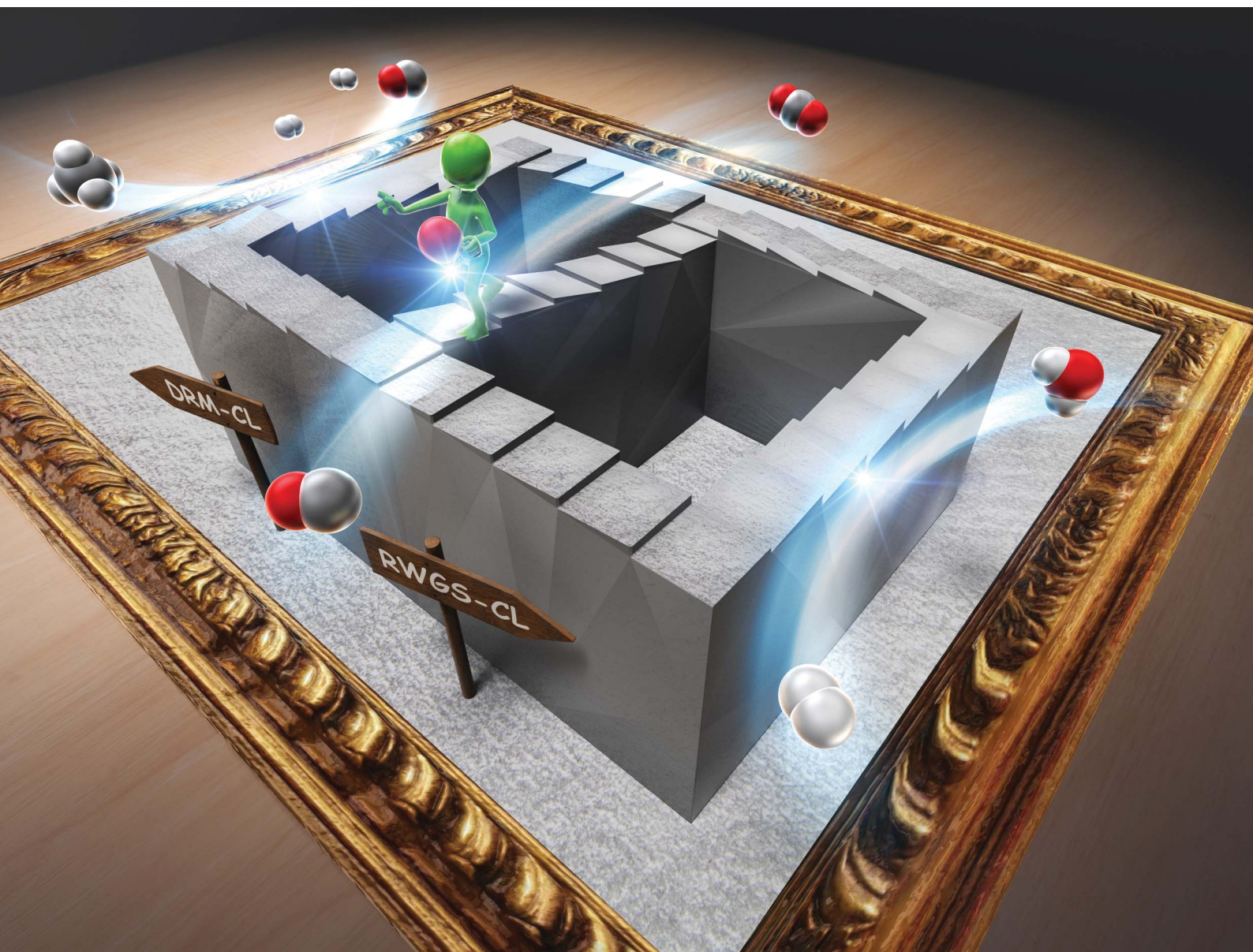


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# CO<sub>2</sub> conversion to CO by reverse water gas shift and dry reforming using chemical looping†

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Chemical looping technology provides an efficient means of sustainable CO<sub>2</sub> conversion to the important chemical intermediate of CO or syngas by changing conventional co-feeding of reactant into alternating feeding. It presents the important benefits of simplified gas separation, improved selectivity, and more independently adjusted operation conditions compared to those of conventional reactions. Oxygen carriers (OCs) are pivotally important for the performance of chemical looping processes. Herein, recent advances of OCs for two representative chemical looping CO<sub>2</sub> conversion technologies to CO are reviewed systematically: reverse water gas shift chemical looping (RWGS-CL) and dry reforming of methane by chemical looping (DRM-CL). The influence of composition along with surface and bulk structures of these OCs on conversion, selectivity, and lattice oxygen reactivity, are discussed to obtain better design and optimisation strategies for the tailored OCs. Moreover, modified Ellingham diagrams that exhibit the thermodynamic properties for potential metal oxides for the effective screening of active OCs of DRM-CL and RWGS-CL are proposed, yielding valuable insights not only into RWGS-CL and DRM-CL but also into other distinct chemical looping processes involving into the same reactions. Finally, a summary and prospects are presented for some challenges and future research orientation for CO<sub>2</sub> conversion to CO *via* chemical looping.

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## Sustainability spotlight

Chemical looping technology provides an efficient means of continuously converting CO<sub>2</sub> into CO or synthesis gas, which are important chemical intermediates or fuels, by changing the conventional co-feeding of reactants to alternate feeding. Compared to conventional catalytic reactions, it has the important advantages of simplifying gas separation, improving selectivity, and allowing more independent adjustment of operating conditions. By continuing to research oxygen carriers (OC) for this purpose, it will be possible to efficiently recycle the carbon dioxide and biogas (a mixture of carbon dioxide and methane) that are emitted. These correspond to SDGs 7, 12, and 13.

## 1. Introduction

With the progressing development of industry worldwide, fossil fuels are increasingly used widely, entailing excessive emissions of carbon dioxide (CO<sub>2</sub>). Incessantly, CO<sub>2</sub> concentrations in the atmosphere reach record high levels. Their continued growth is leading to important environmental difficulties such as global warming, rising sea levels, and ocean acidification.<sup>1,2</sup> As a result, environmentally friendly and economical means of CO<sub>2</sub> elimination are sought. Consequently, to create a carbon-neutral human society, carbon capture and utilisation (CCU) technologies with a sustainable carbon cycle have been developed extensively.<sup>3–7</sup>

Serving as the foundation of C1 chemistry, carbon monoxide (CO) is an important raw material for the synthesis of many organic chemical products and intermediates. Almost all basic

chemicals such as phosgene, alcohol, acid, anhydride, ester, aldehyde, ether, amine, alkanes, and olefin are producible from CO.<sup>8,9</sup> As a major component of syngas, CO is necessary for gas-to-liquid conversion *via* the Fischer–Tropsch (F–T) process.<sup>10–14</sup> Liquid fuels possess characteristics of stable and high calorific value, non-volatility or low-volatility, and higher safety.<sup>12–15</sup> Therefore, sustainable CO<sub>2</sub> conversion, which successfully combines CO<sub>2</sub> reduction with the production of alternative liquid fuels, is regarded as a promising CCU technology.

A representative means of “CO<sub>2</sub> to CO” conversion is the reverse water–gas shift (RWGS) reaction, a non-fossil process, which uses renewable H<sub>2</sub> over a suitable catalyst according to eqn (1). However, CO<sub>2</sub> conversion *via* RWGS is limited by equilibrium because of its reversible nature. Furthermore, higher temperatures must be used for RWGS because of the reactions’ endothermic nature and pressure independence, which are not conducive to connection with F–T processes at low temperatures to use the produced CO or to use various promising catalysts with a lower melting point.<sup>16,17</sup> Furthermore, the unwanted side reactions of methanation in eqn (2)

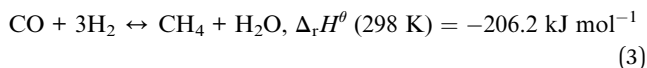
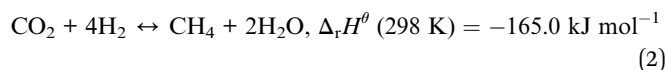
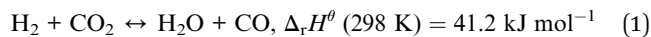
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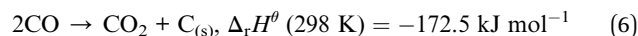
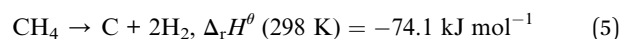


and (3) always proceed in the RWGS process. They are exothermic, providing poor selectivity at lower temperatures with the production of methane (CH<sub>4</sub>) instead of CO.<sup>17</sup> Furthermore, the CH<sub>4</sub> by-product leads to more complicated gas separation. In summary, the development of conventional RWGS is hindered severely by shortcomings such as equilibrium limitation, low energy efficiency, unwanted side reactions, and complex gas separation.



Dry reforming of methane (DRM) described in eqn (4) is another widely investigated method for “CO<sub>2</sub> to CO” conversion because it can convert main greenhouse gases of two kinds (CO<sub>2</sub> and CH<sub>4</sub>) into industrially valuable syngas simultaneously over appropriate catalysts. However, DRM is an endothermic

reaction. The catalysts used to date are composed mainly of expensive noble metals. Moreover, the intrinsic activity of the DRM process is not so high. The side reactions of RWGS entail the co-existence of CO<sub>2</sub> and H<sub>2</sub>, leading to a lower syngas ratio than expected from the DRM process.<sup>18,19</sup> Importantly, carbon deposition, caused mainly by CH<sub>4</sub> decomposition and the Boudouard reaction (eqn (5) and (6)), deactivate the catalysts severely at lower temperatures.<sup>20</sup> These shortcomings strongly hinder the wider application of DRM.



One method to improve these two conventional “CO<sub>2</sub> to CO” processes (RWGS and DRM) is chemical looping (CL),<sup>21,22</sup> whereby one reaction is divided into several sub-reactions that can proceed in segregated steps and sites. Oxygen carriers (OCs) act as important intermediates, recycling the CL reaction by releasing and receiving the oxygen continuously. As exhibited in Fig. 1(a), the CL processes consist of reduction and oxidation steps that can proceed in individual conditions and spaces. During the reduction step, metal oxides (MO<sub>x</sub>) acting as OCs are reduced with the oxygen released. In addition, H<sub>2</sub> is oxidised to H<sub>2</sub>O in RWGS-CL (eqn (7), green in Fig. 1(a)); CH<sub>4</sub> is partially oxidised to CO and H<sub>2</sub> in the DRM-CL (partial oxidation of methane (POM) reaction in eqn (8), blue in Fig. 1(a)). Subsequently, during the common oxidation step of RWGS-CL and DRM-CL, MO<sub>x-δ</sub> is regenerated back to MO<sub>x</sub> by CO<sub>2</sub> with CO production (CO<sub>2</sub> splitting reaction in eq. (9), black in Fig. 1(a)). Reduction and oxidation proceed step by step in CL, bringing several great benefits over those provided by conventional processes. First, the reactant and product gas are inherently separated, avoiding some side reactions, simplifying gas separation, and greatly improving safety. Moreover, the equilibrium barrier of the conventional processes can be circumvented by CL



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*tional catalysis.*



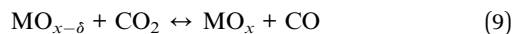
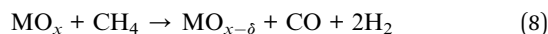
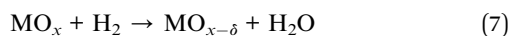
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with repeated cycles of reduction and oxidation, thereby breaking the thermodynamic restraints and further improving the reaction potential using optimal conditions for each step. As a result, CL processes are promising options for effective CO<sub>2</sub> and CH<sub>4</sub> usage. Fig. 1(b) exhibits the overall concept with RWGS-CL or DRM-CL to produce synthesised gas of  $x\text{H}_2 + y\text{CO}$ , yielding valuable and diverse chemicals. F-T fuels (hydrocarbons) and methanol are producible with a syngas ratio (H<sub>2</sub>/CO) of 2, whereas the production of dimethyl ether (DME) and oxo-alcohols (adding olefins) relies on CO-rich syngas. Furthermore, the production of NH<sub>3</sub> and acetic acid respectively requires H<sub>2</sub> and CO.<sup>20</sup>



Actually, OCs are fundamentally important for CL processes. Appropriate OCs require qualified activity to the reactants both during the reduction and oxidation steps, high selectivity to target products, excellent resistance to sintering, carbon deposition and abrasion, as well as low cost. Recently, many efforts have been undertaken to develop appropriate OCs with superior performance for CL. In fact, several excellent reviews have assigned emphasis to the OCs of CL emerged.<sup>21,23–30</sup> However, those reviews mainly overviewed chemical looping combustion (CLC) and chemical looping reforming (CLR) related topics: no investigation specifically examined CO<sub>2</sub> conversion to CO *via* CL. Furthermore, while the history and overview of CCUs by chemical loops have been summarized so far, no review focusing on materials has been done so far.<sup>31,32</sup> Therefore, this review particularly assesses recent advances in OC development on CO<sub>2</sub> conversion to CO *via* chemical looping (mainly RWGS-CL and DRM-CL). After first reviewing recently developed OCs (*e.g.*, perovskites, spinels, metal-based oxides) on RWGS-CL and DRM-CL, we calculate and then present a summary of the thermodynamic properties of potential metal oxides in the

modified Ellingham diagrams for the screening of active OCs for CL processes. Finally, the main conclusion and prospects for meeting some challenges and future research orientation are introduced.

## 2. Reverse water gas shift chemical looping (RWGS-CL)

Actually, RWGS-CL can produce CO from CO<sub>2</sub> without by-products and with superior energy efficiency to that of the conventional RWGS process. The side reaction of methane formation (eqn (2) and (3)) is avoided. Moreover, gas separation for produced CO is simplified by avoiding the simultaneous introduction of carbon and hydrogen species. A recent research report has described the conversion of CO<sub>2</sub> to liquid fuel *via* RWGS (at 1250 K and 30 atm) using solar energy.<sup>4</sup> The provision of H<sub>2</sub> consumes the most energy by heating the reactor and power electrolyzers to the target temperature. The use of H<sub>2</sub> can be reduced in RWGS-CL because stoichiometric reactions are feasible, without requiring excess H<sub>2</sub> to satisfy kinetic and thermodynamic considerations, making it more economically feasible. Furthermore, the operational temperatures for the reduction step in RWGS-CL are lower because of the thermochemical characteristics, typically 673–1223 K. Moreover, some OCs can operate under isothermal conditions.<sup>33–36</sup>

The key aspect of the RWGS-CL process is the choice of oxygen carrier able to strike a balance between the reduction conducted using a strong reducing agent of H<sub>2</sub> and the oxidation driven by a weak oxidising agent of CO<sub>2</sub>. This balance enables both steps to take place at the same temperature, which can cut the inefficiency arising from different operation temperatures during cycling. Furthermore, operating at lower temperatures is fundamentally important because it aligns with the lower temperature requirements for some downstream processes such as methanol and Fischer-Tropsch synthesis, which can be conducted at temperatures lower than 623 K.<sup>14</sup> Furthermore, running at lower temperatures enables the use of more cost-effective materials such as

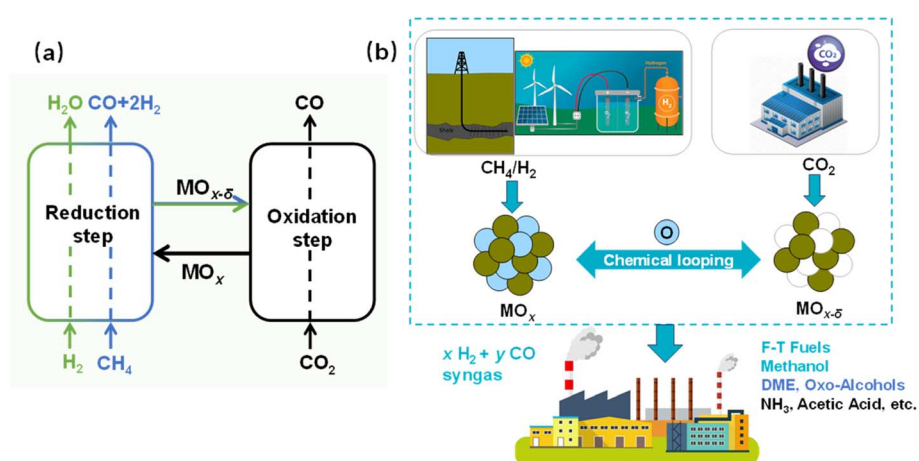


Fig. 1 (a) Schematic diagram of RWGS and DRM by chemical looping and (b) overall concept with RWGS-CL or DRM-CL.



Table 1 CO<sub>2</sub> splitting of composite OCs for RWGS-CL

OCs	CO <sub>2</sub> concentration/%	Space velocity/L min <sup>-1</sup> g <sup>-1</sup>	Temperature/K	CO yield/mmol g <sup>-1</sup>	Average CO <sub>2</sub> splitting rate <sup>a</sup> /μmol g <sup>-1</sup> min <sup>-1</sup>	Reference
LaCo <sub>0.25</sub> Fe <sub>0.5</sub> Mn <sub>0.25</sub> O <sub>3</sub>	10.0	0.67	873	0.90	N/A	Ramos <i>et al.</i> <sup>37</sup>
La <sub>0.75</sub> Str <sub>0.25</sub> CoO <sub>3-δ</sub>	10.0	N/A	923	N/A	14.7 (673 K); 38 (773 K); 20.6 (873 K)	Daza <i>et al.</i> <sup>35</sup>
			1023		65.7 (673 K); 98.4 (773 K); 73.4 (873 K)	
			1123		146.3 (673 K); 172.6 ± 17.4 (773 K); 198.1 (873 K)	
La <sub>0.75</sub> Str <sub>0.25</sub> FeO <sub>3-δ</sub> (LSF)	6.7	0.67(CO <sub>2</sub> /He), 0.65(H <sub>2</sub> /He)	823	0.74–1.09	77.2	Daza <i>et al.</i> <sup>36</sup>
LSF/SiO <sub>2</sub>	10.0	0.67	873	2.60	800.0	Hare <i>et al.</i> <sup>40</sup>
LSF/SBA-15	100.0	0.05	873	2.80	150.0	Jo <i>et al.</i> <sup>42</sup>
Cu/LSF	N/A	0.67	823	N/A	61.3–69.7	Daza <i>et al.</i> <sup>45</sup>
NiO@LSF	10.0	0.50	873	1.15	N/A	Lee <i>et al.</i> <sup>46</sup>
Co <sub>3</sub> O <sub>4</sub> @LSF				1.45		
Co <sub>3</sub> O <sub>4</sub> -NiO@LSF				1.60		
CeO <sub>3</sub> @LSF				0.55		
LSF				0.35		
La <sub>0.4</sub> Ba <sub>0.6</sub> FeO <sub>3</sub>	10.0	0.67	773	0.50	N/A	Shi <i>et al.</i> <sup>49</sup>
La <sub>0.5</sub> Ba <sub>0.5</sub> FeO <sub>3</sub>				0.20		
La <sub>0.25</sub> Ba <sub>0.75</sub> FeO <sub>3</sub>				0.19–1.5		
La <sub>0.3</sub> Ba <sub>0.5</sub> FeO <sub>3</sub> /SiO <sub>2</sub>	10.0	0.17	823	2.20	220.0	Shi <i>et al.</i> <sup>50</sup>
La <sub>2</sub> NiFeO <sub>6</sub>	25.0	0.50	973	2.14	214.0	Lim <i>et al.</i> <sup>51</sup>
Cu <sub>0.4</sub> Co <sub>0.6</sub> Fe <sub>2</sub> O <sub>4</sub>	20.0	1.60	823	N/A	98.3	Qiu <i>et al.</i> <sup>52</sup>
			923	9.10	144.6	
			1023	10.50	347.8	
			1123	11.20	493.1	
			923	7.30	112.5	
			1023	9.20	N/A	
			1123	10.00	N/A	
Ni <sub>0.4</sub> Co <sub>0.6</sub> Fe <sub>2</sub> O <sub>4</sub>	20.0		923	6.60	99.7	
			1023	8.60	N/A	
			1123	9.50	N/A	
			923	4.40	70.6	
			1023	6.00	N/A	
			1123	7.00	N/A	
Mn <sub>0.2</sub> Co <sub>0.8</sub> Fe <sub>2</sub> O <sub>4</sub>	20.0	1.60	823	N/A	100.0	Ma <i>et al.</i> <sup>53</sup>
			923	8.80	142.3	
			1023	N/A	310.0	
			1123	N/A	500.0	

<sup>a</sup> Temperatures in brackets show different reduction temperatures before the CO<sub>2</sub> splitting step.

stainless steel in the reactor. Moreover, it is desirable to maintain the structural stability of OCs because, in many cases, less energy is required to refill the lattice oxygen than to restore the crystalline structure. These facts underscore the important task of developing RWGS-CL OCs that can accommodate the creation of plenty of oxygen vacancies effectively, exhibit suitable kinetics for CO<sub>2</sub> activation and oxygen exchange, and maintain their structural integrity throughout multiple reaction cycles. Actually, in recent years, OCs with diverse active metals, inert supports, and various preparation methods have been screened and selected. Tables 1 and 2 present the CO<sub>2</sub> splitting performance of OCs for RWGS-CL reported in the reviewed literature.

