G3P3 Techno-Economic Analysis of Up-Scaled CentRec® Receiver

Modelling Parameters and Results

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0 Executive Summary

The objective of this report is to evaluate the cost potential of the up-scaled CentRec® particle receiver as part of a complete CSP plant of representative size. The plant configuration was defined by the boundary conditions specified within the US-DoE Gen3 project "G3P3" for a 100 MW_e solar power plant using a high-efficiency supercritical CO_2 (sCO_2) power block.
The study presents the assumptions and the results of the evaluation of the levelized cost of electricity (LCOE) for a particle-based multi-tower CSP plant of 100 MW_e, consisting of 12 identical solar tower modules with about 41 MW_{th} each. The centrifugal particle receiver technology developed by DLR is considered.
As there is still uncertainty in the cost assumptions for some components, lower and upper bounds were used for the tower cost and the primary heat exchanger cost. The nominal upper particle temperature was given as 800°C. In addition, two cases with an increased upper particle temperature of 1000°C were evaluated.
The results show a strong dependency on the cost assumptions both for the tower construction as well as for the primary heat exchanger. For the cases with 800°C upper particle temperature, the estimated LCOE range from 0.05544 $/kWh (lower bound for tower and HX cost) to 0.06435 $/kWh (upper bound for tower and HX cost).
When the upper particle temperature is increased to 1000°C, a significant reduction in LCOE is observed (nearly 9% for the lower bound cases, down to 0.05065 $/kWh). Several components show a significant cost reduction due to the reduced particle mass flow and inventory, as a consequence of the higher temperature spread in the particle subsystem. However, the operation of the heat exchanger at such elevated particle inlet temperatures will require some modifications to the G3P3 baseline design that will introduce additional cost. Nevertheless, the results give strong arguments to investigate this option further. All in all, the results show a clear potential to achieve the SunShot goal of less than 0.06 $/kWh.

1 Introduction

The objective of this report is to evaluate the cost potential of the up-scaled CentRec® particle receiver as part of a complete CSP plant of representative size. The plant configuration was defined by the boundary conditions specified within the US-DoE Gen3 project "G3P3" for a 100 MW_e solar power plant using a high-efficiency supercritical CO_2 (sCO_2) power block.

The CentRec® receiver was developed by DLR over the past years and has already demonstrated its capability to achieve high particle outlet temperatures. During tests in DLR's solar tower test facility in Jülich, Germany, outlet temperatures up to 965°C were achieved. The concept of this receiver is based on a rotating drum. Although the exact size limit is not known yet, it is expected that such receivers cannot be scaled up to the power level required for the Gen3 power plant size. Therefore, a modular (so-called "multi-tower") approach is taken where a number of equal subsystems ("modules") deliver power to a large central power block. Each module consists of the tower, one or several receivers, a storage system with hot and cold storage containers integrated into the tower, and the associated particle lifting units. Transferring the collected energy from the various modules to the central unit is implemented by autonomous trucks transporting hot particles in insulated containers.

To be able to compare the results from different models in the G3P3 project, it is mandatory to agree on a common set of model parameters. Especially for the cost assumptions it turned out that data and correlations are available from various sources (e.g.7[2][3]), but differ significantly. Thus, the team members of the G3P3 project have undertaken efforts of implement a common data set for all considered systems. As far as possible, the techno-economic analysis for the multi-tower systems with CentRec® receiver relied on these common specifications.

1.1. Common Assumptions

Table 1: Common assumptions for techno-economic analysis

Parameter	Value
Particle inlet temperature	550 °C (sCO_2 process: 535°C – 700°C)
Outlet temperature	800°C, 1000°C
Particle mass flow	according to desired outlet temperature and incident power
C_p of solid particles	1200 J/kgK (not temperature dependent)
Receiver power (DP)	500 MW_{th} (total)

Location	Daggett, CA, USA
Latitude, Longitude, Altitude	34.867° north, 116.78° west, 588m asl
Design point (DP)	21.3., solar noon, equinox
DNI @ DP	897 W/m² (value from HFLCAL)
Receiver power (DP)	500 MW_{th} total, 41.67 MW_{th} per module (12 modules)
Power cycle	sCO_2 cycle, heat input at 535°C – 700°C
Net electric power	100MW_e
Net thermal efficiency	48%
Storage capacity	14 h
Solar multiple	2.4

Table 2: Heliostat specifications.

