Optimization of Asymmetric Solar Receiver Design in High-Performance Thermosolar Plant in Synergy with PV-Hybrid Autonomous Heliostats

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Abstract. The PHOTON project, also titled "*High Performance Thermosolar Plants based on PV-Hybrid Autonomous Heliostats and Tailored Receivers*", aims to obtain a new and competitive solar thermal electric plant configuration, simplifying the current assembly and commissioning operations. The project targets increases in the global plant efficiency and improvements of the production/cost ratio making solar power a dispatchable competitive energy source. Within the project, Aalborg CSP A/S collaborates with the four project partners Acciona Industrial, S.A., Thermal Power Engineering, S.L., Applied Research Institute for Prospective Technologies, and Metsolar to reach the project vision. This paper concerns Aalborg CSP's part in the project concerning development, design, and optimization of the solar thermal power tower molten solar receiver (MSR), in synergy with the PV-hybrid autonomous heliostat development. When comparing the MSR geometry, it is found that the asymmetric MSR designs score higher ratings than both the symmetric and base case designs. The 50 MWe asymmetric design is found to be more pronounced than the 100 MWe asymmetric design, since the 50 MWe design case requires a smaller solar field, thereby obtaining a higher optical quality of the heliostats. For the 50 MWe asymmetric design case, more than 20% of the tube material costs can be saved, while for the 100 MWe asymmetric design case, more than 13% of the tube material costs can be saved. The MSR efficiency increases from 91.8 to 92.1 for the 100 MWe design case, and from 91.3 to 92.1 for the 50 MWe design case. However, in all current simulations, Pyromark 2500 has been applied. It should be noted that the MSR efficiency can be further increased based on alternative coating selections (indications show up to 2.94%). As of now, the EPC cost is reduced by 14.41%, and the combination of the solar field, solar receiver and power block optimization has increased the global efficiency of the plant with 2.96%. An LCOE reduction of up to 13.34% has been achieved, resulting in less space requirements (e.g. up to 29.7% for the solar field in the 100 MWe-case with two-facet heliostats) and less solar energy requirements to produce the same amount of electricity annually as the base cases. Furthermore, improvements have been implemented in the power block system to reduce the auxiliary consumptions during normal operation. The project has received financial support from the Eurostars™-2 program as well as funding from Innovation Fund Denmark.

Keywords. Concentrated Solar Power (CSP), solar thermal electric plant, cost optimization, CAPEX, OPEX, heat transfer, flux map, 2D simulation, external solar receiver design, Molten Salt Receiver (MSR), solar receiver optimization, asymmetric design, solar field optimization, Visual Basic (VB).

PROJECT INTRODUCTION

The PHOTON project, also titled "*High Performance Thermosolar Plants based on PV-Hybrid Autonomous Heliostats and Tailored Receivers*" [1], aims to obtain a new and competitive solar thermal electric plant configuration[1], simplifying the current assembly and commissioning operations. Therefore, a new disruptive solar field concept is developed, and a solar receiver is designed and optimized specifically to this concept. The concept allows the solar thermal electric plant to reduce costs, including auxiliary equipment, and increase the global efficiency to improve the production/cost ratio and the LCOE of this technology, regarding State-of-the-Art references.

Thus, the project targets an improvement of the production/cost ratio, including both CAPEX and OPEX, and an increase in the solar thermal electric plant's global efficiency as keys to making solar power a dispatchable competitive energy source. The overall goal of the project is to achieve a cost reduction of 25% and increase the annual electricity production with 5% [1] (or equivalently increase the plant's global efficiency [2]).

The PHOTON project started in October 2017 and lasts for approx. 2 years, ending in January 2020. Within the project, *Aalborg CSP A/S* ("Aalborg CSP") closely collaborates with the four project partners *Acciona Industrial, S.A.* ("Acciona"), *Thermal Power Engineering, S.L.* ("Tewer"), *Applied Research Institute for Prospective Technologies* ("Protech") and *Modern E-Technologies* ("Metsolar") to reach the project's vision, as shown in Fig. 1.

