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Performance analysis of operational strategies for monolithic receiver-reactor arrays in solar thermochemical hydrogen production plants

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HIGHLIGHTS

- A receiver-reactor model is presented and evaluated for boundary conditions of high flux solar concentrators.
- 27 High temperature solar fields have been optimized and flux data for the single receiver-reactors is presented.
- Definition of the array efficiency to quantify operational strategies.
- New strategies for the operation of receiver-reactor arrays improve the array efficiency by 46%.
- Receiver-reactor, solar concentrator and splitting plant performances are analyzed for a large set of configurations.

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ABSTRACT

Solar thermochemical water splitting was successfully demonstrated with monolithic receiver-reactors in field at 50 kW scale. Since monolithic receiver-reactors are limited in size, several of the reactors will have to be combined in receiver-reactor arrays for large-scale plants. In this study, the yearly performance of solar thermochemical plants for hydrogen production implementing receiver-reactor arrays is investigated. Thereto, a transient receiver-reactor model is used in combination with realistic hourly flux profiles from dedicated MW high temperature solar concentrator systems. The batched operation of receiver-reactors leads to particular requirements of the array. Therefore, an array efficiency is introduced and different control strategies for the solar field are analyzed for performance optimization. Advanced strategies have the potential to substantially (~46%) improve the overall performance compared to the base case. Further design and operational optimization approaches are discussed, which allow approaching the theoretical array performance limit.

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Introduction

Hydrogen, produced cost-effectively from renewable energy, is likely to become one central pillar for the transition to a carbon neutral energy economy. Renewable hydrogen can solve open challenges of the transportation sector, of long term renewable energy storage and of the decarbonization of industrial processes [1]. Due to its vast availability solar energy is seen as ideal energy source for competitive large scale hydrogen production. Several technology paths are discussed for the conversion of solar energy into chemical energy stored in hydrogen: electrolysis is the most mature water splitting technology and already available at MW scale [2]. An alternative are thermochemical water splitting cycles which bypass the intermediate electricity production and require almost only thermal energy. Therefore they have been identified as a promising hydrogen production path with high theoretical potential [3]. In addition diversifying hydrogen production paths can mitigate dependencies on critical rare earths.

The thermochemical process is based on a metal oxide redox cycle: a metal oxide releases oxygen in a reduction step at high temperatures. Subsequently, in an oxidation step the reduced metal oxide is able to split water or carbon dioxide while being oxidized again. Over 10 years ago, ceria has been identified as a promising material to perform this cycle [4]. The advantages of ceria are the cycling stability, the fast kinetics and the high reaction enthalpy of the reduction step which permits high conversion rates in the splitting step [5]. On the other hand, ceria requires a relatively high reduction temperature of around 1500 °C, impeding the realization of the cycle. Nevertheless, in the last years significant progress was experimentally demonstrated.

In the EU project SUN-to-LIQUID a monolithic 50 kW ceria receiver-reactor was used for synthesis gas production by co-splitting of water and carbon dioxide. A dense heliostat field at the IMDEA Energy Institute in Móstoles, Spain, provided concentrated solar radiation to the receiver-reactor placed on a solar tower. The synthesis gas was then used for kerosene production in a Fischer-Tropsch reactor located next to the solar tower, demonstrating for the first time the whole production chain from solar energy to Kerosene in field [6].

The used monolithic receiver-reactor consists of a cavity, covered by a quartz window, which contains ceria in form of reticulated porous ceramic (RPC) blocks. During the reduction step, concentrated solar radiation is directed onto the ceria structure to heat and reduce the redox material. Vacuum pumps keep the pressure in the receiver-reactor at around 10 mbar during the reduction step. The reactor has been successfully scaled up from a 4 kW laboratory scale reactor to the pre-commercial 50 kW on-sun facility [6,7]. A similar concept with a monolithic receiver-reactor was investigated in the HYDROSOL projects [8]. Here, a low oxygen partial pressure was obtained by purging with nitrogen instead of using vacuum pumping.

Marxer et al. [9] define a solar-to-fuel energy conversion efficiency $\eta_{\text{solar-to-fuel}}$ as ratio of the higher heating value of the produced fuel (hydrogen, carbon monoxide or a mixture of both) to the energy input (delivered solar energy to the receiver-reactor, gas provision, pump operation). In laboratory tests with the 4 kW receiver-reactor, a maximum efficiency of $\eta_{\text{solar-to-fuel}} = 5.25\%$ was demonstrated. An efficiency like the one above will be considered as reactor efficiency in the following analysis. The overall system efficiency will have to take also the efficiency of the solar concentrator and, as will be introduced in this study, the array efficiency into account.

