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# Oxygen nonstoichiometry and thermodynamic characterization of Zr doped ceria in the 1573–1773 K temperature range†

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This work encompasses the thermodynamic characterization and critical evaluation of Zr<sup>4+</sup> doped ceria, a promising redox material for the two-step solar thermochemical splitting of H<sub>2</sub>O and CO<sub>2</sub> to H<sub>2</sub> and CO. As a case study, we experimentally examine 5 mol% Zr<sup>4+</sup> doped ceria and present oxygen nonstoichiometry measurements at elevated temperatures ranging from 1573 K to 1773 K and oxygen partial pressures ranging from 4.50 × 10<sup>-3</sup> atm to 2.3 × 10<sup>-4</sup> atm, yielding higher reduction extents compared to those of pure ceria under all conditions investigated, especially at the lower temperature range and at higher p<sub>O<sub>2</sub></sub>. In contrast to pure ceria, a simple ideal solution model accounting for the formation of isolated oxygen vacancies and localized electrons accurately describes the defect chemistry. Thermodynamic properties are determined, namely: partial molar enthalpy, entropy, and Gibbs free energy. In general, partial molar enthalpy and entropy values of Zr<sup>4+</sup> doped ceria are lower. The equilibrium hydrogen yields are subsequently extracted as a function of the redox conditions for dopant concentrations as high as 20%. Although reduction extents increase greatly with dopant concentration, the oxidation of Zr<sup>4+</sup> doped ceria is thermodynamically less favorable compared to pure ceria. This leads to substantially larger temperature swings between reduction and oxidation steps, ultimately resulting in lower theoretical solar energy conversion efficiencies compared to ceria under most conditions. In effect, these results point to the importance of considering oxidation thermodynamics in addition to reduction when screening potential redox materials.

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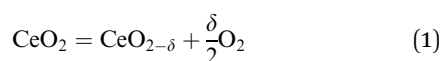
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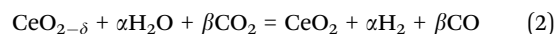
## Introduction

Solar-driven thermochemical redox cycles utilizing nonstoichiometric metal oxides are capable of splitting H<sub>2</sub>O and CO<sub>2</sub> to produce H<sub>2</sub> and CO (syngas), the precursors to the catalytic synthesis of conventional liquid fuels.<sup>1,2</sup> Ceria (CeO<sub>2</sub>) is currently considered a state-of-the-art material because it displays rapid oxidation and reduction kinetics and is morphologically stable over a range of temperatures and reduction extents.<sup>3</sup> The two-step thermochemical cycle using CeO<sub>2</sub> as reactive intermediate is represented by:

Reduction at T<sub>red</sub>:



Oxidation at T<sub>ox</sub>:



where  $\alpha + \beta = \delta$ . In the endothermic first step, eqn (1), ceria is reduced typically under an atmosphere of low oxygen partial pressure (p<sub>O<sub>2</sub></sub>) at elevated temperatures, generally T<sub>red</sub> > 1573 K, where the process heat is delivered by concentrated solar energy. In an exothermic second step, eqn (2), the reduced ceria is re-oxidized with H<sub>2</sub>O or CO<sub>2</sub> at lower temperatures, generally T<sub>ox</sub> < 1573 K, to produce H<sub>2</sub> or CO. The oxygen nonstoichiometry (δ) achieved during reduction depends strongly on T<sub>red</sub> and p<sub>O<sub>2</sub></sub> in the system<sup>4,5</sup> and is directly related to the maximum amount of H<sub>2</sub>/CO capable of being produced per mole ceria in the second step. As ceria is not consumed within the process, the net reactions are H<sub>2</sub>O = H<sub>2</sub> + 1/2O<sub>2</sub> and CO<sub>2</sub> = CO + 1/2O<sub>2</sub>. In contrast to direct thermolysis, two-step redox cycles bypass the separation of fuel and O<sub>2</sub> at high temperatures. Contrary to photochemical processes, solar thermochemical processes utilize the entire solar spectrum and thus offer a thermodynamically favorable path towards fuel production.

Since the reduction extent of ceria is generally lower than those obtained by other appropriate redox materials (e.g. ferrite,

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zinc oxide), its specific fuel production per mass is low.<sup>3,6</sup> This has a direct implication on efficiencies because they are largely dictated by the ratio of fuel produced to that of the thermal energy required to heat the oxide between oxidation and reduction steps.<sup>7</sup> Therefore, in an attempt to increase reduction extents, 4+ valence dopants such as Zr<sup>4+</sup><sup>8–12</sup> and Hf<sup>4+</sup><sup>8,13</sup> are often introduced into the ceria lattice. Cycling studies of Zr<sup>4+</sup> doped ceria have shown favorable reduction extents during reduction, but slower re-oxidation kinetics with CO<sub>2</sub><sup>8,11</sup> or H<sub>2</sub>O<sup>14</sup> were observed compared to pure ceria. Scheffe *et al.*<sup>8</sup> showed that reduction extents of Zr<sup>4+</sup> and Hf<sup>4+</sup> doped ceria increase with increasing dopant concentration up to 15 mol% whereas re-oxidation is generally slower than pure ceria but appeared to be strongly dependent on available surface area. Call *et al.*<sup>11</sup> concluded that reduction extents increase for dopant concentrations up to 22.5 mol%. Le Gal *et al.*<sup>14</sup> observed increasing oxygen release up to dopant concentrations of 25 mol% Zr<sup>4+</sup> but the reduced forms could not be completely re-oxidized with steam at 1323 K. In summary, most of the above studies report consistent results, namely increasing reduction extents with 4+ valence dopant concentration but at the same time slower oxidation kinetics. Comparison between different works is difficult because the detailed experimental conditions (*e.g.* particle size) are generally not reported or controlled, and it is not clear from these studies whether thermodynamic limitations or inherent kinetics hinder the rates.

Thermodynamic studies have been performed at temperatures below the range of interest for thermochemical cycles. For example, Kuhn *et al.*<sup>10</sup> reported oxygen nonstoichiometric measurements of Zr<sup>4+</sup> doped ceria at  $T \leq 1273$  K and dopant concentrations between 5 and 80 mol%. Shah *et al.*<sup>15</sup> reported measurements for Zr<sup>4+</sup> concentrations of 19 and 75 mol% at  $T \leq 1173$  K and  $p_{\text{O}_2} \leq 10^{-10}$  atm. Very recently, Hao *et al.*<sup>12</sup> published nonstoichiometric measurements at higher temperatures for Zr<sup>4+</sup> dopant concentrations up to 20 mol% in the range  $T = 873$  K to 1763 K and  $p_{\text{O}_2} \approx 10^{-27}$  atm to 1 atm. All three studies<sup>10,12,15</sup> indicate a higher oxygen nonstoichiometry of doped ceria compared to pure ceria, which increases with increasing dopant concentration up to 20 mol%, and derive enthalpy and entropy values slightly lower than those for pure ceria.<sup>4,5,16,17</sup>

In this work, we evaluate the thermochemical performance of Zr<sup>4+</sup> doped ceria by using 5 mol% as a case study. Oxygen nonstoichiometry is reported in the operation range of solar reactors ( $1573 \text{ K} \leq T_{\text{red}} \leq 1773 \text{ K}$ ,  $2.3 \times 10^{-4} \text{ atm} < p_{\text{O}_2} < 4.50 \times 10^{-3} \text{ atm}$ ) for 5 mol% Zr<sup>4+</sup> doped ceria (CZO\_5) and undoped ceria (CeO<sub>2</sub>). We develop appropriate defect models to describe the defect chemical equilibria and in turn extract partial molar thermodynamic properties ( $\Delta h_{\text{O}}$ ,  $\Delta s_{\text{O}}$  and  $\Delta g_{\text{O}}$ ). From such data coupled with thermodynamic data from the literature, we determine equilibrium hydrogen yields and theoretical solar-to-fuel energy conversion efficiencies for dopant concentrations as high as 20 mol%. This analysis allows a straightforward and quantitative methodology for evaluating the potential of Zr<sup>4+</sup> doped ceria used in solar thermochemical redox cycles.