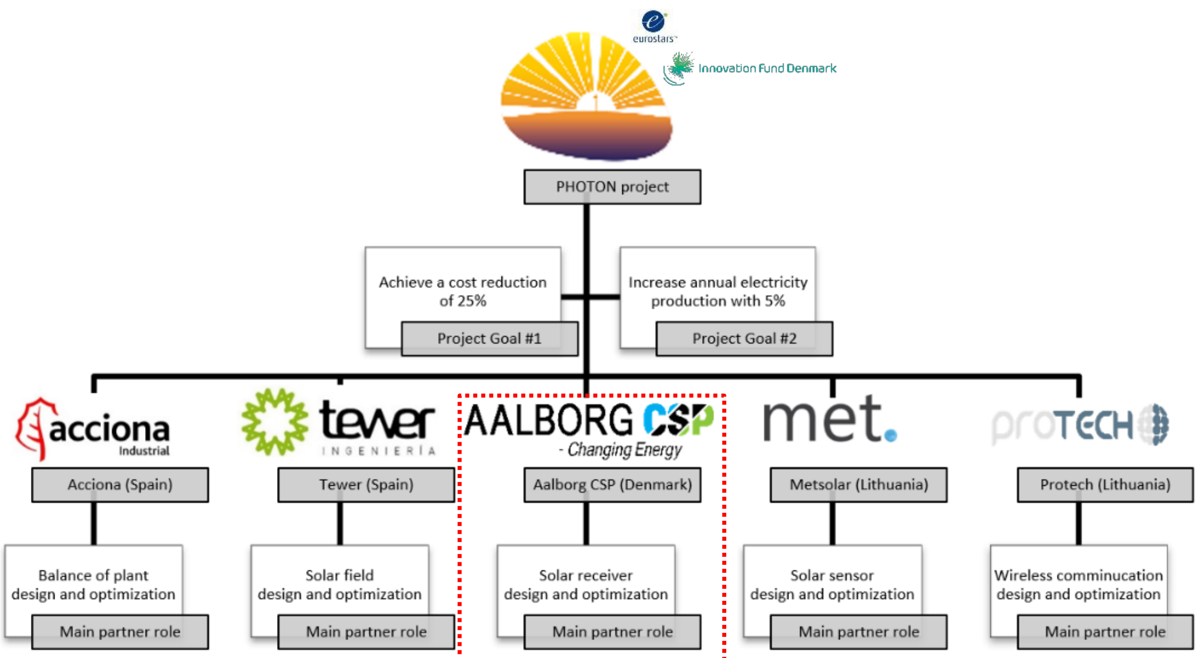


FIGURE 1. The PHOTON project: Project goals, project partners and main partner roles.

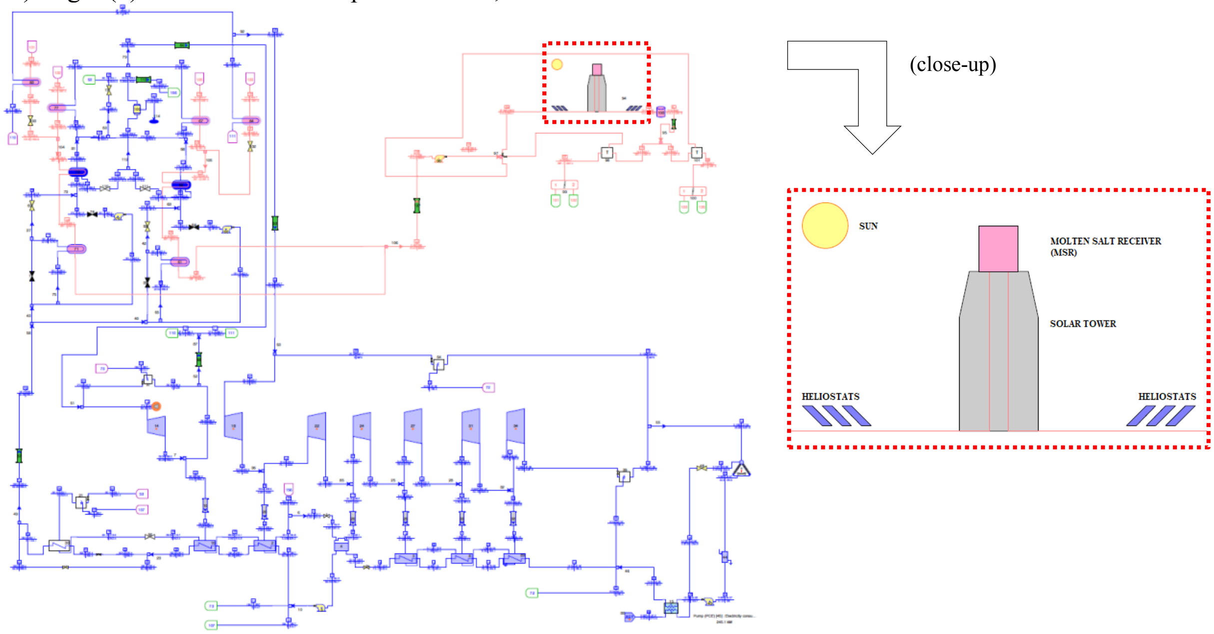
Aalborg CSP's project role (dotted box) mainly concerns the development, design and optimization of the solar thermal power tower receiver. The solar receiver absorbs energy from the sun and utilizes molten salt (MS) as heat transfer fluid. Throughout the project, several alternative case solutions have been investigated and compared to State-of-the-Art references[2].

This paper focuses on the 50 – 100 MWe alternative case solutions obtained so far. These cases are designed in cooperation with project partners to get an ISO-production[3] energy output. Thus, the designs do not have a direct increase in annual electricity production; instead, the designs require overall less space and less solar energy to produce the same amount of annual electricity, as in the base cases (i.e. state-of-the-art references) [2].

[1] Foot note: According to the IEC TC 177.
[2] Foot note: As State-of-the-Art references, the following projects have been used: Atacama I, Noor III, Redstone and Noor Midelt I (proposal) [2].
[3] Foot note: The ISO-production is a base comparison. It is not a specific methodology, however, it is a valid and recommended approach when determining the CAPEX and LCOE-reduction of a project [2].

SOLAR THERMAL ELECTRIC PLANT SYSTEM OVERVIEW

The PHOTON project addresses a solar thermal electric plant system configuration as shown in Fig. 2. In Fig. 2(a), the solar thermal power tower and surrounding solar field (heliostats) are highlighted in the upper right corner (dotted box). Fig. 2(b) illustrates a close-up of the same, shown with labels.



