Parabolic Trough Collectors
- 20,000 tons of Heat Transfer Fluid (HTF) with an outlet temperature of approx. 390 °C
- 4 parallel salt Thermal Energy Storage units with a total of 175,000 tons of molten salt and a total capacity of 6,525 MW_{th},
- a 206 MW turbine with 3 HP preheaters & 4 LP preheaters and
- dry cooling towers.

The Central Tower Plant consists of

- More than 70,000 heliostats,
- a 260 m high tower for the molten salt receiver with an outlet temperature of 560 °C,
- one Thermal Energy Storage units with 30,000 tons of molten salt and a capacity of 3,588 MW_{th},
- a 108.5 MW turbine with 3 HP preheaters & 4 LP preheaters and
- dry cooling towers.

The first Parabolic Trough plant (PT1) and Central Tower (CT) have started its commercial operation in early 2023. The second Parabolic Trough plants (PT2) is commercially operative since September 2023 and the third one (PT3) since February 2024.

The commercial success of the projects depends on maximizing the production by minimizing the necessary resources. A key to achieve the objective is to get reliable process and production data in the most efficient way to identify production deviations and optimize the operation and maintenance of the plant. Therefore, the daily performance monitoring needs to be done with minimum human interaction.

4 ACWA Power's Technology Simulation Platform

ACWA Power has developed in its central office in Dubai a common technology online platform for analysis and optimization tools of its desalination, photovoltaic, battery energy storage systems (BESS) and CSP plants. The platform uses a PostgreSQL database and user interfaces programmed in Python, Flask and Vue.js.

4.1 CSP Online Simulation Platform

The CSP platform covers the parabolic trough and central tower technologies. It provides the following modules:

- Data upload and processing
- Performance models
- Dashboards
- Report library
- User defined data evaluations

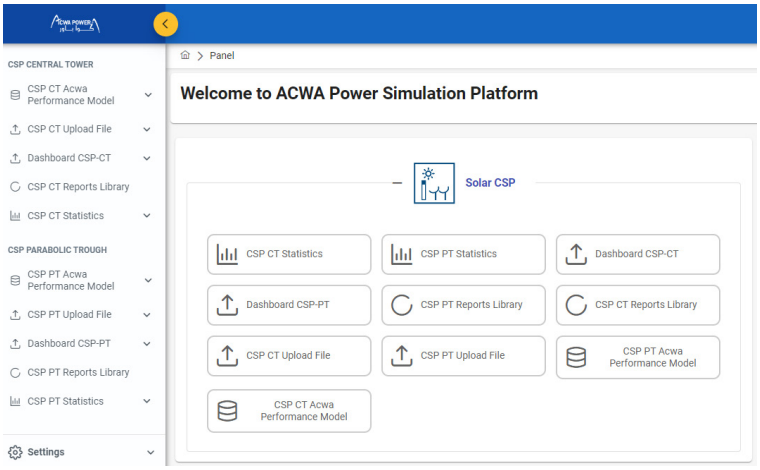


***Figure 2**. User Interface for the CSP Online Simulation Platform*

4.2 Data Processing

There is an easy way to get the daily routine work done quickly. It consists of the following steps:

1. Automatic generation of csv files of relevant data every morning by the plant control system.
2. Import of plant data into an Excel template.
3. Verification of the imported data and adding relevant O&M information.
4. Upload of the completed template to the online platform
5. Automatic execution of the contractual Performance Model
6. Automatic execution of a series of simulation cases with the ACWA Power Performance Model
7. Automatic generation of a daily production report including a loss calculation
8. Verification of the generated report by the performance engineer.
9. Release of report and automatic distribution

The process requires little work to be done from the performance engineer, which mainly consists of verification of the gathered data and prepared report. Figure *3* shows the data flow and structure of the application:

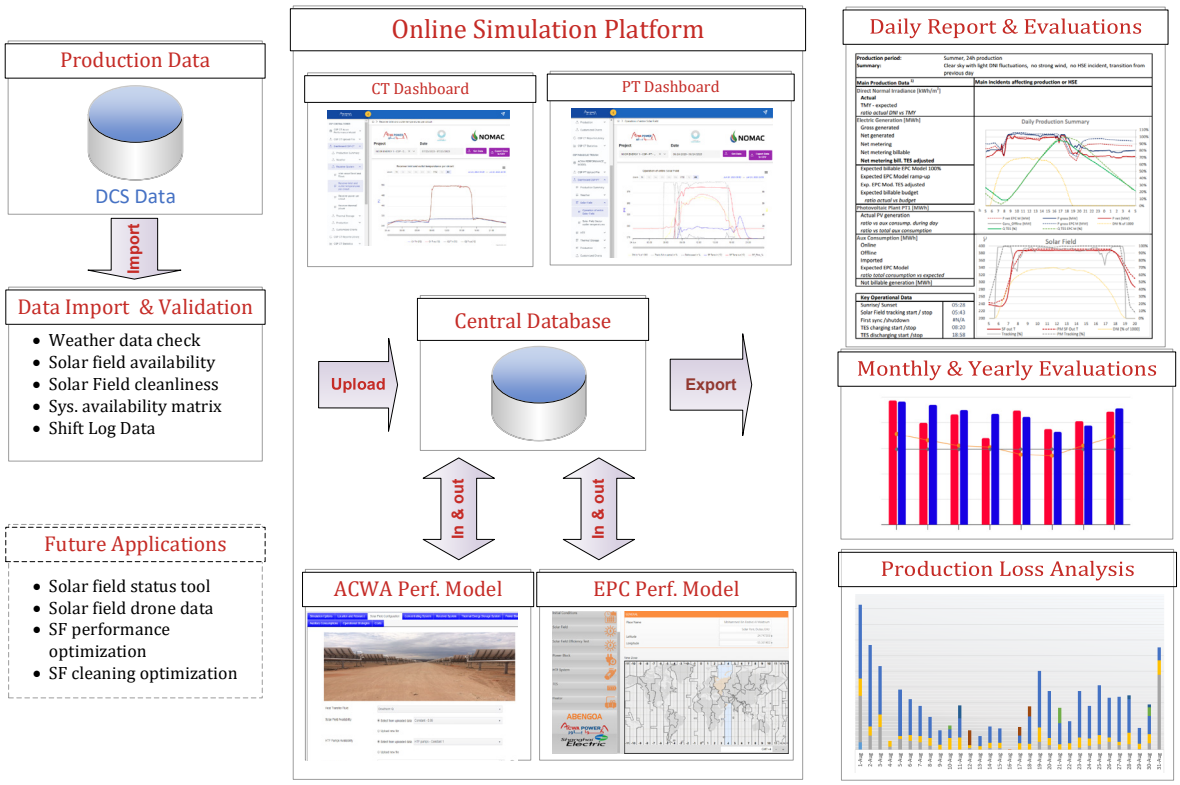


Figure 3. *Schematic of the data structure and flow*

4.2.1 Data Import and Validation

The Decentralized Control System (DCS) of the plant has a data export function, which is automatically exporting 24h production data every day. The plant performance engineer is then importing it by a simple click into an Excel template. The template has several data checks to verify the validity of the plant data and alert if data is invalid or missing.

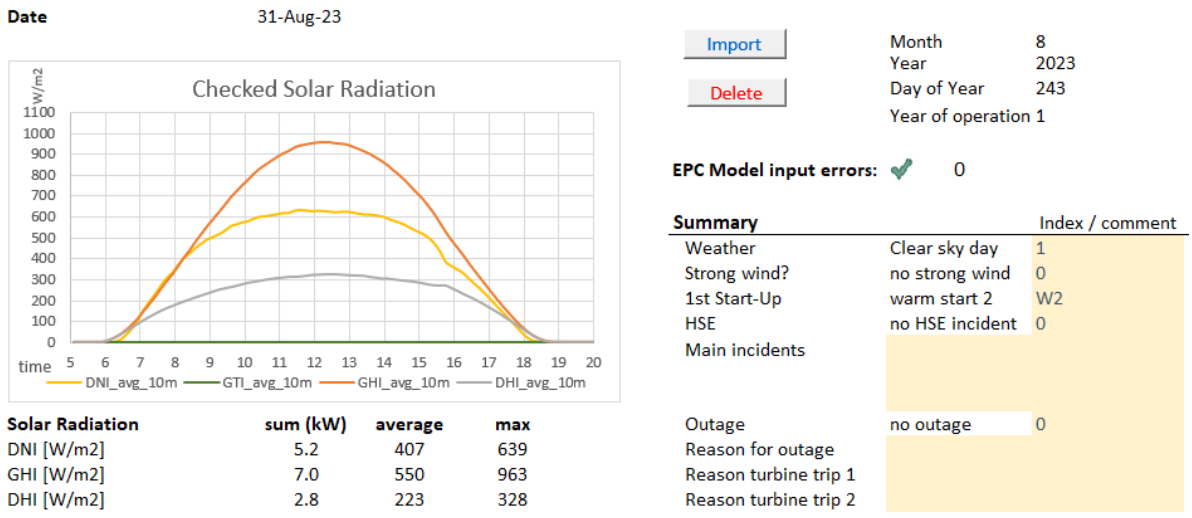


Figure 4*. Extract of the template to import production data of the previous day*