Reactor modelling plays an important role for the estimation of the efficiency potential of receiver-reactors and the prediction of their behaviour under different operational and boundary conditions. A number of different models for the simulation of such receiver-reactors and reactive structures have been developed at various levels of complexity [10–15]. In order to be able to make reliable statements about the overall efficiency of a solar thermochemical hydrogen production plant, the system modelling should be done on an annual basis including the solar concentrator. Pitz-Paal et al. [16] simulated heliostat fields for different high temperature receivers-reactors from 1 to 100 MW reaching optical efficiencies between 52% and 62% for the relevant flux density range. Calle and Bayon [17] focused on a dynamic model for annual performance estimation of a thermochemical syngas production plant, showing that steady-state models calculated at design point conditions overestimate the yearly plant performance. In their plant model ceria particles are looped between a continuously irradiated receiver-reactor and a separate oxidation reactor. A plant model with monolithic receiver-reactors will differ from this in important aspects. First, due to the expected size limitations of monolithic receiver-reactors, several receiver-reactors will have to be used in parallel in receiver-reactor arrays for large plant sizes. Second, strategies how to consider the batch operation within an array will have to be implemented.

Fig. 1 – Scheme of receiver-reactor with a cavity design, compound parabolic concentrator (CPC) and reticulated porous ceramic (RPC) (adapted from Ref. [10]). The 1D model resolves the RPC and the insulation spatially in the main direction of the incoming radiation.

Until now, no studies were reported on the optimal operation and the performance of batched receiver-reactor array systems for solar thermochemical water splitting. In the work presented here, the performances of different plants with receiver-reactor arrays based on the SUN-to-LIQUID technology are analyzed with realistic flux profiles of high flux solar fields over the course of a year. The assessment identifies particular challenges for the operation of the receiver-reactor arrays. New field strategies are introduced and analyzed, showing that the performance of an array critically depends on precise field control capabilities and on recognition of the particularities of batched monolithic receiver-reactor operation.

Receiver-reactor model description

For the simulation of the receiver-reactor (see Fig. 1) as part of a solar thermochemical hydrogen production plant a simplified numerical model has been built. For a detailed description of the model the reader is referred to Ref. [10], here only a brief summary is given.

The model uses a 1D representation of the reactive absorber structure as porous domain and a solid insulation domain with governing equations for energy and mass conservation of the solid and fluid phases. The governing equations are spatially discretized using the finite volume method and calculated using an in-house Python 3.6 code. For the solid phase the following transient energy equation is used:

$$\rho_s c_p \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x} \left(k_{eff}^s \frac{\partial T_s}{\partial x} \right) + \alpha A_V (T_f - T_s) + \dot{q}_{chem} + \dot{q}_{rad} \quad (1)$$

The effective thermal conductivity k_{eff}^s taken from Ref. [12] includes the Rossland diffusion approximation for radiative transport, αA_V is the volumetric heat transfer coefficient, $\dot{q}_{chem}$ describes the reaction enthalpy and $\dot{q}_{rad}$ is a source term for the radiative heat exchange with the surrounding, which is approximated using the effective extinction coefficient [12]. In case of the insulation, on the right hand side of Eq. (1) only the conductivity term is kept.

For the fluid phase, several assumptions have been used: bulk flow, transparent medium, ideal gas law, negligible thermal conductivity. The conservation of energy for the fluid phase is given by:

$$\rho_f c_p \frac{\partial T_f}{\partial t} + \frac{\partial}{\partial x} \rho_f c_p u T_f = \alpha A_V (T_s - T_f) \quad (2)$$

Ceria is used as reactive material in form of a reticulated porous ceramic (RPC). During the reduction step, a pressure drop over the RPC is neglected. The total pressure in the reactor in this step is calculated using a pressure dependent pumping speed (see Table 2). Mass conservation was respected for the different species involved in the different phases. The reduction is modelled assuming local equilibrium between the redox material and oxygen in the gas phase using the reduction extent correlation given by Ackermann et al. [12]. The reduction reaction is described by:

The reduction extent δ reaches the values δ_{red} and δ_{ox} at the end of the reduction and oxidation step respectively. For the validation of the model the reader is referred to Ref. [10]. While in Ref. [10] the reactor performance was analyzed in combination with a heat recovery system, here the receiver-reactor performance is characterized for varying design and operational conditions without heat recovery system to limit the design and operational parameter space of the analysis.

The receiver-reactor model provides the basis for the performance analysis of the solar hydrogen plant with receiver-reactor arrays. The baseline design is a 433 kW receiver-reactor with the properties described in Table 1. The 433 kW size is linked to a design point flux density of 2500 kW/m² (1

Table 1 – Receiver-reactor properties.

Parameter Name	Value (Range)	Unit
Concentration factor at aperture	1500–6000	–
Aperture radius	0.235	m
RPC thickness	0.025–0.055	m
Mass load of ceria	127–466	kg
Number of pores per inch	10	–
Porosity of RPC	0.762	–
Insulation thickness	0.20	m
Length cavity	0.89	m
Thermal conductivity insulation	0.25	W/mK
CPC efficiency	0.80	–
CPC inlet area	0.87	m ²
Oxidation end temperature	1000	K
Reduction end temperature	1500–2100	K
Oxidizer inlet temperature	1000	K

Table 2 – Properties of VPA (with $p_0 = 1$ Pa).