(a) (b)

FIGURE 2. The PHOTON project: Solar thermal electric plant system configuration with highlighted solar thermal power tower (100 MWe case example – property of Acciona) [3].

The solar thermal electric plant is simulated according to Typical Meteorological Year (TMY) data at a given geolocation on the Southern hemisphere (28.3 S, 23.35 E), due to the existence of data from other solar thermal electric plants in that area [4].

Within the scope of the PHOTON project, it has been agreed to address solar thermal electric plants in three sizes: 50/100/150 MWe. The selection of these solar receiver capacities is based – among other things – on the reference plants and market trends within the CSP market. Currently, there are several solar thermal electric plants, in operation and under construction, that include an external solar receiver using molten salt as heat transfer fluid. Table 1 and 2 below illustrate the solar tower power plants in operation and under construction, as of July 2019, within the initial range of the PHOTON project capacity (50/100/150 MWe) [5][6].

TABLE 1. Selected list of solar thermal power tower projects with a net turbine capacity of 50 MWe (July 2019) [5][6].

CSP PROJECT NAME (in short)	TYPE OF CSP PROJECT	GROSS / NET CAPACITY [MWe]	CURRENT STATUS [a)]	HOURS OF STORAGE	HELIOSTAT AREA [m^2]
CPECC Hami	Demo project	50 / 50	UC	13	696,751
Luneng Haixi	CSP plant	50 / 50	UC	12	607,200
Qinghai Gonghe	Demo project	50 / 50	UC	6	N.A.
SUPCON Delingha	Demo project	50 / 50	OP	7	542,700
Yumen Xinneng	Demo project	50 / 50	UC	6	N.A.

[a)] Abbreviations: UC = Under Construction; OP = Operational.

As seen in Table 1, several 50 MWe solar thermal power tower projects exist either in operation or under construction (status as of July 2019).

TABLE 2. Selected list of solar thermal power tower projects with net turbine capacities of 100-150 MWe (July 2019) [5][6].

CSP PROJECT NAME (in short)	TYPE OF CSP PROJECT	GROSS / NET CAPACITY [MWe]	CURRENT STATUS [a)]	HOURS OF STORAGE	HELIOSTAT AREA [m^2]
DEWA CSP Unit 1	CSP plant	100 / 100	UC	15	N.A.
Shouhang Dunhuang	Demo project	100 / 100	OP	11	N.A.
Cerro Dominador	CSP plant	110 / 110	UC	17.5	1,484,000
Crescent Dunes SE	CSP plant	110 / 110	OP	10	1,197,148
Noor III	CSP plant	150 / 134	OP	7	1,036,000

a) Abbreviations: UC = Under Construction; OP = Operational.

In Table 2, it is evident that several 100-110 MWe solar thermal power tower projects exist either in operation or under construction (status as of July 2019), and only one plant has a gross capacity of 150 MWe. Thus, the PHOTON project focuses on two solar thermal electric plant capacities – 50 MWe and 100 MWe – and uses as reference a solar thermal electric plant of 100 MWe (net power) with a storage capacity of 14 hours and a solar field of 1,100,000 m^2 (the Redstone-project) [5].

STATE-OF-THE-ART MSR DESIGN & PHOTON HELIOSTAT DEVELOPMENT

Solar Thermal Electric Plant – Base Case Definitions

In the following sections, the basis for the Aalborg CSP MSR designs are presented and subsequently, details regarding the design and optimization of the Aalborg CSP MSR will follow. Thus, the following sections will support the comparative study shown next. The MSR is designed as an external solar receiver with a cylindrical shape, and the agreed MSR technology base case design geometry and operation limits are listed in Table 3 [8].

TABLE 3. The PHOTON project: PHOTON receiver technology base design geometry and operation limits [8].

PARAMETER		100 MWe DESIGN CASE	50 MWe DESIGN CASE	UNIT
Min. Receiver Rating	:	140	75	[MW_{th}]
Max. Receiver Rating	:	565	300	[MW_{th}]
Centre Height	:	180	155	[m]
Receiver Height	:	20.00	15.00	[m]
Receiver Diameter	:	14.90	12.85	[m]
Heat Transfer Area	:	936.2	605.5	[m^2]
Max. Peak Flux Density	:	1265	1265	[kW/m^2]

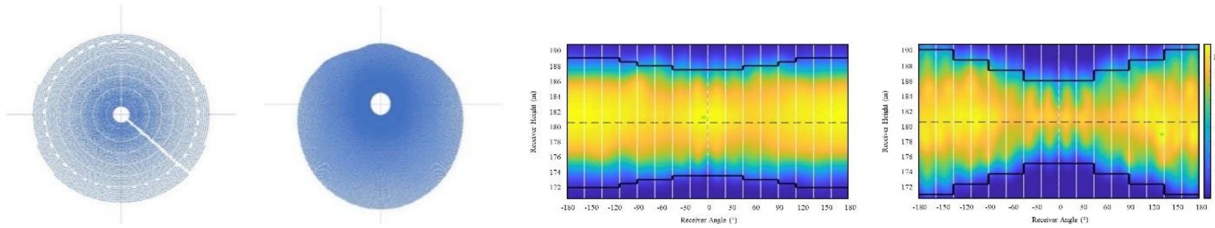
Regarding the 100 MWe case (the 1st case developed), Tewer has informed that within their simulations, the receiver panel heights can go as high as 30 meters to allow interceptions of all the thermal energy without reaching energy densities higher than 1200 kW/m^2 [9]. However, Aalborg CSP has specified that with the special material pipes in the receiver and the relatively high fluxes, it is undesired to have weldings in the high flux areas. Thus, the receiver panel heights are limited by the physical lengths of available pipes.