## Experimental section

### Synthesis technique and sample characterization

5 mol% Zr<sup>4+</sup> doped CeO<sub>2</sub> (CZO\_5) powder was synthesized by sol-gel method as described by Scheffe *et al.*<sup>8</sup> Briefly, Ce(NO<sub>3</sub>)<sub>3</sub>·6H<sub>2</sub>O (Aldrich, catalog number 238538), ZrO(NO<sub>3</sub>)<sub>2</sub>·6.3H<sub>2</sub>O (Aldrich, catalog number 243493) and dry citric acid (Merck, catalog number 818707) in aqueous solution were used to carry out the synthesis. The ratio of the metal cations to the citric acid was 1 : 1.5. CeO<sub>2</sub> powder was purchased from a commercial distributor (Aldrich, catalog number 211575). CeO<sub>2</sub> and CZO\_5 powders were uniaxially cold-pressed at 5 tons and sintered at 1873 K under air atmosphere for 5 hours into ~1250 mg dense cylindrical pellets. The approximate dimensions after sintering were 7 mm diameter and 5 mm height. The CZO\_5 dopant concentration was measured by inductively coupled plasma mass spectrometry (ICP-MS) analysis and was 4.5 mol%. Powder X-ray diffraction (XRD) was performed in the Bragg Brentano geometry using Cu K $\alpha$  radiation (Philips, PANalytical/X'Pert MPD/DY636,  $\lambda = 1.5406 \text{ \AA}$ ,  $2\theta = 20\text{--}100^\circ$ ,  $0.01^\circ \text{ s}^{-1}$  scan rate, 45 kV/20 mA output). Scanning electron microscopy (SEM) of the dense pellets were conducted on a TM-1000 Microscope (Hitachi, 15 kV accelerating voltage). XRD patterns and SEM images are shown in ESI.†

### Experimental measurements

Oxygen nonstoichiometry ( $\delta$ ) was measured using a thermogravimetric analyzer (TGA, Setaram Setsys Evolution). Samples were suspended to the scale with a custom-made platinum hook to ensure good exposure to the purge gas and eliminate gas diffusion limitations. Special care was taken to ensure that reduction and oxidation reactions were not limited by gaseous mass transfer but by solid-state diffusion and/or surface reactions. The  $p_{\text{O}_2}$  of the surrounding gas atmosphere was controlled by mixing Ar (Messer, Argon 4.6) with an O<sub>2</sub>-Ar mixture (Messer, 0.5% O<sub>2</sub> 5.0 in Ar 5.0). Gases were mixed with electronic mass flow controllers (Brooks, Model 5850TR, accuracy  $\pm 1\%$ ) with a constant total flow rate of  $200 \text{ ml min}^{-1}$ . The gas species and concentrations at the outlet were monitored by mass spectrometry (Pfeiffer Vacuum, OmniStar GSD 320). Temperature was varied between 1573 K and 1773 K and  $p_{\text{O}_2}$  between  $4.50 \times 10^{-3} \text{ atm}$  and  $2.3 \times 10^{-4} \text{ atm}$ . In all measurements, the sample mass ( $m_{\text{s}}$ ) was equilibrated at a constant temperature and  $p_{\text{O}_2}$ . Following each equilibrium measurement, the  $p_{\text{O}_2}$  was rapidly changed by adapting the O<sub>2</sub>-Ar gas mixture, resulting in a temporal weight change of the sample due to evolving or uptaking of oxygen until a new equilibrium was reached. To correct for buoyancy, blank runs were performed with Al<sub>2</sub>O<sub>3</sub> sintered pellets of same dimensions. An additional correction was applied for a small amount of sample sublimation ( $< 0.04 \text{ wt\%}$ ) observed above 1723 K.

### Oxygen nonstoichiometry

An exemplary experiment showing the dynamics of the reduction (decreasing  $p_{\text{O}_2}$ ) and oxidation (increasing  $p_{\text{O}_2}$ ) of CZO\_5 and CeO<sub>2</sub> at 1573 K and 1773 K is shown in Fig. 1(a). Initially, their



weights were stabilized at a constant  $p_{\text{O}_2}$ , followed by a rapid  $p_{\text{O}_2}$  decrease to initiate reduction. After stabilization at the new  $m_s$ ,  $p_{\text{O}_2}$  is increased back to its initial value to commence oxidation. At 1573 K, the reduction and oxidation of CZO\_5 are noticeably slower than those of CeO<sub>2</sub>. However, at 1773 K, the kinetic rates are similar for both materials. If surface reactions are assumed not to be limiting – a reasonable assumption at these length scales – this would imply that the activation energy for ambipolar diffusion is higher in the case of CZO\_5.

Fig. 1(b) shows the mass change in wt% of CeO<sub>2</sub> and CZO\_5 as a function of time for  $T = 1673$  K for a broader range of  $p_{\text{O}_2}$  and Fig. 1(c) shows all the reduction and oxidation runs over all temperatures and  $p_{\text{O}_2}$ . Samples were heated to 5 different set point temperatures followed by isothermal reduction and oxidation by stepwise changing  $p_{\text{O}_2}$ . As seen, CZO\_5 released more oxygen than CeO<sub>2</sub> under all measurement conditions. The much slower oxidation of CZO\_5 at 1073 K agrees well with the observation that its activation energy for ambipolar diffusion is higher than CeO<sub>2</sub> (cf. Fig. 1(a) and discussion above). A total sublimated mass of 0.40 mg and 0.32 mg at 1773 K was observed for CeO<sub>2</sub> and CZO\_5, respectively.

Oxygen nonstoichiometry is calculated according to:

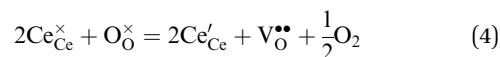
$$\delta = \Delta m_s \cdot \frac{M_s}{M_{\text{O}}} \quad (3)$$

where  $\Delta m_s$  is the relative weight loss at equilibrium,  $M_s$  is the molar mass of the sample and  $M_{\text{O}}$  the molar mass of O. Measured  $\delta$  versus  $p_{\text{O}_2}$  of CeO<sub>2</sub> and CZO\_5 for all temperatures investigated are shown in Fig. 2(a) and (b), respectively. Open symbols show  $\delta$  measurements of this work whereas literature data are shown by closed symbols (Panlener *et al.*<sup>4</sup>) and crossed symbols (Iwasaki *et al.*<sup>18</sup>). Lines indicate defect models used to describe  $\delta$ , presented in the following section. As seen,  $\delta$  of

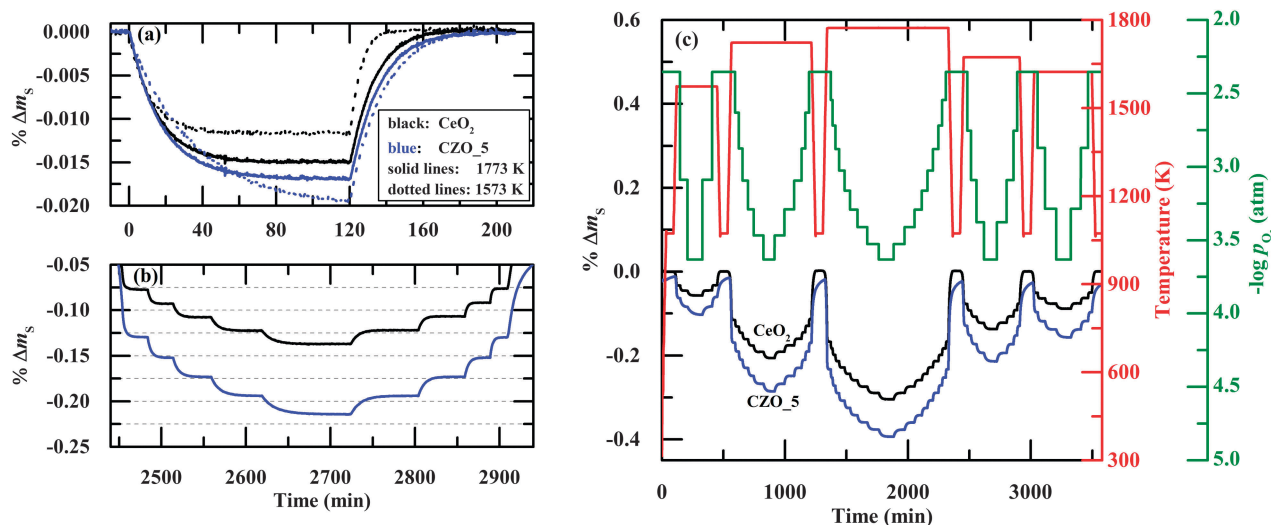
CZO\_5 is higher over the whole measurement range investigated compared to CeO<sub>2</sub>. Improvement in oxygen release is highest at low  $T_{\text{red}}$  and high  $p_{\text{O}_2}$ . For example, at  $T = 1623$  K and  $p_{\text{O}_2} \approx 4.50 \times 10^{-3}$  atm, the improvement is almost 90% per mole of oxide ( $\delta = 0.010$  for CZO\_5 and  $\delta = 0.0055$  for CeO<sub>2</sub>) and around 27% at  $T = 1773$  K and  $p_{\text{O}_2} \approx 2.3 \times 10^{-4}$  atm ( $\delta = 0.042$  for CZO\_5 and  $\delta = 0.033$  for CeO<sub>2</sub>). Nonstoichiometry of CZO\_5 at 1573 K is not shown because the sample weight did not equilibrate completely within the allotted time due to slower kinetics.  $\delta$  values of pure CeO<sub>2</sub> measured in this work are slightly higher than the values reported in literature,<sup>4,18</sup> especially towards higher  $p_{\text{O}_2}$ . The reason for the discrepancy is not clear but may be related to sample impurities and sublimation. Panlener *et al.*<sup>4</sup> performed oxygen nonstoichiometry measurements based on thermogravimetric analysis over a broad range of  $p_{\text{O}_2}$  from 0.01 atm to  $10^{-23}$  atm between 873 K and 1773 K while Iwasaki *et al.*<sup>18</sup> performed measurements only at temperatures up to 1573 K.