$\log_{10} (p/p_0)$ [–]	0	1.05	1.53	2.06	2.5	2.9	3.6	4.4	5
$S_{VPA}/1000$ [m ³ /h]	44.3	56.3	59.1	55.3	49.6	23.6	7.1	3	2
P_{VPA} [kW]	70	75	81	102	148	111	85	76	70

sun = 1 kW/m²) at the aperture and the properties of a hexagonal CPC with an inlet area of 0.87 m². Consequently, a multi MW system consists of multiple reactors, forming together a receiver-reactor array system. As starting condition of the simulations, it is assumed that the receiver-reactor is at the stop temperature of the oxidation step and that the reduction state after the oxidation is determined by the thermodynamic equilibrium value for this oxidation step end temperature and an oxygen atmosphere at ambient pressure. In the analysis this oxidation end temperature is set to 1000 K, which limits the demand of oxidizer [18]. This value was selected in order to keep the operational parameters close to the once used in the experiments for the oxidation step. For overall efficiency maximization, the oxidation temperature also should be optimized like done in other studies [18–20]. The reduction step continues until the hottest part of the RPC reaches the maximum temperature $T_{\max}$ defined for the simulation run. Afterwards the solar input is set to zero, the RPC cools down and is oxidized again by introducing the oxidizer stream.

One important difference in the model presented in this work as compared to Ref. [10], is the use of a realistic large scale pump arrangement instead of a purely scaled version of the vacuum pump used in the lab scale experiments. The pumping speed and the power consumption of this large scale pump arrangement are obtained by the approach presented by Brendelberger et al. [21]. The considered vacuum pump arrangement (referred to below as VPA) comprises 3 stages where the first stage uses two HV40000 (high capacity mechanical booster pump with nominal pumping speed of 40,000 m³/h at 60 Hz), the second stage one HV8000 (high vacuum mechanical booster with nominal pumping speed of 8640 m³/h at 60 Hz), and the third stage two IDX1300 (double-ended dry vacuum pump with nominal pumping speed of 1300 m³/h at 60 Hz).¹ The resulting properties of the pump speed S and of the electrical pumping power demand P_{VPA} at the inlet pressure are given in Table 2 and are shown as linearly interpolated values in Fig. 2.

Coming from high pressures the pumping speed increases steeply and reaches a maximum at around 30 Pa. The pumping power demand has a peak at around 300 Pa of 148 kW. The pumping efficiency at 100 Pa has a value of about 10% and drops to values below 3% at 10 Pa. In this pressure range, one typically finds the efficiency trade-off optimum for continuously operated solar thermochemical water splitting systems [22–25]. In case of the batched reduction step, the reduction step duration and correspondingly the time for oxygen removal is a critical factor, which is mainly determined by the concentration ratio. The impact of the size of the pump arrangement to the receiver-reactor efficiency will be analyzed later in detail. In order to parameterize the size of

the pumping arrangement a pumping number n_{pump} is defined, which is the ratio of pumping speed S of the system compared to the pumping speed of the VPA:

$$n_{\text{pump}} = \frac{S}{S_{VPA}} \quad (4)$$

The pumping power demand is scaled with the same value.

Analysis of receiver-reactor performance

In the following chapter, the characteristics of the receiver-reactor will be described and discussed. The first value of interest is the mean change in reduction extent between the oxidized state and the current state, where oxidized state refers to the state of the RPC at the end of the oxidation step. This value will be abbreviated by “mean $\Delta\delta$ ”. The local reduction extent might deviate significantly from this value since the reduction extent is strongly dependent on the temperature and the directly irradiated front of the RPC reaches much higher temperatures than the back of the RPC. Still, this value is used since it is proportional to the fuel production capacity per mol ceria.

Fig. 3 shows this change in mean $\Delta\delta$ during the reduction step for different flux conditions, defined by the concentration factor C . The reduction step continues until the targeted maximum temperature – here 2100 K - is reached. In general one can see that lower C values lead to a later rise in mean $\Delta\delta$ but also to higher mean $\Delta\delta$ values at the end of the reduction step. While the delayed onset matches with the intuitive expectation due to the slower rise in temperature at lower radiative input, the latter finding might be confusing at first. The reason for higher final mean $\Delta\delta$ values for low flux

Fig. 2 – Pumping speed (a) and electric power demand (b) of the three stage pump arrangement VPA consisting of 2 HV4000, 1 HV8000 and 2 IDX1300 (Edwards vacuum¹).

¹ <http://www.edwardsvacuum.com>.

Fig. 3 – Change in mean reduction extent (mean $\Delta\delta$) as a function of time for different concentration factors reached at the aperture.

conditions is a result of the limited heat transfer into the depth of the RPC. For high flux conditions the front RPC temperature rises very quickly resulting in a large temperature gradient over the thickness of the RPC. Therefore, the maximum temperature is reached early and since the heat has only a short time to reach the deeper layers of the RPC, a large share of the RPC stays too cold to drive the reduction reaction. Furthermore, since the reduction duration is shorter at high flux conditions, the vacuum pumping system has only a short time to remove released oxygen.