As shown in Table 3, for the 100 MWe case, receiver pipes of 20.0 meters are agreed as the maximum length. Similarly, for the 50 MWe, Tewer has reported that a receiver of up to 15.0 meter allows interception of all the thermal energy without defying the allowable energy densities. Thus, receiver pipes of this length are agreed as maximum.

Solar Field Layout Using the Newly Developed PHOTON Heliostats

As stated in Ref. [7], the high optical quality of the PHOTON heliostat, developed by Tewer, "*unveils a new optimization strategy for solar field layout and field-receiver integration*". Herein it is found that the solar field layout, based on the newly developed PHOTON heliostats, has a relatively pronounced eccentricity.

The above can be translated into an asymmetric energy flux in the MSR having an increased energy density at the south side (when the solar thermal electric plant is located on the Southern hemisphere). The following summarizes the findings in Ref. [7].



(a) (b) (c) (d)

FIGURE 3. The PHOTON project: PHOTON heliostat results as shown in Ref. [7] (property of Tewer).

Figure 3 shows comparatively two optimized layouts for a given geolocation at the Southern hemisphere. Fig. 3(a) shows a generic solar field (1.7 mrad), and Fig. 3(b) shows the corresponding PHOTON solar field (0.6 mrad). Fig. 3(c) shows an instant flux map with a generic layout and an aiming strategy targeting a uniform (symmetric) flux distribution on a standard receiver. Fig. 3(d), on the other hand, shows the results when utilizing the asymmetry of the solar field to distribute the flux asymmetrically on the MSR leading to a non-uniform distribution of panel heights. To the rightmost, the color bar shows the heat flux. As stated in Ref. [7], this patent pending innovation "*represents not only a cost-saving advantage, with the receiver panel heights customized according to the flux, but also an efficiency advantage, since the same energy is collected over a smaller surface area, reducing the thermal losses accordingly*". Thus, the above findings have been used as basis for the subsequent PHOTON MSR designs.

IMPLEMENTATION OF THE PHOTON HELIOSTAT RESULTS FOR SYMMETRIC AND ASYMMETRIC SOLAR RECEIVER DESIGNS – A COMPARATIVE STUDY

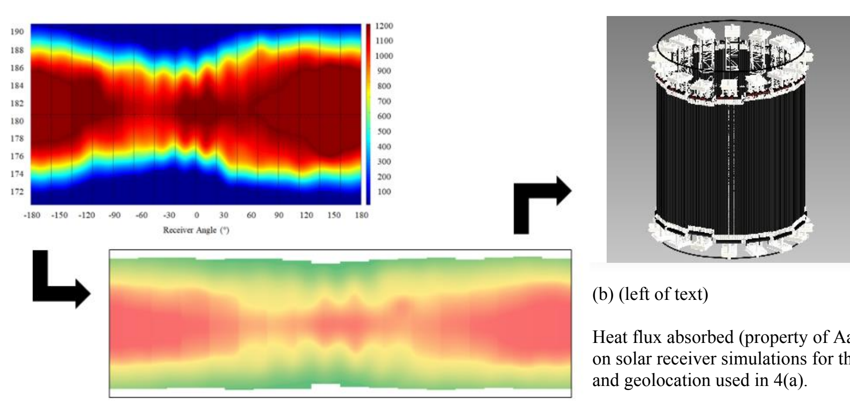
The MSR design and optimization process has been highly dependent on – among other things – the development of Tewer's new solar field concept, e.g. the aiming probability of the heliostats and the possibility of redirecting the heat flux. The development of these heliostats is presented in Ref. [7]. Thus, instant flux maps, developed by Tewer, have been shared between project partners. In the Aalborg CSP subsequent developments, grid resolutions of 65,464 grid cells for the 50 MWe capacity and 77,488 grid cells for the 100 MWe capacity, respectively, have been applied within the design and optimization process to reach the fully optimized asymmetric receiver designs. The designs shown below are developed according to the highest DNI (at proposed geolocation 28.3 S, 23.35 E).

MSR Design Comparison – 100 MWe Symmetric Design vs. 100 MWe Asymmetric Design

While designing the MSR, it has become of great interest to specifically investigate the symmetry of the MSR. Thus, Aalborg CSP has started investigating the possibility of optimizing the height of each MSR panel according to the incident flux in that particular panel. Steps within this process are shown in Fig. 4:

(a)

Instant flux map (property of Tewer) based on solar field simulations for a given date, time and geolocation.



(c) (left of text)

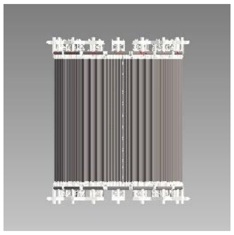
Receiver panel design (property of Aalborg CSP) fully optimized according to the given flux map and heat flux absorbed.