## Defect model

Defect models were used to describe the chemical equilibria of both CeO<sub>2</sub> and CZO\_5. For small reduction extents (as small as  $\delta = 0.01$  for pure ceria and higher with dopant type and dopant concentration<sup>19</sup>) the reduction of ceria and doped ceria can be described in Kröger–Vink notation as:



where oxygen atoms on oxygen lattice sites ( $\text{O}_{\text{O}}^{\times}$ ) and cerium on cerium lattice sites ( $\text{Ce}_{\text{Ce}}^{\times}$ ) are in equilibrium with gaseous oxygen, doubly ionized oxygen vacancies ( $\text{V}_{\text{O}}^{\bullet\bullet}$ ) and electrons localized on cerium lattice sites ( $\text{Ce}'_{\text{Ce}}$ ). Assuming there are no



**Fig. 1** (a) Mass change in wt% as a function of time for the reduction and oxidation of CeO<sub>2</sub> (black) and CZO\_5 (blue) at  $T = 1773$  K where  $p_{\text{O}_2}$  was changed between  $3.0 \times 10^{-4}$  atm and  $2.3 \times 10^{-4}$  atm (solid lines) and at  $T = 1573$  K where  $p_{\text{O}_2}$  was changed between  $8.1 \times 10^{-4}$  atm and  $2.3 \times 10^{-4}$  atm (dotted lines). (b) Mass change in wt% as a function of time for the reduction and oxidation runs of CeO<sub>2</sub> (black) and CZO\_5 (blue) at  $T = 1673$  K and  $\text{O}_2$  partial pressure range  $p_{\text{O}_2} = 4.50 \times 10^{-3}$ – $2.3 \times 10^{-4}$  atm. (c) Mass change in wt% as a function of time for all the reduction and oxidation runs of CeO<sub>2</sub> and CZO\_5 in the temperature range  $T = 1573$ – $1773$  K and  $\text{O}_2$  partial pressure range  $p_{\text{O}_2} = 4.50 \times 10^{-3}$ – $2.3 \times 10^{-4}$  atm.



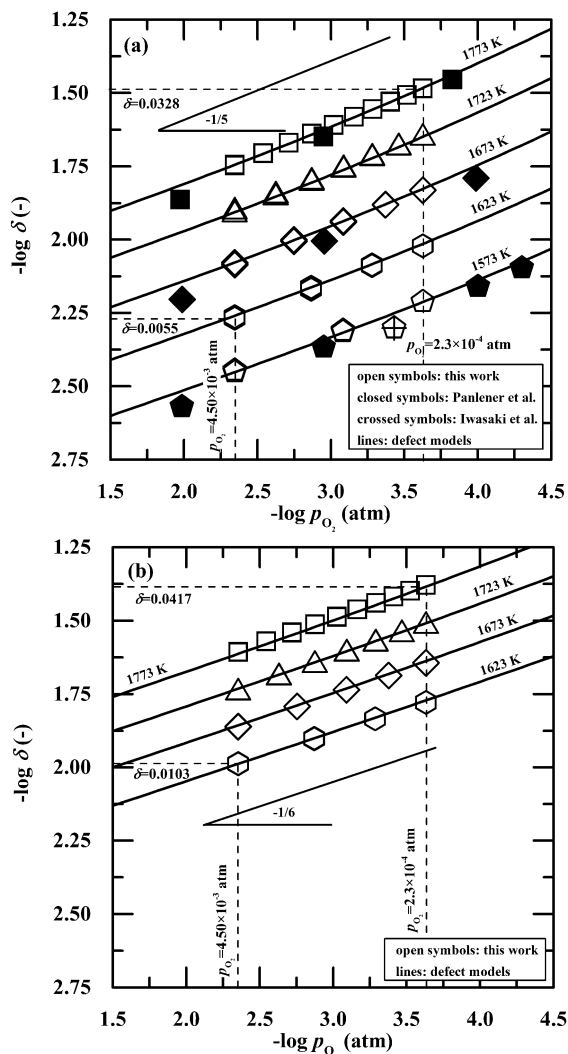


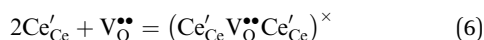
Fig. 2 Measured  $\delta$  (open symbols) of  $CeO_2$  (a) and  $CZO_5$  (b) for  $T = 1573$  K to  $1773$  K and  $p_{O_2} = 4.50 \times 10^{-3}$  atm to  $2.3 \times 10^{-4}$  atm and a comparison to literature data: Panlener *et al.*<sup>4</sup> closed symbols, Iwasaki *et al.*<sup>18</sup> crossed symbols. Lines indicate defect models used to describe  $\delta$ .

cluster formations between the various defects,  $\delta$  can be described by:<sup>10,20</sup>

$$\delta = \text{constant} \cdot p_{O_2}^{-1/6} \Big|_{T=\text{const.}} \quad (5)$$

which implies a slope of  $-1/6$  when plotting  $\log \delta$  versus  $\log p_{O_2}$ .

For larger deviations from stoichiometry, the formation of oxygen vacancy-polaron associations  $(Ce'_{Ce}V_O^{\bullet\bullet}Ce'_{Ce})^{\times}$  should be accounted for, and is described as:



Assuming all defects form associations according to eqn (6),<sup>20</sup>

$$\delta = \text{constant} \cdot p_{O_2}^{-1/2} \Big|_{T=\text{const.}} \quad (7)$$

As seen in the case of  $CeO_2$  (Fig. 2(a)), the slope of  $\log \delta$  vs.  $\log p_{O_2}$  best describing the data is close to  $-1/5$ , indicating that eqn (5) cannot adequately describe its defect equilibria, in

agreement with previous investigations.<sup>4,16,19,21,22</sup> A slope of  $-1/5$  indicates that a combination of both defect models (eqn (4) and (6)) is needed to accurately describe ceria's defect chemistry, as evidenced by Otake *et al.*<sup>19</sup> who showed that the isolated defect model is only valid for very low nonstoichiometries ( $\delta < 0.01$ ). A slope of  $-1/6$ , on the other hand adequately describes the data of  $CZO_5$  over the entire measurement range. This is consistent with observations of 3+ valence dopants such as  $Sm^{3+}$ ,<sup>22,23</sup>  $Gd^{3+}$ ,<sup>22,24,25</sup> and  $Y^{3+}$ ,<sup>19</sup> but in such cases much higher concentrations are required to describe the measurement data with only a single defect model. For example, when doping ceria with 10 mol%  $Y^{3+}$ , a single isolated defect model can only describe the data up to  $\delta \approx 0.02$ , whereas in the case of 20 mol% it is valid until  $\delta \approx 0.03$ . Here, with only 5 mol%  $Zr^{4+}$  a single model appears to adequately describe  $\delta$  at least until  $\delta \approx 0.04$ .

The nonstoichiometry as a function of  $T$  and  $p_{O_2}$  may be modelled by fitting appropriate equilibrium constants from eqn (4) and (6) to the experimental data. To do so, the following site and charge relations for 4+ valence dopants and pure ceria<sup>19</sup> are needed:

$$[Ce_{Ce}^{\times}] = 1 - 2\delta - X \quad (8)$$

$$[O_O^{\times}] = 2 - \delta \quad (9)$$

$$2[V_O^{\bullet\bullet}] = [Ce'_{Ce}] \quad (10)$$

$$2\delta = [Ce'_{Ce}] + 2[(Ce'_{Ce}V_O^{\bullet\bullet}Ce'_{Ce})^{\times}] \quad (11)$$

where  $X = 0.045$  is the dopant concentration of  $Zr^{4+}$  in the case of  $CZO_5$ . Thus, the equilibrium constants  $K_1$  for eqn (4) and  $K_2$  for eqn (6) are given by:

$$K_1 = \frac{[Ce'_{Ce}]^2 [V_O^{\bullet\bullet}] p_{O_2}^{1/2}}{[Ce_{Ce}^{\times}]^2 [O_O^{\times}]} = \frac{4 [V_O^{\bullet\bullet}]^3 p_{O_2}^{1/2}}{(1 - 2\delta - X)^2 (2 - \delta)} \quad (12)$$

$$K_2 = \frac{[(Ce'_{Ce}V_O^{\bullet\bullet}Ce'_{Ce})^{\times}]}{[Ce'_{Ce}]^2 [V_O^{\bullet\bullet}]} = \frac{\delta - [V_O^{\bullet\bullet}]}{4 [V_O^{\bullet\bullet}]^3} \quad (13)$$

