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POLYPHEM

THE FUTURE OF SMALL-SCALE CSP PLANTS

POLYPHEM

Small-Scale Solar Thermal Combined Cycle

D7.4 Final Report on System Model

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SUMMARY	*This document is the deliverable D7.4 of the project POLYPHEM. It is planned in the framework of the Work Package 7* (System Modelling and Performance Assessment). *In this WP, a finalized dynamic simulation model of the overall plant is developed in several steps. This deliverable contains the information for Task 7.4. Also in this task, a techno-economic optimization of the plant has been developed based on the objective costs of the project.* *For this purpose, Fraunhofer ISE has developed the OPTIPHEM tool chain, which is responsible for designing the plant, evaluating the optical performance of the heliostat field, simulating the annual performance of the complete system model and performing the techno-economic optimization.*
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Background: about the POLYPHEM project

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The POLYPHEM project is a research and innovation action funded by the European Union's H2020 program. It is implemented by a European consortium of 4 research centres and 5 industrial partners. The aim is to increase the flexibility and improve the performance of small solar tower power plants. The concept of POLYPHEM consists in implementing a combined cycle formed by a solarized micro gas-turbine and a Rankine organic cycle machine, with an integrated thermal storage device between the two cycles. The need for cooling is minimal.

Developed from a patented technology by CNRS and CEA, the pressurized air solar receiver is integrated in the micro-turbine cycle. The thermal efficiency targeted for the receiver is 80% with a cost of 400 €/kW. The innovative thermal storage uses a thermal oil and a single thermocline tank with a technical concrete filler material.

The main expected impact of this project is to enhance the competitiveness of low-carbon energy production systems through the technology developed. The expected progress is a better fitting of electricity generation to variable local needs, an overall conversion efficiency of solar energy into electricity of 18% for an investment cost of less than 5 €/W and a low environmental impact. By 2030, the cost of electricity production targeted by the POLYPHEM technology is 165 €/MWh for an annual direct normal irradiation of 2600 kWh/m^2/year (North Africa and Middle East) and 209 €/MWh under 2050 kWh/m^2/year (Southern Europe). In addition to decentralized power generation, other applications are considered for the deployment of this technology used in poly-generation: industrial heat production, solar heating and cooling, desalination of seawater or brackish water.

The objective of the project is to validate the technical choices under test conditions representative of actual operating conditions.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 764048

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List of Acronyms and Abbreviations

Acronym/abbreviation	Meaning/full text
µGT	Micro Gas Turbine
AALB	Aalborg CSP
ARRA	Arraela S.L.
CA	Consortium Agreement
CAPEX	Capital Expenditure (Initial Installation Cost)
CEA	Commissariat à l'Energie Atomique
CIEMAT	Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas
CNRS	Centre National de la Recherche Scientifique
CO	Confidential: only for members of the consortium (including the Commission Services)
Colsim CSP	Dynamic simulation tool used for the second step of the OPTIPHEM toolchain
CSP	Concentrated Solar Power
D	Deliverable
DevISE	Proprietary tool of Fraunhofer ISE
DNI	Direct Normal Irradiation
Ebsilon	Commercial software EBSILON® Professional
EU	European Union
EURO	Euronovia
FISE	Fraunhofer Institute for Solar Energy Systems, ISE
HTF	Heat Transfer Fluid
KAE	Kaefer Isoliertechnik GmbH
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Heat
M	Month
MS	Milestone
Nu	Nusselt number
OPEX	Operation Expenditure (Operational Costs)
OPTIPHEM	Tool chain developed by Fraunhofer ISE
ORC	'Orcan Energy AG' or 'Organic Rankine Cycle'
PU	Public
Raytrace 3D	Fraunhofer ISE in-house optical annual simulation tool
TES	Thermal Energy Storage
WP	Work Package

1. INTRODUCTION

The aim of the POLYPHEM project is to improve the flexibility and performance of small-scale concentrated solar power (CSP) plants by the novel concept of integrating a solar-driven micro gas turbine with a secondary power cycle that includes thermal energy storage (TES) and an organic Rankine cycle (ORC). One of the major challenges of the POLYPHEM concept is to optimize the integration of these components for minimizing the levelized cost of electricity (LCOE) and increasing the dispatchability of the technology.

This report presents two case study for the optimization and performance assessment of future commercial POLYPHEM-like plant using the validated models described in previous reports in work package 7. For this optimization, Fraunhofer ISE has developed the OPTIPHEM tool chain which combines design, simulation, LCOE calculation, and optimization tools specifically for POLYPHEM-like plants. Accordingly, ***Section 2*** details the annual simulation model that has been built upon the different submodules discuss in **Deliverable 7.3**. ***Section 3*** explains the functionality of the OPTIPHEM tool chain. Then ***Section 4 & 5*** demonstrate the capabilities of the POLYPHEM simulation tool and OPTIPHEM in two different locations. Finally, ***Section 6*** concludes this study.

2. POLYHPEM ANNUAL SIMULATION MODEL

Even though the POLYPHEM prototype plant was not completed at the time of this report, the individual POLYPHEM components described in **Deliverable 7.3** were modelled and partially validated within ColSimCSP simulation tool to create an entire POLYPHEM plant. ***Figure 1*** shows the ColSimCSP modelling layout for the two power cycles, in addition the simulation model includes multiple nodal measurement points, the heliostat field, weather data, and simulation printers which record the component behaviors at every time step.

The operation of these two power cycles - a 76.5 kW_e solarized µGT in the upper cycle connected to a bottom cycle that feeds the recovered exhaust heat to either a 22kW_e ORC or thermal storage cycle - and the POLYPHEM plant is determined by multiple factors such as available DNI, the ambient temperature, available exhaust heat, thermal storage, and a potential demand curve for electricity production. The following sections elaborate on the different operation modes created for the POLYPHEM plant as well as the resulting operational strategies. The focus here is put on the developments of the control and operation of the simulation model.

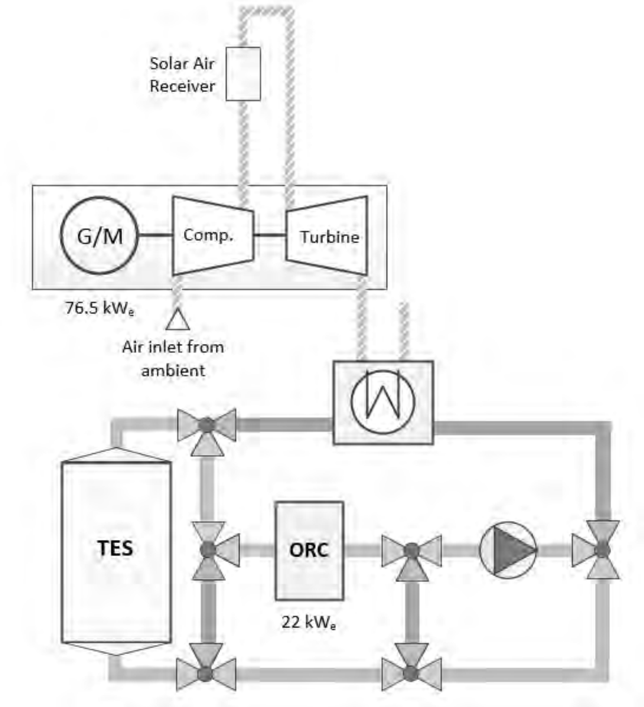

Figure 1: Simplified scheme for POLYPHEM modeled within ColSimCSP

2.1 Operation modes

2.1.1 Controller

The controller, the unit in charge of plant operation, was upgraded according to the modifications in the top cycle and the inclusion of the bottom cycle. The following functionalities were added:

- **Start up and shut down of the Micro Gas Turbine:** The µGT control was upgraded so that the start and stop command depends on the amount of heat that can be absorbed by the air as it passes through the receiver panel. As described in **Deliverable 7.3**, the start point is assumed to be the minimum absorbed thermal power value to operate the turbine at the lowest speed possible. Due to potential perturbations in heat absorption which can result in short interval start-up on/off oscillations, a hysteresis was also implemented similar to other studies (Schöttl et al. 2020) which designates the mass flow as the start-up signal.