(b) (left of text)

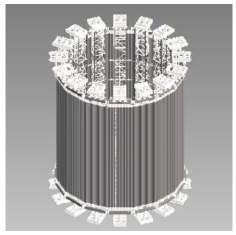
Heat flux absorbed (property of Aalborg CSP) based on solar receiver simulations for the given date, time and geolocation used in 4(a).

FIGURE 4. The PHOTON project: 100 MWe Asymmetric MSR design phase steps based on an incident flux map [12].

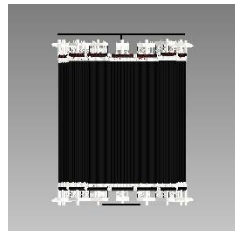
The process of optimizing the height of each MSR panel according to the incident flux in that particular panel is found to increase the MSR efficiency, since the “low flux density areas” (< 100 kW/m^2) are neglected, reaching an overall higher efficiency. For the 100 MWe case, the MSR designs shown in Fig. 5 have been achieved.



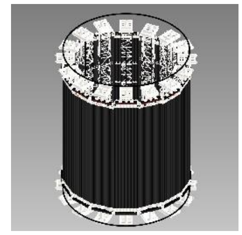
(a)
Design: Symmetric
View: South side
H_{panel}: 15.7 m



(b)
Design: Symmetric
View: Top-corner
H_{panel}: 15.7 m



(c)
Design: Asymmetric
View: South side
H_{panel}: range [14.5-15.9] m



(d)
Design: Asymmetric
View: Top-corner
H_{panel}: range [14.5-15.9] m

FIGURE 5. 100 MWe Symmetric vs. Asymmetric MSR designs – different views. All are property of Aalborg CSP [12].

As seen in Fig. 5, when optimizing according to a symmetric design, in which all MSR panels have the same height, an overall receiver panel height of 15.7 meters is obtained. When optimizing according to the asymmetry of the incident flux map, the difference is visible, however not significant. This is due to the specific flux density, thus the aiming probability of the heliostats etc. The PHOTON receiver designs have been continuously compared to base cases (i.e. reference plant productions). When compared to the 20.0 m base case, current results are listed below:

TABLE 4. The PHOTON project: Symmetric and Asymmetric MSR comparative case study: 100 MWe [12].

		100 MWe **20.0 m** **BASE CASE**	**100 MWe** **15.7 m** **SYMMETRIC CASE**	**100 MWe** **[14.5-15.9] m** **ASYMMETRIC CASE**
CAPEX [a)]	EUR	19,770,000	17,537,000	17,115,000
SAVING	[%]	-	- 11.3%	- 13.4%
$\boldsymbol{\eta_{receiver,max}}$	[%]	91.79 [b)]	92.10 [c)]	92.12 [c)]

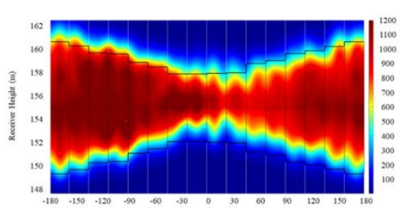
[a)] CAPEX incl. elec. control and instrumentation; receiver w. steel support, insulation and tracing; tanks, supports and hangers; engineering; general project costs. [b)] Results based on optimized solar field only. [c)] Results incl. optimized MSR. Both cases are compared to the 20.0 m.

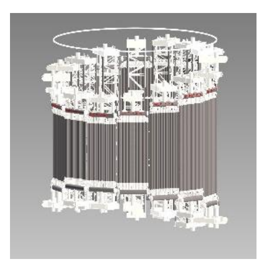
As seen in Table 4, MSR cost savings have been identified for both alternative cases. For the 100 MWe capacity, it is found that more than 13% of the tube material costs can be saved. However, the listed CAPEX does not account for the production of the connection pipes (lengths and materials). As of now, analyses are ongoing, e.g. regarding the solar receiver coating selection, and new results are expected ultimo 2019.

MSR Design Comparison – 100 MWe Asymmetric Design vs. 50 MWe Asymmetric Design

(a)

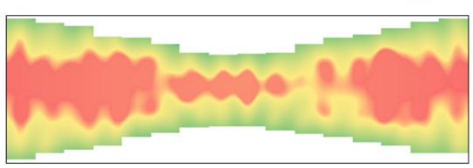
Instant flux map (property of Tewer) based on solar field simulations for a given date, time and geolocation.





(c) (left of text)

Receiver panel design (property of Aalborg CSP) fully optimized according to the given flux map and heat flux absorbed.

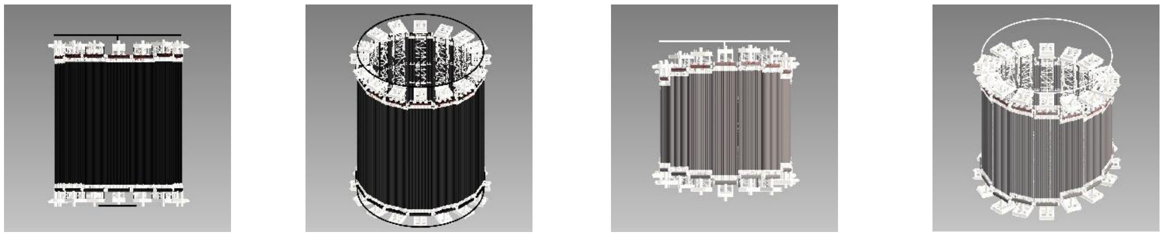


(b) (left of text)