Each plant has several weather stations. Graphs are visualizing the solar radiation, wind, ambient temperature and humidity of all stations and the user may select or deselect the weather data to be used as an input for the performance model. Furthermore, the performance engineer need:

- to import the measured mirror reflectivity of the Solar Field,
- indicate whether components or systems have been unavailable. The possible unavailability of a subsystem is introduced with a time resolution of 10 minutes. If a subsystem is partly available, then the corresponding percentage is introduced. The ACWA Power Performance Model is determining in case of an unavailability the production reduction, which may result.
- select some predefined descriptions which characterize the production of the day in regards of type of weather, start-up, turbine tips if any and plant safety. Short comments of remarkable events or incidents shall be added if necessary.

4.2.2 Data Upload and Processing.

The completed template for a day is then uploaded to the online platform for the corresponding date. During the uploading process the data is checked again and transferred to the corresponding tables of the database. Alarms are generated if data is missing or invalid so that the user may correct it. The necessary calculations are carried out to generate key performance indicators for the day, which are then again saved in the database.

Once the data is checked and valid, then the contractual performance model and ACWA Power performance model are launched automatically.

4.2.3 Performance Models

The NREL CSP best practices study[1)] highlights the importance of thorough production monitoring in the operation phase of a CSP plant with adequate performance models. Each technology, parabolic trough and central tower has its own models. Two types of performance models are used for different purposes.

Contractual Performance Model

The contractual performance model is part of the EPC contract and has been developed by the technology provider of the contractor. It defines the guaranteed plant performance which needs to be achieved during the test period in the first years. It requires meteorological data as input and returns the guaranteed performance. There are two different contractual models, one for the Central Tower and another one for the Parabolic Trough Plants. As the three Parabolic Trough plants are identical, the same model is used for each PT plant.

ACWA Power Performance Models

For each technology there is a Performance Model, developed by ACWA Power. The purpose of the model is like the contractual performance model and uses the same meteorological data as input to calculate the expected production. However, there are two main differences:

- The ACWA Power model allows to introduce availability and efficiency factors for different subsystems of the plant such as the Solar field availability and Solar Field cleanliness of the plant and
- The ACWA Power model is not a black box and may be adjusted if necessary.

While the contractual model is only executed once, the ACWA Power model is executed several times. For each model execution one input parameter is changed and all the other

parameters remain the same. The difference between the simulations is then determining the effect on the production for the corresponding input.

The Performance engineer can introduce availability- or efficiency factors for several subsystems in a 10-minute time resolution and the Performance Model then calculates the generated power for each case. Table *1* shows an example in which just the Photovoltaic plant has a reduced availability of 70% whereas all other systems are fully available.

The example shows that the generated net electricity is affected by the PV plant availability (simulation 7). Production is also reduced because of the Thermal Storage being completely full before the end of the day (simulation 16).

	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]	[0 to 1]
Timestamp	Grid	PV Avail	PB Avail	HTF Avail	TES Avail	Tur_Trip	Operation	SF Av wind	PB Efficien	PB capcity	SGS avail	TES capacity
05:05:00	1.00	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
05:15:00	1.00	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
05:25:00	1.00	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
05:35:00	1.00	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
05:45:00	1.00	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 1. *Example of efficiency and availability factors as input for the ACWA Performance Model*

#	Title	Sum Gross	Sum Net	On-line C	SF Power th	Power th to TES	Power th to PB	Power th TES to PB	Power el PV
1	Design	4,663	4,364	507	13,200	6,375	11,833	6,104	226
2	Curtailment	4,663	4,364	507	13,200	6,375	11,833	6,104	226
3	Power Block availability	4,663	4,364	507	13,200	6,375	11,833	6,104	226
4	SGS availabilty	4,663	4,364	507	13,200	6,375	11,833	6,104	226
5	TES availability	4,663	4,364	507	13,200	6,375	11,832	6,104	226
6	Heat Transfer Fluid System availability	4,663	4,364	507	13,200	6,375	11,832	6,104	226
7	PV availability	4,667	4,305	507	13,200	6,375	11,833	6,107	161
8	Equipment trips	4,667	4,305	507	13,200	6,375	11,833	6,107	161
9	Wind	4,667	4,305	507	13,200	6,375	11,833	6,107	161
10	Solar Field availability	4,667	4,305	507	13,200	6,375	11,833	6,107	161
11	Solar Field cleanliness	4,666	4,304	507	13,200	6,375	11,833	6,104	161
12	Solar Field efficiency factor	4,666	4,304	507	13,200	6,375	11,833	6,104	161
13	Operating strategy load	4,666	4,304	507	13,200	6,375	11,833	6,104	161
14	Defocusing plant startup	4,663	4,303	507	13,200	6,375	11,833	6,104	161
15	Defocusing operation	4,663	4,303	507	13,200	6,375	11,833	6,104	161
16	Defocusing TES fully charged	4,373	4,042	467	11,679	6,425	11,097	6,045	161
17	Power Block Efficiency factor	4,373	4,042	467	11,679	6,425	11,097	6,045	161
18	TES Capacity limitation	4,373	4,042	467	11,679	6,425	11,097	6,045	161