- **Operation modes:** While the operation of the top cycle depends solely on the energy captured in the receiver panel, the bottom cycle depends on the heat recovered at the turbine outlet, the state of charge of the storage, and the demand. A plant operation mode was implemented for each of the situations, which are explained in more detail in ***Section 2.2***. These modes determine:
  - The mode of operation of the TES (charging or discharging)
  - The state of the directional valves that control the flow
  - The ORC operation mode (full load or partial load)
  - The mass flow rate provided by the pump

2.1.2 Mode 1: Solar Driven µGT and Storage Charging

In this mode, the µGT is in operation and the heat recovered in the heat exchanger is used to charge the storage. The low temperature fluid leaving the bottom of the tank is circulated through the heat exchanger to complete the charging cycle without crossing through the ORC unit, as shown in ***Figure 2***.

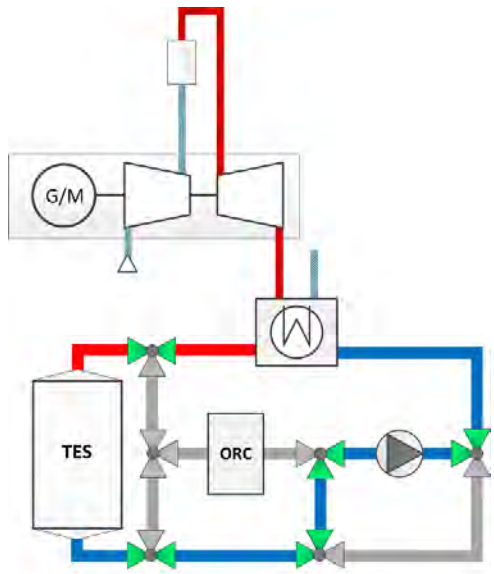

Figure 2: Simplified scheme for Mode 1: Solar driven µGT and Storage charging

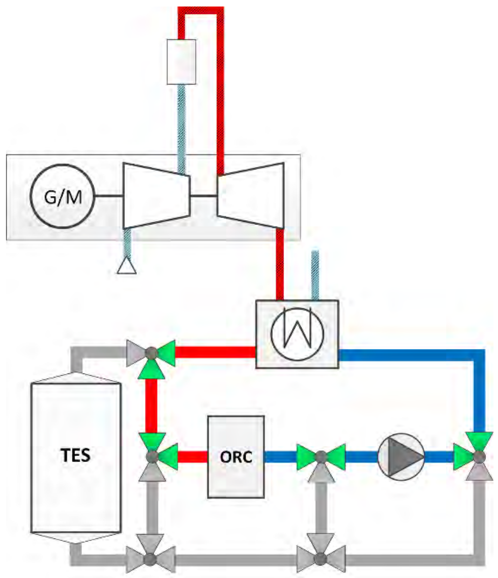

Figure 3: Simplified scheme for Mode 2: Solar driven µGT and ORC

2.1.3 Mode 2: Solar Driven µGT and Direct ORC

This mode can be used in two scenarios. In the first scenario, when the TES is fully charged and the µGT is still operating, the heat recovered in the heat exchanger can be used for full load production in the ORC, as shown in ***Figure 3***. In the second scenario, even if the TES is not fully charged, the HTF is diverted to the ORC and the pump mass flow rate is recalculated for partial load production to increase the total plant generation up to the demand. In the latter scenario, the heat recovered from the Brayton cycle is only partially utilized and thus reduces the overall plant efficiency. This situation is required in Operational Strategy 2, explained in detail in ***Section 2.2.2***.

2.1.4 Mode 3: Storage Driven ORC

This mode occurs during the night or in general in periods where the solar radiation is not sufficient for the operation of the µGT. The energy stored in the TES is used to operate the ORC at full or partial load. The high temperature fluid leaves the TES to feed the ORC, and the cold fluid exiting the ORC heat exchanger is recirculated back to the bottom of the TES tank (ref. *Figure 4*).

2.1.5 Mode 4: Thermocline Management – Bottom side

The charging and discharging of the storage are limited once the thermocline is reached (transition zone between the cold and hot layer of the storage). During the operation of the plant, this zone must be removed; otherwise, the thickness of this layer increases from cycle to cycle reducing the storage capacity and efficiency. Additionally, simulation results show that the oil temperature of part of the thermocline zone is even high enough for power production through the ORC. Therefore, an additional operation mode "Thermocline management" is defined and implemented in the tool to assess its effect on the performance and efficiency of the system.

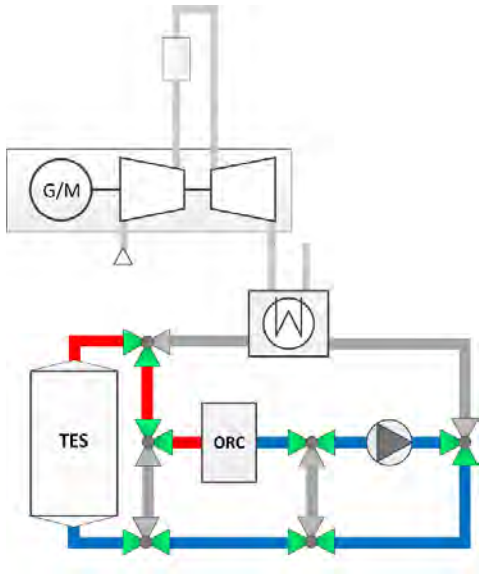

Figure 4: Simplified scheme for Mode 3: Storage driven ORC

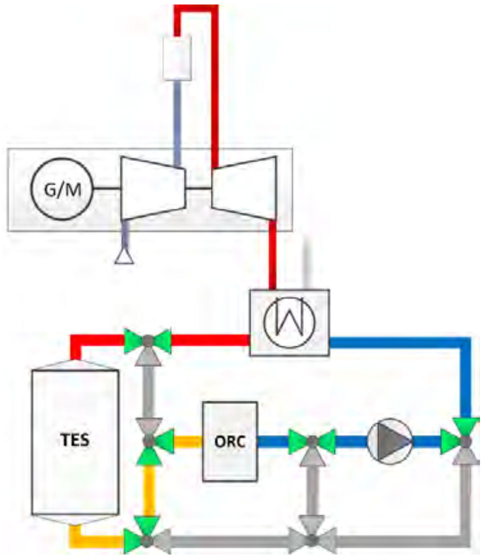

Figure 5: Simplified scheme for Mode 4: Thermocline management – Bottom side

In this operation mode, the oil in the thermocline zone is pushed, at end of a charging process, from the bottom of the tank to the ORC to destroy the thermocline and utilize the thermal energy stored in the thermocline zone. This operation mode will end when outlet temperature of TES reaches TES inlet temperature (TES fully charged + no thermocline). This can only be done as long as the heat input from RHX to secondary cycle is possible, otherwise cold oil would be introduced on top of the charged TES. This operation mode is used to run ORC after the storage is fully charged and there is still solar resource available (***ref. Figure 5***).