Parameter	**Value**	
Area of heliostat	144.375 m²	quadratic, 12.0145m side length, see screenshot below
Reflectivity	0.9025	= 0.95x0.95, see screenshot below
Total reflected image error	3.07mrad	see screenshot below
For HFLCAL: slope error	1.535mrad	= 0.5x3.07
HFLCAL beam error	3.9mrad	Reflected beam, includes sunshape

2 Cost and Performance Assumptions

The cost assumptions to be used for the G3P3 simulations are given in the following paragraph. Whenever possible, assumptions agreed within the G3P3 team were used to enable comparison of the results of different teams.

2.1 Powerblock

The specific sCO_2 power block cost is assumed as 600$/$kW_e$ (cost proposed by DOE). This cost is excluding the primary heat exchanger. For the 100 MW_e power block this results in a power block cost of C_{PB} = 60 M$.

2.2 Primary Heat Exchanger

The primary heat exchanger is based on cost estimates and quotes provided within the G3P3 project. Due to the given uncertainty in the new particle-sCO_2 heat exchanger technology, a lower and a higher bound approach is used. The used correlations are:

$$C_{HX} = c_{HX,A} \cdot A_{HX} + c_{BOP,p} \cdot \dot{m}_p + c_{BOP,sCO2} \cdot \dot{m}_{sCO2} \quad [\$]$$

with

- particle-side specific BOP cost: $c_{BOP,p} = \frac{(8000000+810000 + 1350000)\ \$}{1110\ ^{kg}/_{s}}$
- sCO₂-side specific BOP cost: $c_{BOP,sCO2} = \frac{5000000\ \$}{1052\ ^{kg}/_{s}}$
- particle mass flow: $\dot{m}_p = 1042\ ^{\mathrm{kg}}/_{\mathrm{s}}$
- sCO₂ mass flow: $\dot{m}_{sCO2} = 1052\ ^{\mathrm{kg}}/_{\mathrm{s}}$

The values for the area-specific heat exchanger cost are

- for the lower bound: c_{HX} = 4158 \$/m²
- for the upper bound: c_{HX} = 9031 \$/m²

The required heat transfer area of the primary heat exchanger is calculated using an overall heat transfer coefficient and the logarithmic mean temperature difference:

$$A_{HX} = \frac{^{P_{el}}/_{\eta_{cycle}}}{h_{HX} \cdot \Delta T_{log}}$$

For the convective heat transfer coefficient h_{HX} a value of 496.02 W/m²K was provided by SNL.

2.3 Heliostat Field

Heliostat field cost is assumed as 75 \$/m², including all manufacturing and installation. Heliostat size is 12.0145 m x 12.0145 m, with ideal focusing/canting of the facets. For the layout in the simulation tool HFLCAL a total reflected beam error of 3.9mrad is assumed, based on correlations derived earlier [5]. This includes a simplified sunshape and corresponds to a combined heliostat slope and tracking error of about 1.5mrad.

2.4 Receiver

The receiver is characterized by a circular aperture that is facing north. The aperture area A_{ap} varies according to the selected temperature range and is determined during the solar system optimization. A simplified receiver model is considered, with the absorbed power $P_{rec,abs}$ defined as a function of intercepted power $P_{rec,int}$ and receiver exit temperature $T_{rec,ex}$ by

$$P_{rec,abs} = \alpha \cdot P_{rec,int} - \varepsilon\sigma\, A_{ap}\, T^4_{rec,ex} - h\, A_{ap}\, (T_{rec,ex} - T_{amb})$$

with

effective solar absorptivity: $\alpha = 0.95$
effective thermal emissivity: $\varepsilon = 0.9$
convective heat loss coefficient: $h = 30\ W/m^2K$

Note that in the above correlation all temperatures must be used in [K]. For the ambient temperature, a value of 300K is assumed.

The following graph shows the used correlation “corr” in comparison with the predictions of the detailed ANSYS model. The ANSYS model shows higher efficiency, i. e. the correlation model represents a conservative approach. The ANSYS model so far does not properly reflect potential overtemperatures in the particle film, since they are not known yet. This aspect is currently under investigation and will be implemented in a future version.