Table 2. *Example of a simulation results with the inputs from table 1 for a day*

4.2.4 Dashboards

There is a series of dashboards predefined in the platform, daily reports, and others for any desired period. All data may be downloaded as csv or as a graphic file and can then be further used externally. Any further required dashboard may be added or modified in the future and will then be available for previous and future evaluation periods.

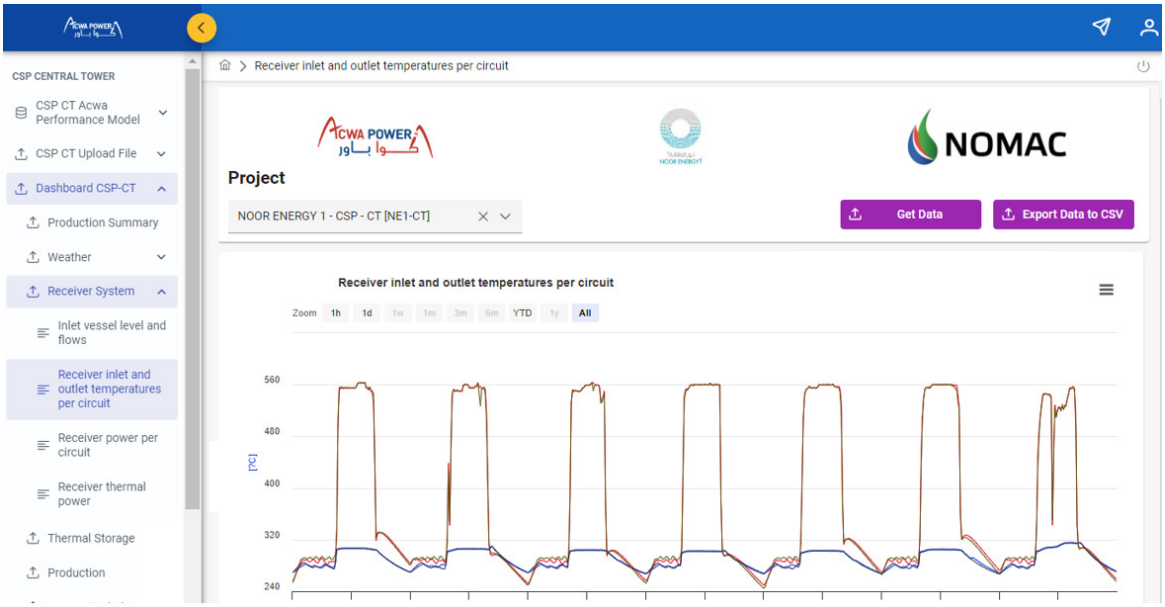


***Figure 5**. Example of dashboard for a freely defined period*

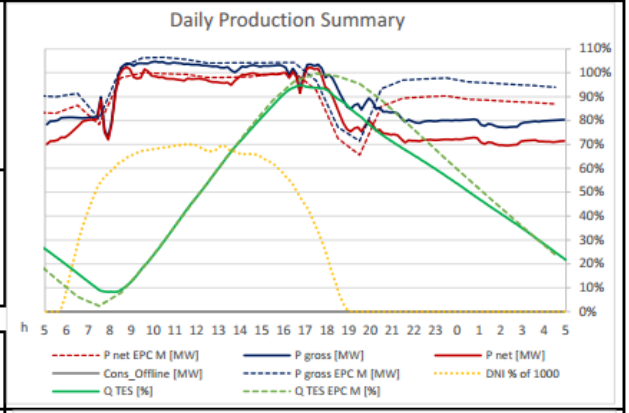
4.2.5 Daily and Monthly Reports

There are predefined daily and monthly reports available for the entire production period since the first day of operation. Further reports may be defined or modified as needed.