2.2 IMPLEMENTED CONTROL STRATEGIES

The plant configuration of the POLYPHEM project represents multiple advantages described in the background of the project. One of the main objectives is to make a more flexible and better performing CSP. To quantify these advantages, scenarios were established that would reflect the operating strategy that the plant would follow. The first scenario aims to increase the number of full load hours to increase the yield regardless of any demand profile. In the second scenario, the objective is to analyze the plant behavior while it follows a specific electricity demand, even with partial loads. However, the electricity production of the µGT in both scenarios is based on the principle to utilize all solar energy or thermal storage available and always operates at the maximum potential. If there is insufficient solar irradiation available or the thermal storage supply has been exhausted, the POLYPHEM plant ceases operations.

2.2.1 Operation Strategy 1: Increased production

This operation strategy aims to maximize the overall electric generation of a POLYPHEM plant. As shown in ***Figure 6,*** the µGT operates at full capacity while charging the thermal storage with its waste heat. As the thermal storage reaches its maximum capacity, the remaining waste heat is directed by the thermocline management to ramp-up the ORC and allow for a smooth transition to nighttime operation. After the DNI becomes insufficient and the µGT ramps down, the ORC continues to operate at full load until the storage is depleted.

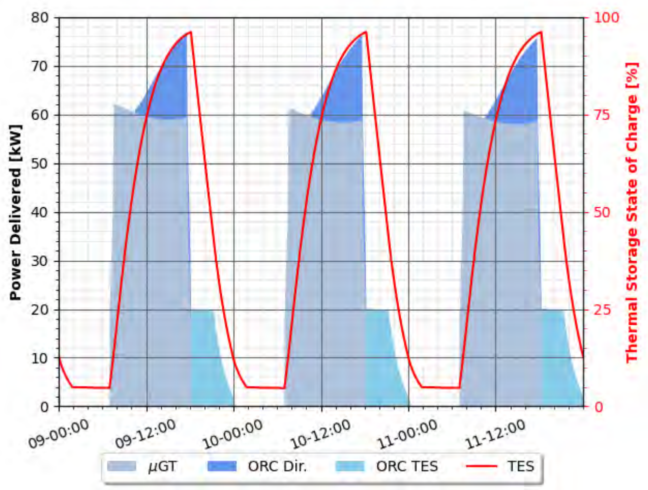

Figure 6: POLYPHEM - operational strategy for increased electricity production [Nov. 9-11]

2.2.2 Operation Strategy 2: Dispatchable production fulfilling a certain electricity demand profile

In this operation strategy, a daily demand profile is assumed for a domestic or industrial demand profile with high, constant intensity during the day and an additional peak in the afternoon (Rubio Cifuentes 2021). In this scenario (shown in ***Figure 7***), partial load operation of the ORC is adapted to complement the µGT generation during the day to meet the given demand profile (dashed line). During the time that the ORC compliments the µGT, the charging of the thermal storage is paused, leaving room for future thermocline management implementation and optimization. The summation of generation required for this operating strategy is 253.4 MWh, while 50.9 MWh (20.1%) is required for night-time dispatch.

Furthermore, modes of operation can be slightly modified for further investigations. For example, partial operation of the ORC can either powered directly by the heat recovered in the heat exchanger, or indirectly from the TES. This would allow to analyze the transient behavior of the system and the penalties caused by increased part load operation required for dispatchability. Or alternatively, the highest efficiency of the ORC is achieved when the ambient temperature is at its minimum, so a late-night demand profile would not only increase the storage production, but also provide generation when electricity production is expensive.

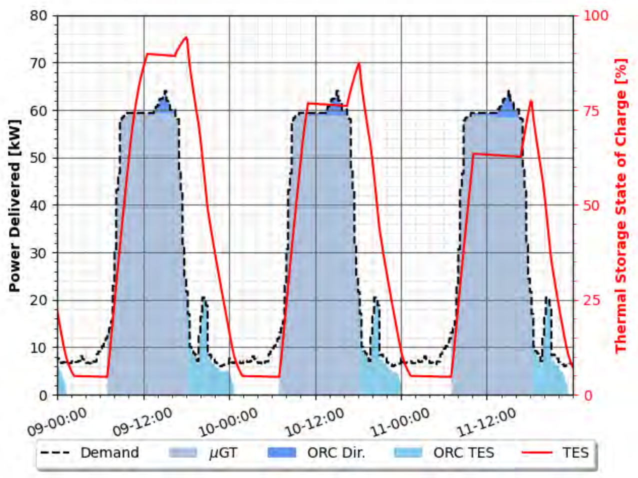

Figure 7: POLYPHEM - operational strategy to meet electricity production demand [Nov. 9-11]

3. OPTIPHEM TOOL CHAIN – The Optimization of POLYPHEM

The OPTIPHEM tool chain has been developed for the design, simulation, and techno-economic evaluation of a POLYPHEM plant. The tool chain assesses the best solution for a given specific location and ambient conditions, providing the optimal size of the plant and each component. The tool also considers different operating strategies, adjusting the sizing of multiple components accordingly. The optimization process is based on a sensitivity analysis using parametric variation approach.

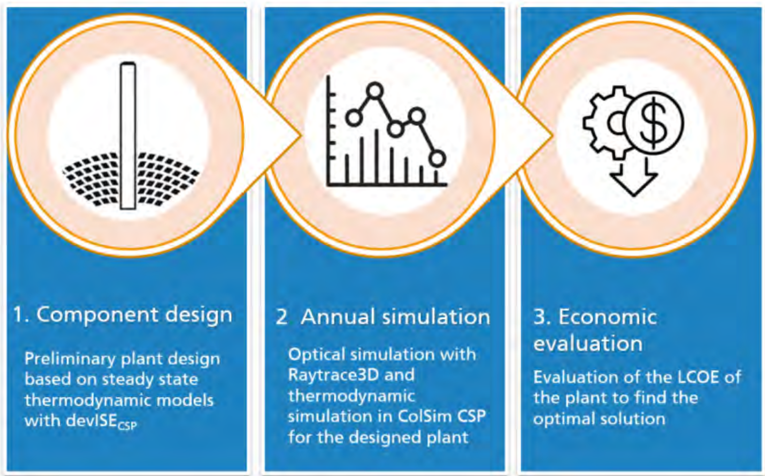

Figure 8: Data flow-chart for OPTIPHEM tool chain

This techno-economic optimization process has been divided into three steps (***Figure 8***):

1. ***Component design***: The preliminary design of the power plant is carried out, for which a simple steady state thermodynamic model of each component was developed. These models are part of DevISE, a proprietary tool of Fraunhofer ISE. In this first step, all component sizes and characteristics are defined based on the desired nominal power block conditions, plant location and storage hours.
2. ***Annual performance simulation****:* An annual simulation is performed for the results obtained from the plant design. First, an optical simulation is performed in Raytrace3D for calculating the annual performance of each Heliostat. Then, the dynamic simulation of the plant is performed based on the system model explained in ***Section 3.2***, determining the electricity output of all possible component sizes of the plant.
3. ***Economic evaluation***: The optimal size of the components of the plant is assessed according to the levelized cost of electricity (LCOE) as well as the ability to cover the demand profile.