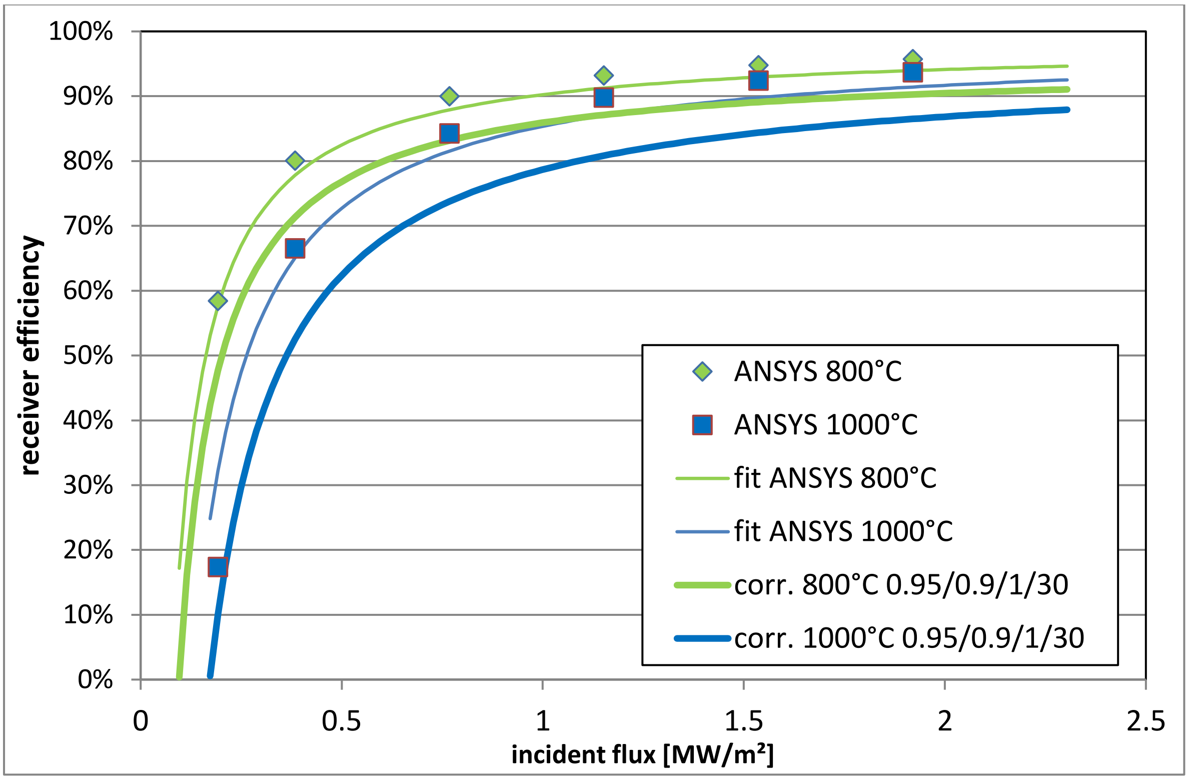

Figure 1: CentRec receiver efficiency characteristic

For the receiver, a specific cost of 76’300 \$/m² aperture area is assumed. Temperature dependence on cost is neglected here. The receiver cost is then

$$C_{rec} = A_{ap} \cdot 76300 \quad [\$]$$

2.5 Tower

For the tower a cylindrical shape concrete tower is assumed. The following two correlations for the tower cost as function of tower height are used. Whenever required, the values were converted from [€] to [$] using the exchange rate.

2.5.1 Lower Bound Correlation

As lower bound, a correlation based on a cost analysis from sbp was used.

$$C_{tower,0} = 0.003404 \cdot {h_t}^4 - 1.4337 \cdot {h_t}^3 + 336.88 \cdot {h_t}^2 - 6243.5 \cdot h_t + 555643 \ [€]$$

Here the parameter h_t describes the height of the tower up to the receiver aperture, excluding additional components like receiver, lifting devices etc.
This correlation is similar to the agreed sbp curve fit, but gives a better representation of the data at low tower heights (see Figure 2).