$K_1$  and  $K_2$  can be determined through a least square minimization of eqn (12) and (13) with the experimental nonstoichiometry data. Results are summarized in Fig. 3(a) and (b) for  $CeO_2$  and  $CZO_5$ , respectively. As expected,  $K_1$  for  $CZO_5$  is higher compared to that for  $CeO_2$  because of its higher reduction extent. Additionally, the slope for  $CeO_2$  is higher than that for  $CZO_5$ , indicating that its reduction enthalpy (at least at low  $\delta$  where the reaction is dominated by  $K_1$ ) is higher and consistent with Kuhn *et al.*<sup>10</sup>  $K_2$  for  $CeO_2$  is decreasing with increasing temperature meaning defect interactions become less predominant at higher temperatures.  $K_2$  for  $CZO_5$  does not show a meaningful trend and values are much smaller than for  $CeO_2$  because defect associations are probably not significant under the conditions investigated. In fact, in the case of  $CZO_5$  at 1573 K, the best fit of  $K_2$  is orders of magnitude below the fits at higher temperatures. These findings directly support the conclusions drawn from Fig. 2, namely that a single isolated defect



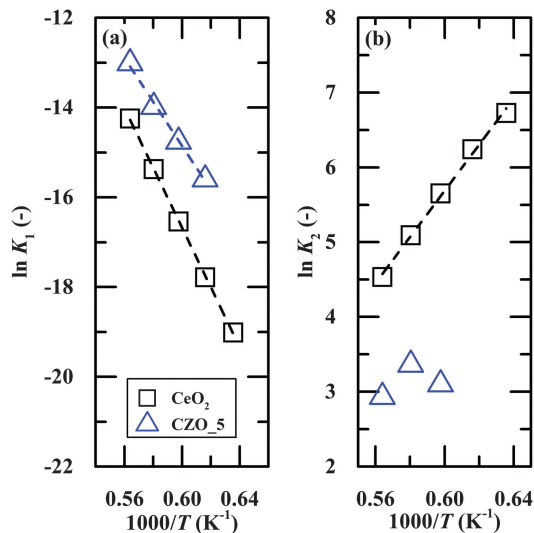


Fig. 3 Equilibrium constants versus inverse temperature for  $\text{CeO}_2$  and  $\text{CZO}_5$ : (a)  $K_1$ ; and (b)  $K_2$ . Dashed lines indicate linear dependence of  $K_1$  and  $K_2$  on  $1000/T$  ( $R^2 > 0.99$ ).

model appears to adequately describe the defect chemistry of  $\text{CZO}_5$ , whereas electron-vacancy associations should be additionally taken into account in the case of  $\text{CeO}_2$ . By fitting  $K_1$  and  $K_2$  over all experimental data, indicated by the lines in Fig. 2(a) and (b), it can be seen that the agreement is very good. When including both defect models, the RMS deviations of the fitted  $\log p_{\text{O}_2}$  (cf. Fig. 2) are 0.013 and 0.005 in the case of  $\text{CeO}_2$  and  $\text{CZO}_5$ , respectively. Both deviations are less than the uncertainty in the  $p_{\text{O}_2}$  setting, equal to 0.017. Considering only the isolated defect model (eqn (4)) the RMS deviations are 0.094 for  $\text{CeO}_2$  and 0.038 for  $\text{CZO}_5$ . This reflects that defect associations are more important in the case of  $\text{CeO}_2$  than in the case of  $\text{CZO}_5$ . The improvement in the RMS deviation for  $\text{CZO}_5$  when including electron-vacancy associations may rather be a result of having an additional fitting parameter than having a more adequate physical model (cf. trend of  $K_2$  for  $\text{CZO}_5$  in Fig. 3(b)).

Based on computational investigations, Yang *et al.*<sup>26</sup> concluded that an oxygen vacancy is most likely created close to a  $\text{Zr}^{4+}$ -dopant which might serve as nucleation center for vacancy clustering. Based on these results, Kuhn *et al.*<sup>10</sup> proposed that the considerably smaller  $\text{Zr}^{4+}$ , compared with  $\text{Ce}^{4+}$ , prefers a 7-fold coordination (instead of 8-fold) with oxygen which can be achieved if an oxygen vacancy is created next to the smaller  $\text{Zr}^{4+}$  cation. Therefore,  $(\text{Zr}_{\text{Ce}}^{\times} \text{V}_{\text{O}}^{\bullet})^{\bullet\bullet}$  instead of  $(\text{Ce}'_{\text{Ce}} \text{V}_{\text{O}}^{\bullet} \text{Ce}'_{\text{Ce}})^{\times}$  associations were also tested, but this did not improve the isolated defect model within the  $\delta$ -range investigated.

## Thermodynamic properties

Thermodynamic properties, namely partial molar enthalpy ( $\Delta h_{\text{O}}$ ), partial molar entropy ( $\Delta s_{\text{O}}$ ) and partial molar Gibbs free energy ( $\Delta g_{\text{O}}$ ), defined per mole of monoatomic oxygen, can be

determined as a function of  $\delta$ , temperature and  $p_{\text{O}_2}$  according to eqn (14) and (15).

$$\Delta g_{\text{O}} = \frac{1}{2}RT \ln p_{\text{O}_2} \quad (14)$$

$$\Delta g_{\text{O}} = \Delta h_{\text{O}} - T\Delta s_{\text{O}} \quad (15)$$

By combining eqn (14) and (15) it is clear that  $\Delta h_{\text{O}}$  and  $\Delta s_{\text{O}}$  as a function of  $\delta$  can both be solved by determining the slope and intercept of  $\ln p_{\text{O}_2}$  versus  $1/T$  for a constant  $\delta$ , as shown in eqn (16).

$$\frac{1}{2} \ln p_{\text{O}_2} = \frac{\Delta h_{\text{O}}}{RT} - \frac{\Delta s_{\text{O}}}{R} \Big|_{\delta=\text{const.}} \quad (16)$$

Constant  $\delta$  values are obtained by interpolating our defect models within the temperature range investigated (1573 K to 1773 K) and a slightly extrapolated  $p_{\text{O}_2}$  range ( $\pm 20\%$  of the measured  $-\log p_{\text{O}_2}$  range). Results of  $\Delta h_{\text{O}}$  and  $\Delta s_{\text{O}}$  versus  $\delta$  are shown in Fig. 4 and 5, respectively, for  $\text{CeO}_2$  (open squares) and  $\text{CZO}_5$  (open triangles) measurements from this work. For reference we have included  $\text{CeO}_2$  data of Panlener *et al.*,<sup>4</sup> Campserveux *et al.*,<sup>17</sup> Bevan *et al.*<sup>5</sup> and Sørensen.<sup>16</sup> Additionally, measurements of  $\text{CZO}_5$  by Kuhn *et al.*<sup>10</sup> and Hao *et al.*<sup>12</sup> are indicated by closed and crossed triangles, respectively. Measurements of 20 mol%  $\text{Zr}^{4+}$  doped  $\text{CeO}_2$  ( $\text{CZO}_{20}$ ) by Kuhn *et al.*<sup>10</sup> and Hao *et al.*<sup>12</sup> are indicated by closed circles and crossed circles, respectively. In general, it can be observed that  $\Delta h_{\text{O}}$  increases with increasing dopant concentration. This is expected due to the ease with which  $\text{Zr}^{4+}$  doped ceria reduces compared to pure ceria.

Towards higher  $\delta$ , the  $\Delta h_{\text{O}}$  values are in good agreement with literature data of  $\text{CeO}_2$ <sup>4,5,16,17</sup> and  $\text{CZO}_5$ .<sup>10,12</sup> However, at lower  $\delta$ , they deviate. The same trend can be observed for  $\Delta s_{\text{O}}$ .

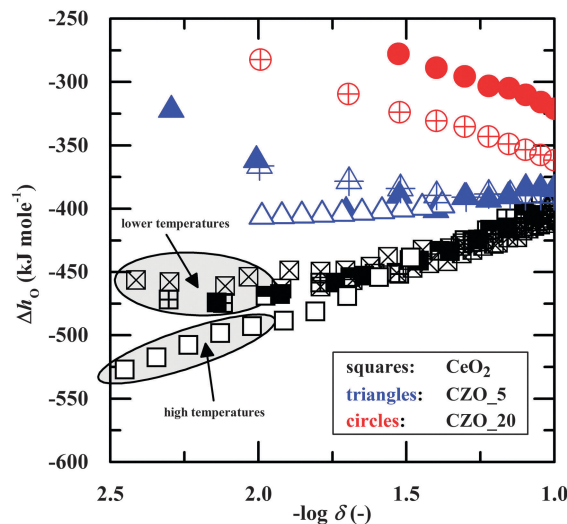


Fig. 4 Partial molar enthalpy of  $\text{CeO}_2$  (open squares) and  $\text{CZO}_5$  (open triangles) as a function of  $\delta$  and a comparison to literature data of  $\text{CeO}_2$  (Panlener *et al.*<sup>4</sup> closed squares, Campserveux *et al.*<sup>17</sup> diagonally crossed squares, Bevan *et al.*<sup>5</sup> half closed squares, Sørensen.<sup>16</sup> crossed squares),  $\text{CZO}_5$  (Kuhn *et al.*<sup>10</sup> closed triangles, Hao *et al.*<sup>12</sup> crossed triangles) and  $\text{CZO}_{20}$  (Kuhn *et al.*<sup>10</sup> closed circles, Hao *et al.*<sup>12</sup> crossed circles).