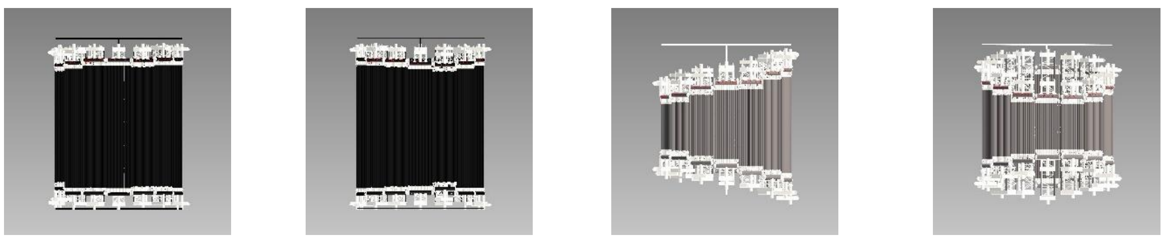
Heat flux absorbed (property of Aalborg CSP) based on solar receiver simulations for the given date, time and geolocation used in 6(a).

FIGURE 6. The PHOTON project: 50 MWe Asymmetric MSR design phase steps based on an incident flux map [12].

As shown in Fig. 6, analyses similar to the 100 MWe case study have been carried out for the 50 MWe design. When comparing Figs. 4 and 6, it is seen that the asymmetry is significantly different depending on the capacity of the receiver. Thus, the asymmetry has been directly compared, regarding the 50 MWe and 100 MWe designs. As shown in Fig. 7, differences are significantly visible.



(a)	(b)	(c)	(d)
Design: Asymmetric View: South side H_{panel}: range [14.5-15.9] m Capacity: 100 MWe	Design: Asymmetric View: Top-corner H_{panel}: range [14.5-15.9] m Capacity: 100 MWe	Design: Asymmetric View: South side H_{panel}: range [6.00-11.8] m Capacity: 50 MWe	Design: Asymmetric View: Top-corner H_{panel}: range [6.00-11.8] m Capacity: 50 MWe



(e)	(f)	(g)	(h)
Design: Asymmetric View: East side H_{panel}: range [14.5-15.9] m Capacity: 100 MWe	Design: Asymmetric View: North side H_{panel}: range [14.5-15.9] m Capacity: 100 MWe	Design: Asymmetric View: East side H_{panel}: range [6.00-11.8] m Capacity: 50 MWe	Design: Asymmetric View: North side H_{panel}: range [6.00-11.8] m Capacity: 50 MWe

FIGURE 7. 100 MWe vs. 50 MWe Asymmetric MSR designs – different views. All are property of Aalborg CSP [12].

When comparing (a)-(h) in Fig. 7, the difference in asymmetry and significant variation in results is due to the required solar thermal electric plant capacity, thus corresponding required solar field area. When optimizing according to the 50 MWe symmetric design, an overall receiver panel height of 9.90 meters is obtained (not depictured). When optimizing according to the asymmetry of the incident flux map, as seen in Fig. 7, the difference is significant. Savings and receiver efficiencies, when compared to the 15.0 m base case, are listed below:

TABLE 5. The PHOTON project: Symmetric and Asymmetric MSR comparative case study: 50 MWe [12].

		50 MWe **15.0 m** **BASE CASE**	**50 MWe** **9.90 m** **SYMMETRIC CASE**	**50 MWe** **[6.00-11.8] m** **ASYMMETRIC CASE**
CAPEX [a)]	EUR	15,956,000	13,060,000	12,642,000
SAVING	[%]	-	-18,2%	-20,8%
$\boldsymbol{\eta_{receiver,max}}$	[%]	91.32 [b)]	91.77 [c)]	92.10 [c)]

[a)] CAPEX incl. elec. control and instrumentation; receiver w. steel support, insulation and tracing; tanks, supports and hangers; engineering; general project costs. [b)] Results based on optimized solar field only. [c)] Results incl. optimized MSR. Both cases are compared to the 15.0 m.

As seen in Table 5, MSR cost savings have been identified for both cases, and the 50 MWe savings are significantly higher than the savings identified for the 100 MWe designs. For the 50 MWe capacity, it is found that more than 20% of the tube material costs can be saved. However, the listed CAPEX does not account for the production of the connection pipes (lengths and materials). As mentioned in the previous section, analyses are ongoing, and new results are expected ultimo 2019.

In the following, a summary of the symmetric and asymmetric MSR comparative case studies are given. The summary is based on a rating system clarifying the lowest CAPEX and the highest MSR efficiency within the investigated alternative cases.

TABLE 6. The PHOTON project: Summary of Symmetric and Asymmetric MSR comparative case studies.

		SYMMETRIC DESIGN CASES		ASYMMETRIC DESIGN CASES	
CAPACITY		100 MWe	50 MWe	100 MWe	50 MWe
CAPEX	a)	●●○○○	●●●●○	●●●○○	●●●●●
$\eta_{receiver,max}$	b)	●●●●○	●●●○○	●●●●○	●●●●○

a) Rating: The <u>lowest</u> CAPEX scores the highest no. of ●. b) Rating: The <u>highest</u> receiver efficiency scores the highest no. of ●.