## 2.1 Composite oxide

Composite oxides with stoichiometric composition and special structures such as perovskites and spinel oxides were investigated widely for RWGS-CL because of their adaptable and stable structures. Table 1 presents a summary of the CO<sub>2</sub> splitting performance data of composite OCs in recent reports for RWGS-CL.

**2.1.1 Perovskites (ABO<sub>3</sub>).** Perovskite oxides (ABO<sub>3</sub>) exhibit versatile redox characteristics because of their substitutable A and B sites, reversible oxygen storage, and high structural stability. These features make them excellent candidates for developing innovative composite oxides for the RWGS-CL process. For instance, Ramos *et al.* concurrently doped transition metals (Co, Fe) into the B site of the LaMnO<sub>3</sub> structure.<sup>37</sup> Their DFT findings highlight the potential of the Fe-rich sample

to support isothermal RWGS-CL and to produce CO without decomposition. Whereas Mn and Co-rich samples formed oxygen vacancies, the Co-rich sample presented difficulties because of its susceptibility to decomposition during RWGS-CL. Additionally, the improved CO<sub>2</sub> conversion performance was found to be related closely to the large surface areas provided by the small crystallite sizes. Undertaking a similar pursuit, Daza and colleagues initially explored La<sub>0.75</sub>Sr<sub>0.25</sub>CoO<sub>3-δ</sub> as a parent material for RWGS-CL, which was transformed to layered perovskite (La<sub>2-y</sub>Sr<sub>y</sub>CoO<sub>4</sub>) after the first redox cycle because of its weak oxidation ability with CO<sub>2</sub>.<sup>35</sup> After H<sub>2</sub> reduction, the oxide phases were changed into metallic cobalt and base oxides. They were subsequently regenerated back to the layered perovskite after CO<sub>2</sub> reoxidation. Nevertheless, this layered perovskite was not stable when contacting with CO<sub>2</sub>. Furthermore, it required different oxidation and reduction temperatures, with the optimal operational temperature remaining high: 1123 K. Furthermore, the best oxidation temperature was related closely to the close contact of La<sub>2-y</sub>Sr<sub>y</sub>CoO<sub>4</sub> and Co. Therefore, their research group later introduced La<sub>0.75</sub>Sr<sub>0.25</sub>FeO<sub>3-δ</sub> (LSF) as a more promising alternative.<sup>38</sup> As Fig. 2(a) and (b) show, LSF exhibited remarkable redox properties, facilitating isothermal operation at the lower temperature of 823 K while maintaining structural stability. Furthermore, its excellent CO<sub>2</sub> splitting performance can be attributed to the strengthened adsorption of CO<sub>2</sub> attributable to the increased oxygen vacancies (Fig. 2(c)).

Because LSF combines the low energy barrier for oxidation-state transitions (Fe<sup>3+</sup>-Fe<sup>2+</sup>) during redox cycles,<sup>39</sup> the CO<sub>2</sub> affinity facilitated by the slight basicity of La,<sup>40</sup> and the enhanced lattice oxygen diffusion from a subtle oxygen

Table 2 Summary of CO<sub>2</sub> splitting performance of metal based-OCs for RWGS-CL

OCs	CO <sub>2</sub> concentration/%	Space velocity/ L min <sup>-1</sup> g <sup>-1</sup>	Temperature/K	CO yield/ mmol g <sup>-1</sup>	Average CO <sub>2</sub> splitting rate/ μmol g <sup>-1</sup> min <sup>-1</sup>	CO <sub>2</sub> conversion/%	Reference
Fe <sub>0.35</sub> Ni <sub>0.65</sub> O <sub>x</sub>	100.0	1.25 <sup>a</sup> (H <sub>2</sub> ), 0.75 <sup>a</sup> (CO <sub>2</sub> )	773	3.20	N/A	N/A	Rojas <i>et al.</i> <sup>54</sup>
Fe <sub>3</sub> O <sub>4</sub> -Ce <sub>0.5</sub> Zr <sub>0.5</sub> O <sub>2</sub>	50.0	1.00	1073	1.00	22.2	N/A	Wenzel <i>et al.</i> <sup>55</sup>
Fe <sub>2</sub> O <sub>3</sub> -LaFeO <sub>3</sub>	20.0	0.50	750	12.10	605.0	N/A	Lee <i>et al.</i> <sup>56</sup>
Fe <sub>2</sub> O <sub>3</sub> /Gd <sub>0.1</sub> Ce <sub>1.9</sub> O <sub>2-δ</sub>	10.0	0.40	1023	N/A	693.0	38.8	Zeng <i>et al.</i> <sup>57</sup>
Fe <sub>2</sub> O <sub>3</sub> /Gd <sub>0.2</sub> Ce <sub>1.8</sub> O <sub>2-δ</sub>				N/A	728.0	40.8	
Fe <sub>2</sub> O <sub>3</sub> /Gd <sub>0.3</sub> Ce <sub>1.7</sub> O <sub>2-δ</sub>				10.79	770.0	43.2	
Fe <sub>2</sub> O <sub>3</sub> /Gd <sub>0.5</sub> Ce <sub>1.5</sub> O <sub>2-δ</sub>				N/A	719.0	40.3	
Cu-In <sub>2</sub> O <sub>3</sub>	10.0	N/A	673	2.90	58.7	30.0	Makiura <i>et al.</i> <sup>58</sup>
			723	3.79	115.0	35.0	
			773	4.80	161.8	30.0	
			823	N/A	340.0	30.0	
			873	N/A	457.0	32.5	
Co-In <sub>2</sub> O <sub>3</sub>	10.0	N/A	723	1.62	127.6	80.0	Makiura <i>et al.</i> <sup>60</sup>
			748	2.29	191.0	N/A	
			773	3.27	280.2	80.0	
			798	4.14	365.7	N/A	
			823	5.15	429.5	N/A	
NiGa <sub>2</sub> O <sub>x</sub>	10.0	N/A	973	4.05	367.4	99.0	Kang <i>et al.</i> <sup>59</sup>
CuGa <sub>2</sub> O <sub>x</sub>				0.80	160.7	99.0	
CoGa <sub>2</sub> O <sub>x</sub>				2.72	138.5	99.0	

<sup>a</sup> The maximum weight of OCs is used for calculation, despite there is a weight range.



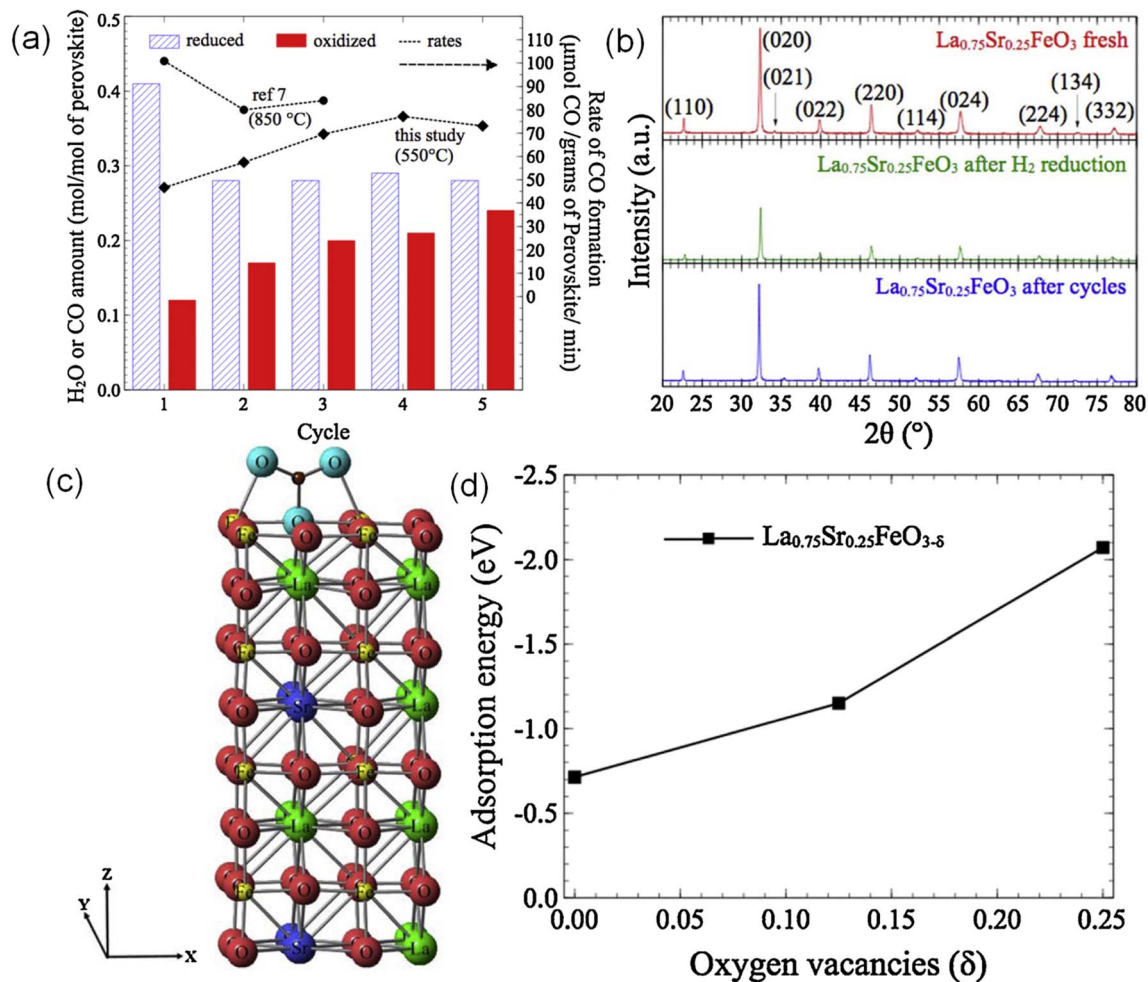


Fig. 2 (a) RWGS-CL performance of  $\text{La}_{0.75}\text{Sr}_{0.25}\text{FeO}_3$  (LSF) at 823 K. (b) XRD data of the LSF powder during RWGS-CL. (c) Adsorption energies of  $\text{CO}_2$  on (1 0 0) facet of stoichiometric LSF. (d) Change of  $\text{CO}_2$  adsorption energy with oxygen vacancies ( $\delta = 0, 0.125, 0.250$ ). Reprinted with permission.<sup>38</sup> Copyright 2014 Elsevier.

deficiency induced by moderate Sr doping,<sup>41</sup> it has shown high industrial potential for RWGS-CL. Therefore, some related research work has contributed to the improvement of LSF by introducing additional components, specifically supports and metals, by changing the introduction method, and by designing the particle structure. Hare *et al.* identified  $\text{SiO}_2$  as superior support when compared to  $\text{CeO}_2$ ,  $\text{ZrO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{TiO}_2$  for LSF in RWGS-CL, enhancing the CO yield of pure LSF by 150%.<sup>42</sup> This better support can be attributed primarily to the decreased perovskite particle size and crystallite size facilitated by  $\text{SiO}_2$ . Furthermore, despite the observation of minor secondary phases at the LSF-support interface, the perovskite oxide phase remained active in generating oxygen vacancies. Subsequently, they reported other work conducted by loading 25 wt% LSF onto  $\text{SiO}_2$ , which yielded impressive performance by increasing the CO yield of LSF by approximately 200% during eight RWGS-CL cycles.<sup>33</sup> These enhancements were attributed to the lattice strain associated with  $\text{SiO}_2$  support and the decreased secondary phases which might obstruct access to active surfaces, in addition to the decreased particle and crystallite

size. Brower and colleagues advanced this line of research by introducing high-surface-area mesoporous  $\text{SiO}_2$  (SBA-15) support to LSF using two methods.<sup>43</sup> The first approach involved the addition of the LSF to SBA-15 through a sonication process using wet  $\text{SiO}_2$  (SWS process), which increased the surface area and pore volume considerably. However, this approach presented a challenge to the maintenance of the desired perovskite stoichiometry because of the presence of secondary phases containing Sr-based oxides. In contrast, the second method incorporated SBA-15 during the sol-gel stage of perovskite oxide formation (ASG process), proving to be more effective at ensuring structural stability, improving CO yields, and increasing surface area and pore volume. Results show that the ASG-synthesised composite with 50% loading of LSF increased the total surface area by approx. 300% and enhanced the CO yields by a factor of 10 compared to pure LSF in six redox cycles at 973 K. Furthermore, Jo and his team used a nanocasting method to synthesise mesoporous LSF and then explored the effects of controlled template removal from the nanocast LSF on its textural properties and redox reactivity.<sup>44</sup> As



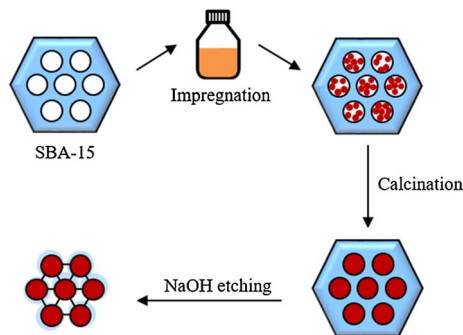


Fig. 3 Synthesis method of nanocast mesoporous LSF. Reprinted with permission.<sup>44</sup> Copyright 2021 Elsevier.

depicted in Fig. 3, LSF was impregnated initially onto SBA-15, a mesoporous silica template, with subsequent template removal through NaOH etching. The decreased residual Si content led to dramatic enhancements in specific surface area, total pore volume, and metal dispersion, but the mesoporous structure collapsed when the Si content became lower than 5 wt%. Moreover, maintaining a specific Si content was important to maintain the atomic ratio of surface oxygen to lattice oxygen to achieve peak CO productivity. Ultimately, mesoporous LSF with optimal Si content of 10 wt% achieved an impressive average CO yield of 2.80 mmol g<sup>-1</sup> for RWGS-CL at 873 K, surpassing that of bulk LSF by a factor of 5.9. Daza and his team, after incorporating Cu in the B site of LSF, found that only perovskites with the lowest Cu substitution of 0.1 and those devoid of Cu exhibited the unique capability to produce CO.<sup>45</sup> This finding is explainable: Cu incorporation altered the oxygen affinity of LSF structure and limited its ability to be re-oxidised using CO<sub>2</sub>. Minbeom and colleagues explored the potential of metal oxide core-perovskite shell OCs for the RWGS-CL process by preparing and testing LSF and MeO<sub>x</sub>@LSF (MeO<sub>x</sub>: CeO<sub>2</sub>, NiO, Co<sub>3</sub>O<sub>4</sub>, and Co<sub>3</sub>O<sub>4</sub>-NiO).<sup>46</sup> Cyclic RWGS-CL experiments demonstrated that NiO@LSF, Co<sub>3</sub>O<sub>4</sub>@LSF, and Co<sub>3</sub>O<sub>4</sub>-NiO@LSF enhanced the LSF performance. Additionally, CeO<sub>2</sub>@LSF exhibited a similar performance to that of LSF because of the low oxygen capacity of CeO<sub>2</sub>. Actually, Co<sub>3</sub>O<sub>4</sub>-NiO@LSF, which maintained stable CO production over 20 cycles, emerged as an optimal OC because it combined the benefits of both Co<sub>3</sub>O<sub>4</sub>@LSF and NiO@LSF. Furthermore, the investigated core-shell-structured OCs can form and consume oxygen defects efficiently, even at lower temperatures.

Apart from LSF, La<sub>1-x</sub>Ba<sub>x</sub>FeO<sub>3</sub> (LBF) was also identified from DFT calculation and stable structures indicated by proper Goldschmidt tolerance factor as a promising OC because of its comparable oxygen vacancy formation energy to that of LSF.<sup>47,48</sup> Shi *et al.* prepared LBF ( $x = 0.25-0.75$ ) perovskites for efficient and stable CO production by RWGS-CL.<sup>49</sup> Their findings show that La<sub>0.25</sub>Ba<sub>0.75</sub>FeO<sub>3</sub> exhibited efficient CO production but faced partial decomposition, whereas La<sub>0.5</sub>Ba<sub>0.5</sub>FeO<sub>3</sub> exhibited excellent stability, but only after inefficient CO production. A balance between stability and yield was struck with La<sub>0.4</sub>Ba<sub>0.6</sub>FeO<sub>3</sub>, which showed high stability and efficient CO production at the low temperature of 773 K. The enhanced stability and

lowered reaction temperature were attributed to La on the A site, whereas the increased CO production was attributed to the introduction of Ba. The surface oxidation mechanism was inferred as the following: CO<sub>2</sub> was adsorbed onto the reduced surface, forming carbonates even at room temperature, which were dissociated into C-O and O at temperatures higher than 523 K. The dissociated C-O and O desorbed at temperatures higher than 773 K, respectively producing CO and regenerating the LBF to its initial state. Shi and his team further explored the potential of 25 wt% La<sub>0.5</sub>Ba<sub>0.5</sub>FeO<sub>3</sub> supported on SiO<sub>2</sub> for industrial use for RWGS-CL.<sup>50</sup> Their results indicate that the CO<sub>2</sub> adsorption was enhanced from 18.3 to 62.2 μmol g<sup>-1</sup> LBF by introducing the SiO<sub>2</sub> support, which increased CO production from 0.2 to 2.2 mmol g<sup>-1</sup> LBF. To ensure industrial applicability, SiO<sub>2</sub>-supported La<sub>0.5</sub>Ba<sub>0.5</sub>FeO<sub>3</sub> was processed into high-strength pellets using optimised tableting and extrusion methods. The CO<sub>2</sub> oxidation temperature of LBF/SiO<sub>2</sub> pellets was 823 K, which was 50 K higher than that of LBF. The redox performance of all pellets remained stable throughout 50 cycles of semi-batch reactor tests. Additionally, deactivated pellets can be regenerated through thermal treatment with air.

Recently, double perovskite structures (A<sub>2</sub>BB'O<sub>6</sub>) have also garnered extensive attention because of their synergistic interaction and induced distortion in BO<sub>6</sub> octahedra by the incorporation of different B and B' cations. Lim *et al.* synthesised a double perovskite of La<sub>2</sub>NiFeO<sub>6</sub> to elucidate the role of interaction between binary Ni and Fe sites in enhancing CO<sub>2</sub> conversion when compared to single LaNiO<sub>3</sub> and LaFeO<sub>3</sub> perovskites.<sup>51</sup> The Ni site played a pivotal role in facilitating hydrogen atom adsorption, the formation of surface oxygen vacancies, and the transfer of lattice oxygen. Additionally, the Ni site promoted the poor reduction of Fe cations. Furthermore, the Fe site prevented the strong adsorption of CO<sub>2</sub> molecules on the La sites, facilitating their direct dissociation into CO molecules on the oxygen vacant sites or the reduced transition metal sites. The incorporation of Fe into the B site of LaNiO<sub>3</sub> addressed the poor CO<sub>2</sub> splitting activity observed in the single LaNiO<sub>3</sub> perovskite. The double La<sub>2</sub>NiFeO<sub>6</sub> perovskite emerged as a high-performing option, with an average CO productivity of 2.14 mmol g<sup>-1</sup> and a maximum CO production rate of 1.69 mmol g<sup>-1</sup> min<sup>-1</sup> at 973 K, respectively surpassing those of single perovskites by factors of more than 4.7 and 10.

**2.1.2 Spinels (AB<sub>2</sub>O<sub>4</sub>).** In addition to perovskite, spinel is a viable family of metal oxides for OCs in RWGS-CL processes. Spinels' potential benefits derive from their adaptable and highly thermally stable crystal structure. In fact, both the A and B positions within their structures can be occupied by readily available Earth-abundant metals. Qiu *et al.* found that Cu<sub>0.4</sub>Co<sub>0.6</sub>Fe<sub>2</sub>O<sub>4</sub> exhibits an impressive CO<sub>2</sub> splitting rate and total CO production even at moderate temperatures, which was attributed to the reduction ability of cobalt ferrite by doping Cu and the reversible phase change after CO<sub>2</sub> oxidation.<sup>52</sup> Furthermore, Ma *et al.* reported that Mn<sub>0.2</sub>Co<sub>0.8</sub>Fe<sub>2</sub>O<sub>4</sub> exhibited the highest CO<sub>2</sub> splitting performance among all prepared OCs with a different doping amount of Mn at 923 K.<sup>53</sup> The enhanced redox activity might be attributed to the increased reduction depth during the reduction process and the high reversibility



during CO<sub>2</sub> splitting. The decreased performance with higher levels of Mn doping was attributed to the low phase reversibility of the MnFe alloy.

## 2.2 Metal-based oxides

Metal-based oxides are attractive OCs for commercial-scale processes because of their accessibility and high oxygen storage capacities. However, because of their strong tendency to be sintered at a low temperature, deactivation of particles occurs easily. The OC performance cannot be maintained during long-term experimentation. Numerous research endeavours have been pursued to improve the performance of pure metal oxides by modifying and introducing other metal oxides, composite oxides, or supports. Table 2 presents a summary of the CO<sub>2</sub> splitting performance of metal-based OCs used in the following literature found for RWGS-CL.