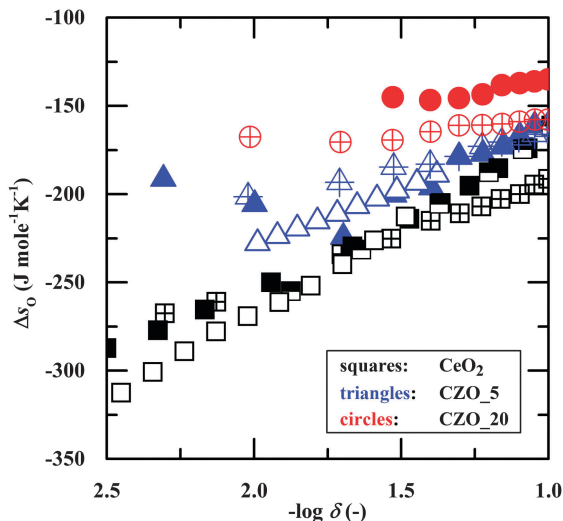
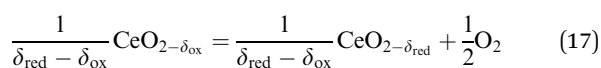


Fig. 5 Partial molar entropy of CeO<sub>2</sub> (open squares) and CZO<sub>5</sub> (open triangles) as a function of  $\delta$  and a comparison to literature data of CeO<sub>2</sub> (Pantlener *et al.*<sup>4</sup> closed squares, Bevan *et al.*<sup>5</sup> half closed squares, Sørensen<sup>16</sup> crossed squares), CZO<sub>5</sub> (Kuhn *et al.*<sup>10</sup> closed triangles, Hao *et al.*<sup>12</sup> crossed triangles) and CZO<sub>20</sub> (Kuhn *et al.*<sup>10</sup> closed circles, Hao *et al.*<sup>12</sup> crossed circles).

Deviations can be attributed primarily to different measurement temperatures and to a lesser extent to differences in nonstoichiometry measurements. For example, the literature data shown in Fig. 4 and 5 were calculated based on measurements below 1573 K<sup>5,10,16,17</sup> or as an average of measurements at higher (>1573 K) and lower temperatures (<1573 K),<sup>4,12</sup> whereas values of this work are based on measurements only above 1573 K. Although it is often assumed that  $\Delta h_{\text{O}}$  and  $\Delta s_{\text{O}}$  are independent of temperature, this simplifying assumption is not always valid. For example, a temperature dependence of  $\Delta h_{\text{O}}$  is observed for the case of CeO<sub>2</sub> where two reactions dictate the defect chemistry. The degree of dependence varies in accordance with the magnitude of  $K_2$  in regards to  $K_1$ . Sørensen<sup>16</sup> has showed that the slope of  $\Delta g_{\text{O}}$  vs.  $T$  (see eqn (15)) is constant at  $T < 1623$  K and  $\delta < 0.08$ , but decreases at higher temperatures due to the formation of sub-phases. The more negative  $\Delta h_{\text{O}}$  values at low  $\delta$  from this work are in agreement with Sørensen.<sup>16</sup> Deviations in the measurements of CZO<sub>5</sub> can be additionally attributed to differences in Zr<sup>4+</sup> dopant concentrations. For example, in this work the dopant concentration is 4.5 mol% compared to 5.2 mol% in the work of Hao *et al.*<sup>12</sup>

The reduction of nonstoichiometric ceria is represented by:



The standard Gibbs free energy change of eqn (17),  $\Delta g_{\text{red}}$ , can be calculated by integrating  $\Delta g_{\text{O}}$  over the range of  $\delta$ :<sup>16</sup>

$$\Delta g_{\text{red}} = \frac{\int_{\delta_{\text{red}}}^{\delta_{\text{ox}}} \Delta g_{\text{O}} d\delta}{\delta_{\text{red}} - \delta_{\text{ox}}} \quad (18)$$

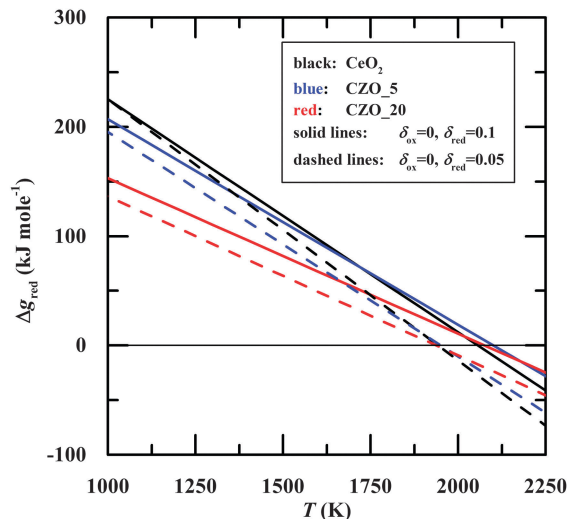
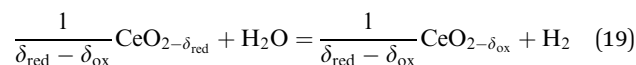


Fig. 6 Gibbs free energy change versus temperature for the reduction of CeO<sub>2</sub> (black), CZO<sub>5</sub> (blue) and CZO<sub>20</sub> (red) from  $\delta_{\text{ox}} = 0$  to  $\delta_{\text{red}} = 0.1$  (solid lines) and  $\delta_{\text{ox}} = 0$  to  $\delta_{\text{red}} = 0.05$  (dashed lines).

where  $\delta_{\text{ox}}$  is the nonstoichiometry before reduction and  $\delta_{\text{red}}$  is the nonstoichiometry after reduction.  $\Delta g_{\text{red}}$  as a function of temperature for the reduction of CeO<sub>2</sub>, CZO<sub>5</sub>, and CZO<sub>20</sub> from  $\delta_{\text{ox}} = 0$  to  $\delta_{\text{red}} = 0.05$  (dashed lines) and from  $\delta_{\text{ox}} = 0$  to  $\delta_{\text{red}} = 0.1$  (solid lines) is shown in Fig. 6. For all materials, the reduction at standard pressure is thermodynamically favorable ( $\Delta g_{\text{red}} < 0$ ) at  $T > 1950$  K for  $\delta_{\text{red}} = 0.05$  and at  $T > 2100$  K for  $\delta_{\text{red}} = 0.1$ . At lower temperatures, where  $\Delta g_{\text{red}} > 0$ , reduction would only proceed if additional work is performed to the system, *e.g.* lowering  $p_{\text{O}_2}$  by vacuum pumping or flushing with inert gas. Therefore, this implies that at lower temperatures (<2000 K), CZO<sub>20</sub> can be reduced more easily compared to CZO<sub>5</sub> and CeO<sub>2</sub>, which is related to its less negative  $\Delta h_{\text{O}}$  and consistent with experimental observations. For all materials, a higher  $\Delta g_{\text{red}}$  for  $\delta_{\text{red}} = 0.1$  compared to  $\delta_{\text{red}} = 0.05$  is related to the increasing  $\Delta s_{\text{O}}$  with increasing  $\delta$  (*cf.* Fig. 5).