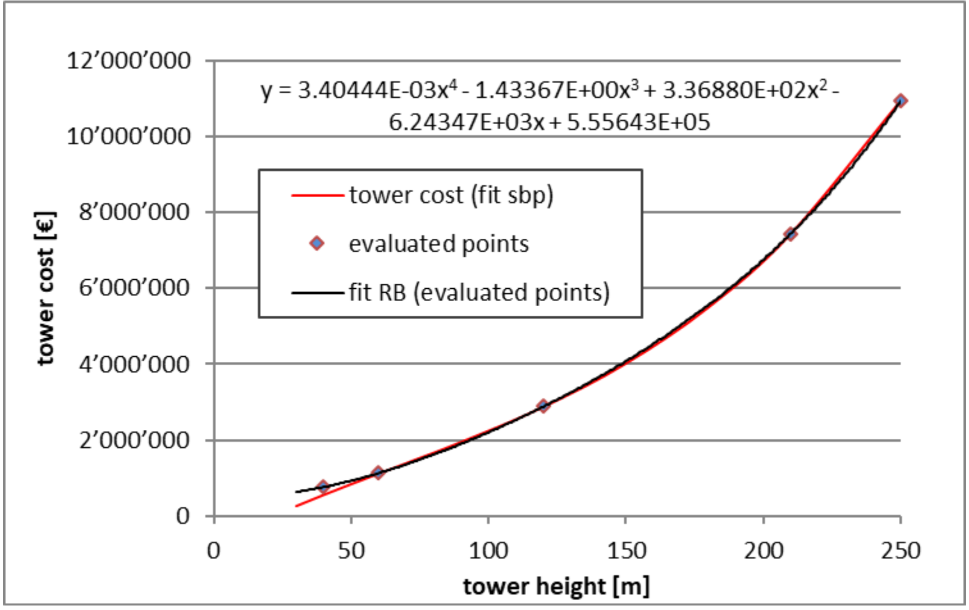

Figure 2: Lower bound tower cost correlation

2.5.2 Upper Bound Correlation

$$C_{tower,0} = 3000000 \cdot e^{\left(0.0113\frac{1}{m}\cdot(h_t-7)\right)} - \frac{28000}{R_{exch}} h_t \ [\$]$$

Once again, the parameter h_t describes the height of the tower up to the receiver aperture.

2.5.3 Hot Piping Cost

In both cases, a cost contribution for the hot piping between the receiver outlet and the storage inlet is considered, with a specific cost of 3000 €/m pipe length. The length of the pipe is defined as the distance between receiver aperture center and the upper level of the storage section in the tower, as obtained from the storage layout. The final tower cost is then obtained as

$$C_{tower} = C_{tower,0} + h_{t,total} \cdot \frac{3000}{R_{exch}} \ [\$]$$

In the lower bound case $\mathrm{C}_{\mathrm{tower},0}$ is first converted to $.

2.6 Particle Inventory

For the particles a specific cost of 1$/kg is assumed. An extra particle amount of 5% is added to the required storage inventory, to account e.g. for non-moving particles in the storage (to enable simpler storage geometries). The particle cost is

$$C_p = m_{st} \cdot 1 \, {}^{\$}/_{kg} \quad [\$]$$

2.7 Vertical Particle Transport (Particle Lift)

The particle lift cost C_{lift} per module is calculated as follows

$$C_{lift,mod} = 58.37 \cdot h_{lift} \cdot \dot{m}_{p,mod,DP} \quad [\$]$$

The lift height h_{lift} includes the additional height above the receiver, required for handling and controling the particle stream. The design-point particle mass flow $\dot{\mathrm{m}}_{\mathrm{p,mod,DP}}$ (per module) is obtained from the energy balance for the receiver, and is a function of the selected temperature difference in the particle stream. The total lift cost is then

$$C_{lift} = C_{lift,mod} \cdot n_{mod} \quad [\$]$$

2.8 Ground Transport

This cost item applies to the multitower approach. For transportation between the solar tower modules and the central power station a number of trucks (or transport vehicles) are foreseen, each transporting insulated containers (one for hot and another for cold particles). As the paths between the solar tower modules and the central power block are clearly defined, fully autonomous trucks are foreseen. The cost of each truck system is estimated as $C_{tr,h}$ = 100’000 $. Such truck systems are known as Automated Guided Vehicles (AGV), commercial solutions are for example available from VDL Automated Vehicles (https://www.vdlautomatedvehicles.com/products) or KAMAG (https://www.kamag.com/products/logistics-transporters/e-wiesel-agv.html). Note that discussions with transport concept experts within DLR indicated that for the given transport task a train system might be more cost effective and have lower parasitics.