The selection of the maximum temperature plays an important role for the receiver-reactor performance. This can be seen in Fig. 4, where the final change in mean $\Delta\delta$ is shown over the concentration factor for different maximum temperature values. Typically, in solar thermochemical cycles based on ceria as redox material reduction temperatures of 1773 K are considered [7,20,23,26]. As shown in the figure, higher maximum temperature values allow reaching

Fig. 4 – Importance of maximum temperature selection. Final change in mean $\Delta\delta$ as a function of the concentration factor.

significantly larger mean $\Delta\delta$ values. These high values seem very attractive for the production of hydrogen with the redox cycle but the required energy input has to be considered as well to evaluate the performance, so the receiver-reactor efficiency is analyzed.

The receiver-reactor efficiency is defined as:

$$\eta_{\text{reactor}} = \frac{m_{\text{H}_2} \text{HHV}_{\text{H}_2}}{(Q_{\text{solar}} + Q_{\text{parasitics}})} \quad (5)$$

where m_{H_2} refers to the amount of hydrogen produced in one cycle, Q_{solar} is the solar input into the receiver-reactor (only the reduction is on sun, so only this period is considered) and $Q_{\text{parasitics}}$ refers to an equivalent solar energy demand of the pumping system. Since no sweep gas is used for oxygen removal and sufficient waste heat is available to heat the oxidizer stream, no parasitic energy demand for the gas provision is considered.

In Fig. 5 the receiver-reactor efficiency is shown, as a function of the concentration factor for different temperature limits. Comparable to the mean $\Delta\delta$ results in Fig. 4, also here, higher efficiency values are reached for higher maximum temperatures, but the efficiency is now not monotonic increasing with decreasing concentration factor. For example, with $T_{\text{max}} = 1500$ K at $C = 1500$, the mean $\Delta\delta$ is 0.0022 and at $C = 6000$ the mean $\Delta\delta$ is 0.0007 which translates into efficiency values of 0.0045 and 0.0049 respectively. While with $T_{\text{max}} = 2100$ K at $C = 1500$, the mean $\Delta\delta$ is 0.2036 and at $C = 6000$ the mean $\Delta\delta$ is 0.0822 which translates into efficiency values of 0.0507 and 0.0834 respectively. This is related to an increase in solar energy input due to longer reduction step durations at low concentration factors, especially for high maximum temperatures.

The operation of the receiver-reactor is limited to a minimum concentration factor of 1500 due to the strong increase in reduction step duration at lower values (this will be discussed in detail in the context of Fig. 8). For concentration factors above this limit, high maximum temperatures seem advantageous. It should be noted, that the numerical correlations used in Ref. [11] and also in this study to describe the

Fig. 5 – Receiver-reactor efficiency for different maximum temperature values as function of the concentration factor.

reduction extent as function of temperature and pressure are based on experimental work for temperatures of up to 1773 K [27]. Even though it can be expected that the trend is correct and ceria shows a growing reduction extent for higher temperatures, for temperatures above this limit, there is an increased uncertainty for the absolute values. The correlations given by Bulfin et al. [28] shows at $p_{O_2} = 100$ Pa and $T = 2100$ K a reduction extent which is smaller by about 16%. Therefore, the absolute values should be handled with care. Nevertheless, the efficiency benefit is so pronounced, that either way, high final temperatures will stay favorable and the maximum temperature value should be selected as high as possible considering material constraints. In the study of Calle and Bayon [17] efficiency maxima have been found even close to operation temperatures of 2300 K for a concentration factor of 3000.

Even though ceria has a melting point well above 2100 K [29,30], sublimation might be a problem at lower temperatures and reduced pressures [31] and will have to be considered for the maximum temperature selection. The first experimental campaigns in combination with numerical simulations [11] suggest that temperatures above 2000 K at the RPC front have been reached for the investigated systems and significant material degradation has not been reported for these experiments. Based on these considerations, the maximum temperature is set to 2100 K in the following analysis.

Next, the effect of the pumping system sizing on the efficiency is analyzed. As parameter for the pumping system size the above introduced pumping number n_{pump} (see Eq. (4)) is used. In Fig. 6 the receiver-reactor efficiency is shown as function of n_{pump} for the case when the pump parasitics are included and for the case without pumping parasitics. The electrical energy demand is converted into a heat equivalent with a conversion efficiency of 30% and added to the parasitics in the efficiency calculation (see Eq. (5)). As shown in the figure, for the case with pump parasitics the receiver-reactor efficiency has an efficiency plateau starting at about

Fig. 6 – Analysis of pumping power parasitics on reactor efficiency. Different pump arrangement sizes are represented by the pump number n_{pump} .

$n_{pump} = 0.2$. For $n_{pump} > 0.3$ the efficiency drops due to the increasing pump power demand. Since higher pump number values are correlated with higher costs for the pumping system the lower range of this plateau with $n_{pump} = 0.2$ is used for the following analysis. One should notice the moderate improvements in the receiver-reactor efficiency above this value for substantially enlarged pumping systems.