The oxidation of nonstoichiometric ceria and doped ceria with H<sub>2</sub>O is described by:



$\Delta g_{\text{ox}}$ ,  $\Delta g_{\text{H}_2\text{O}}$ , and  $\Delta g_{\text{ox,H}_2\text{O}}$  are the standard Gibbs free energy change of ceria oxidation with oxygen ( $-\Delta g_{\text{red}}$ ), of water dissociation, and of ceria oxidation with H<sub>2</sub>O (eqn (19)). Thus,  $\Delta g_{\text{ox,H}_2\text{O}} = \Delta g_{\text{ox}} + \Delta g_{\text{H}_2\text{O}}$ , where  $\Delta g_{\text{H}_2\text{O}}$  is obtained from NIST-JANAF thermochemical tables and  $\Delta g_{\text{ox}} = -\Delta g_{\text{red}}$ . Calculations indicate that oxidation with H<sub>2</sub>O becomes thermodynamically less favorable as the Zr<sup>4+</sup> concentration increases. This is shown in Fig. 7, where  $\Delta g_{\text{ox,H}_2\text{O}}$  of CeO<sub>2</sub> (black), CZO<sub>5</sub> (blue), and CZO<sub>20</sub> (red) is plotted as a function of temperature for the oxidation with H<sub>2</sub>O from  $\delta_{\text{red}} = 0.1$  to  $\delta_{\text{ox}} = 0$  (solid lines) and  $\delta_{\text{red}} = 0.05$  to  $\delta_{\text{ox}} = 0$  (dashed lines).  $\Delta g_{\text{ox,H}_2\text{O}}$  is negative at  $T \leq 1200$  K for CeO<sub>2</sub>, at  $T \leq 1000$  K for CZO<sub>5</sub>, and at  $T \leq 500$  K for CZO<sub>20</sub>. Above the mentioned temperatures, oxidation is



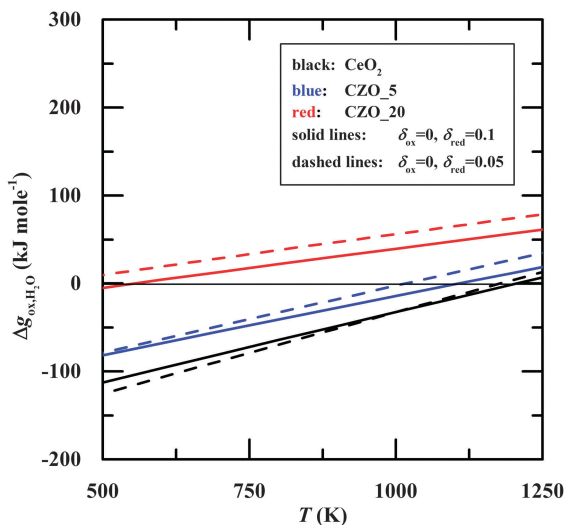


Fig. 7 Gibbs free energy change versus temperature for the oxidation of  $\text{CeO}_2$  (black),  $\text{CZO}_5$  (blue), and  $\text{CZO}_{20}$  (red) with  $\text{H}_2\text{O}$  from  $\delta_{\text{red}} = 0.1$  to  $\delta_{\text{ox}} = 0$  (solid lines) and  $\delta_{\text{red}} = 0.05$  to  $\delta_{\text{ox}} = 0$  (dashed lines).

thermodynamically favorable only if additional work is added to the system.

By combining the reaction equilibrium constant of water dissociation ( $K_{\text{W}}$ )

$$K_{\text{W}} = \frac{n_{\text{H}_2} p_{\text{O}_2}^{1/2}}{(n_{\text{H}_2\text{O},i} - n_{\text{H}_2})} \quad (20)$$

with eqn (14), equilibrium  $\text{H}_2$  yields can be calculated according to:

$$\Delta g_{\text{O}}(\delta_{\text{ox}} = \delta_{\text{red}} - n_{\text{H}_2}) = RT \ln \left[ \frac{K_{\text{W}}(n_{\text{H}_2\text{O},i} - n_{\text{H}_2})}{n_{\text{H}_2}} \right] \quad (21)$$

where  $n_{\text{H}_2}$  is the molar amount of  $\text{H}_2$  produced at equilibrium per mole oxide, and  $n_{\text{H}_2\text{O},i}$  is the initial molar amount of  $\text{H}_2\text{O}$  in the system per mole oxide.  $n_{\text{H}_2}$  is obtained by iteratively solving eqn (21) and is shown in Fig. 8 versus temperature for  $\text{CeO}_2$  (black),  $\text{CZO}_5$  (blue), and  $\text{CZO}_{20}$  (red).  $n_{\text{H}_2\text{O},i}$  is set equal to  $\delta_{\text{red}}$  (solid lines) and  $100 \times \delta_{\text{red}}$  (dashed lines), where  $\delta_{\text{red}}$  is the nonstoichiometry achieved after reduction at  $T_{\text{red}} = 1773 \text{ K}$  and  $p_{\text{O}_2} = 2.3 \times 10^{-4} \text{ atm}$ . The calculations reaffirm that the oxidation with  $\text{H}_2\text{O}$  becomes thermodynamically less favorable with increasing  $\text{Zr}^{4+}$  dopant concentrations. For example, for  $n_{\text{H}_2\text{O},i} = \delta_{\text{red}}$ , maximum  $n_{\text{H}_2}$  is reached at  $T \leq 900 \text{ K}$  for  $\text{CeO}_2$ ,  $T \leq 700 \text{ K}$  for  $\text{CZO}_5$ , and  $T < 400 \text{ K}$  for  $\text{CZO}_{20}$ . If  $n_{\text{H}_2\text{O},i}$  is increased by a factor of hundred, these oxides can be oxidized at higher temperatures but at the expense of heating excess  $\text{H}_2\text{O}$ . In this case, maximum  $n_{\text{H}_2}$  is obtained at as high as  $1200 \text{ K}$  for  $\text{CeO}_2$ ,  $1100 \text{ K}$  for  $\text{CZO}_5$ , and  $500 \text{ K}$  for  $\text{CZO}_{20}$ . For  $\text{CZO}_{20}$ ,  $n_{\text{H}_2}$  is only shown up to  $0.042$  moles because  $\Delta h_{\text{O}}$  and  $\Delta s_{\text{O}}$  are not available at  $\delta \leq 0.03$ . Because  $\Delta h_{\text{O}}$  and  $\Delta s_{\text{O}}$  of  $\text{CeO}_2$  and  $\text{CZO}_5$  are not measured over the range  $\delta = 0$  to  $0.1$ , they are assumed to be constant for low  $\delta$  and taken as the average from literature data<sup>4,5,10,16,17</sup> for high  $\delta$ .

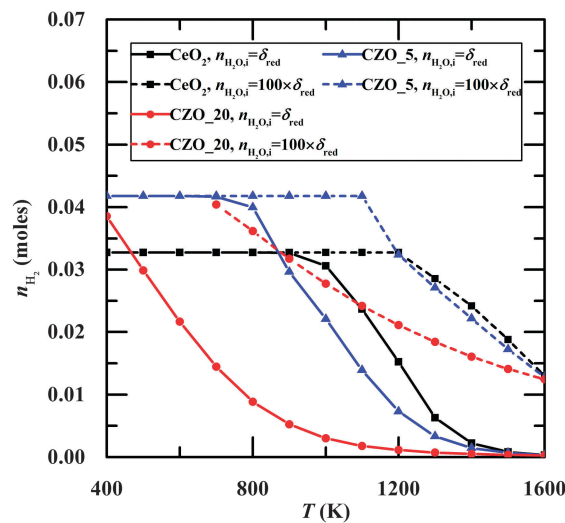


Fig. 8 Molar amount of  $\text{H}_2$  produced by oxidation of  $\text{CeO}_2$  (black),  $\text{CZO}_5$  (blue) and  $\text{CZO}_{20}$  (red) with  $\text{H}_2\text{O}$  as a function of temperature assuming  $n_{\text{H}_2\text{O},i} = \delta_{\text{red}}$  (solid lines) and  $100 \times \delta_{\text{red}}$  (dashed lines) where  $\delta_{\text{red}}$  is the nonstoichiometry achieved after reduction at  $T_{\text{red}} = 1773 \text{ K}$  and  $p_{\text{O}_2} = 2.3 \times 10^{-4} \text{ atm}$  ( $\delta_{\text{red}} = 0.0328$  for  $\text{CeO}_2$ ,  $\delta_{\text{red}} = 0.0417$  for  $\text{CZO}_5$ , and  $\delta_{\text{red}} = 0.0725$  for  $\text{CZO}_{20}$ ).