The number of required truck systems is based on the transportation distance, the time for loading/unloading and the velocity profile during transportation. Standard 20ft ISO containers are assumed for particle ground transport. For such containers a lot of handling equipment is available. The containers are equipped with a 30cm internal insulation (different type for hot and cold particle containers). For a hot particle container a cost of 90’000 $ is assumed, for a cold particle container 60’000 $, with the difference stemming from the different insulation type and thickness according to the temperature level. A container set consists of one hot particle and one cold particle container. Thus, the respective containers are always charged with particles of the same temperature, so periodical thermal gradients are minimized.

Figure 3: Automated guided vehicles from VDL (left) and KAMAG (right)

The energy content of a container is calculated from the temperature difference between hot and cold status of the particles, specific heat capacity and particle mass. A standard 20ft ISO container has the size 5.898m x 2.352m x 2.385m (length x width x height). This results in a particle volume of 16.57 m³, taking the insulation thickness of 30cm on all walls into account. The particle mass in the container is then (assuming a filling level of 90%):

$$m_{p,ISOcont} = 0.9 \cdot V_{ISOcont} \cdot \rho_p = 29823\ kg$$

The energy content is then calculated as:

$$E_{p,ISOcont} = m_{p,ISOcont} \cdot c_{p,p} \cdot \left(T_{p,\text{ex}} - T_{p,in}\right)$$

This results in an energy content of $E_{p,ISOcont}$= 25.6 J = 7.1 MWh.

The total path length is obtained by assuming the separate heliostat fields as hexagons, sized according to the module field area (ground area). This is shown in Figure 4 (left), with the blue dot being the central module where all transport paths are ending. Each field has its own tower and storage (i. e. the starting point of the transport path) at the bottom center of its enclosing hexagon. The transport trucks are then moving along the side lines of the hexagons. The total path length of all paths, as derived from the hexagon approach, is obtained by the multiplier factor (plotted in Figure 4 right) and the side length of the hexagon.

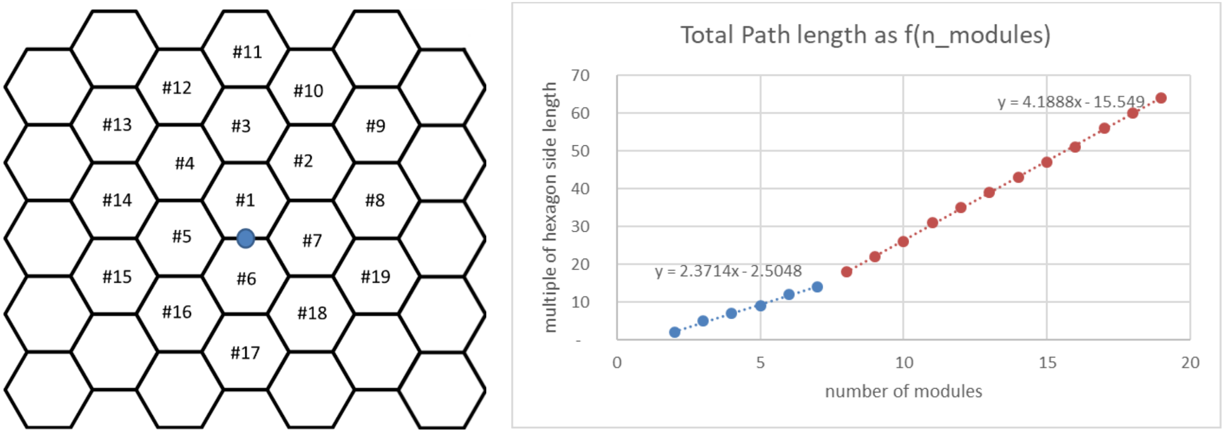

Figure 4: Multitower field layout for path length calculation, resulting path length ratios