**2.2.1 Fe-based OCs.** Iron oxides are promising because of their cost-effectiveness, environmental friendliness, and widespread availability. However, their limited activity at low temperatures and susceptibility to sintering at high temperatures pose challenges for industrial use. Numerous research efforts have been undertaken to improve the activity and the sintering resistance of iron oxides, with a notable emphasis on incorporating them with other metal oxides and depositing them onto refractory ESIs.† Rojas *et al.* thermodynamically screened various ferrites using thermodynamic analyses and the calculation of phase diagrams (CALPHAD) simulations for RWGS-CL metal oxides.<sup>54</sup> They found that Fe<sub>0.35</sub>Ni<sub>0.65</sub>O<sub>x</sub> exhibits remarkable theoretical CO yield at 773 K (Fig. 4(a)). Moreover, its CO yield is closely related to the temperature and CO<sub>2</sub>/CO ratio, as depicted in Fig. 4(b). A marked degree of 17.7% CO<sub>2</sub> conversion at 773 K was predicted, with a sharp increase in CO yield as the CO<sub>2</sub>/CO ratio rises, indicating a phase change in the metal oxide. The 17.7% conversion prediction was subsequently validated through TGA experiments. The phase change was affirmed by the “sweet spot” marked by a stark discontinuity in molar enthalpy and entropy values in thermodynamic phase diagrams in Fig. 4(c) and by the important jumps in oxygen content plots in Fig. 4(d). Furthermore, as portrayed in Fig. 4(e), the redox performance of Fe<sub>0.35</sub>Ni<sub>0.65</sub>O<sub>x</sub> was compared with the Mn<sub>0.4</sub>Co<sub>0.6</sub>Fe<sub>2</sub>O<sub>4</sub> spinel with the highest CO yield in an earlier report, revealing that Fe<sub>0.35</sub>Ni<sub>0.65</sub>O<sub>x</sub> exhibited higher oxygen capacity, CO yield, and stability at 773 K, which were attributed to the spinel-to-metallic phase transition.<sup>53</sup> Wenzel *et al.* introduced Ce<sub>0.5</sub>Zr<sub>0.5</sub>O<sub>2</sub> to modify pure Fe<sub>2</sub>O<sub>3</sub>: the 80 wt% Fe<sub>2</sub>O<sub>3</sub>–Ce<sub>0.5</sub>Zr<sub>0.5</sub>O<sub>2</sub> displayed stability over 500 redox cycles.<sup>55</sup> Despite experiencing initial deactivation in the first 100 cycles, subsequent cycling led to consistent CO yield per cycle over the remaining 400 cycles. The initial material deactivation resulted from surface sintering, which increased crystallite sizes and induced phase segregation into Fe-rich and Ce–Zr-rich regions. This phenomenon strongly affected the reaction kinetics and CO yield. The sintering of pure Fe<sub>2</sub>O<sub>3</sub> can also be improved by adding perovskite. Lee *et al.* introduced a small quantity of LaFeO<sub>3</sub> into Fe<sub>2</sub>O<sub>3</sub> for RWGS-CL, aiming to offer the high oxygen storage capacity of Fe<sub>2</sub>O<sub>3</sub> and the redox stability of

LaFeO<sub>3</sub>.<sup>56</sup> In fact, Fe<sub>2</sub>O<sub>3</sub>–LaFeO<sub>3</sub> exhibited both increased CO yield and enhanced stability, with CO yield (12.1 mmol g<sup>−1</sup>) and CO production rate (605 μmol g<sup>−1</sup> min<sup>−1</sup>) for 50 redox cycles at 750 K. The incorporation of LaFeO<sub>3</sub> perovskite served as a sintering barrier, preventing the migration of metallic cations between adjacent particles and alleviating the Kirkendall effect by changing the oxide growth direction. This strategic intervention mitigates structural deformations, thereby facilitating sustained CO<sub>2</sub> conversion. Moreover, the addition of LaFeO<sub>3</sub> enhances the electrical conductivity of the particles, facilitating the conduction of O<sup>2−</sup>. In addition, to avoid a trade-off between reactivity and the stability caused by the addition of inert supports to Fe<sub>2</sub>O<sub>3</sub>, Zeng *et al.* proposed a novel approach using ion-conductive Gd<sub>x</sub>Ce<sub>2−x</sub>O<sub>2−δ</sub> (GDC) to prepare supported OCs.<sup>57</sup> The resulting Fe<sub>2</sub>O<sub>3</sub>/GDC materials exhibited both high reactivity and stability. Specifically, Fe<sub>2</sub>O<sub>3</sub>/Gd<sub>0.3</sub>Ce<sub>1.7</sub>O<sub>2−δ</sub> showed remarkable CO productivity (approx. 10.79 mmol g<sup>−1</sup>) and a high CO production rate (approx. 0.77 mmol g<sup>−1</sup> min<sup>−1</sup>), surpassing those of Fe<sub>2</sub>O<sub>3</sub>/Al<sub>2</sub>O<sub>3</sub> by twofold, while maintaining stability over 30 cycles. The study also established a linear relation between O<sup>2−</sup> conductivity and CO yield (Fig. 5(a)). This relation was validated using reference samples (Fig. 5(b)). The identified correlation served as a basis for predicting and designing OCs. However, its applicability under different conditions requires further investigation.

**2.2.2 In-based and Ga-based OCs.** In the authors' group, Makiura *et al.* prepared the parent material of Cu<sub>2</sub>In<sub>2</sub>O<sub>5</sub> using a complex polymerisation method, which was converted to the oxide structure consisting of reduced Cu supported on In<sub>2</sub>O<sub>3</sub> (Cu–In<sub>2</sub>O<sub>3</sub>) after the first RWGS-CL cycle.<sup>58</sup> Cu–In<sub>2</sub>O<sub>3</sub> showed superior CO<sub>2</sub> conversion at the low temperatures of 673–773 K and accomplished the RWGS-CL process by the redox of indium species accompanied by the formation and re-oxidation of Cu–In alloy. The structured state of Cu–In<sub>2</sub>O<sub>3</sub> played an important role in its high oxidation performance, but the Cu-supported In<sub>2</sub>O<sub>3</sub> and pure In<sub>2</sub>O<sub>3</sub> prepared directly using an impregnation method exhibited only low performance. The excellent redox performance of Cu–In<sub>2</sub>O<sub>3</sub> can be attributed to two characteristics: First, it has high reducibility by H<sub>2</sub>, even at low temperatures, which was promoted by Cu species. Second, the Cu–In alloy particle surface has a highly reduced state maintained even when oxidised using CO<sub>2</sub>, leading to its high CO<sub>2</sub> splitting rate. As depicted in Fig. 6, the interesting oxidation behaviour was attributed to rapid O<sup>2−</sup> migration from the surface to the bulk of the Cu–In alloy and to the preferential oxidation of the interface between the alloy and In<sub>2</sub>O<sub>3</sub>. Although Cu–In<sub>2</sub>O<sub>3</sub> showed outstanding kinetics performance, it still presents shortcomings such as poor stability and insufficient CO<sub>2</sub> conversion compared to conventional RWGS, which hinders its practical application.<sup>59</sup> Therefore, Makiura *et al.* later introduced another In-based material, Co–In<sub>2</sub>O<sub>3</sub>, which not only further improved the high CO<sub>2</sub> splitting rate of Cu–In<sub>2</sub>O<sub>3</sub> at 723–823 K, but also remained stable even after 10 cycles.<sup>60</sup> Actually, it showed maximum CO<sub>2</sub> conversion of approximately 80%. This figure greatly exceeded the equilibrium conversion of catalytic RWGS in the mid-temperature range and efficiently decreased the cost for gas separation of CO<sub>2</sub> from the product gas of CO.



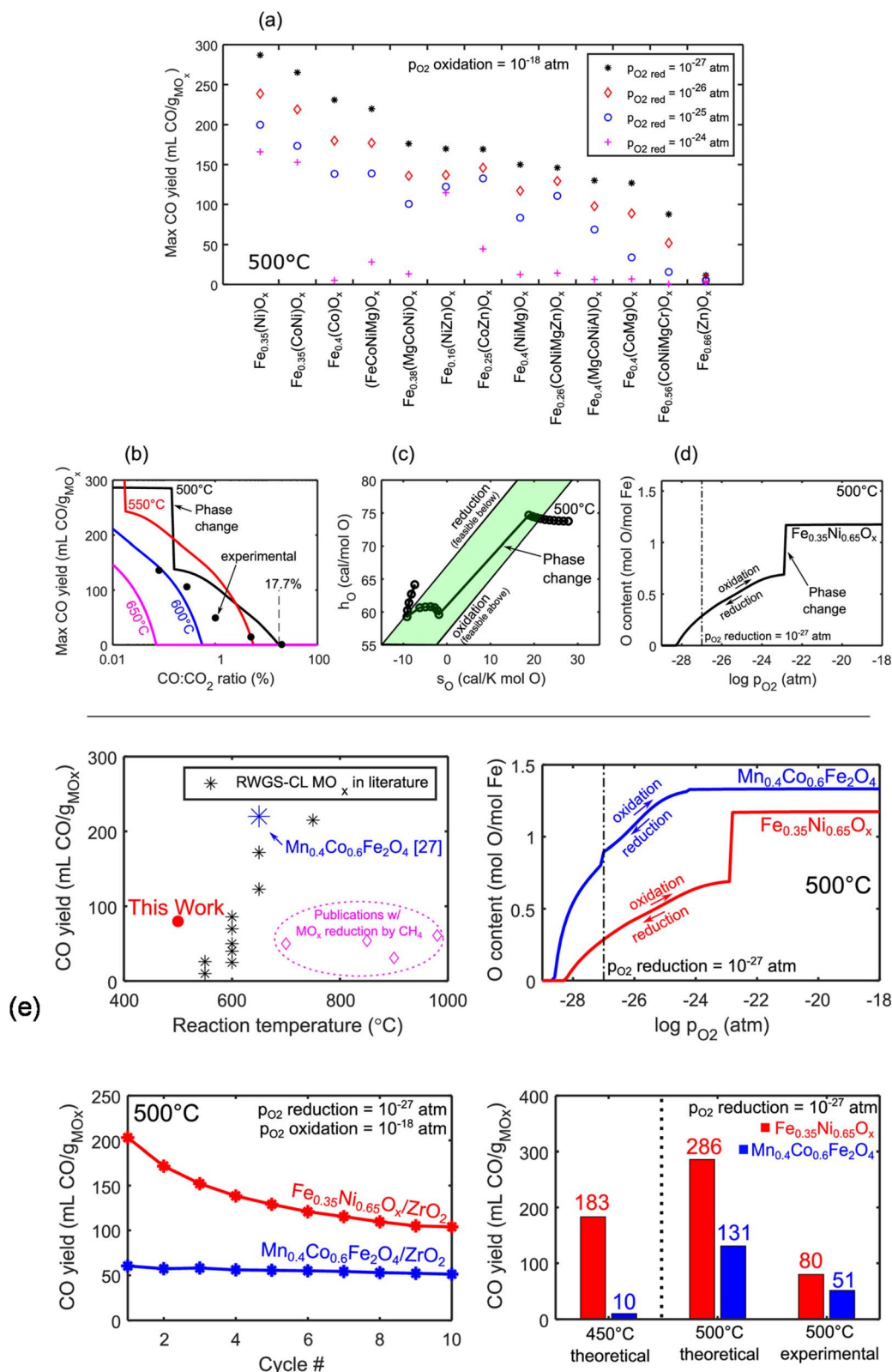


Fig. 4 Thermodynamic screening and verification by experimentation of RWGS-CL oxygen carriers. (a) Thermodynamic CO yield of promising RWGS-CL OC candidates with different reduction  $p_{O_2}$ . (b) Thermodynamic CO yield of Fe<sub>0.35</sub>Ni<sub>0.65</sub>O<sub>x</sub> with CO/CO<sub>2</sub> ratio as a function of temperature. (c) Thermodynamically calculated molar enthalpy with entropy plot of Fe<sub>0.35</sub>Ni<sub>0.65</sub>O<sub>x</sub>. (d) Thermodynamically calculated oxygen content with  $p_{O_2}$  phase diagram of Fe<sub>0.35</sub>Ni<sub>0.65</sub>O<sub>x</sub> at 500 °C. (e) Comparison of Fe<sub>0.35</sub>Ni<sub>0.65</sub>O<sub>x</sub> to other reported RWGS-CL metal oxides. Reprinted with permission.<sup>54</sup> Copyright 2022 American Chemical Society.



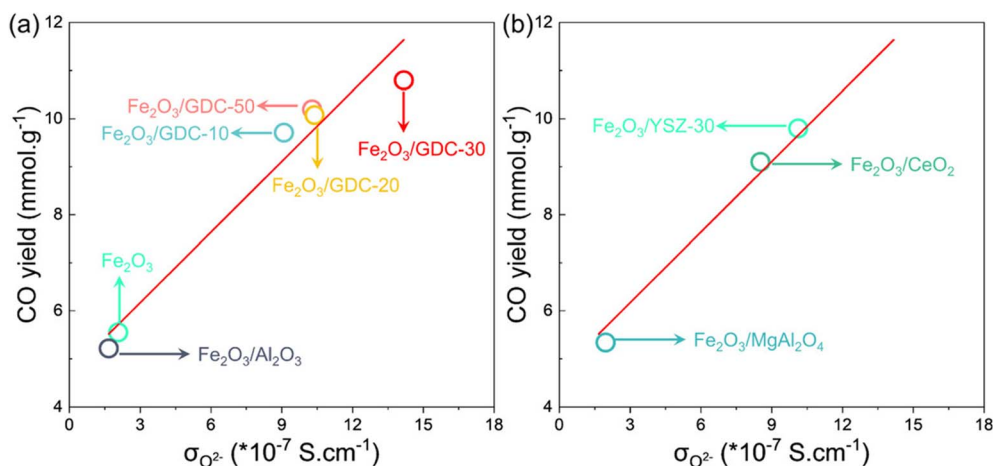


Fig. 5 (a) Fitted linear curve relation between  $O^{2-}$  conductivity and CO yield to predict activity of supported  $Fe_2O_3$  and (b)  $O^{2-}$  conductivity and CO yield for reference samples to validate the fitted curves. Reprinted with permission.<sup>57</sup> Copyright 2020 American Chemical Society.

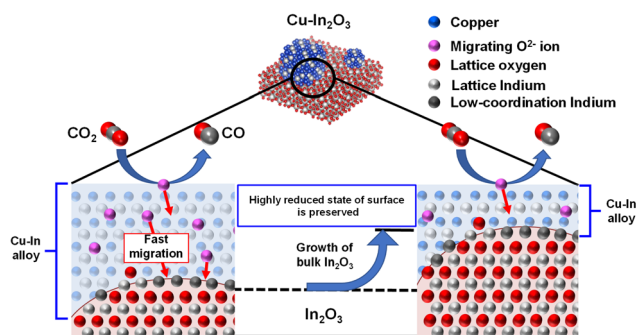


Fig. 6 Proposed mechanism of  $CO_2$  splitting on the reduced  $Cu-In_2O_3$ . Reprinted with permission.<sup>58</sup> Copyright 2021 RSC Publishing.

However, the high splitting rate of  $Co-In_2O_3$  was measured without the presence of CO. Moreover, the equilibrium  $CO_2$  conversion can be improved further. To conserve energy and decrease costs further, Kang *et al.* developed  $MGa_2O_x$  ( $M = Ni, Cu, Co$ ) materials, by which the RWGS-CL was able to achieve nearly 100%  $CO_2$  conversion even when operated at temperatures as low as 673 K.<sup>59</sup> This high performance at a low temperature made it possible for RWGS to proceed without equilibrium constraints, even at low temperatures. Additionally, the  $CO_2$  splitting rate and CO yield were evaluated with highly concentrated CO, which more closely matched the practical conditions. The results showed Ni to be a better dopant than either Co or Cu, which can be attributed to its excellent redox and CO adsorption abilities and to its large surface area. The redox cycle over  $NiGa_2O_x$  was accomplished by the redox of  $Ga^{3+} \leftrightarrow Ga^0$  with Ni in the metallic state through RWGS-CL, and by the presence of CO decreasing the  $CO_2$  oxidation performance by restraining the oxygen amounts that can be re-filled by Ga species.

### 2.3 Summary and prospects for RWGS-CL

The reverse water gas shift chemical looping (RWGS-CL) process efficiently converts  $CO_2$  into CO with lower energy requirements

than conventional RWGS. It can be operated at moderate temperatures (673–1223 K) and aligns with downstream processes like methanol synthesis. Oxygen carriers (OCs) are crucial, enabling simultaneous reduction with  $H_2$  and oxidation with  $CO_2$ .

Perovskites exhibit high oxygen storage and stability, enhanced by doping and structural modifications. Spinel shows high CO yields. Doping and hybridization are effective for enhancing the durability of iron-based oxides.  $Cu-In_2O_3$  is excellent at low temperatures and has efficient redox properties, but it has stability issues.

RWGS-CL has significant industrial potential thanks to its energy efficiency, lower operating temperatures, and adaptability. Continued innovation in OC development, including

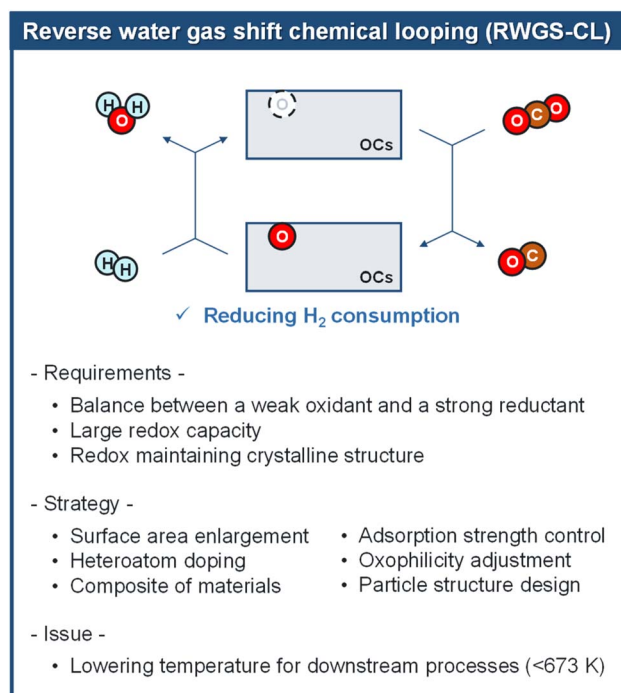


Fig. 7 Overview of material development for RWGS-CL.





Table 3 Summary of redox performance of composite OCs for DRM-CL

OCs	Reduction step					Oxidation step					Reference
	Temperature/ K	CH <sub>4</sub> concentration/ %	Space velocity/ L min <sup>-1</sup> g <sup>-1</sup>	CH <sub>4</sub> conversion/ %	Syngas or CO selectivity/ %	Syngas or CO concentration/ mmol g <sup>-1</sup>	Space velocity/ L min <sup>-1</sup> g <sup>-1</sup>	CO <sub>2</sub> conversion/ %	CO <sub>2</sub> conversion/ %	CO yield/ mmol g <sup>-1</sup>	
			t/min				t/min				
LaFeO <sub>3</sub>	1123	10	0.10	4	26	57	1.20	10	19	0.32	Zhang <i>et al.</i> <sup>64</sup>
La <sub>0.75</sub> Ca <sub>0.25</sub> FeO <sub>3</sub>					54	73	2.50		53	0.98	
La <sub>0.5</sub> Ca <sub>0.5</sub> FeO <sub>3</sub>					83	90	4.20		92	1.65	
La <sub>0.75</sub> Ce <sub>0.25</sub> FeO <sub>3</sub>					52	79	2.50		59	1.05	
CeFeO <sub>3</sub>					10	55	0.44		5	0.08	
LaFeO <sub>3</sub>	1123	5	0.20	30	N/A	N/A	10.05	5	N/A	5.00	Sastre <i>et al.</i> <sup>65</sup>
La <sub>0.9</sub> Sr <sub>0.1</sub> FeO <sub>3</sub>					N/A	N/A	17.50		N/A	9.25	
La <sub>0.7</sub> Sr <sub>0.3</sub> FeO <sub>3</sub>					N/A	N/A	15.55		N/A	7.18	
La <sub>0.5</sub> Sr <sub>0.5</sub> FeO <sub>3</sub>					N/A	N/A	3.44		N/A	1.65	
La <sub>0.3</sub> Sr <sub>0.7</sub> FeO <sub>3</sub>					N/A	N/A	1.84		N/A	1.37	
La <sub>0.1</sub> Sr <sub>0.9</sub> FeO <sub>3</sub>					N/A	N/A	1.59		N/A	1.11	
SrFeO <sub>3</sub>					N/A	N/A	2.52		N/A	1.86	
SrMnO <sub>3</sub>	1173	100	3.13	20	N/A	84	9.39	100	N/A	1.26	Riaz <i>et al.</i> <sup>66</sup>
La <sub>0.25</sub> Sr <sub>0.75</sub> MnO <sub>3</sub>					N/A	84	10.79		N/A	2.47	
La <sub>0.5</sub> Sr <sub>0.5</sub> MnO <sub>3</sub>					N/A	91	11.84		N/A	1.88	
LaMnO <sub>3</sub>					N/A	84	5.45		N/A	0.99	
LaFe <sub>0.8</sub> Al <sub>0.2</sub> O <sub>3</sub>	1173	50	0.30	2.5	85	99	3.40	50	79	N/A	Xia <i>et al.</i> <sup>67</sup>
LaFe <sub>0.8</sub> Ga <sub>0.2</sub> O <sub>3</sub>					78	99	3.10		72	N/A	
LaFeO <sub>3</sub>					58	97	2.70		62	N/A	
LaFe <sub>0.8</sub> Sc <sub>0.2</sub> O <sub>3</sub>					48	96	2.00		57	N/A	
10 wt% SrFeO <sub>3-δ</sub> -CaO	1253	4	0.38	6.59	88	96	9.90	5	N/A	5.12	Yu <i>et al.</i> <sup>68</sup>
30 wt% SrFeO <sub>3-δ</sub> -CaO				7.9	64	90	9.60		N/A	4.23	
60 wt% SrFeO <sub>3-δ</sub> -CaO				16.6	44	100	15.30		N/A	6.34	
80 wt% SrFeO <sub>3-δ</sub> -CaO				34.4	39	96	27.30		N/A	10.19	
SrFeO <sub>3-δ</sub>				16.5	35	100			N/A	3.71	
S-La <sub>0.9</sub> Sr <sub>0.1</sub> FeO <sub>3</sub> /YSZ	1123	5	0.20	30	85-88	N/A	10.00	5	N/A	5.00	Sastre <i>et al.</i> <sup>69</sup>
M-La <sub>0.9</sub> Sr <sub>0.1</sub> FeO <sub>3</sub> /YSZ					72	N/A	11.50		N/A	6.70	
BaFe <sub>2</sub> Al <sub>10</sub> O <sub>19</sub>	1123	5	0.08	10	55-90	58-64	1.92-3.76	5	6-20	N/A	Zhu <i>et al.</i> <sup>70</sup>
(for 10 cycles)											
BaFe <sub>3</sub> Al <sub>9</sub> O <sub>19</sub>					65-78	64-88	2.38-3.26		13-38	N/A	
(for 10 cycles)											
BaFe <sub>2</sub> MnAl <sub>9</sub> O <sub>19</sub>					55-60	59-85	1.69-2.72		10-30	N/A	
(for 10 cycles)											
BaFe <sub>2</sub> NiAl <sub>9</sub> O <sub>19</sub>					100	55-70	3.16-4.21		22-56	N/A	
(for 10 cycles)											
BaFe <sub>2</sub> CoAl <sub>9</sub> O <sub>19</sub>					81-97	68-80	2.77-4.26		27-52	N/A	
(for 10 cycles)											
LaFe <sub>3</sub> Al <sub>9</sub> O <sub>19</sub>	1123	5	0.08	10	55-82	75-90	1.89-3.44	5	N/A	N/A	Zhu <i>et al.</i> <sup>71</sup>
(for 50 cycles)											
Fe <sub>2</sub> O <sub>3</sub> -Al <sub>2</sub> O <sub>3</sub>					33-53	33-85	0.65-2.16		N/A	N/A	
(for 10 cycles)											



Table 3 (Contd.)