## Efficiency analysis

The theoretical solar-to-fuel energy conversion efficiency ( $\eta_{\text{solar-to-fuel}}$ ) for the case of hydrogen production is defined as:

$$\eta_{\text{solar-to-fuel}} = \frac{\text{HHV}_{\text{H}_2} n_{\text{H}_2}}{Q_{\text{input,min}}} \quad (22)$$

where  $\text{HHV}_{\text{H}_2} = 285.5 \text{ kJ mol}^{-1}$  is the higher heating value of  $\text{H}_2$ .  $Q_{\text{input,min}}$  is the minimum input of energy required to produce  $n_{\text{H}_2}$  and comprises the solar process heat for driving the reduction, for heating the redox material from  $T_{\text{ox}}$  to  $T_{\text{red}}$ , and for generating steam at  $T_{\text{ox}}$ , as well as the equivalent minimum work to drive the reduction for the case of  $\Delta g_{\text{red}} > 0$ . Assuming no heat recuperation between the redox steps,

$$Q_{\text{input,min}} = \frac{1}{\eta_{\text{absorption}}} \cdot \left[ \Delta h_{\text{red}}(\delta_{\text{red}} - \delta_{\text{ox}}) + \int_{T_{\text{ox}}}^{T_{\text{red}}} c_{\text{p}} dT + \Delta h_{\text{H}_2\text{O}}|_{298\text{K} \rightarrow T_{\text{ox}}} n_{\text{H}_2\text{O},i} + \frac{\Delta g_{\text{red}}}{\eta_{\text{Carnot}}}(\delta_{\text{red}} - \delta_{\text{ox}}) \right] \quad (23)$$

where  $\Delta h_{\text{red}}$  is the enthalpy change of the reduction (eqn (17)),

$$\Delta h_{\text{red}} = \frac{\int_{\delta_{\text{red}}}^{\delta_{\text{ox}}} \Delta h_{\text{O}} d\delta}{\delta_{\text{red}} - \delta_{\text{ox}}} \quad (24)$$

$\Delta h_{\text{H}_2\text{O}}|_{298\text{K} \rightarrow T_{\text{ox}}}$  is the thermal energy required to heat  $\text{H}_2\text{O}$  from ambient temperature to  $T_{\text{ox}}$  (obtained from NIST-JANAF tables),  $n_{\text{H}_2\text{O},i}$  is the initial molar amount of  $\text{H}_2\text{O}$  determined by eqn (21), and  $c_{\text{p}}$  is the specific heat capacity of pure ceria.<sup>27</sup> The excess  $\text{H}_2\text{O}$  needed is calculated for  $n_{\text{H}_2}$  approaching  $\delta_{\text{red}}$ . Note that the maximum  $\eta_{\text{solar-to-fuel}}$  may not be attained by completely re-oxidizing the material, as shown by Chueh *et al.*<sup>28</sup> and Furler *et al.*<sup>29</sup> but an



overall optimization routine is outside the scope of this work. Due to the low dopant concentration of  $Zr^{4+}$ ,  $c_p$  of CZO\_5 and CZO\_20 are assumed to be identical to that of pure  $CeO_2$ .  $Q_{input,min}$  is assumed to be delivered by concentrated solar energy. The solar absorption efficiency ( $\eta_{absorption}$ ) for a blackbody cavity-receiver is given by:<sup>30</sup>

$$\eta_{absorption} = 1 - \frac{\sigma T_{red}^4}{IC} \quad (25)$$

where  $\sigma$  is the Stefan-Boltzmann constant,  $I = 1 \text{ kW m}^{-2}$  the direct normal irradiation (DNI) and  $C = 2000$  the solar flux concentration ratio. The fourth term in eqn (23) is the minimum work required to drive the reduction at conditions for which  $\Delta g_{red} > 0$ ; when  $\Delta g_{red} \leq 0$  this term is omitted.  $\eta_{Carnot}$  is the efficiency of an ideal heat engine converting solar heat at  $T_{red}$  to work.<sup>30</sup>

A contour plot of  $\eta_{solar-to-fuel}$  shown as a function of  $\delta_{red}$  and  $T_{ox}$  is shown in Fig. 9 for  $CeO_2$  (a) and CZO\_5 (b) respectively.  $p_{O_2} = 10^{-6} \text{ atm}$  is assumed for the efficiency calculations resulting in reduction temperatures of 1744 K for  $CeO_2$  and 1741 K for CZO\_5 needed to reach  $\delta_{red} = 0.1$  and 1564 K and

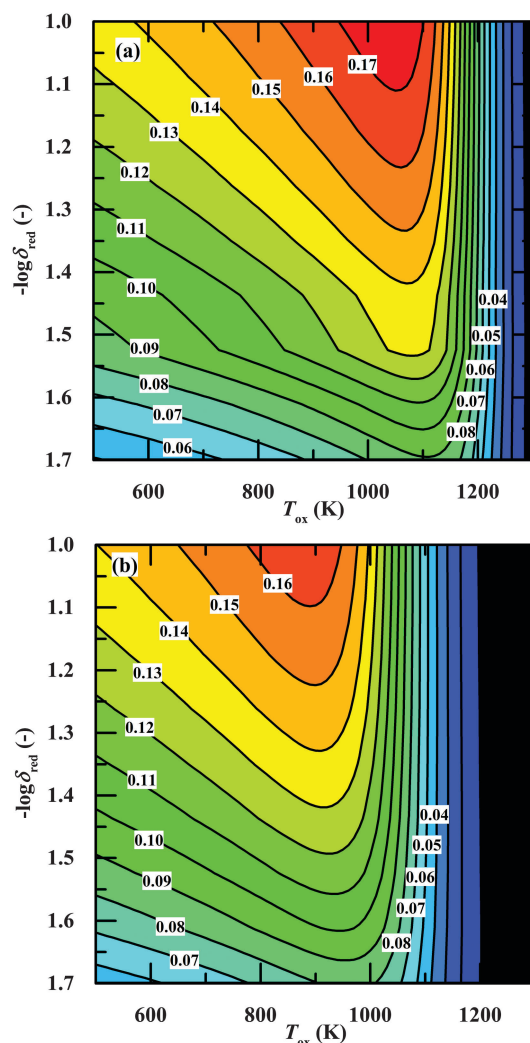


Fig. 9  $\eta_{solar-to-fuel}$  shown as contour lines for  $CeO_2$  (a) and CZO\_5 (b) as a function of  $\delta_{red}$  and  $T_{ox}$  assuming reduction at  $p_{O_2} = 10^{-6} \text{ atm}$  and subsequent complete re-oxidation with steam.

1510 K respectively to reach  $\delta_{red} = 0.02$ . It is shown that the maximum efficiency for  $CeO_2$  is slightly higher compared to CZO\_5.  $\eta_{solar-to-fuel}$  is slightly greater than 17% at  $\delta_{red} = 0.1$  ( $T_{ox} = 1050 \text{ K}$ ) for  $CeO_2$  and slightly greater than 16% at  $\delta_{red} = 0.1$  ( $T_{ox} = 880 \text{ K}$ ) for CZO\_5. Simply stated, the energy savings during reduction of CZO\_5 cannot compensate the additional energy inputs due to the less favorable re-oxidation with  $H_2O$  (lower  $T_{ox}$  and/or higher  $n_{H_2O,i}$  compared to  $CeO_2$ ). In general  $\eta_{solar-to-fuel}$  rapidly decreases towards higher  $T_{ox}$  as the re-oxidation with  $H_2O$  gets thermodynamically less favorable and an increasing amount of excess steam has to be heated in order to fully oxidize the reduced material. Towards lower  $T_{ox}$ ,  $\eta_{solar-to-fuel}$  decreases as the temperature difference between oxidation and reduction increases and towards lower  $\delta_{red}$  it decreases as the amount of  $H_2$  produced (equal to  $\delta_{red}$ ) decreases compared to the sensible energy required to heat the oxide. Qualitatively these results are in agreement with calculations reported in literature for pure ceria,<sup>7,31,32</sup> and indicate the tradeoffs between an isobaric redox cycle driven by temperature swing and an isothermal redox cycle driven by pressure swing. Heat recovery, not accounted for in Fig. 9, can significantly boost  $\eta_{solar-to-fuel}$ .<sup>7</sup> When heat recovery is used for generating steam at  $T_{ox}$ ,  $\eta_{solar-to-fuel}$  peaks at 19% for  $CeO_2$  and 18% for CZO\_5. If, in addition, heat recovery is used to heat the redox material from  $T_{ox}$  to  $T_{red}$ ,  $\eta_{solar-to-fuel}$  peaks at 41% and 44% for  $CeO_2$  and CZO\_5, respectively. Results for CZO\_20 are not shown because thermodynamic data are not available at  $\delta \leq 0.03$  and also because calculations always predict maximum  $\eta_{solar-to-fuel}$  at lowest  $T_{ox}$  (400 K) and highest  $\delta_{red}$  (0.1).

Maximum  $\eta_{solar-to-fuel}$  as a function of  $p_{O_2}$  is shown in Fig. 10 for  $CeO_2$  (solid lines), CZO\_5 (dashed lines) and CZO\_20 (dotted lines) where  $\delta_{red} = 0.1$  (a) and  $\delta_{red} = 0.05$  (b). Additionally,  $T_{red}$  where maximum  $\eta_{solar-to-fuel}$  is obtained is shown in Fig. 10. Estimates of

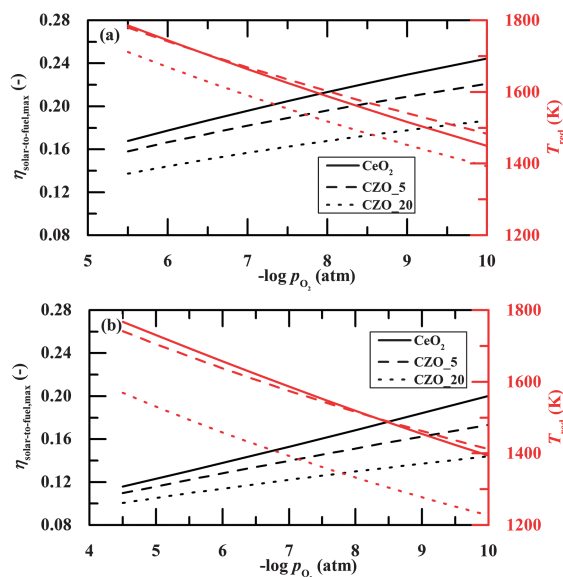


Fig. 10 Maximum  $\eta_{solar-to-fuel}$  and  $T_{red}$  versus  $p_{O_2}$  for  $CeO_2$  (solid lines), CZO\_5 (dashed lines) and CZO\_20 (dotted lines) assuming  $\delta_{red} = 0.1$  (a) and  $\delta_{red} = 0.05$  (b).