The next analyzed parameter is the thickness of the RPC d_{RPC} . In the experimental campaigns of [9] a RPC with a thickness of 0.025 m was used. This value was also used in the numerical performance investigation presented in Ref. [10,11]. In Fig. 7 the efficiency is shown as function of the concentration factor for different RPC thicknesses. A total maximum of 8.6% can be identified for $d_{RPC} = 0.035$ m at a concentration value of about 3500. Thicker RPCs show small efficiency advantages at smaller concentration values but have disadvantages at larger concentration values. Since the solar fields, which will be described in the next chapter, provide concentration factors below 3500 on the receiver-reactors in more than 82% of the sun hours (see Fig. 14) a RPC thickness of 0.045 m is selected for the plant simulation.

The reduction step duration is the last analyzed receiver-reactor characteristic. If the duration can be tailored by design choices, additional flexibility for the optimization of a receiver-reactor array is provided. The thickness of the RPC has a significant impact on the reduction step duration as shown in Fig. 8. Thinner RPCs reach the maximum temperature faster and have therefore shorter reduction step durations. In the relevant concentration factor range RPCs with a thickness of 0.015 m reach the maximum temperature in less than half the time a RPC with a thickness of 0.055 m requires at the same concentration factor. For very high concentration factor values (>5000), the time becomes rather independent from the thickness of the RPC. Therefore, at moderate concentration factor values, the RPC thickness can be useful to optimize receiver-reactor arrays.

Fig. 7 – Performance characteristics of receiver-reactors with different RPC thicknesses. A maximum of 8.6% can be identified for a thickness of 0.035 m at a concentration factor of 3500.

Fig. 8 – Reduction step duration as function of the concentration factor C for different RPC thicknesses.

Solar field design

The next step towards the plant simulation is the design of the solar field and its properties for a MW plant. A solar tower system is selected as the most suitable option to design a MW-scale pre-commercial plant concept dedicated to solar thermochemical fuel production. To define the most appropriate configuration for the solar concentrator, a series of parametric studies is performed.

As fixed input values for these studies, Chile is selected as the location of the plant due to its high radiation levels on the Atacama Desert (around 3300 kWh/m²y), and the considered heliostat is the one implemented in the SUN-to-LIQUID pilot plant with a size of 3 m². Three parameters of the solar concentrator were varied during the study: the nominal incident power, the tower height and the expected time that the plant can work at nominal power (through the variation of heliostats on each nominal thermal power level). This last parameter is characterized by the Operation Ratio (OR) and is explained in detail below. A variation of heliostat sizes was omitted in this study but would be an interesting aspect to be included in future works. In total 27 cases have been examined. Further 27 cases have been evaluated for a second receiver-reactor size, but results show similar trends and are not included here for reasons of clarity. A summary of the parameters is displayed in Table 3.

Table 3 – Solar field study parameters.

Parameter Name	Value	Unit
DNI yearly sum	3300	kWh/m ² y
Heliostat size	3	m ²
CPC acceptance angle	25	
Solar receiver array nominal incident power	10, 30, 50	MWt
Solar receiver array operation ratio	65, 75, 85	%
Solar receiver array midpoint height	60, 80, 100 (80, 100, 120 for 50MWt)	m

As design point flux density a value of 2500 kW/m² at the aperture is selected. A secondary concentrator is deemed necessary to reach these high values. The use of the secondary concentrator implies a limitation in the incident angle of the arriving radiation [32], reducing the available solar field to an acceptance angle of 25° from the receiver. The selected compound parabolic concentrator (CPC) has an assumed efficiency of 80% and increases the flux density by a factor of 4 (this is a conservative assumption compared to previously published values between 86% and 92% [16,32]). Therefore, the field is laid out to provide an average flux density to the CPC of 625 kW/m² at design point.

The cyclic operation of the receiver-reactors can be separated into three phases (reduction, cooling, oxidation). Only during one of the phases - reduction - solar input is needed. To make continuous use of the solar field, and to avoid losing sun hours, three receivers-reactor arrays are installed on the tower. The three arrays are operated in turn. During the reduction phase of the first array, where the heating and reaction need thermal energy, all the heliostats of the field are focused on the selected receiver-reactor array. When the reduction step is finished, the field is moved to the next receiver-reactor array to start the reduction step. In this way, the solar field can always be pointed to one of the three receiver-reactor arrays and there is no loss of energy due to inactivity. Of course, this operational pattern is only realistic if the reduction step duration is 1/3 of the total cycle duration. Looking at the cycle times in Ref. [9] this is acceptable as a first estimate. Still, since the reduction step duration will vary depending on the current irradiation conditions, one will need a means to actively control the duration of the other two phases. This could be reached for example by using an inert heat transfer gas to actively cool the receiver-reactors during the cooling step (see Ref. [10]), adapt the oxidizer flow rate and inlet temperature or by having some means to physically change the size of the aperture to increase or decrease the heat losses. While the first two options seem easier to be applied, the latter one seems technically more challenging. If the times of the different steps are not such, that the reduction step can be adjusted to be about a third of the total cycle duration, one could also change the total number of receiver-reactor arrays to have a better match with the cycle durations. A scheme of the proposed tower configuration can be seen in Fig. 9.