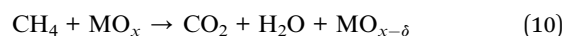
OCs	Reduction step				Oxidation step						Reference	
	Temperature/ K	CH <sub>4</sub> concentration/ %	Space velocity/ L min <sup>-1</sup> g <sup>-1</sup>	CH <sub>4</sub> conversion/ %	Syngas or CO selectivity/ %	Syngas yield/ mmol g <sup>-1</sup>	CO <sub>2</sub> concentration/ %	Space velocity/ L min <sup>-1</sup> g <sup>-1</sup>	CO <sub>2</sub> conversion/ %	CO yield/ mmol g <sup>-1</sup>		
CeO <sub>2</sub> /BaFe <sub>3</sub> Al <sub>9</sub> O <sub>19</sub> -700 (for 10 cycles)	1173	5	0.05	77–80	49–75	1.09–1.78	5	0.07	10	N/A	N/A	Cheng <i>et al.</i> <sup>72</sup>
CeO <sub>2</sub> /BaFe <sub>3</sub> Al <sub>9</sub> O <sub>19</sub> -800 (for 10 cycles)				77–84	49–75	1.11–1.72				N/A	N/A	
CeO <sub>2</sub> /BaFe <sub>3</sub> Al <sub>9</sub> O <sub>19</sub> -900 (for 10 cycles)				85–90	56–75	1.29–2.02				N/A	N/A	
CeO <sub>2</sub> /BaFe <sub>3</sub> Al <sub>9</sub> O <sub>19</sub> -1000 (for 10 cycles)				81–88	52–73	1.23–1.86				N/A	N/A	

structural optimization and support material integration, is essential for enhancing performance and stability as shown in Fig. 7. This technology offers a sustainable pathway for CO<sub>2</sub> utilization, aligning with global decarbonization goals.

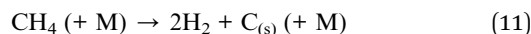
### 3. Dry reforming of methane chemical looping (DRM-CL)

Given the ample and recoverable global reserves of natural and shale gas, DRM-CL, substituting CH<sub>4</sub> for H<sub>2</sub> in RWGS-CL, has emerged as a novel technology for co-producing syngas in reduction steps and CO in oxidation steps using two greenhouse gases. In comparison to conventional DRM, DRM-CL offers notable benefits: First, the carbon deposited in the reduction can be eliminated *via* reverse eqn (6) in the oxidation step by CO<sub>2</sub> with additional CO produced. Secondly, the side reaction of RWGS is avoided because the H<sub>2</sub> produced in the reduction step lacks contact with CO<sub>2</sub>. Furthermore, unlike the strong oxidation of oxygen, the milder oxidant CO<sub>2</sub> facilitates the controlled oxidation of OCs with various valences (*i.e.* Fe species), which reportedly enables the selective CH<sub>4</sub> conversion to syngas.<sup>61,62</sup> Recent advancements in the introduction of concentrated solar power to supply the heat required for the endothermic reactions (*i.e.* DRM-CL, RWGS-CL) allow these processes to be operated with low carbon emissions and with sustainable, renewable properties.<sup>63</sup> Consequently, DRM-CL is acknowledged as a promising approach for producing high-quality, efficient, and cost-effective syngas. However, because of the existence of the side reactions of total oxidation of methane (TOM; eqn (10)) and carbon deposition (eqn (11)) in the reduction step, it still entails challenges in developing OCs with high selectivity to syngas, efficient regeneration through CO<sub>2</sub>, marked oxygen storage capacity, effective mobility of lattice oxygen, and stable redox properties. During the last decade, remarkable progress has been made in developing various OCs for DRM-CL. The discussion presented hereinafter specifically examines representative OCs to establish a comprehensive structure–activity relation, offering valuable insights into the design rationale of future OCs.

Total oxidation of methane:



Methane pyrolysis:



#### 3.1 Composite oxides

Composite oxides such as perovskites and hexaaluminate materials are also investigated widely for DRM-CL. Table 3 presents a summary of the redox performance of composite OCs used in reviewed reports about DRM-CL.

**3.1.1 Perovskites (ABO<sub>3</sub>).** Perovskite oxides (ABO<sub>3</sub>) have received extensive attention in DRM-CL because of their flexibility to alter the composition, their high oxygen mobility rate, and their more or less high structural stability. The redox

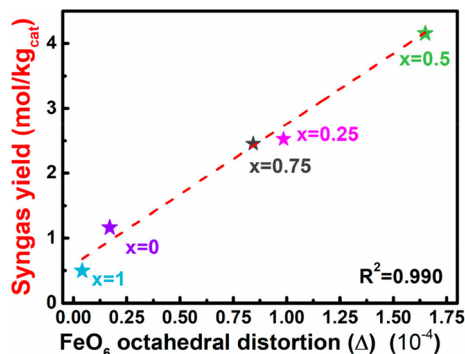


Fig. 8 Linear relation between the syngas yield and the  $\text{FeO}_6$  octahedral distortion in  $\text{La}_{1-x}\text{Ce}_x\text{FeO}_3$ . Reprinted with permission.<sup>64</sup> Copyright 2020 American Chemical Society.

properties of perovskites can be tailored by substituting or replacing the cations in sites A or B. Substituting a divalent atom (e.g., Sr) for the regular trivalent A-site element can engender an increased valence charge on the B-site transition metal and can engender the potential formation of oxygen vacancies, prompting the redox performance. A few reports of relevant research have described the effects of changing the doping content in the A site in perovskites on the redox properties for DRM-CL. For instance, Zhang *et al.* manipulated the distortion in  $\text{FeO}_6$  octahedra by substituting different contents of  $\text{Ce}^{3+}$  in  $\text{La}_{1-x}\text{Ce}_x\text{FeO}_3$  ( $x = 0, 0.25, 0.5, 0.75, 1$ ).<sup>64</sup> They discovered that the syngas yield is related linearly to the  $\text{FeO}_6$  octahedral distortion, as presented in Fig. 8. The increased  $\text{FeO}_6$  octahedral distortion not only enhanced the bulk oxygen mobility and CO selectivity by inhibiting carbon deposition; it also prompted surface reactivity. Consequently,  $\text{La}_{0.5}\text{Ce}_{0.5}\text{FeO}_3$ , with the highest  $\text{FeO}_6$  distortion, exhibited outstanding syngas productivity. In another case, Sastre *et al.* investigated the influence of strontium contents on the DRM-CL performance of  $\text{La}_{1-x}\text{Sr}_x\text{FeO}_3$  (LSF) perovskites.<sup>65</sup> The oxygen storage capacity of LSF was correlated positively with the introduction content of strontium when  $x \leq 0.7$ , which was attributed to the facile reduction of  $\text{Fe}^{4+}$  to  $\text{Fe}^{3+}$ . The oxygen storage capacity of LSF tended to be stable when  $x > 0.9$ . However, structural instabilities occurred during  $\text{CH}_4$  reduction, with the formation of Brownmillerite  $\text{Sr}_2\text{Fe}_2\text{O}_5$  and segregated  $\text{LaFeO}_3$ . In fact, LSF with  $x \leq 0.3$  exhibited superior  $\text{CH}_4$  reforming performance, which was attributable to the  $\text{CH}_4$  decomposition enhanced with strontium content increasing. It is noteworthy that perovskite recovery occurred in  $\text{CH}_4$ - $\text{CO}_2$  cycles and that  $\text{H}_2/\text{CO}$  control and production stability can be improved by higher-frequency cycles. The resilience of LSF perovskites enabled reactivity recovery even without optimal operating conditions. As part of a similar effort, Riaz *et al.* investigated the redox behaviours of  $\text{La}_x\text{Sr}_{1-x}\text{MnO}_3$  (LSM) for both DRM-CL and steam reforming of methane CL, using  $\text{H}_2\text{O}$  as a reoxidation medium (SRM-CL).<sup>66</sup> Although greater structural decomposition in LSM perovskites occurred during DRM-CL than during SRM-CL, the DRM-CL process still showed higher fuel-production efficiencies because of the reduced carbon deposition through

strontium carbonates formed only by the reoxidation medium of  $\text{CO}_2$ . The introduction of lanthanum with  $x = 0.5$  can enhance syngas yields to a different degree compared to those from pure  $\text{SrMnO}_3$  and  $\text{LaMnO}_3$  perovskites. However, the introduction of lanthanum with  $x > 0.5$  altered the redox dynamics from stoichiometric to nonstoichiometric, leading to an overall decrease in syngas yields. This decrease was attributed to the incorporation of the important role of La in inhibiting the structural breakdown in the reduction step and in facilitating the adoption of nonstoichiometric redox reaction pathways. Furthermore, although the structure of LSM disintegrated over the redox cycles which are particularly evident at high strontium concentrations, Mn species actively participated in the processes and their oxidation states were closely related to the content of La and reoxidation medium ( $\text{CO}_2$  or  $\text{H}_2\text{O}$ ). Moreover, populating the B site with transition metals that possess diverse redox capabilities can influence the charge balance through oxidation or the creation of oxygen vacancies, which directly influence the reactivity of perovskites. For instance, Xia *et al.* incorporated redox-inert cations of Al, Ga, Fe, and Sc into the B site of  $\text{LaFe}_{0.8}\text{M}_{0.2}\text{O}_3$  and found that manipulation of the tilting degree of the  $\text{FeO}_6$  octahedron and the Fe–O bond length can be achieved through the doping of cations with varying radii.<sup>67</sup> It is noteworthy that the influence of the former was found to be predominant, strongly affecting both the oxygen mobility and Fe–O bond covalency. These factors, in turn, exert a strong effect on the reactivity of lattice oxygen and the consequent DRM-CL performance (Fig. 9). The accumulated findings demonstrated that  $\text{LaFe}_{0.8}\text{Al}_{0.2}\text{O}_3$  showed enhanced oxygen exchange kinetics, improved methane activation capacity, and provided superior surface reaction activity by reducing  $\text{FeO}_6$  octahedral tilting through smaller B-site cation doping.

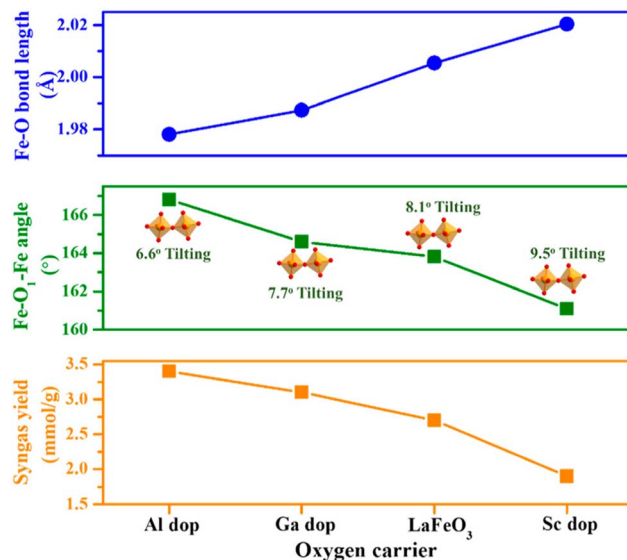


Fig. 9 Correlation between structural distortion and the  $\text{CH}_4$  conversion performance in the first cycle over  $\text{LaFe}_{0.8}\text{M}_{0.2}\text{O}_3$ . Reprinted with permission.<sup>67</sup> Copyright 2022 American Chemical Society.



Furthermore, the redox performance of perovskites is reportedly improved by introducing additional potential components of matrix or supports. To overcome the challenges of SrFeO<sub>3-δ</sub> perovskite posed by low stability and kinetics, Yu *et al.* encapsulated it within a CaO matrix and investigated the effects of the compositing perovskite weight percentage on the DRM-CL reactivity of *x* wt% SrFeO<sub>3-δ</sub>-CaO nanocomposites at 1253 K.<sup>68</sup> The 10 wt% SrFeO<sub>3-δ</sub>-CaO exhibited the highest syngas production rate and CH<sub>4</sub> conversion, whereas the 80 wt% SrFeO<sub>3-δ</sub>-CaO nanocomposite showed higher syngas productivity. A tradeoff was found between the quantity and speed of syngas production. The findings indicated that CaO primarily enhances the reduction of SrFeO<sub>3-δ</sub> by methane and the stability for cycling. Additionally, it contributed oxygen species for the POM reaction, although to a limited extent. Furthermore, based on their earlier study demonstrating the remarkable DRM-CL activity of La<sub>0.9</sub>Sr<sub>0.1</sub>FeO<sub>3</sub> perovskite,<sup>65</sup> Sastre *et al.* dispersed it on yttria-stabilised zirconia (YSZ) with excellent oxygen transport capacity and high stability using two preparation methods of ball milling and perovskite synthesis.<sup>69</sup> Both samples prepared using different methods exhibited stable but unsatisfactory CO<sub>2</sub> and CH<sub>4</sub> conversion in the conventional DR process at 1123 K. However, La<sub>0.9</sub>Sr<sub>0.1</sub>FeO<sub>3</sub>/YSZ exhibited better redox performance with high syngas production during DRM-CL. This better performance might be attributed to the improved CH<sub>4</sub> cracking and reverse Boudouard reactions. Moreover, despite its smaller surface area, the perovskite-synthesised composite exhibited better peak conversion in both CH<sub>4</sub> and CO<sub>2</sub> stages, along with enhanced H<sub>2</sub> production, possibly because of improved interaction among the components.

**3.1.2 Hexaaluminates (MAL<sub>2</sub>O<sub>19</sub>).** Hexaaluminates, with their unique layered structure and stability up to 1873 K, are excellent choices for high-temperature CH<sub>4</sub> conversion applications. Their structure, featuring alternating γ-Al<sub>2</sub>O<sub>3</sub> spinel blocks and mirror planes with large cations (Ba, La, Sr), not only ensures exceptional sintering resistance; it also exhibits remarkable methane activation capabilities. Investigations of hexaaluminate composites include tailoring substitution by metal dopants and by introducing additional components. Zhu *et al.* prepared the Fe-substituted hexaaluminates, including BaFe<sub>2</sub>Al<sub>10</sub>O<sub>19</sub> and BaFe<sub>3</sub>Al<sub>9</sub>O<sub>19</sub>, as well as bimetallic BaFe<sub>2</sub>MAl<sub>9</sub>O<sub>19</sub> (M = Mn, Ni, and Co) as OCs for DRM-CL and investigated the effects of Mn, Ni, and Co doping on the structure, reactivity, and stability.<sup>70</sup> Results indicated that the pure Fe-substituted OCs exhibited the coexistence of β-Al<sub>2</sub>O<sub>3</sub> and magnetoplumbite (MP) hexaaluminate phases, transitioning from MP to β-Al<sub>2</sub>O<sub>3</sub> during the CH<sub>4</sub>/CO<sub>2</sub> redox process. In contrast, bimetallic BaFe<sub>2</sub>MAl<sub>9</sub>O<sub>19</sub> (M = Mn, Ni, and Co) crystallised exclusively in the β-Al<sub>2</sub>O<sub>3</sub> hexaaluminate phase, retaining the β-Al<sub>2</sub>O<sub>3</sub> structure even during CH<sub>4</sub> reduction. In actuality, Mn doping reduced the release of lattice oxygen, whereas Ni doping led to pronounced CH<sub>4</sub> pyrolysis. It is noteworthy that BaFe<sub>2</sub>-CoAl<sub>9</sub>O<sub>19</sub> exhibited excellent reactivity and stability in CH<sub>4</sub>/CO<sub>2</sub> redox cycles, with high CH<sub>4</sub> conversion and syngas yield as well as a desirable H<sub>2</sub>/CO ratio around 2, which can be attributed to their enhanced oxygen-donation ability and the retention of the

hexaaluminate phase across the DRM-CL redox cycles. Another case is that in which Zhu *et al.* investigated the feasibility of Fe-substituted La-hexaaluminate (LF3A) as an OC for the DRM-CL process.<sup>71</sup> Findings indicate that LF3A exhibited superior reactivity and stability over 50 cycles compared with conventional Fe-Al oxide (F3A, without La). The introduction of La led to the formation of the MP La-hexaaluminate structure, maintaining stability during deeper reduction for producing syngas. This introduction of La also enhanced the CH<sub>4</sub> reactivity toward syngas and the subsequent CO<sub>2</sub> usage. Within the MP La-hexaaluminate structure of LF3A, the distinct oxygen sites of O<sub>6</sub>-Fe<sup>3+</sup> (Oh) functioned mainly for total oxidation of methane (TOM), whereas O<sub>5</sub>-Fe<sup>3+</sup> (Tr) and O<sub>4</sub>-Fe<sup>3+</sup> (Th) played important roles in POM reaction. Moreover, the selective recovery of O<sub>5</sub>-Fe<sup>3+</sup> (Tr) and O<sub>4</sub>-Fe<sup>3+</sup> (Th) during CO<sub>2</sub> oxidation, as opposed to the regeneration of O<sub>2</sub> for O<sub>6</sub>-Fe<sup>3+</sup> (Oh), made CO<sub>2</sub> the preferred oxidant for improving synthesis gas selectivity. Because hexaaluminates have their own excellent stability, Cheng *et al.* used them as a support and loaded CeO<sub>2</sub> on BaFe<sub>3</sub>Al<sub>9</sub>O<sub>19</sub> (BF-3) hexaaluminate at different calcination temperatures (973–1273 K) to investigate the effects of CeO<sub>2</sub>-hexaaluminate interaction on the DRM-CL redox performance.<sup>72</sup> Fresh CeO<sub>2</sub>/BF-3 comprised CeO<sub>2</sub>, β-Al<sub>2</sub>O<sub>3</sub>, and MP hexaaluminate. Elevating the calcination temperature from 973 K to 1173 K strengthened the interaction between CeO<sub>2</sub> and hexaaluminate, thereby facilitating the diffusion of lattice oxygen to the surface. However, 1273 K calcination induced sintering of the oxygen carrier, thereby impeding lattice oxygen migration. Among the various CeO<sub>2</sub>/BF-3-T (*T* = 973–1273 K) configurations, CeO<sub>2</sub>/BF3-1173 K emerged as a standout performer, exhibiting not only high CH<sub>4</sub> conversion (approx. 85%) and syngas yield (1.28–2.02 mmol g<sup>-1</sup>) with an ideal H<sub>2</sub>/CO ratio (approx. 2) but also exceptional CO<sub>2</sub> activation ability and stability during the redox cycles. The superior performance was attributed to the highest concentrations of Ce<sup>3+</sup> and Fe<sup>2+</sup>, abundant oxygen vacancies, and the formation of CeFe<sub>*x*</sub>Al<sub>1-*x*</sub>O<sub>3</sub>.