3.1 Component Design in DevISE

The initial sizing of the components are assessed based on ambient conditions, the desired electrical power output, and the capacity of storage. For this purpose, a design model for each component of the plant was developed. Additionally, based on these component design models, a function for implementing possible sizes of the plant was developed.

3.1.1 Component design models

Component design models are component models based on steady state thermodynamic equations. Each component design model determines, with the given inputs, the most relevant parameters for the basic design and configuration of CSP plants. The µGT, heat exchanger, ORC and TES design models were initially developed in (Sasso 2019). In (Ferreres 2021), these component design models were further improved, and additionally, the air receiver and heliostat field design model were developed too.

3.1.2 Plant design function

The aim of the plant design function is to give a range of possible plant configuration, for ultimately, studying how these changes affect the annual production and cost of the plant. The function relates the output and inputs parameters of all the component design models previously defined. The function takes the gas turbine operation point from the model as starting point, and it deduces the design point of the rest of components. Then, the function defines a range below this operation point, with a deviation set by the user, for all the components.

The operation point of each component is designed for ideal conditions. Therefore, when conditions differ from this ideal situation, different sizing from the ones calculated at the design point could present a better performance. For this reason, the plant design function must be able to give a range of operation apart from the design point.

All parameters of the gas turbine are determined from either the ambient conditions, the electrical power output, or the capacity of storage. The gas turbine component design model calculates the required thermal power from the receiver at the design point. The function creates a range below this value in order to obtain the possible solar receiver geometries. In the same way, for each solar receiver, a parameter variation of the required thermal power from the heliostat field is performed, leading to several heliostat fields for each solar receiver.

The process is replicated for the bottom cycle. For sizing the heat exchanger, the exchanged thermal power between the high temperature exhaust air and the HTF were varied. For that, a variation from the nominal HTF mass flow is done, obtaining different models of the heat exchanger. Consequently, for each exchanger, the thermal storage parameters are calculated. The design point of the storage is calculated for the case in which the charging time of the TES is largest. In other words, the charging time is defined by the maximum daily high DNI hours of a year. By varying the charging time of the TES, storage tanks of different thermal capacities are defined. Similarly, changing the operation time of the ORC for each thermal storage leads also to several ORC sizes. The maximum operating time of the ORC is defined by the largest evening electricity consumption peak hours.

3.2 Annual Simulation

The annual simulation of the POLYPHEM plant is performed in two parts. First, the optical annual simulation is conducted using the Fraunhofer ISE in-house tool Raytrace3D, which determines the flux distribution on the receiver surfaces using transient sky discretization and flux map/load level interpolation. A detailed description of this methodology for POLYPHEM can be found in Deliverable D7.3.

The annual optical simulation profiles are then incorporated into the POLYPHEM system simulation model within ColSimCSP. From ColSimCSP, the annual performance of a POLYPHEM plant can be analyzed and evaluated due to the 60-second resolution of the results. Detailed information about ColSimCSP can be found in Deliverable D7.3 and Deliverable D7.1.

3.3 TECHNO-ECONOMIC EVALUATION

The last step in the optimization process is the performance evaluation of each simulated case (variation of size of the components). For this purpose, the levelized cost of electricity (LCOE) is used as the economic indicator while the demand coverage is also evaluated as a figure of merit to avoid the optimization tool selecting a configuration with low LCOE but also very low demand coverage.

The LCOE represents the electricity selling price per unit of generated electricity that would be required to recover the costs of investment and operation of the power plant over its lifetime. LCOE is widely used for comparing the economic competitiveness of different electricity generation systems. Additionally, it is used to determine required governmental financial support or as consistent basis for comparison of offers in competitive tenders.

As described in the following equation (Christoph Kost et al. 2021), the LCOE is calculated by the sum of the costs divided by the discounted energy production of the power plant over the lifetime:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t + F_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

where I_0 corresponds to the initial capital expenditure, A_t refers to the annual operational costs, F_t refers to the annual fuel or electricity purchased in year t, $M_{t,el}$ is the electricity generated (kWh) by the plant in year t, i is the real interest rate, t is the operational year, and n is the lifetime of the plant in years.

According to previous studies (Ferreres 2021), the lifetime is taken as 30 years and the operational costs (OPEX) were taken as 2% of initial installation cost (CAPEX). The production cost figures, shown in ***Table 1***, were determined in Deliverable D8.2 and are assumed to be the benchmark investment cost. Additionally, country specific real interest rates were assumed (2.5% for Chile and 7.5% for Namibia).

Table 1: Investment cost based on Target cost of POLYPHEM project

Component	Production Cost [€]	Size - Capacity
Solar Field	87.3 €/m²	1920-2100 m²
Solar Receiver	454 €/kW_{th}	534.6 kW_{th}
Solar Tower	625 €/m	40 m
Solarized micro Gas Turbine	1530 €/kW_{el}	76.5 kW_{el}
Heat exchanger	317.5 €/m²	126 m²
Organic Rankine Cycle	1800 €/kW_{el}	22 kW_{el}
Thermal Energy Storage	37.5 €/kWh	1600 kWh
Plant Controls	50 000 €	-
Balance of Plant	34 000 €	-
Contingencies	10% of Hybrid Solar Cycle (Top & Bottom)	

3.4 BOUNDARY CONDITIONS

For this report, the POLYPHEM system was analyzed in two different locations with two different operating strategies. The capacities of the solar field, receiver capacity, the thermocline storage was parameterized according to values shown in ***Table 2*** in order to investigate their impact on the overall system LCOE. The two locations, the Antofagasta region in Chile and region surrounding Keetmanshoop in Namibia, have accumulated DNI over 2900 kWh/m² per year. The design point condition for both locations was considered to have a design DNI of 950 W/m² and an ambient temperature of 15 C°.

Table 2: Optimization Range for the different POLYPHEM Parameters

Component	Range
Solar Field Area	700 – 2200 m²
Solar Receiver Size	±15% of Design Point
Thermal Storage Size	1.0 – 2.6 MWh_{th}

For the Antofagasta region, the first operating strategy, where POLPYHEM generates the maximum amount of generation possible, was considered since there is a large mining industry in the area. The optimization process for this location will also be detailed and what assumptions are taken to determine an optimized POLPYHEM configuration. For the location surrounding Keetmanshoop, the results of both operation strategies, maximum generation and the following of a demand curve, were investigated to demonstrate the respective performance of both strategies.