Each receiver delimits an area on the ground where the acceptance angle condition is fulfilled, and an area where all heliostats can aim to all the positions on the receiver. To satisfy the conditions of acceptance angle and aiming point in the 3 receivers at the same time, the inner part of the solar layout is defined by the two upper receivers. The beginning point of the layout is determined by the highest aimed position on the upper receiver and the end line of the layout is determined by the lowest aimed position on the lower receiver. For this study, the optimum tilt of the receiver's surface is determined in each iteration.

The use of a single field in a 50 MW tower leads to an inefficient configuration with heliostats far away from the receiver. To increase the efficiency and reduce the maximum distances, multi-field configurations are proposed. Four configurations are studied, and a single field configuration was

Fig. 9 – Arrangement of three receiver-reactor arrays on solar tower.

selected for 10 MW and a three field configuration for 30 MW and 50 MW (see Fig. 10).

Assuming that the window is one of the size limiting factors, the size of each receiver-reactor is limited mostly by the size of the external window. To achieve values on the MW scale, several receiver-reactors are positioned in an array configuration (Fig. 11) to conform the receivers. Each reactor has an external hexagonal shape, formed by the secondary concentrator [32]. This shape allows a good array integration maintaining advantageous optical properties. For simulation

purposes, this shape is simplified into rectangles with the same aperture areas.

The solar resource is not a constant energy input - it varies day by day and along the day. For that reason, it is difficult to define a nominal power for a solar plant as it has been traditionally done for standard power plants. In solar to electric power plants, the nominal power of the plant is defined by the power block. The solar field is oversized to ensure minimum hours of operation, or a thermal energy storage system is used to decouple the availability of solar energy from the

Fig. 10 – Field configurations under study (External lines are boundary limits, red for selected heliostats and blue for available heliostats). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 11 – Positioning of receiver-reactors within an array configuration.

production. In a thermochemical fuel production plant without power block, the production is not constant, and it depends on the available solar input. Therefore, an operation ratio (OR) is defined to provide a metric on how close the nominal expected production is reached on a yearly basis.

The operation ratio is defined by the annual energy provided to the receiver-reactors fulfilling the minimum flux requirement divided by the energy received if the receiver-reactor worked 100% of the sun hours at nominal power.

$$OR = \frac{\text{useful received energy}}{\text{number of sun hours} \times P_{\text{nominal}}} \quad (6)$$

The different operation ratios used in this study (65%, 75% and 85%) are achieved by modifying the number of heliostats in each case.

For the simulation process, a ray tracing simulation is performed using in-house software of Abengoa. For each simulation, the described process is as followed: A first set of simulations is done for a total of twelve representative days of the year (one for each month). In this first set of simulations, a high number of heliostats are simulated, using as the aiming point the centre of the receiver. The most efficient heliostats and the optimum receiver tilt are selected through an iterative process. The second set of simulations is done for three representative days at nominal conditions, using the previously selected heliostats. In this second set of simulations, the aiming strategy is implemented, and the flux maps are obtained (see Fig. 12)).

For obtaining the aiming strategy, several iterations are needed in order to fulfil the flux density requirements and maximize the efficiency of the field. The last set of simulations is done for the whole year, using the selected heliostats of the first set of simulations and the aiming strategy obtained in the second set of simulations. In this last set, the efficiency of each heliostat on each instant of the year is obtained. All simulations are done on an hourly basis (one simulation every hour). The final global solar concentrator efficiency η_{field} is the mean value of the efficiency of each heliostat on each instant (hourly basis) for the whole year. The results are presented in Fig. 13. Similar efficiencies have been previously reported for high temperature solar tower systems [16,17,33].

From an efficiency standpoint, the results suggest that a modular low power configuration is preferable. These results

were expected due to the south field (above also referred to as single field) being the best option in a pure efficiency analysis due to the cosine effect (the plant location is in the southern hemisphere), and the closer the heliostat to the tower the better its performance.

As a result of the solar field design study, the flux density values at each receiver-reactor for a full year are obtained for the different field configurations. In Fig. 14 the receiver-reactor hours within certain concentration factor ranges are counted and displayed for different OR values. As can be seen higher OR values shift the distribution to higher concentration values. The maximum of the distributions is in the concentration value range of 2000–2500. The highest concentration values obtained are above 5000, but only for a very limited number of receiver-reactors and hours. A minimum concentration value of 1500 leads to significant losses reflected in the solar concentrator efficiencies. An optimized plant should make better use of these low flux hours.

The information about the flux density on each receiver-reactor on an hourly basis during the year is used together with the characteristics of single receiver-reactors to calculate the splitting plant performance.