From Table 6, it is seen that the asymmetric MSR designs in general score higher ratings compared to the symmetric designs. Obviously, the 50 MWe asymmetric case design has the lowest CAPEX due to lowest capacity and usage of materials. Therefore, this case has a complete number of filled circles. The circles related to the maximum receiver efficiency, $\eta_{receiver,max}$, range from 3 to 4 filled circles. This is due to the ongoing receiver coating studies currently indicating a receiver efficiency increase of up to 2.94%, if the investigated coatings become commercially ready [10]. Thus, such results would release a complete number of filled circles regarding $\eta_{receiver,max}$.

When comparing Table 4, 5 and 6, one should notice that the high variation in costs and savings between the 50 MWe and 100 MWe design cases can be partly explained by the application of two different receiver tube materials, selected based on maximum receiver tube lengths.

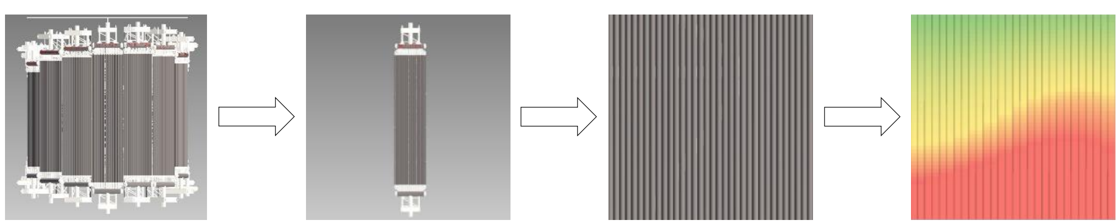
It is assessed, that the 50 MWe asymmetry is more pronounced since this design requires a smaller solar field, thus obtains a higher optical quality of the heliostats, and fewer losses are reflected in the results. Within the optimized layout, only a 0.6 mrad error is achieved in the solar field. This introduces the ability to better see the asymmetric effects, translated from the solar field onto the MSR. On the other hand, for the 100 MWe design case, the far field is "quite far", resulting in higher losses. Thus, this asymmetry is present, however less visible [11].

RESULTS AND REMARKS

Solar Receiver Design – Results & Remarks

As shown in the sections above, symmetric and asymmetric MSR design proposals have been investigated within the project framework of the PHOTON project. These are based on instant, incident flux map simulations from an optimized solar field. Due to the layout of the given flux maps, it has been possible to design the MSR such that "low flux density areas" are minimized, while "high" and "evenly distributed" flux areas are maximized, within given boundaries. However, this must at all times correspond to the desired CSP plant outcome, e.g. 50 MWe. Thus, the receiver panel heights are determined within a limited range.

As part of the Aalborg CSP role in the project, a high-level 2D external MSR performance model software has been developed in VB programming language to simulate instant conditions at various component levels, illustrated in Fig. 8.



(a) Level 1: Solar receiver component

(b) Level 2: Solar receiver panel (full panel)

(c) Level 3: Solar receiver panel section (10 x 10 cm ≃ 2 tubes/panel)

(d) Level 3: Solar receiver panel section (10 x 10 cm ≃ 2 tubes/panel) (2D software simulation results)

FIGURE 8. The PHOTON project: A 2D external MSR performance model software has been developed to simulate instant conditions at various component levels (property of Aalborg CSP) [12].

In “Level 3” shown above, the 50 MWe design case uses grid cells of size 10.2 x 9.00 cm, while the 100 MWe design case uses grid cells of size 10.2 x 12.0 cm, ensuring a high calculation accuracy (~10 x ~10 cm) [12]. An overview of the instant solar thermal electric plant conditions, simulated at various component levels, are listed below.

- Level 1: Solar receiver component:
  - Performance summary incl. final summations and maximum outputs tracked during simulation.
  - Individual loss summary incl. reflection, radiation and convection losses.
  - Efficiency matrices according to incident flux and wind speed (in steps).
- Level 2: Solar receiver panel:
  - Molten salt mass flows and velocities in each receiver panel.
  - Temperature of molten salt into and out of each receiver panel.
  - Pressure losses in each receiver panel.
- Level 3: Solar receiver panel section: (corresponding to 2 tubes/grid cell with 9-12 cm section heights)
  - Incident and absorbed heat fluxes (e.g. see Fig. 4 and 6) and the corresponding efficiencies.
  - Mean salt temperatures, film temperatures, inner and outer tube wall temperatures.
  - Strain in solar receiver tubes according to temperatures and molten salt flows.

All MSR simulation results are validated against literature and/or existing solar thermal power tower plants and are assessed applicable for the purpose of designing and optimizing an MSR with symmetric/asymmetric receiver panel heights. Significant performance impacts of the asymmetric MSR design can be listed as:

- The asymmetric MSR design is fully optimized according to the newly designed, eccentric solar field concept, utilizing a new optimization strategy for solar field layout and field-receiver integration, supporting the development of a new and competitive solar thermal electric plant configuration.
- The asymmetric MSR design allows the solar thermal electric plant to reduce costs in the form of decreasing the MSR CAPEX (though dependent on plant capacity), and also decreasing the MSR OPEX (though dependent on the solar receiver coating material), since less receiver tube material is needed.
- The asymmetric MSR design increases the solar receiver performance, thus the global efficiency of the solar thermal electric plant, since “low flux density areas” (< 100 kW/m^2) are neglected, reaching an overall higher efficiency. The increased efficiency helps improve the production/cost ratio and the LCOE, regarding State-of-the-Art references, and works towards fulfilling the overall goals of the project. This is further addressed in the subsequent section.