In the case of distributed storage the trucks are continuously operated whenever the power cycle is producing electricity, e. g. also during night time. The required continuous power for truck transport is:

$$P_{required} = (n_{mod} - 1)\frac{P_{th,DP,mod}}{SM}$$

The average time for a truck cycle is:

$$t_{truckcycle} = 2 \cdot \frac{total\ path\ length}{(n_{mod} - 1\ \cdot) w_{avg}} + 2 \cdot t_{takeup}$$

with

$total\ path\ length$: total accumulated length of all interconnecting pathways between central module and all other modules (estimated from field size and number of modules)

w_{avg}: average truck speed incl. acceleration/deceleration (assumed: 5m/s = 18km/h)

t_{takeup}: time to take up the hot and cold containers (assumed: 600s)

The time-averaged power per truck is:

$$P_{avg,truck} = E_{p,ISOcont}/t_{truckcycle}$$

and the number of required trucks:

$$n_{truck} = int\left(\frac{P_{required}}{P_{avg,truck}}\right) + 1$$

In addition to the truck and container cost, for each tower a loading system was accounted for, with cost of 50’000 $ per tower. The total ground transport cost is calculated as

$$C_{transport} = C_{truck} \cdot n_{truck} + C_{containerset} \cdot n_{truck} + C_{loading} \cdot n_{mod} \quad [\$]$$

In multi-tower configurations additional annual thermal losses of 2% are assumed, reducing the annual yield by this amount. This loss is associated with the thermal losses of the containers and the losses due to filling/emptying procedures.

2.9 Storage

The storage consists of two storage containers (bins) integrated into the bottom of the tower structure. Since in the modular system approach the tower height is relatively small (< 100m) this is possible even in regions with high seismic activity.
The following correlations are used:

- storage capacity per tower module: $E_{st} = \frac{t_{st}}{n_{mod}} \cdot \frac{P_{el}}{\eta_{el}}$
- particle inventory per tower module: $m_p = 1.05 \cdot \frac{E_{st}}{c_{p,p} \cdot (T_{p,out} - T_{p,in})}$
  (includes a 5% addition for particles in other components)
- cost of particle inventory: $C_p = m_p \cdot C_{sp,p}$
  with specific particle cost $C_{sp,p}$ = 1 $/kg

The size of a storage container is calculated as

- volume of storage bin: $V_{cont} = \frac{m_p}{\rho_p \cdot VUF}$
  with volume use fraction VUF = 0.8 (reflecting the empty space in a cylindrical bin, stemming from the angle of repose of the particle stack)

For a cylindrical container with height-to-diameter ratio $H/_D$ = 1.6 the dimensions evaluate to

- container height: $H_{cont} = H/_D \cdot D_{cont}$

The outer surface of the container, requiring insulation, is then

$$A_{cont} = \frac{2\pi}{4} \cdot D_{cont}^2 + \pi \cdot D_{cont} \cdot H_{cont}$$

The total height of the two storage containers with insulation and some free space inbetween is then calculated as

$$H_{st} = 2 \cdot (H_{cont} + 2 \cdot s_{iso}) + D_{cont}$$

with insulation thickness s_{iso} = 0.6m.

Since the storage containers are integrated into the tower structure, the tower walls serve as outer container wall. The (additional) total cost of the storage consists then mainly of the cost of the required insulation

$$C_{storage} = \{A_{cont} \cdot C_{A,sp,is}(T_{r,ex}) + A_{cont} \cdot C_{A,sp,is}(T_{r,in})\} \cdot n_{mod} \quad [\$]$$

with a temperature-dependent specific insulation cost of

$$C_{A,sp,is}(T) = 2000 \cdot \left(1 + 0.3 \cdot \frac{T - 600}{400}\right) \quad (T \text{ in °C})$$

2.10 Balance of plant

For the balance of plant cost a fix value of 102 $/kW$_e$ was assumed, leading to

$$C_{BOP} = 10200000 \quad [\$]$$

2.11 Land Cost

Specific land cost is assumed as 10’000$/acre = $2.471/m². The total land cost is then calculated as

$$C_{land} = A_{field,mod} \cdot n_{mod} \cdot 2.471 \quad [\$]$$

2.12 Other cost items

The following table gives some additional values required for the cost assessment.