Production period:	Summer, 24h production
Summary:	Clear sky with light DNI fluctuations, no strong wind, no HSE incident, transition from previous day

Main Production Data [1]	**Main incidents affecting production or HSE**
Direct Normal Irradiance [kWh/m^2]	
Actual	
TMY - expected	
ratio actual DNI vs TMY	
Electric Generation [MWh]	
Gross generated	
Net generated	
Net metering	
Net metering billable	
Net metering bill. TES adjusted	
Expected billable EPC Model 100%	
Expected EPC Model ramp-up	
Exp. EPC Mod. TES adjusted	
Expected billable budget	
ratio actual vs budget	
Photovoltaic Plant PT1 [MWh]	
Actual PV generation	
ratio vs aux consump. during day	
ratio vs total aux consumption	
Aux Consumption [MWh]	
Online	
Offline	
Imported	
Expected EPC Model	
ratio total consumption vs expected	
Not billable generation [MWh]	

Key Operational Data	
Sunrise/ Sunset	05:28
Solar Field tracking start / stop	05:43
First sync /shutdown	#N/A
TES charging start /stop	08:20
TES discharging start /stop	18:58



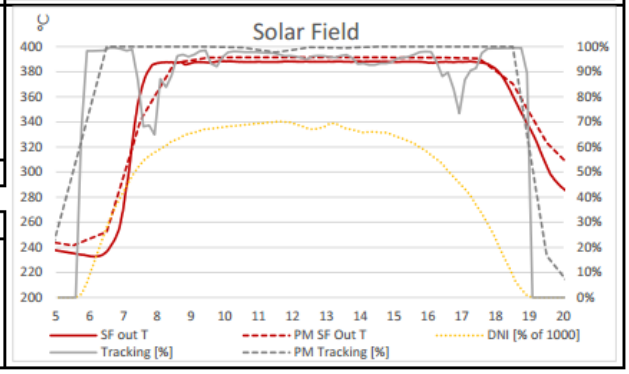


***Figure 6.** Example of dashboard for a freely defined period*

4.2.6 Customized Reports and Report Library

All uploaded or calculated data can be combined in user defined selections and downloaded for the entirely available period. Selections can be saved so that user defined reports may be available for future evaluations and for other users. The data can be downloaded and used in external applications.

4.2.7 Integration of External Data and Applications

Besides the plant performance evaluation other evaluation tools have been developed by ACWA Power such as a Solar Field maintenance tool and a Solar Field performance tool. There is also plant data available from external service providers such as data from drone surveys of a Solar Field. It is intended to integrate the existing data and applications so that the data may be linked to each other, which may lead to further conclusions and further automatize the Operation & Maintenance of the CSP plants.

5 Conclusion and Benefits

A lot of production data and applications are available to do the performance assessment of a CSP plant. Most of them are spread in different files and locations. The information may then be difficult to allocate and accessible to all involved parties. Data may be lost when employees leave the company or change their responsibility. Data may be corrected, new parameters added, and it is then often difficult to find out which is the latest and valid revision. Distributed data in individual files, for example daily and monthly reports are difficult to combine to do long term evaluations. The online database approach provides the following benefits:

- Minimum time needed to get reports through high degree of automation,
- Centralized access for all involved parties.
- Availability of the latest and valid data,
- KPI comparison of different assets for example between the four NE1 phases,
- Future evaluations can be applied to historic data,
- Data can be linked to other applications such as Solar Field performance evaluations, drone survey of the solar field etc.
- Long term trends assist to evaluate possible degradation of components,
- Data basis for condition-based maintenance,
- Data basis for the design of future CSP plants or hybridization with different technologies,
- Data basis for evaluations with artificial intelligence…

The project has recently been implemented and is an ongoing process. It is intended to integrate more available data, which has been gathered from other existing applications such as, for example, a Solar Field status tool or from other sources such as drone evaluations from Solar Field inspections. The same shall then be extended to other CSP plants.

Acknowledgement

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Data availability statement

The Technology Performance Assessment Platform has been developed and is property of ACWA Power. The program code and its simulation results are not publicly accessible. The results are used and are accessible to the ACWA Power and NOMAC employees of the corresponding projects.

Author contributions

Oliver Vorbrugg: Concept, Methodology, Writing, Khaled Azab: Software development, Juan Ramon Vaquero: Validation, Jose Barragan: Reviewing, Thomas Altmann: Supervision

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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