### 3.2 Metal-based OCs

As a prerequisite, proper thermodynamic properties of OCs can be well illustrated by a modified Ellingham diagram, which portrays the change of standard Gibbs free energies of reactions ( $\Delta G$ ) with temperature (*T*). Modified Ellingham diagrams for OCs such as Fe-, Ce-, W-, Ni-, Cu-, and Co-based materials are presented as Fig. 10(a) and (b) for chemical looping combustion (CLC) using air instead of CO<sub>2</sub> for the oxidation step compared to DRM-CL; the one of supplemented and modified V-based oxides for DRM-CL is presented in Fig. 10(c).<sup>73,74</sup> In Fig. 10(b) and (c), materials in the combustion zone possess strong oxidising properties, suitable for CLC. In Fig. 10(b), the OCs only proceeded by a partial oxidation reaction are shown in the syngas production zone, which is also included as part of the partial oxidation zone for DRM-CL in Fig. 10(c) because of the unique ability of DRM-CL to mitigate carbon deposition through oxidation steps. Materials in the inert zone are inert and unsuitable as OCs. Moreover, the Gibbs free energy lines lower than that of CO<sub>2</sub> can proceed in CO<sub>2</sub> oxidation. Therefore,



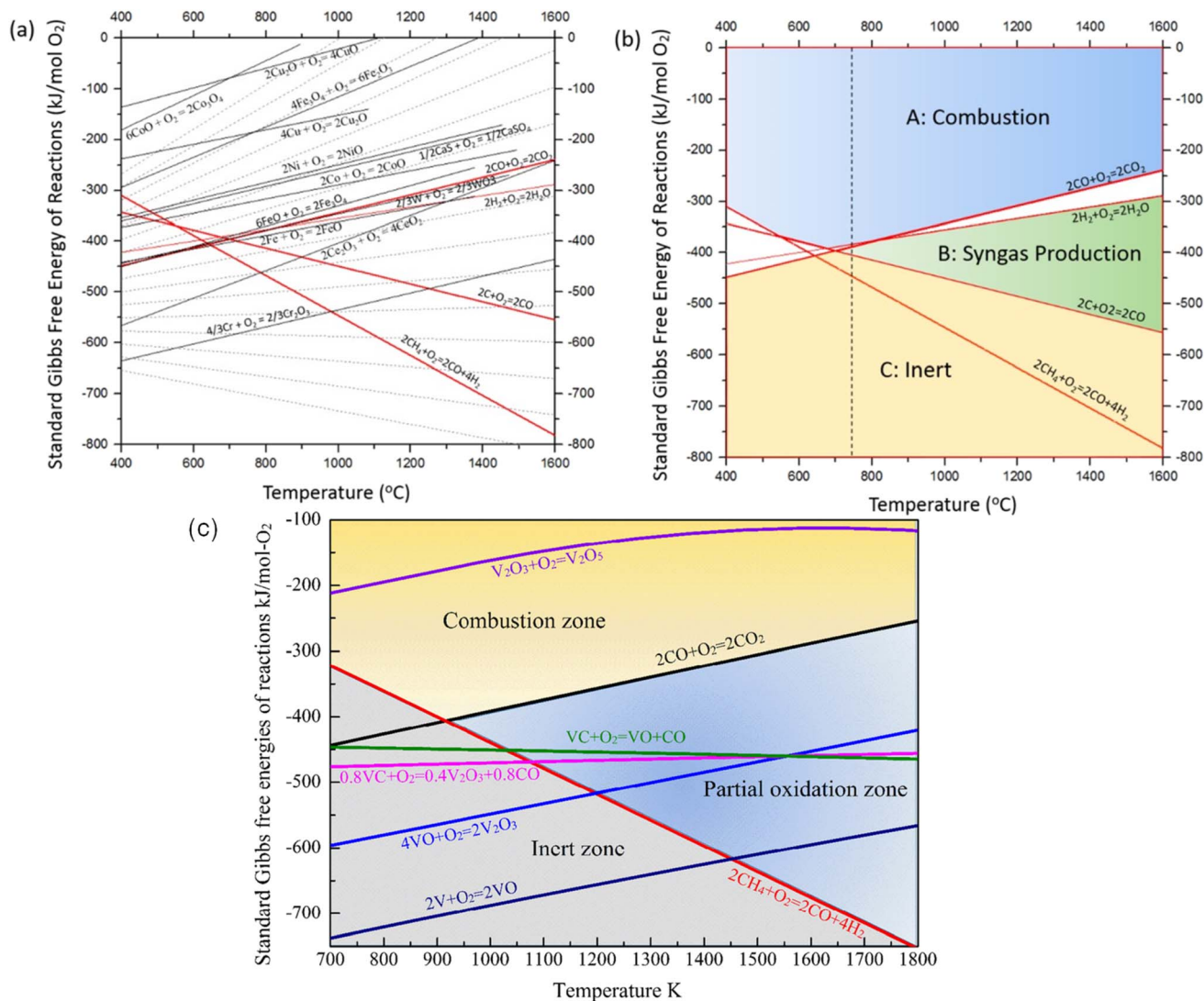


Fig. 10 Modified Ellingham diagrams for (a) standard Gibbs free energy changes of oxidation reactions of some OCs and (b) reaction zone division for CLC and syngas production applications. Reprinted with permission.<sup>73</sup> Copyright 2014 John Wiley and Sons. (c) V<sub>2</sub>O<sub>3</sub>-related species for DRM-CL. Reprinted with permission.<sup>74</sup> Copyright 2019 John Wiley and Sons.

according to Fig. 10(a), the lines of NiO, CoO, and CuO intersect within the combustion zone but are higher than the line of CO<sub>2</sub>, indicating thermodynamic infeasibility in the CO<sub>2</sub> reoxidation step. The WO<sub>3</sub> line, which lies on the boundary between the combustion and partial oxidation zone, is lower than the CO<sub>2</sub> line, representing the potential for both partial oxidation and CO<sub>2</sub> oxidation. The Fe<sub>2</sub>O<sub>3</sub> line lies close to the boundary between the combustion and partial oxidation zone, suggesting that the transformation from Fe<sub>2</sub>O<sub>3</sub> to Fe<sub>3</sub>O<sub>4</sub> is inclined toward combustion, whereas FeO to Fe is inclined toward partial oxidation of CH<sub>4</sub> (also thermodynamic favourability in CO<sub>2</sub> oxidation). In fact, CeO<sub>2</sub>, which is situated in the partial oxidation zone, stands out as a candidate for DRM-CL with high syngas selectivity. As shown in Fig. 10(c), the curve of the V<sub>2</sub>O<sub>3</sub>-VC pair crosses over the middle of the partial oxidation zone, illustrating its desirable thermodynamic potential for both partial oxidation reaction and CO<sub>2</sub> oxidation reaction. In

summary, Ce-, Fe-, W-, and V-based oxides are thermodynamically feasible and potential OCs for DRM-CL and these OCs. A handful of studies of metal-based OCs for DRM-CL have been conducted using this as a prerequisite assumption. Table 4 presents a summary of the DRM-CL performances of metal-based OCs described in recent reports.

**3.2.1 Fe-based OCs.** Because of their natural abundance, good environmental compatibility, and high CO<sub>2</sub> reoxidation activity, Fe-based OCs have received particular attention. Unfortunately, pure iron oxides are adversely affected by particle agglomeration, carbon deposition, and low CH<sub>4</sub> reactivity towards syngas. To overcome the limitations imposed upon pure iron oxide OCs, research efforts have assigned particular emphasis to the introduction of additional components of metal dopants, matrices or supports and have highlighted the design of the particle structure. A study by Zhang *et al.* examined iron-containing mixed metal oxides as highly





Table 4 Summary of redox performance of metal-based OCs for DRM-CL

OCs	Reduction step					Oxidation step					Reference		
	Temperature/ K	CH <sub>4</sub> concentration/ %	Space velocity/ L min <sup>-1</sup> g <sup>-1</sup>	t/min	CH <sub>4</sub> conversion/ %	Syngas or CO selectivity/ %	Syngas yield/ mmol g <sup>-1</sup>	CO <sub>2</sub> concentration/ %	Space velocity/ L min <sup>-1</sup> g <sup>-1</sup>	t/min		CO <sub>2</sub> conversion/ %	CO yield/ mmol g <sup>-1</sup>
Sr <sub>3</sub> Fe <sub>2</sub> O <sub>7</sub> -Ca <sub>0.5</sub> Mn <sub>0.5</sub> O (for 30 cycles)	1173	10	0.21	14.5	N/A	>95	1.53-4.42	10	0.21	6	N/A	1.56-1.8	Zhang <i>et al.</i> <sup>75</sup>
SrFeO <sub>3</sub> -CaO (for 30 cycles)	1253	10		15	59	90.0	4.63	10		10	98	2.17	
Fe <sub>2</sub> O <sub>3</sub> /Al <sub>2</sub> O <sub>3</sub> (for 10 cycles)	1073	100	0.22	60	73-93	10-18	N/A	100	0.22	60	68-85	N/A	Tang <i>et al.</i> <sup>76</sup>
Ce-Fe <sub>2</sub> O <sub>3</sub> /Al <sub>2</sub> O <sub>3</sub> (for 10 cycles)					77-86	10-13	N/A				73-76	N/A	
La <sub>0.33</sub> Ce <sub>0.67</sub> -Fe <sub>2</sub> O <sub>3</sub> /Al <sub>2</sub> O <sub>3</sub> (for 10 cycles)					77-83	9-10	N/A				65-76	N/A	
La <sub>0.67</sub> Ce <sub>0.33</sub> -Fe <sub>2</sub> O <sub>3</sub> /Al <sub>2</sub> O <sub>3</sub> (for 10 cycles)					81-90	8-9	N/A				75-80	N/A	
La-Fe <sub>2</sub> O <sub>3</sub> /Al <sub>2</sub> O <sub>3</sub> (for 10 cycles)					82-92	9-10	N/A				76-81	N/A	
0.5 wt% Rh/LaCeO <sub>3.5-x</sub>	923	10	0.05	2	90	90.0	0.50	2	0.05	N/A	100	N/A	Haribal <i>et al.</i> <sup>82</sup>
8.8 wt% Ni/CeO <sub>2</sub>	973	5	0.50	1	80	29.0	N/A	5	0.50	1	80	N/A	Löfberg <i>et al.</i> <sup>83</sup>
0.1 wt% Ni/CeO <sub>2</sub>	1173	5	0.08, 0.50 (kinetic regime)	8	100	100	3.41	5	0.08, 0.50 (kinetic regime)	8	100	N/A	Han <i>et al.</i> <sup>84</sup>
Co/CeO <sub>2</sub>	873	5	0.50	1	11	N/A	N/A	5	0.50	1	14	N/A	Guerrero- Caballero <i>et al.</i> <sup>86</sup>
Ni-phylllosilicate@ Ce <sub>0.8</sub> Fe <sub>0.2</sub> O <sub>2-δ</sub> (for 30 cycles)	923				26	-100	N/A				28	N/A	
Fe <sub>0.88</sub> Ni <sub>0.12</sub> -CeO <sub>2</sub>	973				51	-100	N/A				53	N/A	
Physical mixture of 88%Fe + 12%Ni	1023				68	-100	N/A				71	N/A	
V <sub>2</sub> O <sub>3</sub>	1073				79	-100	N/A				84	N/A	
Ni/WO <sub>3</sub> (10)/ZrO <sub>2</sub> (for 180 cycles)	893	5	0.25	8	79	83.0	4.50	5	0.25	8	N/A	2.81	Wang <i>et al.</i> <sup>87</sup>
Fe <sub>0.88</sub> Ni <sub>0.12</sub> -CeO <sub>2</sub>	1273	16.7	0.06	10	99	≥90%	N/A	16.7	0.06	10	90	N/A	More <i>et al.</i> <sup>61</sup>
Physical mixture of 88%Fe + 12%Ni	1173	16.7	1.20	20	>95%	~70%	N/A	37.5	1.20	11	N/A	N/A	More <i>et al.</i> <sup>62</sup>
V <sub>2</sub> O <sub>3</sub>	1123	45	0.07	25-35	80-85	>99.5	N/A	40	0.06	25-35	N/A	N/A	Ge <i>et al.</i> <sup>74</sup>
Ni/WO <sub>3</sub> (10)/ZrO <sub>2</sub> (for 180 cycles)	1023	30	2.50	2	70	>97%	N/A	30	2.50	3	45	N/A	Miyazaki <i>et al.</i> <sup>88</sup>

effective agents for a hybrid solar–redox scheme with DRM-CL.<sup>75</sup> Unsupported  $\text{Sr}_3\text{Fe}_2\text{O}_{7-\delta}$  exhibited exceptional DRM-CL activity at 1173 K, but it was hindered by deactivation over redox cycles. However, dispersing  $\text{Sr}_3\text{Fe}_2\text{O}_{7-\delta}$  in a  $\text{Ca}_{0.5}\text{Mn}_{0.5}\text{O}$  matrix not only improved the redox stability considerably; it also achieved 96% syngas selectivity in the reduction step and nearly 100%  $\text{CO}_2$  conversion in the oxidation step at 1173–1253 K. Furthermore, the hybrid solar–redox scheme with DRM-CL achieved remarkable CO production rates and productivity, surpassing state-of-the-art solar-thermal  $\text{CO}_2$ -splitting schemes at lower temperatures. Process simulation results show marked reductions in fossil energy consumption and in  $\text{CO}_2$  emissions along with higher acetic acid production than those achieved using the conventional coal-based scheme. Tang *et al.* found that co-doping of La–Ce in  $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$  oxygen carrier efficiently enhanced its resistance to aggregation and decreased the carbon deposition, increasing the stability over redox cycles and ensuring the  $\text{CO}_2$  activation for lattice oxygen replenishment.<sup>76</sup> These findings can be attributed to synergistic effects of La–Ce because of the abundant oxygen defects enhanced by intimate contact among active phases (LaFeO<sub>3</sub>, CeFeO<sub>3</sub>, CeO<sub>2</sub>, Fe oxides, and Fe<sub>3</sub>C) and surface dispersion of active phases and oxygen defects enhanced by CeO<sub>2</sub>. Furthermore, Sun *et al.* synthesised  $\text{Fe}_2\text{O}_3/\text{MgO}$  microspheres with a core–shell structure using a hydrothermal method tailored for direct use in fluidised beds for DRM-CL.<sup>77</sup> The superior stability for DRM-CL was attributed to the presence of magnesium in the surface layer, which hindered iron ion diffusion and thereby avoided iron enrichment on the particle surface.

**3.2.2 Ce-based OCs.** For DRM-CL, Ce-based materials are highly appealing because of their oxygen mobility and storage

capacity. From a thermodynamic perspective, the oxidation of reduced ceria by  $\text{CO}_2$  is favourable across a wide temperature range, from 298 K to temperatures higher than 1273 K.<sup>78</sup> Additionally, reduction from  $\text{CeO}_2$  to  $\text{Ce}_6\text{O}_{11}$  has been observed by Otsuka *et al.*, occurring as low as 923 K, which is consistent with thermodynamic calculations.<sup>79</sup> However, challenges arise because of the slow kinetics at lower temperatures. For conventional DRM, a consensus prevails that the kinetically relevant step is the activation of the C–H bond in  $\text{CH}_4$  in conventional DRM, which should also initiate the DRM-CL process.<sup>18,80</sup> Consequently, numerous studies have introduced active additives for promoting the C–H bond activation to overcome the shortcomings of single  $\text{CeO}_2$  related to the low kinetics of  $\text{CH}_4$  conversion. Noble metals possess high resistance to coke deposition, with notable stability and  $\text{CH}_4$  activation despite high cost and limited availability.<sup>81</sup> Also, Haribal *et al.* modified  $\text{CeO}_2$  by La with the Ce/La ratio of 1 and promoted by Rh (0.5 wt%) for DRM-CL involved in the hybrid redox process (Fig. 11(a)).<sup>82</sup> The resultant Rh/LaCeO<sub>3.5-x</sub> exhibited 90%  $\text{CH}_4$  conversion with a suitable  $\text{H}_2$ :CO ratio of 2:1 for methanol synthesis and 100%  $\text{CO}_2$  conversion to CO below 973 K. This high conversion can be attributed to the enhanced low-temperature bulk redox properties by La and improved surface properties for  $\text{CH}_4$  activation by Rh. Operation at lower temperatures enables the integration with industrial waste heat, allowing a considerable reduction in energy requirements and  $\text{CO}_2$  emissions for acetic acid production. Non-noble metals, especially Ni, were also used widely in  $\text{CeO}_2$ -based OCs because of their low cost, ready availability, and high  $\text{CH}_4$  activation ability despite their higher carbon deposition compared to the noble metals. Löfberg *et al.* investigated Ni/

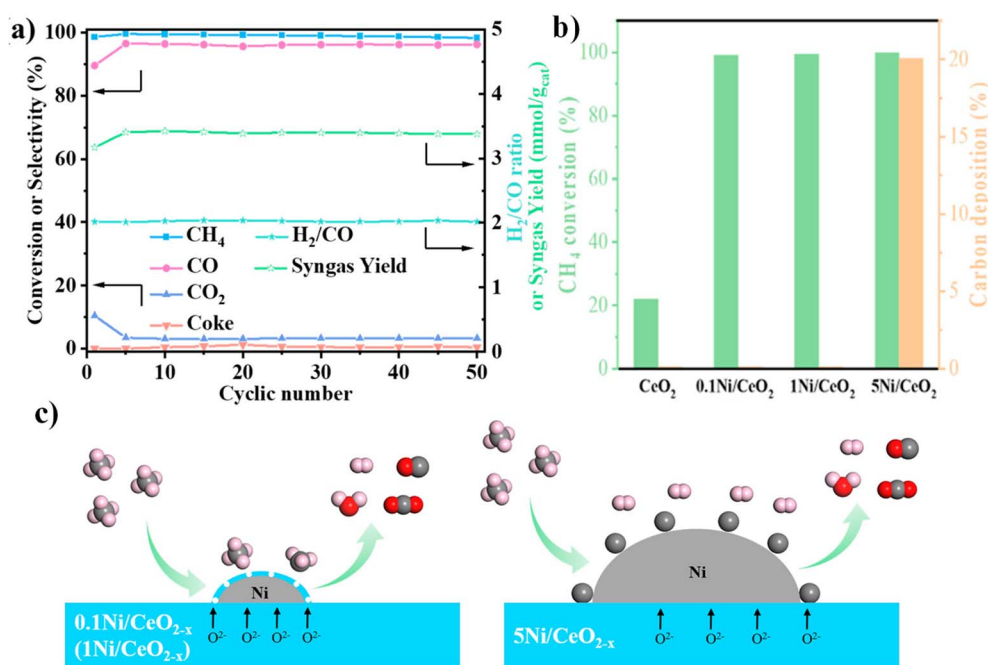


Fig. 11 (a) Performance over 0.1Ni/CeO<sub>2</sub> in the partial oxidation of methane step during 50 cycles. (b) Comparison of CH<sub>4</sub> conversion and carbon deposition between CeO<sub>2</sub>, 0.1Ni/CeO<sub>2</sub>, 1Ni/CeO<sub>2</sub> and 5Ni/CeO<sub>2</sub>. (c) Proposed reaction pathways for the reduction step by CH<sub>4</sub> over 0.1Ni/CeO<sub>2</sub> (1Ni/CeO<sub>2</sub>) and 5Ni/CeO<sub>2</sub>. Reprinted with permission.<sup>84</sup> Copyright 2021 American Chemical Society.