Receiver-reactor array and splitting plant performance

The next step is the analysis of the receiver-reactor array in combination with the flux provided by the solar concentrating system. The flux profiles have been determined in the field optimization campaign and so far receiver-reactor characteristics are not directly considered in the optimization procedure. Therefore, different control strategies will be analyzed for the operation of the field to better align with the characteristics of the receiver-reactors operated in batch. To represent these field operation strategies after the field simulations, further assumptions have to be made. In all described strategies a receiver-reactor array is irradiated with a flux given by the hourly flux profiles obtained during the field performance simulations. It is assumed that the hourly flux provided by the field performance simulation cannot be increased further by the field operation strategies, but only be decreased by defocusing parts of the field.

The first investigated field control strategy is called “Full Focus Shift” (FFS) and considered as base case. As described above, for the termination of the reduction step of a single receiver-reactor a maximum temperature of the RPC is defined. As soon as the front of the RPC reaches this maximum temperature, the reduction step is stopped and the cooling step starts. In FFS the same principle is used for the operation of a complete array. As soon as the maximum temperature is reached in any of the receiver-reactors the reduction step of the receiver-reactor array is stopped and the aim points are shifted to the next receiver-reactor array to start the reduction step there.

As a result of this approach, most of the receiver-reactors within an array will not reach the targeted maximum temperatures. The consequences of the early termination of the reduction step for the yield of the single receiver-reactors are shown in Fig. 15.

Fig. 12 – Flux distribution for an 10 MW receiver-reactor array. The receiver-reactor numbers are given for better interpretation of Fig. 17.

The receiver-reactor within the array that reaches the maximum temperature is the one that has the highest concentration factor during that hour. The other ones have a lower radiative input and are heating up more slowly. In Fig. 15 the yield of a receiver-reactor is shown as a function of the concentration at the receiver-reactor, considering that the

highest concentration factor (C_{max}) during the selected hour is 3000, 4000 or 5000. As can be seen the yield drops quickly for concentration values below the maximum value and the higher C_{max} the lower the yield of a receiver-reactor at a given concentration factor. This is due to the fact, that the receiver-reactor with the highest concentration value determines the reduction step duration. The higher the maximum concentration value, the shorter the reduction step duration and consequently the lower the temperature and

Fig. 13 – Solar concentration efficiencies for the different field and tower parameters. The connected points show the efficiency dependency on the tower height for a combination of nominal incident power and operation ratio (P10_OR65 stands for a nominal power of 10 MW and an operation ratio of 65%).

Fig. 14 – Hourly counts of solar concentration values (including CPC) on all receiver-reactors of an array during a year for a 50 MW plant and a tower height of 80 m.

Fig. 15 – Receiver-reactor yield as function of the hourly concentration factor if the reduction step is terminated earlier due to the maximum temperature being reached in a receiver-reactor with the highest hourly concentration factor C_{max} . At a given concentration factor a receiver-reactor has a lower yield the higher C_{max} .

mean reduction extent change reached in another receiver-reactor for a given concentration factor.

For quantifying the resulting performance loss an array efficiency is defined as:

$$\eta_{array} = \frac{yield}{yield_{MAX}} \quad (7)$$

It relates the yield of an array for a given flux distribution and operation strategy to the hypothetical yield one would obtain for the same flux distribution but a completely independent operation of the single receiver-reactors ($yield_{MAX}$). The total efficiency of the plant η_{plant} is then given by:

$$\eta_{plant} = \eta_{field} \eta_{array} \eta_{reactor} \quad (8)$$

For the above introduced field designs and resulting flux conditions the array efficiencies for different operational strategies are calculated and displayed for systems with a tower height of 80 m in Fig. 16. The results for the other tower heights show similar trends and have comparable absolute values.

First the FFS array efficiencies are discussed. The FFS array efficiencies for the cases shown in Fig. 16 reach values between 52% and 68% (average 57%). The variations of the investigated solar concentrator designs have only a relatively small impact on the efficiency. The main reason for the losses is the bad off-design performance of receiver-reactors if the reduction step is stopped before the maximum temperature is reached. This is especially pronounced for strongly inhomogeneous flux distributions. As shown in Fig. 14 larger OR values shift the maximum of the concentration value distribution to larger values. Therefore, a larger OR value can have a negative effect on the array efficiency. An example of the variations in relative flux density resulting from the investigated solar concentration systems can be seen in Fig. 17.

Fig. 16 – Array efficiencies for the different solar concentrator designs (e.g. P10: nominal incident power = 10 MW; OR65: operation ratio = 65%) and operational strategies (HOM, LD, FFS).

Fig. 17 shows the flux ratio, defined as the local flux at one receiver-reactor divided by the maximum flux within the array during the same hour, for different receiver-reactors within an array of 19 receiver-reactors over the course of a year. Several receiver-reactors within the array reach average flux ratios well below 0.8, resulting in the low performance values of these receiver-reactors when the FFS strategy is applied. Receiver-reactor number 10 has the highest flux ratio during almost all hours of the year.