4. OPTIMIZATION RESULTS: ANTOFAGASTA REGION, CHILE

For the Antofagasta region optimization process, over 180 different cases were evaluated from the parameter ranges given in ***Table 2***. As seen in ***Figure 9***, as the simulations increase, the annual yield increases while the LCOE trends downward. The initial design point simulation had a solar field area of 960 m² and annual yield of 200 MWh and a LCOE of 23.8 c€/kWh. Alternatively, the optimized simulation case had a solar field area of 1920 m², a 10% increase in solar receiver size, and a thermal storage capacity of 1.6 MWh. The annual yield of the optimized configuration generated 270.6 MWh of electricity, where the micro gas turbine accounted for nearly 80% of the generation while generation directly from the heat exchanger or thermal storage to the ORC accounted for 10% each (ref. ***Figure 10***). While these improvements increased the CAPEX from €759 000 to €834 200, they ultimately reduced the LCOE by 12.1% to achieve 20.9 c€/kWh.

Considering that the optimized solution does not have the highest annual yield, lowest LCOE, and a relatively large solar field area, how was the optimized simulation case determined? The following sections will discuss the different impacts the solar field sizing due to cost assumptions and the thermal storage size have on the optimization process.

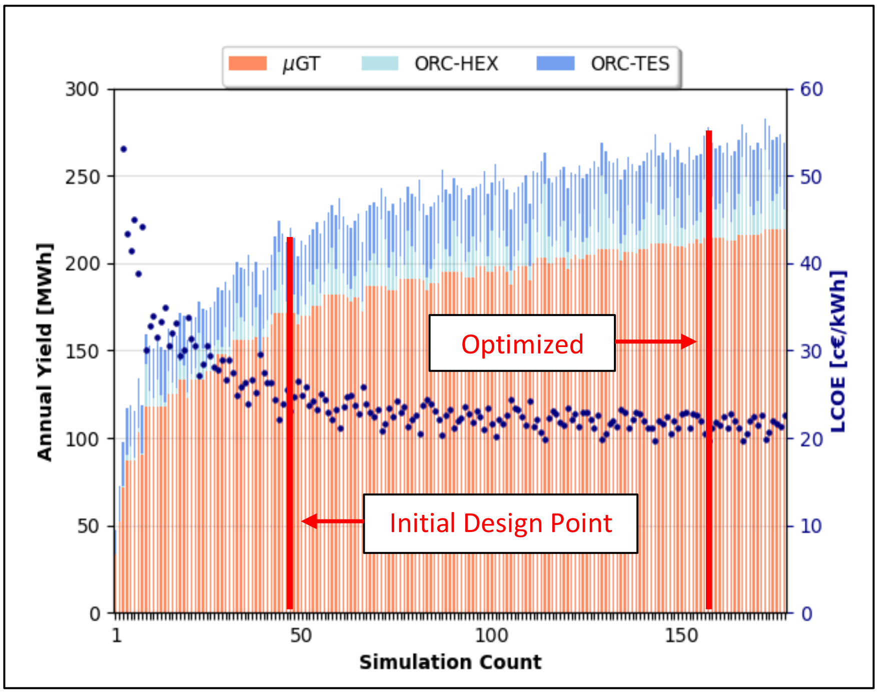

Figure 9: POLYPHEM - Annual Yield vs LCOE of the OPTIPHEM Parameterization in the Antofagasta Region, Chile (blue dots represent the LCOE on the left Y-axis)

4.1 Optimization of Solar Field

The initial design point POYLPHEM configuration has a solar field area of 960m² and a receiver area of 0.93 m² while the optimized has double the solar field area, 1920 m² and a slightly larger receiver area of 1.02m². As seen in ***Figure 10***, with the optimized improvements, the yield increases by 69.5 MWh or 34.3%, Since the micro-gas turbine is the primary source of electricity production for POLYPHEM, the 26% increase of the micro gas turbine yield allows for a further increase for the ORC production directly from the heat exchanger (+44%) and the ORC from the storage (+4.8%).

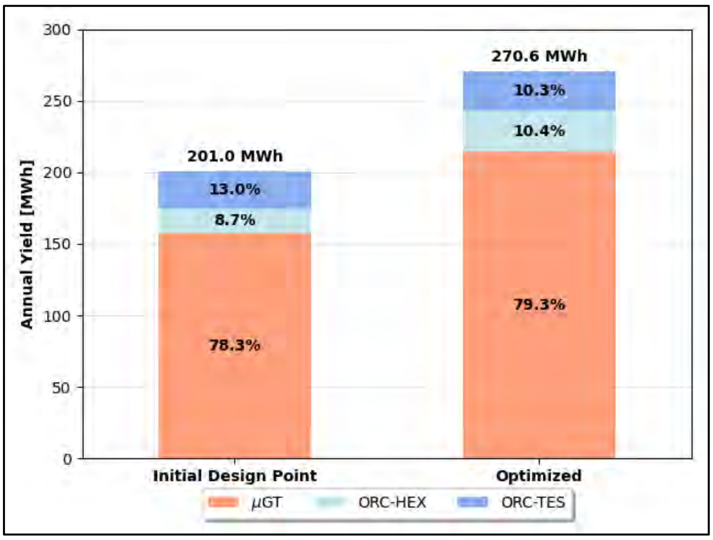

Figure 10: POLYPHEM - Annual Yield Evaluation – Initial Design Point vs. Optimized Configuration

From ***Figure 11***, the three winter days demonstrates the benefit of increasing the solar field size. On the third day there is a sufficient amount of DNI so the initial configuration can absorb a large portion of the available heat without dumping, while the optimized configuration is able to extend operation in the morning and evening but must dump or defocus a significant amount of the available heat. Alternatively, the insufficient DNI during the first two days reduces the absorption capabilities for the initial design while the optimized design has a sufficient amount of heat available.

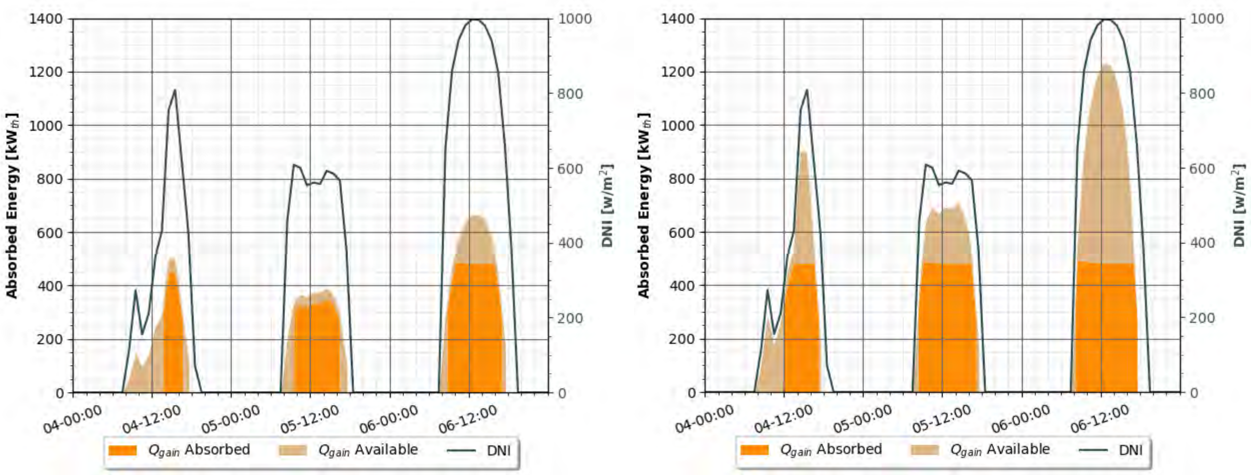

Figure 11: POLYPHEM - Evaluation of Heat Absorption – Initial Design Point vs. Optimized Configuration

Overall, the optimized POLYPHEM configuration increased the overall energy absorption by 19% while the dumped energy increased from 29% to 46%. It is important to note (reference ***Figure 12***), that the annual heliostat field efficiency of the heliostat field only slightly decreased from 67.4% to 61.2%. It is clear that the increase of solar field and panel receiver area can improve the operational performance of the POLYPHEM configuration, but are the costs justified?