CeO<sub>2</sub> with intermediate loading (approx. 8.8%).<sup>83</sup> It exhibited high selectivity toward H<sub>2</sub>/CO without a high content of by-product H<sub>2</sub>O produced. The deposited carbon was fully removed during the reoxidation step using CO<sub>2</sub>. This removal was attributed to a synergistic effect at intermediate loadings of Ni, involving CH<sub>4</sub> activation facilitated by metallic Ni and enhanced oxygen mobility through the formation of a surface Ce–O–Ni solid solution. This effect is absent at low (2%) and high loadings (38%), for which insufficient active sites or surface solid solution species caused lower CH<sub>4</sub> conversion or coke formation. Moreover, Han *et al.* concentrated on the investigation of low loadings of Ni and found that loading of only 0.1 wt% or 1 wt% Ni on CeO<sub>2</sub> markedly enhanced the DRM-CL performance, with nearly 100% CH<sub>4</sub> conversion, CO selectivity, high syngas yields over 50 redox cycles, but without coke formation or reactivity degradation (Fig. 11(a)).<sup>84</sup> This superior performance is attributed to the encapsulation of Ni nanoparticles by CeO<sub>2</sub>, preventing a considerable degree of Ni sintering during redox cycles and providing more oxygen vacancies for CH<sub>4</sub> activation (Fig. 11(c)). In contrast, 5 wt% Ni/CeO<sub>2</sub> exhibited severe carbon deposition because of the absence of encapsulation, leading to Ni nanoparticle sintering and CH<sub>4</sub> decomposition (Fig. 11(b) and (c)). Furthermore, Miyazaki *et al.* studied the redox properties of Ni/CeO<sub>2</sub>, obtaining similar results showing low Ni loading reducing the coke deposition and effective enhancement of the DRM-CL performance.<sup>85</sup> However, immobilisation of other base metals (Fe, Co, Cu) did not enhance CO production. Apart from these efforts, they also investigated the redox properties of Ce species in 0.1 wt% Ni/CeO<sub>2</sub> using *operando* XANES and revealed that the DRM-CL process was accomplished by the reduction of Ce<sup>4+</sup> to Ce<sup>3+</sup> by CH<sub>4</sub> with syngas production followed by the subsequent reoxidation of Ce<sup>3+</sup> to Ce<sup>4+</sup> by CO<sub>2</sub>, thereby confirming the crucially important role of CeO<sub>2</sub>. Although a strong metal support interaction (SMSI) was observed in the previously described Ni/CeO<sub>2</sub> OCs, some potential exists for enhancing coking resistance because of Ni sintering and improving redox performance

at lower temperatures. Strategies such as doping basic metal oxides and structurally tailoring the ceria support to anchor Ni nanoparticles have proven effective at reinforcing the SMSI effect, leading to improved coking resistance and lower operation temperatures.<sup>86,87</sup> Guerrero-Caballero *et al.* conducted a study of various ceria-based oxygen carriers based on the Ni/CeO<sub>2</sub>, which is only active and selective at higher temperatures (>923 K).<sup>86</sup> Their findings indicate that Ni loading on homemade CeO<sub>2</sub> *via* impregnation and coprecipitation methods leads to similar redox performance, but that commercial CeO<sub>2</sub> is inactive. Actually, Zr doping enhanced the thermal stability of Ni/CeO<sub>2</sub> but adversely affected DRM-CL reactivity by enhancing the side reactions of methane total oxidation and carbon deposition. Notably, Co/CeO<sub>2</sub> exhibited promising performance, particularly at lower temperatures (873–923 K), providing a balance between surface activation and bulk oxygen species mobility. However, Fe/CeO<sub>2</sub> showed limited promise at 873–1073 K. Wang *et al.* combined the strategies of tailoring the structure and doping, and proposed sandwich and core-shell Ni-phyllsilicate@Ce<sub>0.8</sub>M<sub>0.2</sub>O<sub>2-δ</sub> (M = Fe, Co, Ni) composites at lower temperatures (873–923 K).<sup>87</sup> These composites featured Ni-phyllsilicate cores and transition metal-doped CeO<sub>2</sub> shells, preventing over-sintering *via* an SMSI effect. As presented in Fig. 12, Ni nanoparticles were immobilised on spherical nuclei. The outermost doped CeO<sub>2</sub> shell acts as an oxygen donor. In fact, Ni-phyllsilicate@Ce<sub>0.8</sub>Fe<sub>0.2</sub>O<sub>2-δ</sub> showed the best redox performance, with superior stability, oxygen storage capacity, and selectivity to syngas. *In situ* studies revealed that active intermediates (CH<sub>x</sub> and deposited carbon) were formed on the surface and were then oxidised selectively by lattice oxygen toward syngas, with the formation of oxygen vacancies and Fe<sup>0</sup>. These were subsequently re-oxidised to Ce<sup>4+</sup> and Fe<sup>3+</sup> during the CO<sub>2</sub> oxidation step.

**3.2.3 Other metal-based OCs (V-based, W-based and Mo-based).** For DRM-CL, OCs based on metals such as V, W, and Mo have also been explored, aside from the extensively investigated Ce-based and Fe-based OCs described earlier. Ge *et al.* found

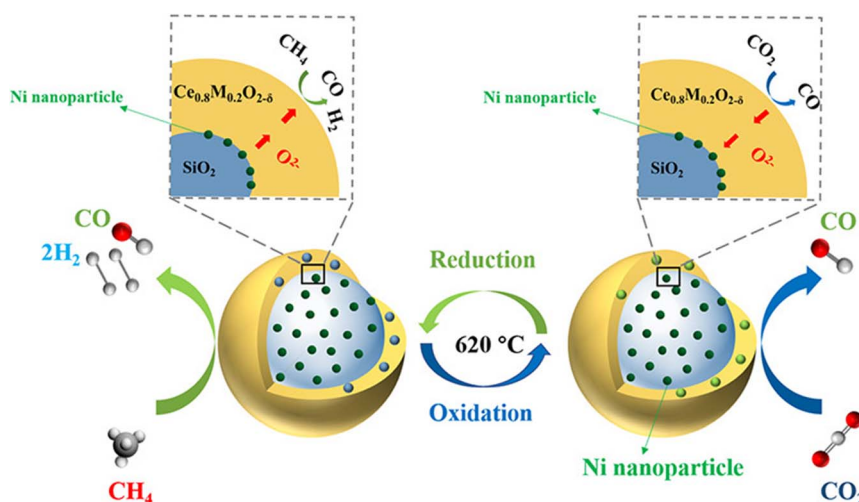
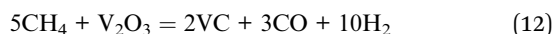


Fig. 12 Proposed reaction model for sandwich and core-shell Ni-phyllsilicate@Ce<sub>0.8</sub>M<sub>0.2</sub>O<sub>2-δ</sub> (M = Fe, Co, Ni) composites. Reprinted with permission.<sup>87</sup> Copyright 2022 Elsevier.



that novel  $V_2O_3$ -based OC exhibited high syngas selectivity (>99.5%),  $CO_2$  regeneration ability, and oxygen storage capacity because of the redox transformation between  $V_2O_3$  and VC. Incorporating Pt-SiO<sub>2</sub> into pure  $V_2O_3$  enhanced redox stability and kinetics.<sup>74</sup> The activation of C-H bonds, along with structural modification, was attributed to Pt-SiO<sub>2</sub>- $V_2O_3$  interfaces, featuring coordinatively unsaturated Pt atoms and an oxygen-rich surface. The  $CH_4$  reduction step (eqn (12)) involved a series of reactions, with VO serving as an intermediate connecting the reduction of  $V_2O_3$  to VO (eqn (13)) and the subsequent transformation from VO to VC (eqn (14)). The introduction of Pt-SiO<sub>2</sub> boosted the kinetics of eqn (13) considerably, thereby influencing the rate-controlling step. After Miyazaki *et al.* investigated various  $WO_3$ -loaded materials with different loadings (6.2, 10.0, 19.5, and 30.0 wt%) and supports ( $ZrO_2$  and  $Al_2O_3$ ), they found Ni/ $WO_3(10)/ZrO_2$  to be an ideal candidate OC for DRM-CL.<sup>88</sup> The results demonstrated that Ni-modified surface dispersed tungstate species on  $ZrO_2$  were uniquely active as oxygen storage sites, with  $ZrO_2$  and Ni contributing through reverse hydrogen spillover and hydrogen species recombination. The dispersed state in Ni/ $WO_3(10)/ZrO_2$  was maintained during cycles; the DRM-CL process was achieved by the redox between  $W^{6+}$  and  $W^{0-3+}$ . Furthermore, Maeno *et al.* reported an effective Ni-modified  $MoO_3/ZrO_2$  OC, which might work under isothermal conditions at 923 K.<sup>89</sup> They also showed an onset temperature of approximately 833 K in the  $CH_4$ -TPSR process. Optimal DRM-CL activity was achieved with 9.0 wt%  $MoO_3$  loading because of the formation of predominantly two-dimensional molybdate species. The DRM-CL process was accomplished using a redox between  $Mo^{6+}$  and  $Mo^{4+}$ .



**3.2.4 Mixed metal-based OCs.** Mixed metal-based OCs usually show enhanced performance by leveraging the advantages of the respective metal components. This smart combination of two metals gives broader potential for CL processes, allowing the reconciliation of contradictory demands in the coupled half-cycles. However, the stability of mixed metal-based OCs under the extreme conditions of high-temperature redox processes must be carefully considered because it might be a limiting factor in many cases, especially when compared with single-metal-based OCs. For instance, nickel oxides are often paired with iron oxides to harness the high reactivity of nickel for methane activation, complemented by the good selectivity of iron oxides for syngas formation. Additionally, the presence of iron contributes to the reduction of  $CO_2$  to CO. More *et al.* reported that  $Fe_{0.88}Ni_{0.12}$  alloy exhibited excellent performance for DRM-CL, achieving greater than 90% methane and  $CO_2$  conversions at 1273 K.<sup>64</sup> The synergistic effects of Fe and Ni in the alloy enhanced methane reactivity. The presence of Fe enabled Ni oxidation with  $CO_2$ , a thermodynamically restricted process for pure Ni. This oxidation indicated strong metal coupling through oxygen transport in the solid carrier. The  $Fe_xNi_y$  carriers demonstrated stable operation without permanent dealloying within 50 cycles. As presented in Fig. 13, the  $CO$  selectivity and yield in the reduction step depend on the oxidation states of Fe during the reoxidation step, thereby highlighting the benefits of using a weak oxidant such as  $CO_2$ , which limited overoxidation thermodynamically and which allowed controlled oxidation state modulation because of slow kinetics. Later, their group found that such synergistic effects of Fe and Ni can be achieved even by physically mixing  $Fe_2O_3$  and  $NiO$ .<sup>62</sup> In contrast to alloy carriers relying on the shared use of lattice oxygen, the DRM-CL process over the physical mixtures

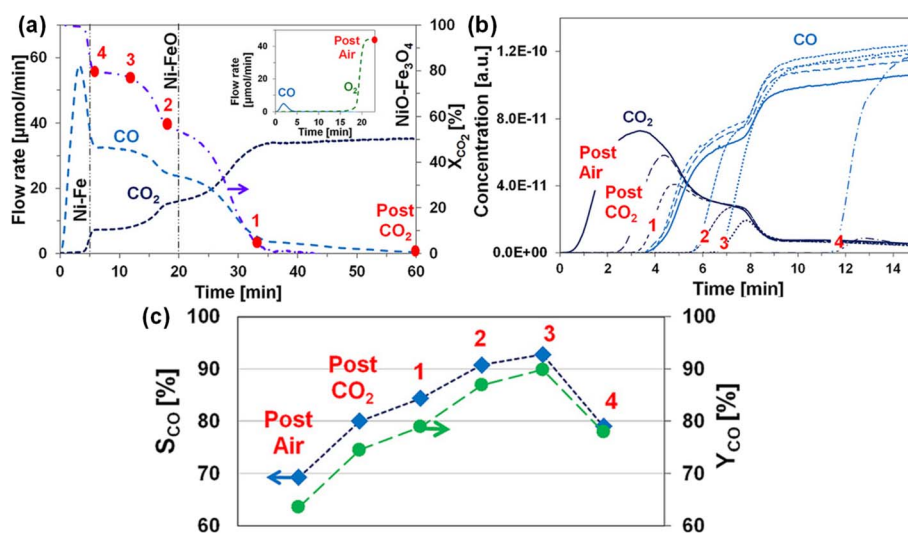


Fig. 13 (a) Reoxidation of  $Fe_{0.88}Ni_{0.12}-CeO_2$  by  $CO_2$  showing two regions of  $CO_2$  conversion (>60% and <40%). (b)  $CO_2$  and  $CO$  concentration profiles. (c)  $CO$  selectivity and yield. (All experiments were conducted after reduction by  $CH_4$  at 1273 K. Red dots denote the time when the reoxidation was stopped. The inset in Fig. 12(a) shows reoxidation by  $O_2$ . Reduction half-cycles with  $CH_4$  at 1273 K after different oxidation times, as indicated by the numbered spots.) Reprinted with permission.<sup>64</sup> Copyright 2019 John Wiley and Sons.



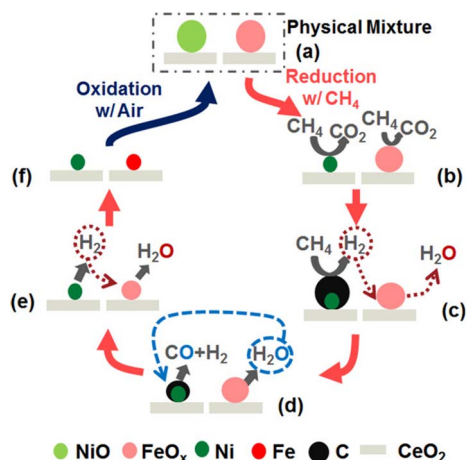


Fig. 14 Proposed reaction mechanism for Fe–Ni physical mixture. Reprinted with permission.<sup>62</sup> Copyright 2016 John Wiley and Sons.

of Ni and Fe was accomplished through the gas-phase mediated cooperative mechanism presented in Fig. 14.<sup>61</sup> Specifically, methane was cracked over Ni, forming carbon and H<sub>2</sub> (Fig. 14(c)). The intermediate H<sub>2</sub> was oxidised over Fe<sub>x</sub>O<sub>y</sub>, with the production of steam, which subsequently gasified carbon on Ni, yielding final products CO and H<sub>2</sub> (Fig. 14(d)). This intricate process combined high methane activation rates over Ni with good syngas selectivity over Fe oxides, achieving near-complete methane conversion with syngas yields of approximately 70%. Expressed on a conceptual basis, H<sub>2</sub> acts as a gas-phase catalyst, catalysing iron oxide reduction and reforming from H<sub>2</sub>O in carbon gasification. The process involved two nested catalytic cycles, constituting an intricate coupling for metal (oxide)-

catalysed dry reforming reactions. Moreover, cerium oxides are paired with iron oxides because of their high oxygen storage capacity and excellent redox properties of cerium. A report by García-García *et al.* confirmed the increased syngas yields observed when using mixed oxides of iron and cerium instead of single-metal oxides.<sup>90</sup> These higher yields can be attributed to the synergetic interaction between Fe<sub>2</sub>O<sub>3</sub> and CeO<sub>2</sub>, the well dispersed Fe<sub>2</sub>O<sub>3</sub> on CeO<sub>2</sub> support and the formation of perovskite structure (*i.e.* CeFeO<sub>3</sub>). As concluded from Fig. 15, through precise manipulation of the Fe<sub>2</sub>O<sub>3</sub>/CeO<sub>2</sub> mass ratio, the initial oxidation state and reaction duration, the performance of the mixed oxides can be finely tuned to promote the oxidation of methane towards syngas. Simultaneously, this approach helped discourage the side reactions of both the complete oxidation of methane and coke formation.

### 3.3 Summary and prospects for DR-CL

DRM-CL is an innovative process using CH<sub>4</sub> and CO<sub>2</sub> to co-produce syngas and CO, offering advantages over conventional DRM, including carbon removal and selective CH<sub>4</sub> conversion. Challenges remain in developing oxygen carriers (OCs) with high syngas selectivity, efficient CO<sub>2</sub> conversion, and stable redox properties as shown in Fig. 16.

Perovskites and hexaaluminates are promising OCs thanks to their redox properties and structural stability. Tailored doping, such as Sr or Ce in perovskites, improves oxygen mobility and syngas yields. Hexaaluminates, particularly metal-doped variants, exhibit superior CH<sub>4</sub> reactivity and stability. Mixed and modified metal oxides (*e.g.*, Fe, Ce, V-based) optimise syngas production, highlighting future potential.

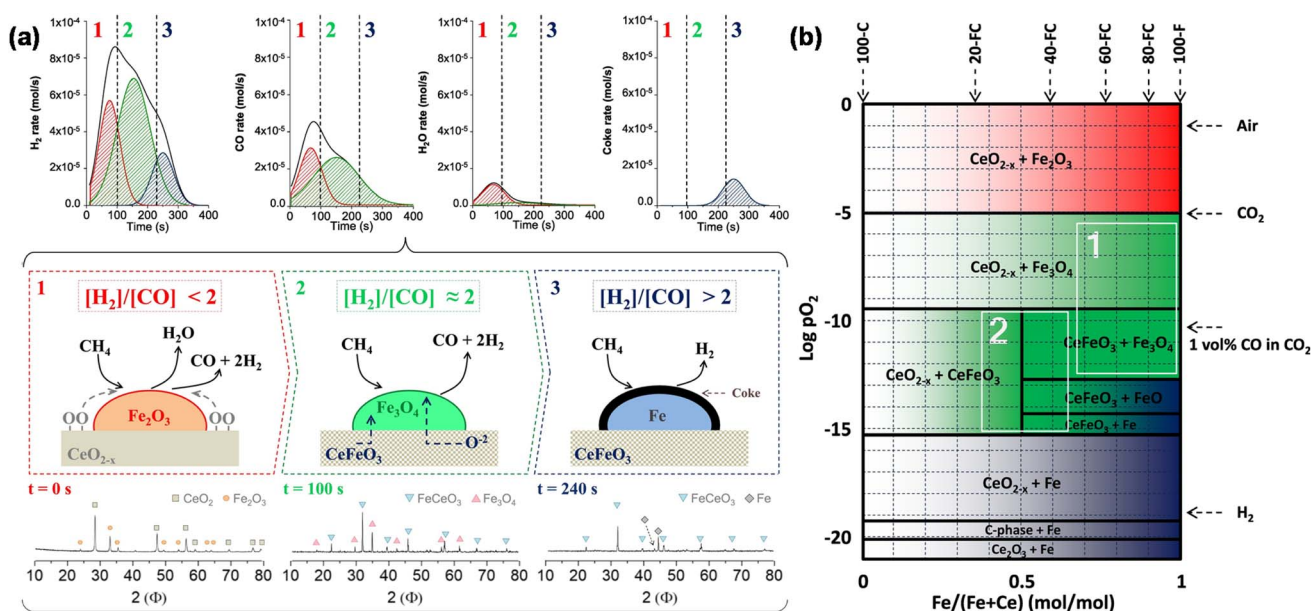


Fig. 15 (a) This schematic diagram portrays the evolution and correlation between the product selectivity of 40-FC with its oxidation state during the reduction step of the CLR process, following activation in carbon dioxide (*i.e.*, 90 min using 1.5 L min<sup>-1</sup> (STP)). (b) Iron-cerium phase diagram to outline the phases and product selectivity to be anticipated during the reduction step of the CRM process at equilibrium for various combinations of iron-cerium contents and oxygen chemical potential at  $T = 1173$  K and  $P = 1$  atm. Reprinted with permission.<sup>90</sup> Copyright 2021 Elsevier.



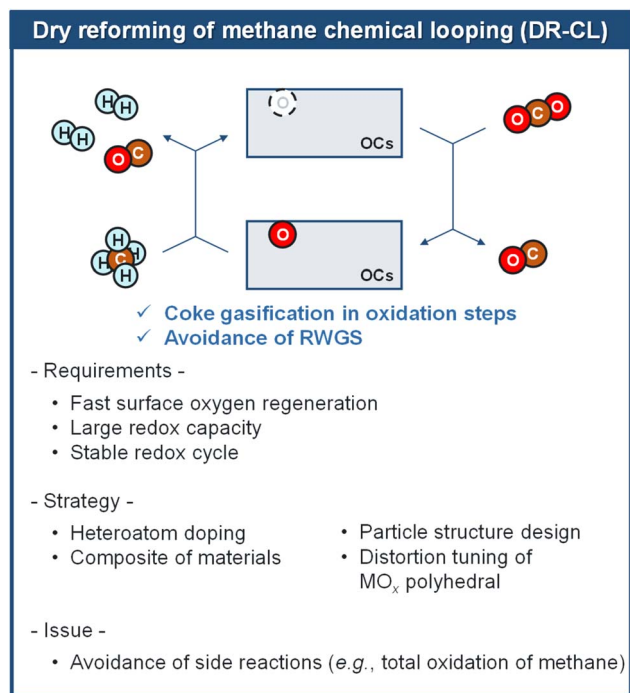


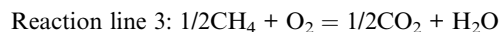
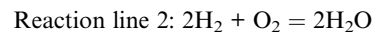
Fig. 16 Overview of material development for DR-CL.