Two further operational strategies are analyzed. For these strategies it is assumed that the hourly flux distribution can be considered as upper limit, which can be modified at least by

Fig. 17 – Flux ratio variations over the course of a year for one representative field design and a number of selected receiver-reactors within the array. The figure on the right shows a histogram of the flux ratios. The positions of the receiver-reactors within an array are shown in Fig. 12.

locally reducing the flux by defocusing selected heliostats. Further, it is assumed that this can be done such, that only selected receiver-reactors are affected.

The first of these two strategies is called “Local Defocus” (LD). In this strategy the reduction step is stopped for selected receiver-reactors by defocusing the heliostats that point onto these receiver-reactors. This is done for a share of receiver-reactors (the number of which is optimized on an hourly basis), which reach the maximum temperature and start already to cool down while the rest of the receiver-reactors is still in the reduction step. The reduction step duration is consequently defined by the receiver-reactor with the smallest concentration factor that still reaches the maximum temperature. Interestingly, as a result of this strategy, the array efficiency values compared to the ones of the FFS strategy can be improved by about 34% even though heliostats are actively defocused (see Fig. 16).

Further efficiency improvement (46% compared to FFS) can be obtained by a strategy which is called “Homogenization” (HOM). With this strategy one attempts to obtain a more homogeneous flux distribution and to rather increase the spillage by defocusing heliostats. The flux of a share of receiver-reactors with the highest flux values is reduced to a target value. Also here the share has been optimized on an hourly basis. In contrast to LD, the defocusing is done right at the start of the reduction step and not only when the first receiver-reactors have reached the maximum temperature. As a result a number of receiver-reactors have the same current maximum flux value, which is below the highest flux value before the flux profile has been homogenized. When reducing the highest fluxes, the reduction duration is increased, giving the other receiver-reactors more time to heat up. This gives another improvement of about 9% relative to the LD case but it is still about 17% smaller than the maximum performance potential (see Fig. 16).

The discussion here shows that not only high fluxes are required for a good performance of a solar thermochemical splitting plant, but also an optimized flux distribution on the receiver-reactor array. This can be reached by precise heliostat control with low tracking error and optimized operational strategies. Additionally properties of the single receiver-reactors within an array can be tailored to better perform in an array considering the actual flux distribution pattern. Thereto one could, for example, increase the thickness of the RPC of receiver-reactors in the center of an array with high flux densities and reduce the ones at the edge or optimize the used CPC or aperture size locally. By this, more similar reduction durations and higher efficiencies could be obtained.

Summary and outlook

The batched operation of monolithic receiver-reactors results in new challenges when used in arrays for large-scale plants. The performance analysis of these systems is the aim of this study. A model of a monolithic receiver-reactor with ceria as

redox material serves as the basis for the analysis. The model has been used to simulate the receiver-reactor for boundary conditions, which are expected during batched operation in a solar thermochemical water splitting plant. Selected receiver-reactor operation and design parameters have been varied and the most promising system has been characterized for the splitting plant application.

In a dedicated campaign, solar fields providing the required high fluxes for the thermochemical redox cycle have been optimized for 27 different sets of parameters. As a result hourly flux maps for receiver-reactor arrays have been obtained for a large set of solar concentration system designs with variations in plant size, tower height and operational ratio.

When operating a set of batched receiver-reactor arrays, one has to develop new operational strategies for the field, which consider the characteristics of the single receiver-reactors. An array efficiency is introduced to quantify the performance of an operational strategy compared to the hypothetical case of the completely independent operation of all single receiver-reactors given the provided hourly flux distributions. The base strategy FFS leads to an off-design operation of a large share of the receiver-reactors resulting in an array efficiency of about 57%. The solar concentration system design parameters show only limited impact on the FFS performance.

Improved heliostat tracking quality and aim point strategies could help generating flux profiles with higher yield. The performance can already be significantly improved if the field can be controlled such, that the flux at single receiver-reactors is reduced by defocusing selected heliostats. With the LD strategy the array efficiency can be improved by about 34% compared to the simple FFS. Further improvements can be obtained by reducing upfront the peaks in the flux distribution as investigated in the HOM strategy (46% compared to FFS).

Additionally, the optimized design of single receiver-reactors within an array can help coping with inhomogeneous flux distributions. Even more important, the receiver-reactor characteristics should be directly included in the field optimization considering the special characteristics for a receiver-reactor array with more flexible aim point strategies.

However, all these efforts are limited by the performance of single monolithic receiver-reactors. Its improvement is mandatory to advance the potential of this technology. So far, up-scaling results only in small improvements due to the characteristics of the considered ceria RPCs. It will be important to optimize the redox material as well as the RPC structures to allow a better usage of the entire redox material. Also new heat recovery systems and strategies for receiver-reactor arrays will have to be elaborated and implemented.

Some of these challenges are particular to the monolithic batched technology assessed in this study and might be prevented by other approaches like concepts with continuously operated receivers [17,26,34,35]. Further optimization potential could be made accessible by indirect concepts [23], where the absorption of concentrated solar radiation is decoupled

from the reduction step, easing also the burden on the oxygen removal system. Thus, even though significant progress has been reported for the monolithic receiver-reactors in the last years, more effort is required to overcome the efficiency challenges at large scale of this technology.

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