$T_{\text{red}}$  of CZO\_20 were calculated according to the methodology described by Yang *et al.*<sup>33</sup> using the thermodynamic data of Kuhn *et al.*<sup>10</sup> It is observed that CeO<sub>2</sub> shows the highest  $\eta_{\text{solar-to-fuel}}$  under all conditions investigated and CZO\_20 shows the lowest  $\eta_{\text{solar-to-fuel}}$ . Although CZO\_20 reduces at substantially lower temperatures compared to CZO\_5 and CeO<sub>2</sub>, the lower energy input during reduction cannot compensate the higher energy input during oxidation with H<sub>2</sub>O. In general,  $\eta_{\text{solar-to-fuel}}$  increases with decreasing  $p_{\text{O}_2}$ , meaning less energy is required to reduce the oxide by lowering  $p_{\text{O}_2}$  compared to increasing  $T_{\text{red}}$ .

## Conclusions

Oxygen nonstoichiometry measurements of Zr<sup>4+</sup> doped ceria at elevated temperatures presented in this work are largely in agreement with the trends observed in works performed at lower temperatures (<1573 K), namely: for a given  $T_{\text{red}}$  and  $p_{\text{O}_2}$  the reduction extent increases and the reduction enthalpy decreases with increasing Zr<sup>4+</sup> concentration. Extracted thermodynamic properties are also largely in agreement with previous data, but they deviate at low nonstoichiometries especially for the case of pure ceria. This is likely due to the fact that they are slightly temperature dependent, especially at higher temperatures (>1623 K) where different sub-phases can be expected.<sup>16</sup> Interestingly, in the case of 5 mol% Zr<sup>4+</sup> doped ceria, a single defect model is capable of describing the nonstoichiometry data over the entire measurement range ( $\delta = 0.01$  to 0.04) and therefore the thermodynamic properties can be assumed to be independent of temperature. This is an important distinction when extrapolating nonstoichiometries to conditions that have not yet been measured experimentally.<sup>33</sup> Although the nonstoichiometry increases with increasing Zr<sup>4+</sup> dopant concentration, oxidation with steam becomes thermodynamically less favorable and has to be conducted at lower temperatures or with excess amounts of steam. This ultimately results in lower theoretical solar-to-fuel energy conversion efficiencies compared to that for pure ceria. Therefore, when screening potential redox materials it is important to consider both steps of the cycle, *i.e.* the materials ability to release lattice oxygen and its oxidation potential with H<sub>2</sub>O and CO<sub>2</sub>. We have assumed that reduction and oxidation are driven to completion, but maximum efficiencies may be found at lower extents. In general, when we compare with the thermodynamic properties of pure ceria, a relatively lower partial molar enthalpy and a relatively higher partial molar entropy are desired, resulting in  $\Delta g_{\text{red}} < 0$  at lower  $T_{\text{red}}$  and  $\Delta g_{\text{ox,H}_2\text{O}} < 0$  at higher  $T_{\text{ox}}$ , which in turn yields a smaller temperature swing between the redox steps. Besides thermodynamic aspects, fast reaction kinetics and long term chemical and morphological stability are obviously essential.

## Nomenclature

|                                  |  |
|----------------------------------|--|
| $C$                              | Flux concentration ratio of incident radiation (—) |
| $\text{Ce}_{\text{Ce}}^{\times}$ | Cerium atom on cerium lattice site                 |
| $\text{Ce}_{\text{Ce}}^{\prime}$ | Electron localized on cerium lattice site          |

|   |  |
|---|--|
| $(\text{Ce}_{\text{Ce}}^{\prime} \text{V}_{\text{O}}^{\bullet\bullet} \text{Ce}_{\text{Ce}}^{\prime})^{\times}$ | Oxygen vacancy–polaron association   |
| $c_p$   | Heat capacity of CeO <sub>2</sub> (kJ mol <sup>-1</sup> K <sup>-1</sup> )                            |
| $\Delta g_{\text{H}_2\text{O}}$   | Standard Gibbs free energy change of H <sub>2</sub> O dissociation (kJ mol <sup>-1</sup> )           |
| $\Delta g_{\text{O}}$   | Partial molar free energy (kJ mol <sup>-1</sup> )  |
| $\Delta g_{\text{ox}}$  | Standard Gibbs free energy change of ceria oxidation (with O <sub>2</sub> ) (kJ mol <sup>-1</sup> )  |
| $\Delta g_{\text{ox,H}_2\text{O}}$  | Standard Gibbs free energy change of ceria oxidation (with H <sub>2</sub> O) (kJ mol <sup>-1</sup> ) |
| $\Delta g_{\text{red}}$   | Standard Gibbs free energy change of ceria reduction (kJ mol <sup>-1</sup> )                         |
| $\Delta h_{\text{H}_2\text{O}}$   | Energy to heat water (kJ mol <sup>-1</sup> )   |
| $\text{HHV}_{\text{H}_2}$   | Higher heating value of H <sub>2</sub> (kJ mol <sup>-1</sup> )                                       |
| $\Delta h_{\text{O}}$   | Partial molar enthalpy (kJ mol <sup>-1</sup> )   |
| $\Delta h_{\text{red}}$   | Enthalpy change of reduction (kJ mol <sup>-1</sup> )   |
| $I$   | Normal beam insolation (W m <sup>-2</sup> )  |
| $K_1$   | Ideal solution model equilibrium constant (—)  |
| $K_2$   | Defect interaction model equilibrium constant (—)  |
| $K_{\text{W}}$  | H <sub>2</sub> O dissociation equilibrium constant (—)   |
| $M_{\text{O}}$  | Molar mass of O (g mol <sup>-1</sup> )   |
| $m_s$   | Weight of reactive sample (mg)   |
| $M_s$   | Molar mass of reactive sample (g mol <sup>-1</sup> )   |
| $\Delta m_s$  | Relative weight loss of reactive sample (—)  |
| $n_{\text{H}_2}$  | Molar amount of H <sub>2</sub> at equilibrium (mol)  |
| $n_{\text{H}_2\text{O},i}$  | Initial molar amount of H <sub>2</sub> O (mol)   |
| $\text{O}_{\text{O}}^{\times}$  | Oxygen atom on oxygen lattice site   |
| $p_{\text{O}_2}$  | Oxygen partial pressure (atm)  |
| $Q_{\text{input,min}}$  | Minimum amount of input energy to produce H <sub>2</sub> (kJ mol <sup>-1</sup> )                     |
| $R$   | Universal gas constant (J mol <sup>-1</sup> K <sup>-1</sup> )  |
| $\Delta s_{\text{O}}$   | Partial molar entropy (J mol <sup>-1</sup> K <sup>-1</sup> )   |
| $T$   | Temperature (K)  |
| $T_{\text{ox}}$   | Oxidation temperature (K)  |
| $T_{\text{red}}$  | Reduction temperature (K)  |
| $\text{V}_{\text{O}}^{\bullet\bullet}$  | Doubly ionized oxygen vacancy  |
| $X$   | Molar dopant concentration of Zr <sup>4+</sup> (—)   |
| $\alpha$  | Stoichiometric coefficient of H <sub>2</sub> O (—)   |
| $\beta$   | Stoichiometric coefficient of CO <sub>2</sub> (—)  |
| $\delta$  | Degree of oxygen nonstoichiometry (—)  |
| $\delta_{\text{ox}}$  | Degree of oxygen nonstoichiometry after oxidation (—)  |
| $\delta_{\text{red}}$   | Degree of oxygen nonstoichiometry after reduction (—)  |
| $\eta_{\text{absorption}}$  | Solar absorption efficiency (—)  |
| $\eta_{\text{Carnot}}$  | Carnot efficiency (—)  |
| $\eta_{\text{solar-to-fuel}}$   | Solar-to-fuel energy conversion efficiency (—)   |
| $\sigma$  | Stefan–Boltzmann constant (W m <sup>-2</sup> K <sup>-4</sup> )                                       |

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