## 4. Thermodynamic principles for screening oxygen carriers

The design of active OCs for CL processes necessitates the use of properties that ensure durability and sustained chemical reactivity through multiple redox cycles. To meet those cyclic behaviour requirements, specific characteristics must be incorporated into the OCs. Different chemical looping applications, such as DRM-CL and RWGS-CL, require distinct oxygen carrier properties to control product selectivity by addressing side reactions such as total oxidation of methane (TOM), carbon deposition for DRM-CL, and reduced conversion caused by reverse reactions in the oxidation step for RWGS-CL. Thermodynamic properties are regarded as prerequisites because they indicate the suitability of oxygen carriers for specific reactions and product selectivity. The following section presents an examination of the thermodynamic principles guiding the selection of active metal oxides for RWGS-CL and DRM-CL. The Ellingham diagram, a widely adopted tool in metallurgical studies, is useful for assessing the relative reduction potential of metal oxides at different temperatures.<sup>91,92</sup> It can be adapted further to evaluate the thermodynamic performance of metal oxides as OCs in various CL processes.<sup>93</sup>

In Fig. 18–22, we present modified Ellingham diagrams tailored for the effective classification and screening of oxygen carriers in the context of DRM-CL and RWGS-CL. Calculation details have been added to ESI† (text and Tables in Appendix). Here, 1 mol of  $\text{O}_2$  was used as a virtual consumed oxygen species and a reaction intermediate. The overall Gibbs energy change ( $\Delta G$ ) of gas–solid reactions is calculable by subtracting  $\Delta G$  of solid reactions with  $\text{O}_2$  from those of reactant gas reactions with

$\text{O}_2$ , which engenders cancellation of  $\text{O}_2$  in the reaction equations. This approach eases the assessment of the thermodynamic properties of metal oxides as OCs for CL, enabling selection based on specific process requirements. For instance,  $\Delta G$  for the overall reaction  $2\text{CH}_4 + \text{MO}_x = \text{MO}_{x-\delta} + 2\text{CO} + 4\text{H}_2$  ( $\Delta G_0$ ) can be ascertained from  $\Delta G$  of the reactions of  $2\text{CH}_4 + \text{O}_2 = 2\text{CO} + 4\text{H}_2$  ( $\Delta G_1$ ) and  $\text{MO}_{x-\delta} + \text{O}_2 = \text{MO}_x$  ( $\Delta G_2$ ), through the calculation equation of  $\Delta G_0 = \Delta G_1 - \Delta G_2$ . Therefore, the feasibility of the corresponding overall gas–solid reactions for CL processes can be assessed easily according to the relative positions of the reactant gas reaction line and the solid reaction line on the modified Ellingham diagrams. When the solid material reaction line is above the gas reactant reaction line, the corresponding gas–solid reaction can occur. It is notable that the region below the line representing  $2\text{CO} + \text{O}_2 = 2\text{CO}_2$  signifies the occurrence of  $\text{CO}_2$  splitting reactions, given that  $\text{CO}_2$  splitting is the reverse reaction of  $2\text{CO} + \text{O}_2 = 2\text{CO}_2$ . Based on these principles, in Fig. 17, oxide materials can be classified into five zones (No  $\text{CO}_2$  splitting, Isothermal RWGS-CL, Total oxidation of methane (TOM), Partial oxidation of methane (POM), and an Inert Zone) according to their redox capability outlined by the following four key reactions:



### 4.1. No $\text{CO}_2$ splitting zone

Metal oxides positioned above reaction line 1 exhibit reduction properties that are too weak to accomplish a  $\text{CO}_2$  splitting reaction in the common oxidation steps for both DRM-CL and RWGS-CL, rendering them unsuitable as materials for these two processes.

### 4.2. RWGS-CL zone

Metal oxides in this region are located between reaction lines 1 and 2; they exhibit thermodynamic conditions suitable for isothermal RWGS-CL reaction.

### 4.3. TOM zone

Metal oxides in this region, situated above reaction lines 2 and 3 but below line 1, are suitable OCs for the total oxidation of methane in DRM-CL, encompassing region B. However, because of their strong oxidizing properties, they are unsuitable for the partial oxidation of methane, rendering them unsuitable for DRM-CL.

### 4.4. POM (DRM-CL) zone

Metal oxides in this region are located between reaction lines 3 and 4. They are able to work as OCs for POM because of their



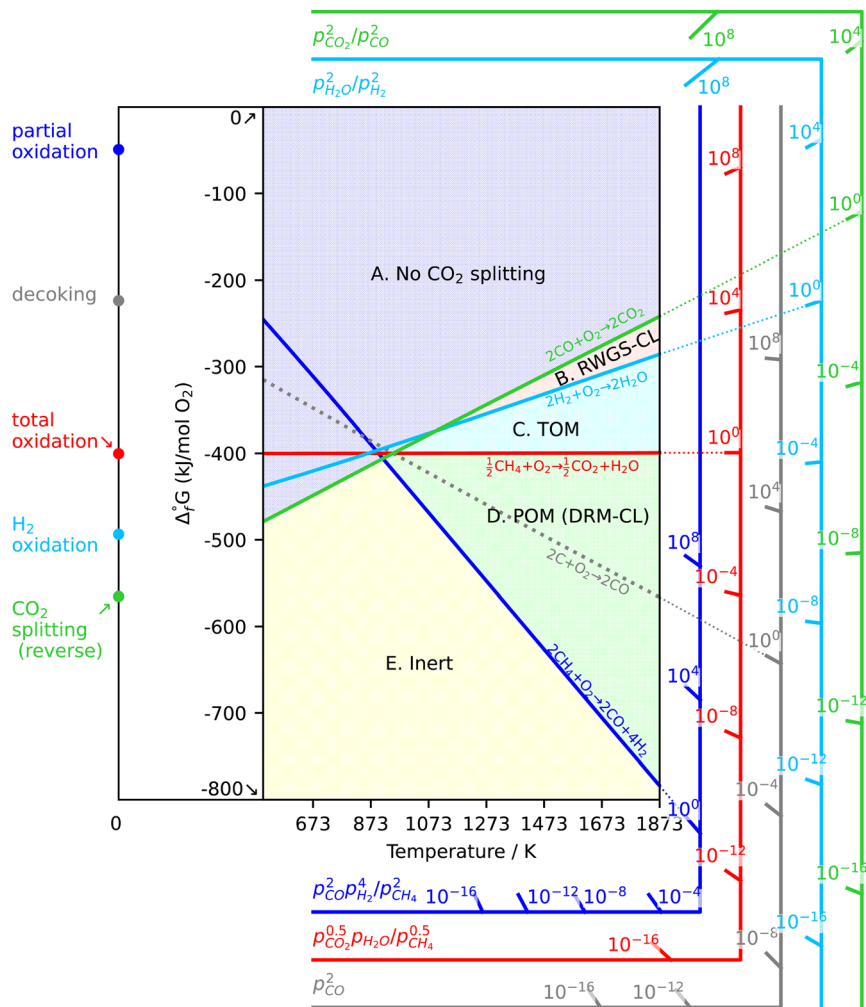


Fig. 17 Different zones for chemical looping processes. Reaction line 1:  $2\text{CO} + \text{O}_2 = 2\text{CO}_2$ . Reaction line 2:  $2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$ . Reaction line 3:  $\frac{1}{2}\text{CH}_4 + \text{O}_2 = \frac{1}{2}\text{CO}_2 + \text{H}_2\text{O}$ . Reaction line 4:  $2\text{CH}_4 + \text{O}_2 = 2\text{CO} + 4\text{H}_2$ .

moderate oxidising properties. These properties make them thermodynamically suitable for isothermal DRM-CL.

#### 4.5 Inert zone

Metal oxides in this zone below line 4 lack the requisite oxidising properties to function as oxygen carriers. They are classified as inert materials for both RWGS-CL and DRM-CL.

The classification of metal oxides into specific zones underpins valuable insights into their suitability as OCs, not only for RWGS-CL and DRM-CL but also for other distinct CL processes that involve the outlined gas reaction lines (presented in Table 5). It is noteworthy that the dashed line corresponding to the reaction of  $2\text{C} + \text{O}_2 = 2\text{CO}$  is indicative of the side reaction of carbon deposition in the reduction step of DRM-CL. Although it is not included in the classification zone because of the unique ability of DRM-CL to mitigate carbon deposition through oxidation steps, it plays an important role in guiding other relevant CL processes (e.g., POM-CL, SRM-CL; in Table 5). Moreover, the reaction lines in the diagrams correspond to  $\Delta G$  under atmospheric pressure conditions (partial pressure ratio of 1). The rationale behind the use of these classification zones

in the figures is to screen materials under isothermal conditions. If non-isothermal conditions are applied to the oxidation and reduction steps, then more eligible materials might be available, but that discussion is not presented here. The partial pressure axes of the involved gas are also included to elucidate the effects of partial pressure on the thermodynamic properties of different metal oxides, which can be achieved by connecting the point at 0 K to the line representing the specific partial pressure ratio on the axis of the target reaction.

As shown in Fig. 18, several transition metal oxides ( $\text{FeO}_x$ ,  $\text{MnO}_x$ ,  $\text{CeO}_x$ ,  $\text{VO}_x$ ,  $\text{PrO}_x$ ,  $\text{CuO}_x$ ,  $\text{CoO}_x$ ,  $\text{NiO}_x$ ) and some common noble metal oxides ( $\text{RhO}_x$ ,  $\text{RuO}_x$ ,  $\text{PdO}_x$ , and  $\text{PtO}_x$ ) with broad valence states and high oxygen capacity have been investigated as potential OCs. The comprehensive range of chemical redox reactions between different valence states for each metal oxide is considered. Some reaction lines of  $\text{FeO}_x$  and  $\text{MnO}_x$  are observed in the RWGS-CL region. Additionally, metal oxides such as  $\text{FeO}_x$ ,  $\text{MnO}_x$ ,  $\text{CeO}_x$ ,  $\text{VO}_x$ , and  $\text{PrO}_x$  are apparent within the DRM-CL region. It is important to highlight that metal oxides such as  $\text{FeO}_x$  and  $\text{MnO}_x$  with multiple valence states require precise valence control to achieve optimal activity and



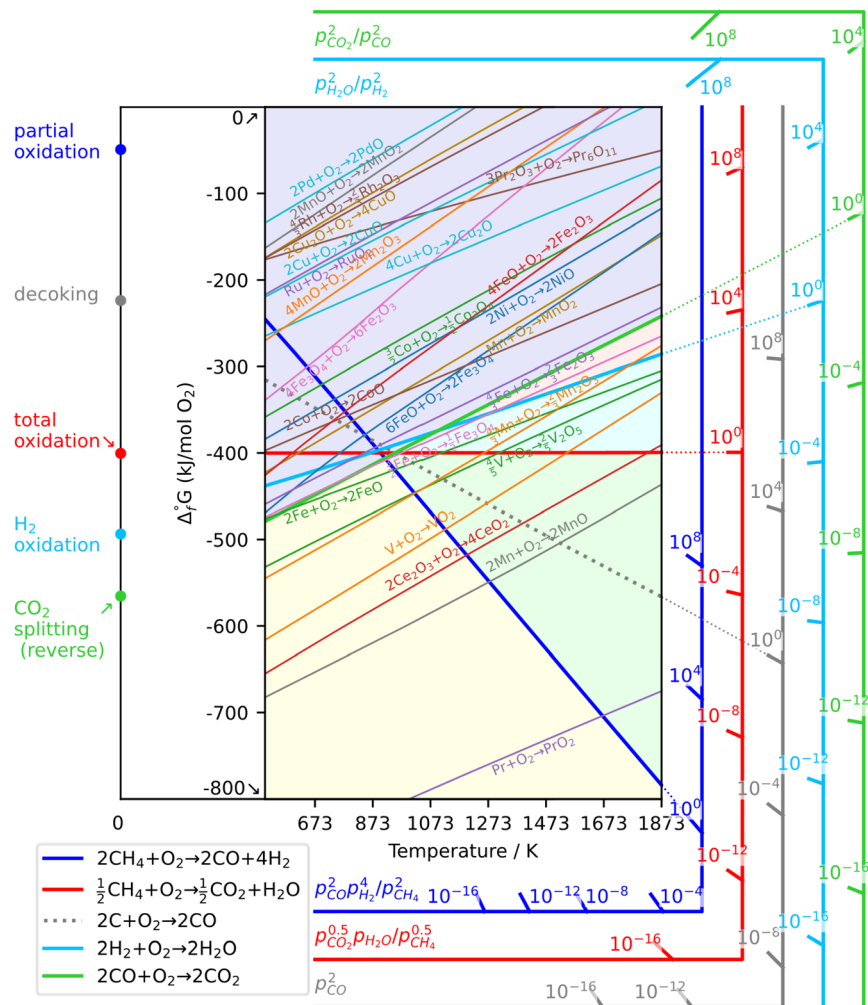


Fig. 18 Modified Ellingham diagram for single metal oxides as oxygen carriers for chemical looping.

selectivity from the thermodynamic results. Remarkably, the reaction lines of various valence states of  $\text{CuO}_x$ ,  $\text{CoO}_x$ ,  $\text{NiO}_x$ ,  $\text{RhO}_x$ ,  $\text{RuO}_x$ ,  $\text{PdO}_x$ , and  $\text{PtO}_x$  are all located in the no  $\text{CO}_2$  splitting zone, indicating them as unsuitable OCs for  $\text{CO}_2$ -splitting-related CL processes such as DRM-CL and RWGS-CL. The reaction line of  $\text{PtO}_x$  does not appear in the figure because  $\Delta G > 0$  is within the investigated temperature range.

Single-metal oxide OCs have limited selectivity and reactivity. Introducing additional components has proved to be effective in enhancing their selectivity and reactivity. Metal oxides located in the no  $\text{CO}_2$  splitting zone are regarded as promising additives for single-metal oxide OCs because of their distinctive thermodynamic properties preventing oxidation by  $\text{CO}_2$ , allowing them to remain as metal and form alloys with some OCs during the redox cycle. Alloys of these kinds involved in OCs have been widely reported for RWGS-CL and DRM-CL.<sup>54,61,62</sup> Herein, the thermodynamic results of potential alloys formed by the secondary metal oxides in no  $\text{CO}_2$  splitting zone in Fig. 16 and metal oxides with multiple valence states such as  $\text{FeO}_x$  and  $\text{MnO}_x$  are presented in Fig. 19, with the filtered results displayed in Fig. 20. Figures showing Fig. 19 divided by metal combination to avoid line densification is shown in Fig. S1–

S14.† Gibbs energies at representative temperatures in Fig. 19 are summarized in Tables S3 and S4.† It is readily apparent that most are distributed in the RWGS-CL and DRM-CL zone, underscoring the crucially important role of alloy formation for altering the thermodynamic properties of single metal OCs. Moreover, the application of some metal oxides such as  $\text{Ga}_2\text{O}_3$  and  $\text{In}_2\text{O}_3$  as OCs is restricted by the low melting point of their corresponding metals. According to findings from our earlier research,<sup>58–60</sup> forming alloys with a proper secondary metal from no  $\text{CO}_2$  splitting zone in Fig. 18 was proved to increase their melting points effectively, thereby allowing the application of low-melting-point metals in RWGS-CL and DRM-CL. Based on these findings, various Ga-related and In-related alloy reaction lines were calculated. They are presented in Fig. 21 with the filtered results displayed in Fig. 22. Figures showing Fig. 21 divided by metal combination to avoid line densification is shown in Fig. S15–S28.† Gibbs energies at representative temperatures in Fig. 21 are listed in Tables S5 and S6.† Many of these alloys are found in both the RWGS-CL and DRM-CL zones, illustrating the high potential of applying the Ga-based and In-based alloy OCs in CL.



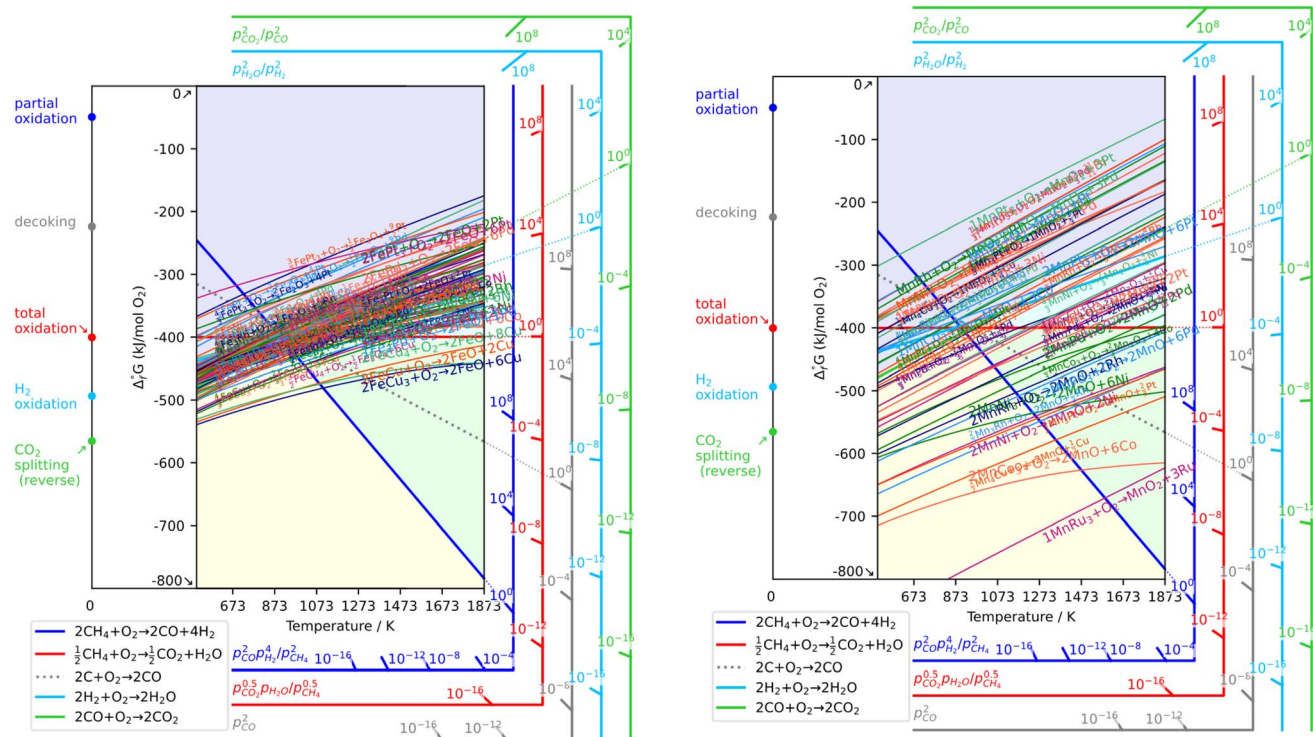


Fig. 19 Modified Ellingham diagram for all possible Fe-based or Mn-based alloy oxygen carriers during chemical looping.

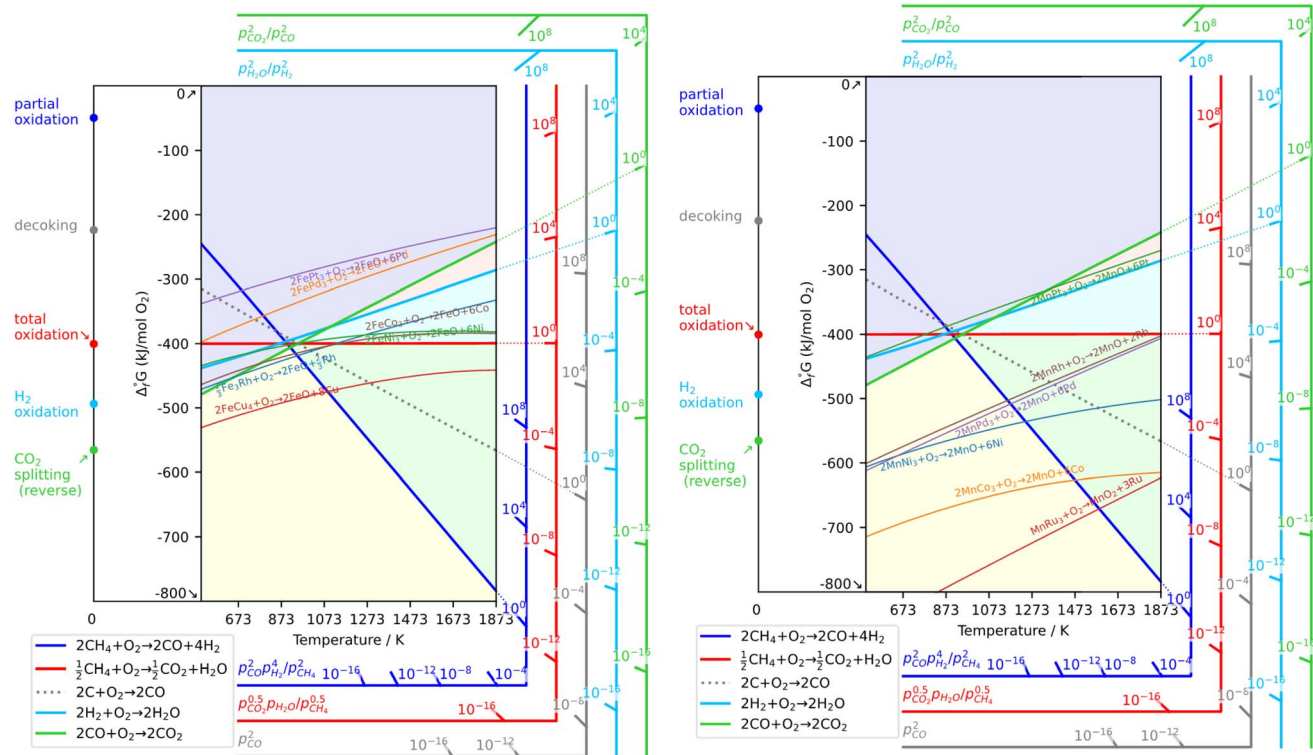


Fig. 20 Modified Ellingham diagram for oxygen carriers involving Fe- (left) or Mn- (right) based alloy formation during chemical looping.