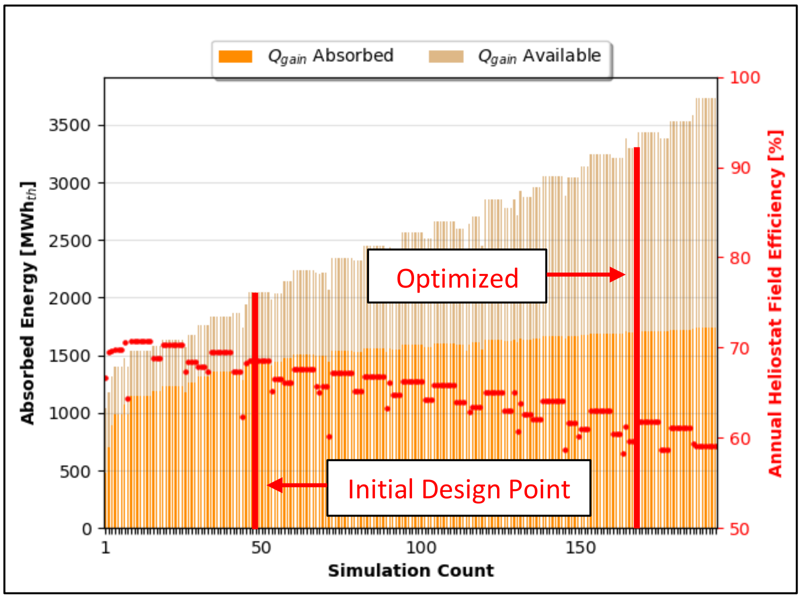

Figure 12: Annual Absorbed Energy vs Heliostat Field Efficiency Results of the OPTHIPHEM Parameterization in the Antofagasta Region, Chile

By increasing the solar field area, the CAPEX increased by 9.5%, but reduced the LCOE by 12%. Alternatively, the sensitivity analysis, shown in ***Table 3***, demonstrates the pricing of the solar field components do have impact the techno-economic optimization. If the solar field component cost was increased to 90 – 110 €/m², the size of the optimized solar field decreases by 7%. Moreover, if the solar field cost was to exceed 115 €/m², then the optimized solar field size would decrease by 14%.

Table 3: Sensitivity analysis of POLYPHEM Solar Field Component Costs for Chile

Percentage Increase of Solar Field Comp. Cost	Optimized Solar Field Area	Annual Yield	Percentage Increase of CAPEX	Estimated LCOE
0%	1920 m²	270.6 MWh	-	20.9 c€/kWh
5 – 30%	1780 m²	266.6 MWh	-0.5% – 4.1%	21.1 – 22.1 c€/kWh
35 – 50%	1650 m²	262.0 MWh	3.2% – 5.8%	22.3 – 22.8 c€/kWh

4.2 Optimization of Thermal Storage Size

Since the ORC and thermal storage function as a waste heat recovery cycle, the bottom cycle is limited to the micro gas turbine exhaust. If maximum generation was the main target of POLYPHEM, the recovery heat exchanger would feed directly to the ORC and the thermal storage would not be considered due to its costs. However, since night-time generation is a valuable asset, the sizing of the thermal storage becomes a question of optimization based on costs and utilization.

One method of measuring the utilization of the thermocline storage is to count how many days per year the storage state of charge meets a pre-defined threshold. The three summer days, for example, shown in ***Figure 13*** shows that the POLYPHEM configuration with 1.6 MWh of storage achieves 95% storage state of charge and is therefore fully charged. Alternatively, if the days were winter or the storage size was larger, then the state of charge might only achieve 85%.

With this approach, simulations cases with increasing solar field per increasing thermal energy storage size can be evaluated in ***Figure 13*** and ***Figure 14***, where the blue dot shows the LCOE per simulation case. In ***Figure 13***, the thermal storage sizes smaller than 2.0 MWh are charged greater than 85% nearly the entire year while the largest storage size considered, 2.6 MWh, cannot meet the 85% threshold more than half of the year. Furthermore, as the storage size increases, the LCOE gradually increases which is due to heat losses within the thermal storage but mainly greater costs for a larger storage system. Additionally, for storage sizes greater than 1.0MWh, the 1920 m² was the optimized solar field area for every storage size. This is likely due to small contribution the bottom cycle has on the overall generation of the POLYPHEM plant.

In ***Figure 14***, the ability for the thermal storage sizes to achieve 95% storage state of charge decreases notably. Storage sizes greater than 2.0 MWh never exceed the 95% threshold throughout the year, implying that they are consequentially oversized. Conversely, the smaller sizes of 1.0 and 1.4 MWh are undersized, since they are fully charged almost every day of the year. While a storage size of 1.8 MWh can occasionally meet the 95% threshold, the storage size of 1.6 MWh meets this target more than 200 days per year. While further optimization can be conducted, the configuration (shown with the red line in both figures) with 1.6 MWh and a solar field area of 1920 m² was determined since the storage islarge enough to meet after-operation demands but small enough that it is fully charged approximately two thirds of the year.

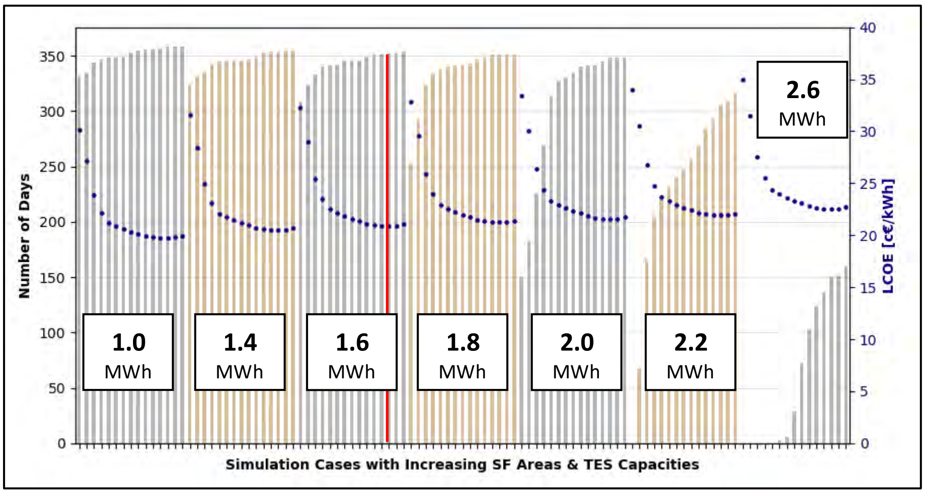

Figure 13: Days per Year where a POLYPHEM Configuration Storage State of Charge (S.o.C) surpasses 85% in the Antofagasta Region, Chile