Table 3: Other costs for LCOE calculation

Plant life	N	years	30	DOE requirement
Contingency costs	f_{cont}	-	0.1	DOE requirement
Construction costs	f_{const}	-	0.09	DOE requirement
Discount rate	f	-	0.07	DOE requirement
inflation	i	-	0.025	
real discount rate	f'		0.0439	
fixed O&M costs	OM_{fix}	$/kW-year	40	DOE suggestion
variable O&M cost	OM_{var}	$/kWh	0.003	DOE suggestion
Currency exchange rate	R_{exch}	$/€	1.18	

2.13 LCOE calculation

The correlations for the LCOE calculation are:

Capital cost:

$$C_{cap} = C_{field} + C_{rec} + C_{tower} + C_{lift} + C_{transport} + C_{storage} + C_{HX} + C_{cycle} + C_{BOP}$$

Total cost:

$$C_{total} = C_{direct} + C_{indirect}$$

Direct cost

$$C_{direct} = \left(1 + f_{contingency}\right) \cdot C_{cap}$$

indirect cost

$$C_{indirect} = f_{construction} \cdot C_{direct} + C_{land}$$

LCOE

$$LCOE = \frac{C_{total} \cdot CRF + OM_{fix} \cdot P_{el}}{E_{el,net}} + OM_{var}$$

with

- real discount rate: $f' = \frac{(1+f)}{(1+i)} - 1$
- capital recovery factor: $CRF = \frac{f' \cdot (1+f')^N}{(1+f')^N - 1}$

3 Results

The above assumptions were implemented in the DLR solar system layout tool HFLCAL [4], using specific user-defined subroutines for calculation of the G3P3-specific data. Then optimization runs were carried out for the following configurations:

- lower / upper sCO$_2$ temperatures in primary heat exchanger: 535°C / 700°C
- multi-tower system with 12 identical modules
- total / module receiver power (DP): 500 MW$_{th}$ / 41.67 MW$_{th}$
- storage time: 14h
- solar multiple: 2.4
- optimization for 2 different receiver outlet temperatures: 800°C, 1000°C
- use of lower and upper bound correlations for tower cost
- use of lower and upper bound correlations for primary HX cost
- optimization based on 97 time points, on 6 representative days (21.12., 21.01., 21.02., 21.03., 21.04., 21.05., 21.06.), hourly time steps

Potential dumping losses due to limited storage capacity are not considered in this layout stage. The main results are given in the tables below. The naming convention for the cases is as follows:

- DLR XXX: XXX = upper particle temperature level [°C]
- ll: lower bounds for tower and PHX cost
- lu: lower bound for tower cost, upper bound for PHX cost
- ul: upper bound for tower cost, lower bound for PHX cost
- uu: upper bounds for tower and PHX cost

Table 4: Layout results for the considered configurations

	unit	DLR 800 uu	DLR 800 lu	DLR 800 ul	DLR 800 ll	DLR 1000 ll	DLR 1000 lu
Upper particle temperature	°C	800	800	800	800	1000	1000
Lower particle temperature	°C	550	550	550	550	550	550
Receiver mass flow (DP)	kg/s	1666.7	1666.7	1666.7	1666.7	925.9	925.9
Annual electricity generation	GWh/a	584.02	583.06	584.02	582.06	567.84	569.63
Heliostat area	m²	1112073	1086090	1105144	1079161	1151913	1191754
Tower height[1]	m	76.34	78.59	76.47	82.08	83.66	80.19
Receiver area	m²	420.13	422.85	426.54	391.54	414.14	414.22
Primary HX area	m²	9374.23	9374.23	9374.23	9374.23	4414.87	4414.87
Particle mass	t	36750	36750	36750	36750	20417	20417

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[1] tower height = center of receiver aperture