From Table 6 (previous page), it is seen that the asymmetric MSR designs in general score higher ratings, when comparing to the symmetric designs, and the asymmetric 50 MWe design case scores the highest rating overall when compared to the remaining alternative cases shown.

Here it should be noted that, when comparing the symmetric and asymmetric design cases, the MSR surface areas are not the same, since the asymmetric case in general uses less material. However, even though the asymmetric MSR has a smaller surface area and receives less incident flux than the symmetric case, still, the overall MSR efficiency is higher, since the incident flux density in general is higher, and energy spillage is neglected.

Solar Thermal Electric Plant – Results & Remarks

For the overall solar thermal electric plant, as of now, the following results have been obtained [13]. All numbers are related to the 100 MWe-case with two-facet heliostats [2]:

- The EPC cost is reduced by 14.41%.
- The combination of the solar field, receiver and power block optimization has increased the global efficiency of the solar thermal electric plant with 2.96%.
- An LCOE reduction of up to 13.34% has been achieved.
- The explored alternative cases result in less space requirements (e.g. 27.5-29.7% for the solar field) and less solar energy requirements to produce the same amount of electricity annually as the base cases.
- Improvements have been implemented in the power block system to reduce the auxiliary consumptions during normal operation.

CONCLUSIONS AND FUTURE PLANS

The current conclusions and findings within the PHOTON project framework are highlighted in the following:

- As agreed between the PHOTON project partners, Aalborg CSP has developed, designed and optimized the solar thermal power tower receiver of the proposed capacities of 50 MWe and 100 MWe. A high-level 2D external MS receiver performance model software has been developed in VB programming language to simulate instant conditions at various component levels, leading to fully optimized symmetric/asymmetric receiver designs.
- Both symmetric and asymmetric MSR design proposals, based on instant, incident flux map simulations from an optimized solar field, have been investigated. This results in several interesting and promising MSR designs, the asymmetry in particular.
- When comparing the MSR geometry (symmetry vs. asymmetry), it is found that the asymmetric MSR designs in general score higher ratings. The asymmetric 50 MWe design case scores the highest rating overall, regarding CAPEX and MSR efficiency, when being compared to the remaining alternative cases. Thus, the 50 MWe asymmetric design is found to be more pronounced than the 100 MWe asymmetric design, since the 50 MWe design case requires a smaller solar field, thereby obtaining a higher optical quality of the heliostats, and fewer losses are reflected in the results.
- For the 50 MWe asymmetric design case, it is found that more than 20% of the tube material costs can be saved (not accounting for the production of the connection pipes).
- For the 100 MWe asymmetric design case, it is found that more than 13% of the tube material costs can be saved (not accounting for the production of the connection pipes).
- The MSR efficiency, based on solar receiver optimization only, is found to increase from 91.8 to 92.1 for the 100 MWe design case, and from 91.3 to 92.1 for the 50 MWe design case. However, it should be noted that the MSR efficiency can be further increased (indications show more than 2%) based on an alternative coating selection. In all current simulations, Pyromark 2500 has been applied.
- So far, the possible improvement aspects, identified by Aalborg CSP, regarding the MSR design concern: Material selection; Coating selection; Receiver panel height selection.
- Part of the solar thermal electric plant design and optimization is conducted under a pending patent [14], owned by Tewer, and further results are expected available ultimo 2019.

For the remaining part of the project framework – and as ideas for any similar future projects – additional investigations should include:

- Assessment of the solar receiver manufacturing feasibility and its performance interaction with key solar thermal electric plant components, based on additional performance calculations.
- Selection of the final receiver coating. In the current simulations, the State-of-the-Art solar receiver coating Pyromark 2500 has been addressed, as this is the only commercial option currently available. However, several newly developed solar receiver coatings are being investigated, and their activities are closely followed by Aalborg CSP, in hopes of finding an attractive candidate for the solar receiver coating.
- Assessment of the final receiver costs, incl. accountancy of the production of e.g. connection pipes and the MSR OPEX calculations. Here, it should be noted that the final solar receiver coating selection will highly affect e.g. the MSR OPEX regarding coating lifetime[4].
- Finalization of the MSR design cases based on the evolution of the pre- and conceptual designs. The detailed engineering of the MSR is planned to include CFD modelisation, fatigue analysis, verification of the energy distribution, technical specification elaboration, technical drawings and final 3D designs.

Ultimo 2019, new results are expected available, as the PHOTON project ends in January 2020.

[4] Foot note: Solar receiver coating lifetime: The amount of time before the coating absorptance/emittance reaches a pre-defied “low level”, and re-painting the receiver tubes is necessary to maintain the required solar receiver performance. As an example, the Pyromark 2500 lifetime is typically stated as 2 years, whereas several promising developments claim higher lifetimes and better performances.

Available results, milestones, deliverables etc. are expected available at the official PHOTON project web page [15], when approved and completed. Illustrations, figures, values etc. must not be reproduced without proper consultancy with and citation of the owners, i.e. paper authors.

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