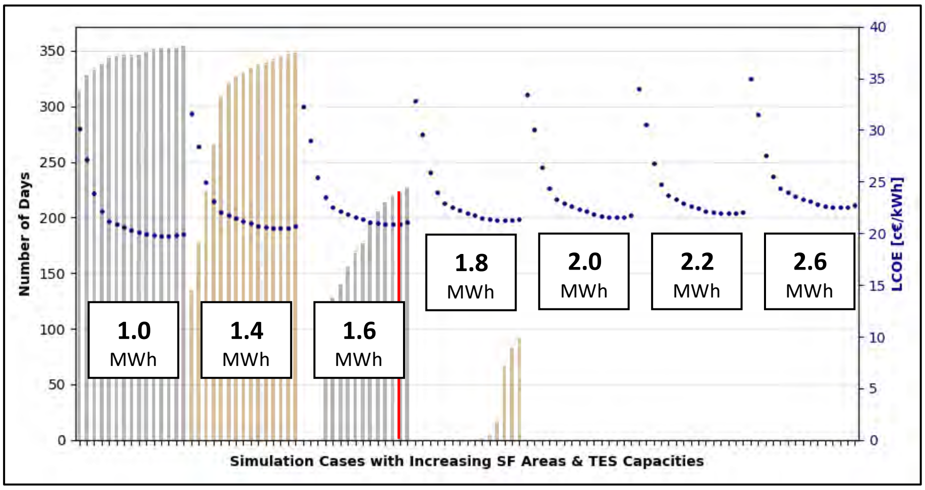

Figure 14: Days per Year where a POLYPHEM Configuration Storage State of Charge (S.o.C) surpasses 95% in the Antofagasta Region, Chile

5. OPTIMIZATION RESULTS: KEETMANSHOOP REGION, NAMIBIA

In the previous section, the OPTIPHEM optimization process focused on the first operating strategy, maximum yield generation, and explored the different reasons how the optimized configuration was determined. In this section, the second operating strategy, following a demand curve, is investigated for the region surrounding Keetmanshoop, Namibia. In order to do so, the optimization for Operation Strategy 1, as described in ***Section 4***, was conducted in order to determine the configuration with the highest yield potential. After the configuration was determined, the second operating strategy was employed with increasing thermal storage sizes for evaluation.

5.1 OPTIPHEM WITH OPERATION STRATEGY 1: MAXIMUM YIELD

For the Keetmanshoop region study, nearly 100 different cases assuming the maximum yield operating strategy were evaluated with the same parameter ranges given in ***Table 2***, but just with fewer steps. While the trend in ***Figure 15*** is similar to ***Figure 9***, a slightly lower annual yield, caused by the lower DNI, and an increased LCOE by approximately 60%, caused by higher real interest rate (7.5% compared to 2.5% in Chile), are seen. As the simulations increase, the annual yield increases while the LCOE trends downward.

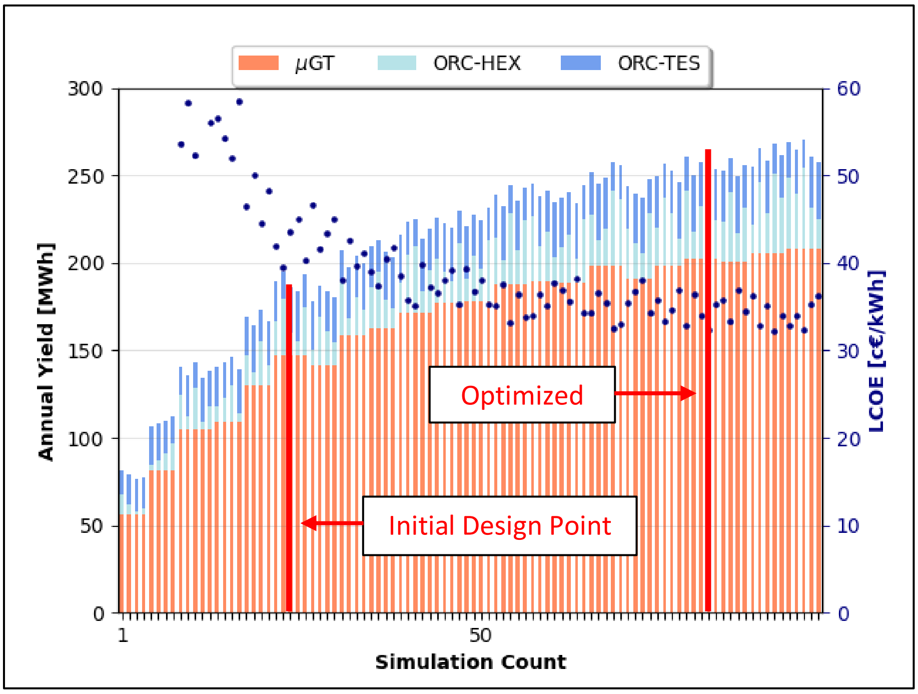

Figure 15: POLYPHEM - Annual Yield vs LCOE of the OPTIPHEM Parameterization in the Keetmanshoop Region, Namibia

The initial design point simulation had a solar field area of 970 m², annual yield of 169 MWh, and an LCOE of 46.3 c€/kWh. Using same optimization process discussed in ***Section 4***, the optimized POLYPHEM configuration had a solar field area of 2100 m², a 10% increase in solar receiver size, and a thermal storage capacity of 1.6 MWh. The annual yield of the optimized configuration generated 261.6 MWh of electricity, where the micro gas turbine accounted for 78.5% of the generation while ORC generation directly from the heat exchanger or thermal storage accounted for 12% and 9.5% respectively.

Similarly, a sensitivity analysis of the solar field costs was performed and is shown in ***Table 4***. The CAPEX of the optimized system, 849 900€, is only a 1.2% increase compared to the Antofagasta configuration, but the higher real interest rate assumed makes the cost of the solar field less sensitive to increases in pricing. Only when the solar field component pricing exceeds 105 €/m² is the optimization effected.

Table 4: Sensitivity analysis of POLYPHEM Solar Field Component Costs for Namibia

Percentage Increase of Solar Field Comp. Cost	Optimized Solar Field Area	Annual Yield	Percentage Increase of CAPEX	Estimated LCOE
0 – 15%	2100 m^2	261.9 MWh	1% – 2.1%	34.0 – 34.7 c€/kWh
20 – 50%	1940 m^2	257.1 MWh	1.3% – 8.2%	35.1 – 37.5 c€/kWh

5.2 OPTIPHEM WITH OPERATION STRATEGY 2: FOLLOWING A DEMAND CURVE

In ***Section 4.2***, the size of the thermal storage, how many days it can fully charge, and its corresponding impact on the LCOE for the maximized yield operation strategy were discussed and analyzed. However, the thermal storage system has a crucial function to meet the coverage demand in the second operational strategy, specifically during the hours where the µGT does not operate.

Using the optimized configuration with a panel receiver area increased by 10% (1.03 m^2) and a 2100 m^2 solar field area, the second operation strategy was evaluated against increasing storage sizes. Overall, the annual yield of the second operating strategy was 7 to 11% less than the first operating strategy. Seen in ***Figure 16***, as the storage size increases, the difference in annual night-time yield between the two operating strategies also increases from 15% to 22%. The first operation strategy experiences an 83% improvement when the 1.0 MWh storage is compared against the 2.6 MWh storage while the second operating strategy experiences a 69% improvement.