Table 5: Cost summary of the considered configurations

Cost item	unit	DLR 800 uu	DLR 800 lu	DLR 800 ul	DLR 800 ll	DLR 1000 ll	DLR 1000 lu
Heliostat field	M$	83.405	81.457	82.886	80.937	86.393	89.382
Tower	M$	48.545	23.55	48.607	25.041	26.095	24.594
Receiver	M$	32.056	32.263	32.545	29.875	31.599	31.605
Lift	M$	8.108	8.326	8.120	8.666	4.900	4.712
Ground transport	M$	9.600	9.600	9.600	9.600	5.600	5.600
Power block	M$	60.000	60.000	60.000	60.000	60.000	60.000
Primary HX	M$	99.196	99.196	53.516	53.516	32.895	54.408
Particles	M$	36.750	36.750	36.750	36.750	20.417	20.417
Storage	M$	44.280	44.280	44.280	44.280	32.049	32.049
BOP	M$	10.200	10.200	10.200	10.200	10.200	10.200
Capital cost	M$	432.140	405.622	386.504	358.865	310.148	332.967
Land	M$	10.992	10.735	10.923	10.666	11.386	11.779
Direct	M$	475.354	446.184	425.154	394.752	341.163	366.264
Indirect	M$	49.885	47.241	45.708	42.964	39.299	41.746
Total	M$	525.239	493.425	470.863	437.715	380.462	408.010
LCOE	**$/kWh**	**0.06435**	**0.06115**	**0.05871**	**0.05544**	**0.05065**	**0.05343**

The results indicate a strong impact of the cost for the tower and the primary HX. In addition, the LCOE decreases strongly when the receiver outlet temperature is increased. However, several of the considered configurations achieve LCOE well below the cost goal of 6$Ct/kWh.

4 Discussion and Conclusions

The study presents the assumptions and the results of the evaluation of the levelized cost of electricity (LCOE) for a particle-based multi-tower CSP plant of 100 MW_e, consisting of 12 identical solar tower modules with about 41 MW_{th} each. The centrifugal particle receiver technology developed by DLR is considered.

As there is still uncertainty in the cost assumptions for some components, lower and upper bounds were used for the tower cost and the primary heat exchanger cost. The nominal upper particle temperature was given as 800°C. In addition, two cases with an increased upper particle temperature of 1000°C were evaluated.

The results show a strong dependency on the cost assumptions both for the tower construction as well as for the primary heat exchanger. For the cases with 800°C upper particle temperature, the estimated LCOE range from 0.05544 $/kWh (lower bound for tower and HX cost) to 0.06435 $/kWh (upper bound for tower and HX cost).

When the upper particle temperature is increased to 1000°C, a significant reduction in LCOE is observed (nearly 9% for the “ll” cases, down to 0.05065 $/kWh). Several components show a significant cost reduction due to the reduced particle mass flow and inventory, as a consequence of the higher temperature spread in the particle subsystem. This mainly affects the storage size and the particle lift and transport capacity. In addition, the driving temperature in the heat exchanger is increased, resulting in a smaller and less expensive heat exchanger.

However, it should be noted that the operation of the heat exchanger at such elevated particle inlet temperatures will require some modifications to the G3P3 baseline design. This will introduce additional cost. Also, the receiver cost was assumed independent of particle temperature, while in reality a slight increase in receiver cost will appear. Nevertheless, the results give strong arguments to investigate this option further.

All in all, the results show a clear potential to achieve the SunShot goal of less than 0.06 $/kWh.

5 Nomenclature

Symbols	**Unit**	**Description**
A	$[m^2]$	area
C	*[$]*	cost
c_p	$[J/kgK]$	heat capacity
E	$[J]$	energy
H, h	$[m]$	height
h_{HX}	$[W/m^2K]$	convective heat transfer coeff.
m	$[kg]$	mass
n_{mod}	$[-]$	number of solar tower modules
$LCOE$	*[$/kWh]*	levelized cost of electricity
P	$[W]$	power
T	$[°C]; [K]$	temperature
ρ	$[kg/m^3]$	density
η	$[-]$	efficiency
σ	$[W/m^2K^4]$	Stefan–Boltzmann constant

Subscripts	
abs	absorbed
annual	annual value
ap	aperture
el	electric
ex	exit
field	field
h	horizontal
in	inlet
int	intercepted
is	insulation structure
mod	(solar tower) module
p	particle
PB	power block
rec	receiver
st	storage

Abbreviations

CSP: concentrating solar power

DNI: direct normal insolation

DP: design point

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7 References

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