The main reason for these differences is primarily the fact that the second operating strategy does not have the thermocline management integrated. During the operational periods where the ORC assists the µGT generation, the storage charging stops, and the ORC operates. If an improved thermocline management strategy were introduced to simultaneously charge the storage and assist the µGT, these differences would reduce significantly.

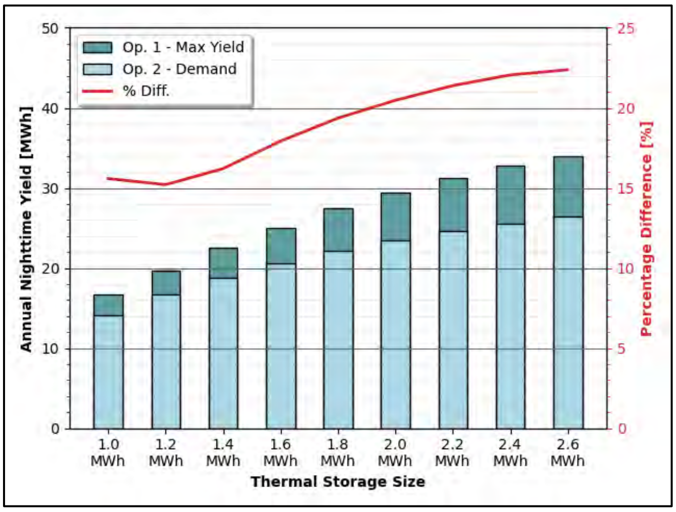

Figure 16: POLYPHEM - Comparison of Annual Night-time Yield for Both Operation

Considering that the night-time yield could be further improved for the second operating strategy, this would also increase the ability of POLYPHEM to meet the total demand coverage. As the operating strategy currently performs, POLYPHEM meets 76.5 – 81.2% of the total coverage demand (ref. ***Figure 17***). Since the solar field area and the resulting µGT generation is not affected by the bottom cycle, the improved performance is due to the increased storage size. Increasing the size of storage from 1.0MWh to 2.6 MWh improves the ability for POLYPHEM to meet the night-time demand coverage from 34% to nearly 60%, a 70% overall improvement. This translates to a 6% improvement in POLYPHEM's ability to meet the total demand coverage, where the night-time requirements account for 20% (MWh) of the 253.41 MWh total annual coverage demand.

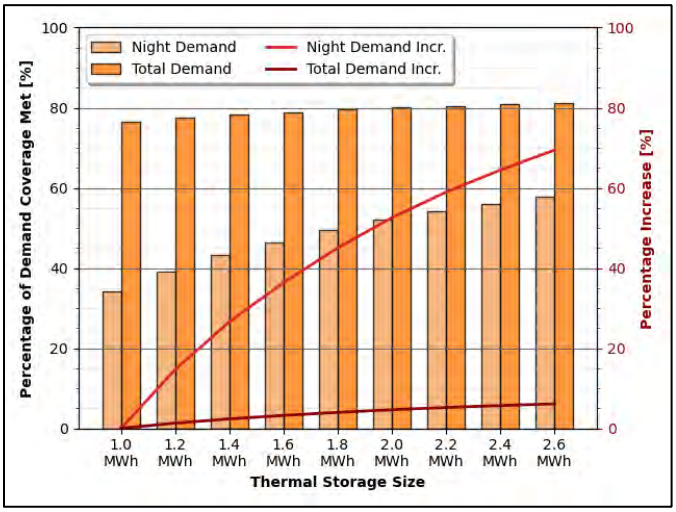

Figure 17: Comparisons of POLYPHEM's Ability to Meet the Night-Time and Total Demand Coverage

While a larger thermal storage size increases POLYPHEM's ability to meet the night-time demand curve, it also increases the overall CAPEX. From ***Figure 18***, there is a linear increase in the overall POLYPHEM CAPEX from 0% to approximately 6%. The contribution of the thermal storage cost to the overall POLYPHEM CAPEX is also linear, accounting for 3.4% of the total CAPEX for 1.0 MWh of storage and 8.2% for a 2.6 MWh.

The linear increase can also be compared against the concave percentage increase of the ability for POLYPHEM to meet the total demand (also shown in ***Figure 17***). For a storage size of 1.2 or 2.6 MWh, the relative percentage difference between the CAPEX increase and the increase of total demand is approximately 0.5%. Alternatively, for the 1.6, 1.8 and 2.0 MWh storage sizes, a relative percentage difference of 0.99%, 1.01%, and 0.94% is experienced respectively. From this information, this relative difference offers a potential area for further techno-economic optimization when deciding which configuration meets the highest demand for the least amount of capital. However, the optimized configuration for the second operation strategy ultimately depends on the importance and financial incentive of meeting the demand curve.

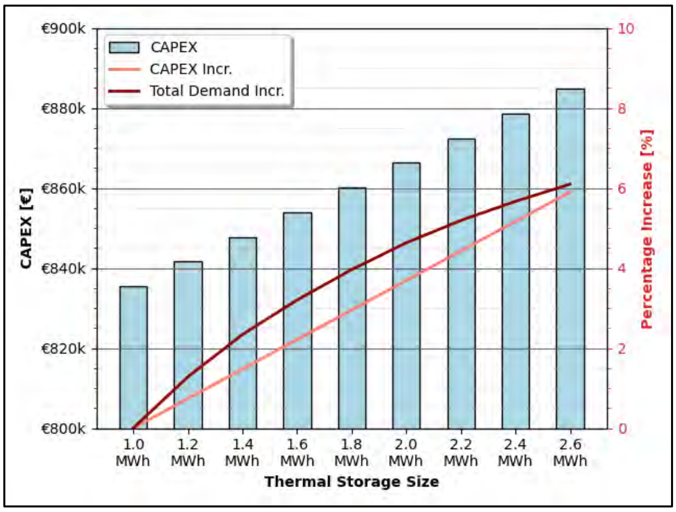

Figure 18: POLYPHEM - Comparison Thermal Storage Cost and Total Demand Coverage Met

6. CONCLUSION

The OPTIPHEM tool chain indicates advantages for the design, simulation, and optimization of small-scale CSP tower plants. The variability of parameters in the execution of simulations allows finding operation strategies that optimize the production for specific purposes. Two operating strategies in two different locations with favourable meteorological conditions were investigated. In the region surrounding Antofagasta, Chile an operation strategy to provide maximum generation was investigated and, in the region, surrounding Keetmanshoop, Namibia the strategy for POLYPHEM to follow a demand curve was considered. For the maximum generation, thermocline management was incorporated which allowed for the simultaneous operation of charging the thermal storage and operation of the ORC.

The simulation results show that while an optimized LCOE for the maximum generation operation strategy can be achieved, factors including the sizing of the solar field, solar field component cost and the thermal storage can alter the “optimized” configuration. Low component costs with a low real interest rate resulted in an oversized solar field, which increased the total heat available per year which ultimately increased the annual generation and decreased the LCOE. Depending on the economic conditions, optimized configurations in areas with low real interest rate are more sensitive to component costs than areas with a high real interest rate.

The importance of the thermal storage was demonstrated when POLYPHEM was required to follow a demand curve. Depending on the size of the thermal storage, POLYPHEM was able to meet up to 81% of the total demand. However, this operational strategy could be further optimized by including thermocline management.

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