Combining quantitative secondary components with single-metal oxides to form composites with specific structures and properties is another important strategy for improving the

performance of single-metal-based OCs in RWGS-CL and DRM-CL. Based on the performance summaries in Tables 2 and 3, the La-based and Sr-based components are regarded as promising



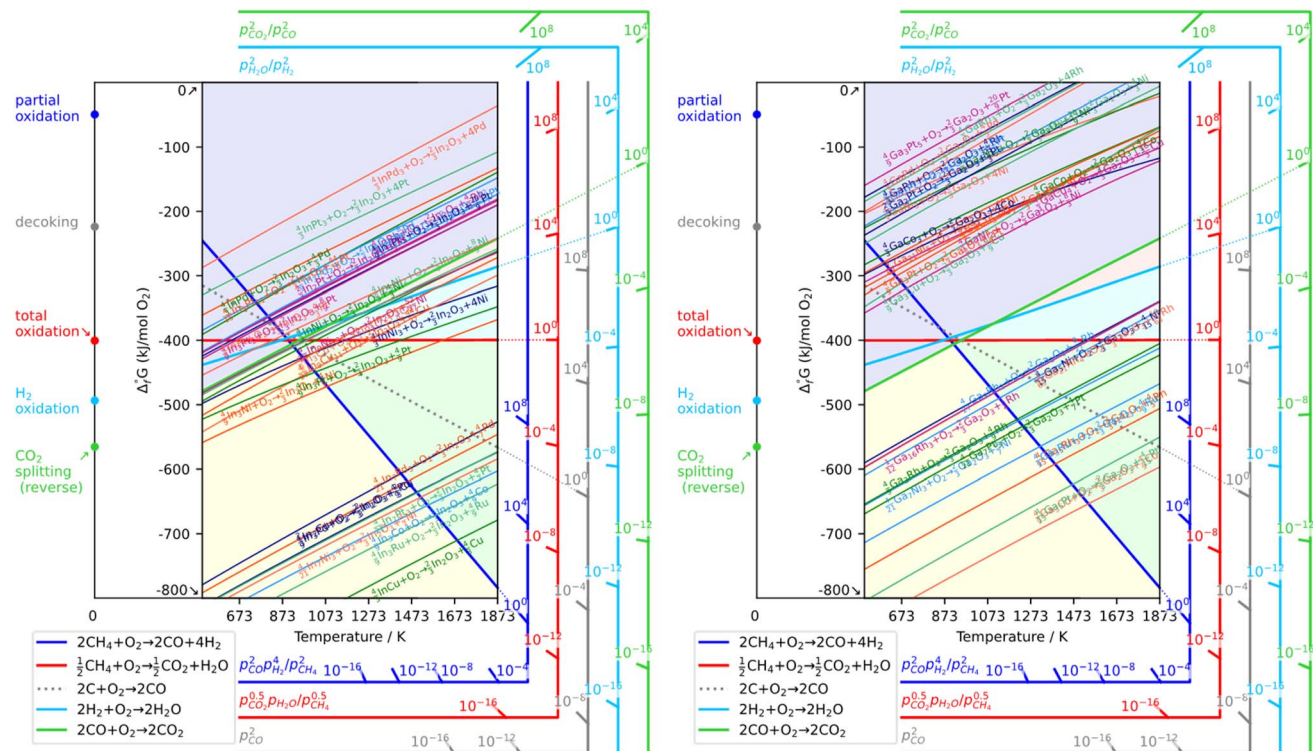


Fig. 21 Modified Ellingham diagram for all possible In-based or Ga-based alloy oxygen carriers during chemical looping.

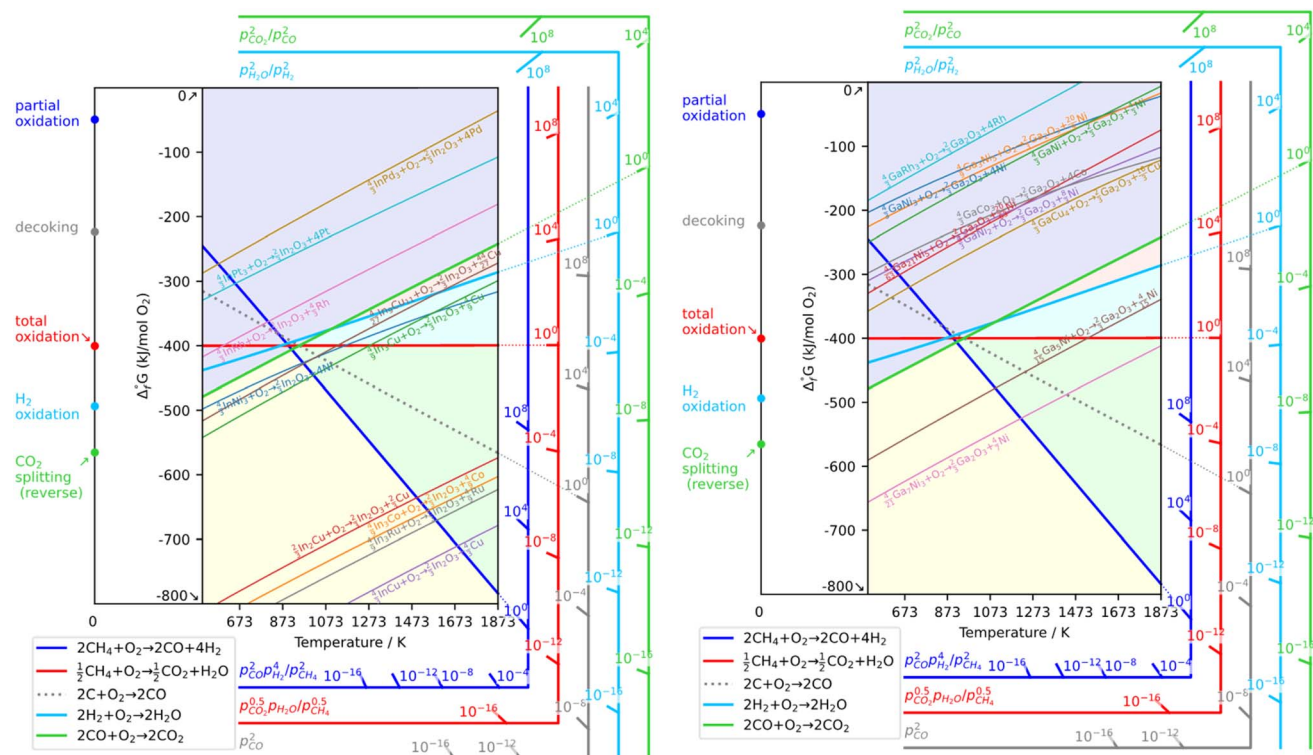


Fig. 22 Modified Ellingham diagram for oxygen carriers involving In- (left) or Ga- (right) based alloy formation during chemical looping.



Table 5 Chemical looping processes that involve the outlined gas reaction lines

Process name	Feedstock	Products	Product generation	Balance of the loop
RWGS-CL	CO <sub>2</sub>	CO	$\text{MO}_{x-1} + \text{CO}_2 \rightarrow \text{MO}_x + \text{CO}$	$\text{MO}_x + \text{H}_2 \rightarrow \text{MO}_{x-1} + \text{H}_2\text{O}$
Thermochemical splitting	H <sub>2</sub> O	H <sub>2</sub>	$\text{MO}_{x-1} + \text{H}_2\text{O} \rightarrow \text{MO}_x + \text{H}_2$	$\text{MO}_x \rightarrow \text{MO}_{x-1} + 1/2\text{O}_2$
WGS-CL				$\text{MO}_x + \text{CO} \rightarrow \text{MO}_{x-1} + \text{CO}_2$
POM-CL	CH <sub>4</sub>	Syngas	$\text{MO}_x + \text{CH}_4 \rightarrow \text{MO}_{x-1} + \text{CO} + 2\text{H}_2$	$\text{MO}_{x-1} + \text{O}_2 \leftrightarrow \text{MO}_x$
SRM-CL		Syngas, H <sub>2</sub>		$\text{MO}_{x-1} + \text{H}_2\text{O} \leftrightarrow \text{MO}_x + \text{H}_2$
DRM-CL		Syngas, CO		$\text{MO}_{x-1} + \text{CO}_2 \leftrightarrow \text{MO}_x + \text{CO}$
Epoxidation-CL	C <sub>2+</sub> hydrocarbon	Ethylene oxide	$\text{C}_2\text{H}_4 + \text{MO}_x \rightarrow \text{MO}_{x-1} + \text{C}_2\text{H}_4\text{O}$	$\text{MO}_{x-1} + \text{CO}_2 \leftrightarrow \text{MO}_x + \text{CO}$
ODH-CL		Ethylene	$\text{C}_2\text{H}_6 + \text{MO}_x \rightarrow \text{MO}_{x-1} + \text{C}_2\text{H}_4 + \text{H}_2\text{O}$	
ODH-CL		Propylene	$\text{C}_3\text{H}_8 + \text{MO}_x \rightarrow \text{MO}_{x-1} + \text{C}_3\text{H}_6 + \text{H}_2\text{O}$	
Selective oxidation-CL		Propionaldehyde	$1/2\text{C}_3\text{H}_8 + \text{MO}_x \rightarrow \text{MO}_{x-1} + 1/2\text{C}_3\text{H}_6\text{O} + 1/2\text{H}_2\text{O}$	
Selective oxidation-CL		Maleic anhydride	$1/7\text{C}_4\text{H}_{10} + \text{MO}_x \rightarrow \text{MO}_{x-1} + 1/7\text{C}_4\text{H}_2\text{O}_3 + 4\text{H}_2\text{O}$	
ODH-CL		Butadiene	$\text{C}_4\text{H}_8 + \text{MeO}_x \rightarrow \text{MeO}_{x-1} + \text{C}_4\text{H}_6 + \text{H}_2\text{O}$	
Oxidative cracking-CL		Ethylene	$\text{C}_6\text{H}_{14} + \text{MeO}_x \rightarrow \text{MeO}_{x-1} + 3\text{C}_2\text{H}_4 + \text{H}_2\text{O}$	

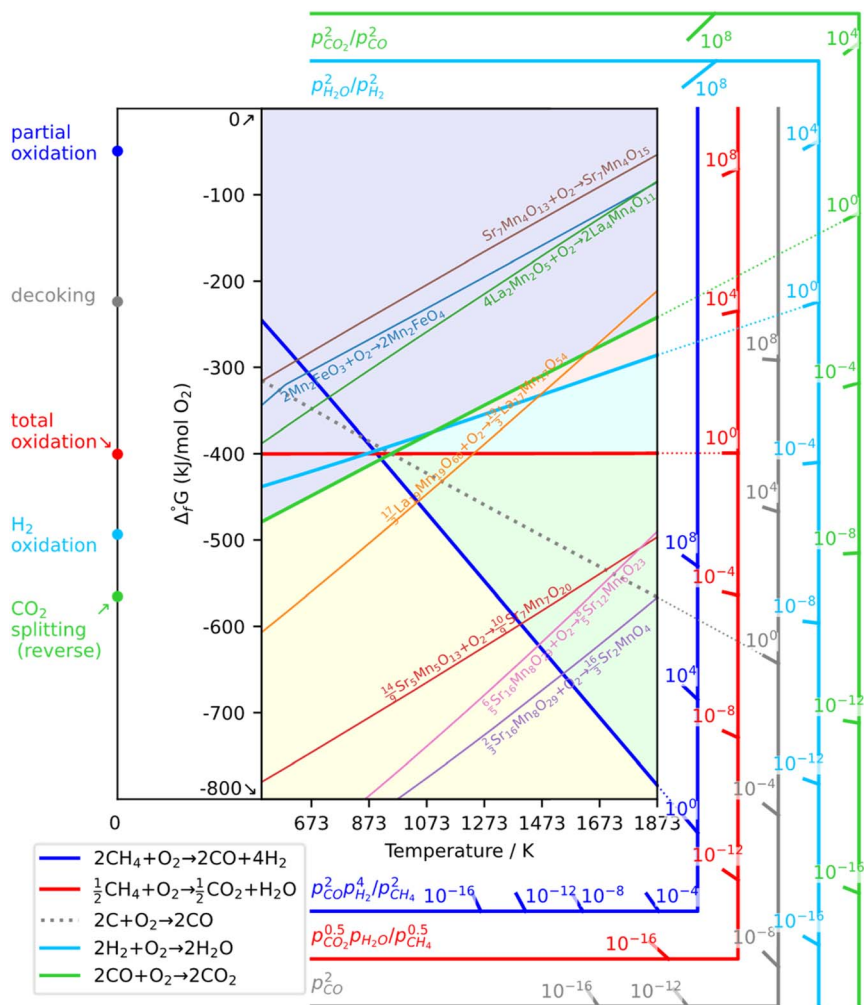


Fig. 23 Modified Ellingham diagram for composite oxides as oxygen carriers for chemical looping.

additives. Therefore, the thermodynamic results of some relevant example oxides are depicted in Fig. 23. The La<sub>x</sub>Mn<sub>y</sub>O<sub>z</sub> demonstrate thermodynamic feasibility for both RWGS-CL and DRM-CL, whereas the Sr<sub>x</sub>Mn<sub>y</sub>O<sub>z</sub> is thermodynamically feasible for DRM-CL.

## 5. Conclusion and future prospects

For CO<sub>2</sub> conversion, RWGS-CL and DRM-CL stand out as highly promising technologies, presenting versatile platforms for generating value-added chemicals efficiently with reduced



pollutant emissions and using simplified product separation processes. Therefore, we have presented summaries of recent research on various OC developments in RWGS-CL and DRM-CL. Moreover, we introduced the thermodynamic principles for screening active OCs by proposing the modified Ellingham diagrams.

In the RWGS-CL process,  $H_2$  facilitates the reduction of OCs, whereas  $CO_2$  enables their regeneration. Achieving a balance between the strong reducing agent ( $H_2$ ) and the weak oxidising agent ( $CO_2$ ) is crucially important when screening OCs, allowing for lower isothermal operation temperatures in RWGS-CL. In fact,  $La_{0.75}Sr_{0.25}FeO_{3-\delta}$  and  $La_{1-x}Ba_xFeO_{3-\delta}$  emerge as superior OC candidates for RWGS-CL, showcasing exceptional  $CO_2$  splitting performance even at temperatures as low as 823 K. To enhance their reactivity and stability, various approaches have been explored with specific examination of composition, particle size, porosity, structure, and specific surface area. Among metal-based OCs, Fe-based, In-based and Ga-based OCs all show promise because of their high oxygen capacity and outstanding  $CO_2$  splitting performance. Generally, metal-based OCs exhibit higher oxygen capacity but are adversely affected by phase instability, whereas composite OCs offer better stability but lower oxygen capacity. Therefore, the synergistic combination of metal-based and composite OCs holds important potential, providing a balanced solution between oxygen capacity and stability.

With regard to DRM-CL, it proceeds by replacing  $H_2$  with  $CH_4$  in the reduction step. The selectivity of OCs toward partial oxidation of  $CH_4$  for syngas generation is an important screening criterion for OCs. Moreover, although the replacement of commonly used air by  $CO_2$  to regenerate OCs in the oxidation step presents opportunities to produce extra CO, it requires OCs to possess higher reactivity because of the weak oxidation ability of  $CO_2$  compared to that of air. Composite OCs for DRM-CL demonstrate outstanding thermal stability and customisable redox properties through ion substitutional doping. To enhance the reactivity and redox stability of perovskites, manipulating the structural distortion of active sites by introducing different dopants or different contents of the same dopant can modify both bulk and surface properties. Additionally, incorporating supports and matrices can disperse segregated phases. Regarding hexaaluminates, choosing proper metal dopants and calcination temperatures can be attempted to retain the structure stability. Metal-based OCs, including Fe-, Ce-, V- and W-based OCs, have been examined extensively. Findings have revealed that Fe-based OCs are adversely affected by carbon deposition because the deeper reduction which facilitates the formation of CO engenders  $CH_4$  decomposition on FeO sites. Introducing a support or matrix to control the particle size and designing a structure to encapsulate FeO represent efficient strategies to prevent carbon deposition. It is known that Ce-based OCs are adversely affected by inferior  $CH_4$  conversion because of incomplete reduction of  $Ce^{4+}$  to  $Ce^{3+}$ . Introducing surface promoters such as Ni and doping  $CeO_2$  with additives can lower the  $CH_4$  activation energy and promote stoichiometric redox solid-phase reactions, respectively. Consequently, these materials can ensure the complete

reduction of  $Ce^{4+}$  to  $Ce^{3+}$ , increasing the syngas yield. The V-based and W-based OCs, which are recently developed OCs for DRM-CL, have also shown great potential superior redox properties. They represent another promising research direction for future investigation.

Beyond the properties and performances of OCs detailed earlier, modified Ellingham diagrams that exhibit the thermodynamic properties of potential metal oxides for the effective screening of active OCs of DRM-CL and RWGS-CL were first proposed, offering valuable insights not only for RWGS-CL and DRM-CL but also for other distinct CL processes involve similar reactions.

Enhancing the redox performance of OCs at lower temperatures is crucially important for both RWGS-CL and DRM-CL. This enhancement involves an emphasis on improving the dispersion of metal nanoparticles, ensuring optimal exposure of active sites for efficient methane and  $CO_2$  activation. Although the current understanding of “ $CO_2$  to CO” CL technologies remains limited, remarkable progress is necessary for elucidating redox mechanisms, refining structure design, optimising reactor and process operations, and scaling up processes. By integrating synthetic chemistry, computational chemistry, and various *in situ* characterisation techniques such as spectroscopy, diffraction and microscopy, CL for the production of CO or syngas from  $CO_2$  has emerged as a largely unexplored and exceptionally promising area of research with important potential applications.

The design of active oxygen carriers (OCs) for chemical looping (CL) processes requires durability and sustained reactivity across multiple redox cycles. Each CL process, such as reverse water gas shift (RWGS-CL) or dry reforming of methane (DRM-CL), necessitates specific OC properties to optimise product selectivity and mitigate side reactions, like carbon deposition or side reactions. Thermodynamic properties are essential for evaluating OCs, with tools like modified Ellingham diagrams aiding in classification and selection based on reaction feasibility. In these diagrams, the Gibbs energy change ( $\Delta G$ ) of gas–solid reactions is calculated by subtracting  $\Delta G$  values of solid and gas reactions involving oxygen. This approach enables easy assessment of whether a reaction can occur, depending on the relative positions of reaction lines. Materials are classified into several zones (*e.g.*, RWGS-CL, DRM-CL, no  $CO_2$  splitting) based on redox capability, guiding their suitability for specific CL processes.  $FeO_x$  and  $MnO_x$  show promise in RWGS-CL and DRM-CL, though their multiple valence states require precise control for optimal performance. Single-metal OCs often have limited selectivity and reactivity, but alloy formation with secondary metals enhances these properties. Metal oxides from the no  $CO_2$  splitting zone, when alloyed with others like  $FeO_x$  and  $MnO_x$ , can improve melting points and expand applicability. For example, Ga- and In-based alloys have been shown to increase melting points and demonstrate potential in RWGS-CL and DRM-CL. Further optimisation using various methods, including informatics or machine learning,<sup>94</sup> also helps us to obtain better materials. The integration of thermodynamic principles with alloy design has



advanced the development of versatile and efficient OCs for diverse CL processes.

## Data availability

The data supporting this article have been included as part of the ESI.†

## Conflicts of interest

There are no conflicts to declare.

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## References

- 1 S. J. Davis, K. Caldeira and H. D. Matthews, Future CO<sub>2</sub> Emissions and Climate Change from Existing Energy Infrastructure, *Science*, 2010, **329**, 1330–1333.
- 2 M. Aresta, A. Dibenedetto and A. Angelini, Catalysis for the Valorization of Exhaust Carbon: from CO<sub>2</sub> to Chemicals, Materials, and Fuels. Technological Use of CO<sub>2</sub>, *Chem. Rev.*, 2014, **114**, 1709–1742.
- 3 S. Perathoner and G. Centi, CO<sub>2</sub> Recycling: A Key Strategy to Introduce Green Energy in the Chemical Production Chain, *ChemSusChem*, 2014, **7**, 1274–1282.
- 4 D. S. Mallapragada, N. R. Singh, V. Curteanu and R. Agrawal, Sun-to-Fuel Assessment of Routes for Fixing CO<sub>2</sub> as Liquid Fuel, *Ind. Eng. Chem. Res.*, 2013, **52**, 5136–5144.
- 5 J. Artz, T. E. Müller, K. Thenert, J. Kleinekorte, R. Meys, A. Sternberg, A. Bardow and W. Leitner, Sustainable Conversion of Carbon Dioxide: An Integrated Review of Catalysis and Life Cycle Assessment, *Chem. Rev.*, 2018, **118**, 434–504.
- 6 F. V. Vázquez, J. Koponen, V. Ruuskanen, C. Bajamundi, A. Kosonen, P. Simell, J. Ahola, C. Frilund, J. Elfving, M. Reinikainen, N. Heikkinen, J. Kauppinen and P. Piermartini, Power-to-X technology using renewable electricity and carbon dioxide from ambient air: SOLETAIR proof-of-concept and improved process concept, *J. CO<sub>2</sub> Util.*, 2018, **28**, 235–246.
- 7 P. G. Loutzenhiser, M. E. Gálvez, I. Hischer, A. Stamatiou, A. Frei and A. Steinfeld, CO<sub>2</sub> Splitting via Two-Step Solar Thermochemical Cycles with Zn/ZnO and FeO/Fe<sub>3</sub>O<sub>4</sub> Redox Reactions II: Kinetic Analysis, *Energy Fuels*, 2009, **23**, 2832–2839.
- 8 S. Fujimori and S. Inoue, Carbon Monoxide in Main-Group Chemistry, *J. Am. Chem. Soc.*, 2022, **144**(5), 2034–2050.
- 9 R. M. B. Carrilho, M. J. F. Calvete, G. Mikle, L. Kollár and M. M. Pereira, Carbon Monoxide as C1 Building Block in Fine Chemical Synthesis, *Chin. J. Chem.*, 2024, **42**, 199–221.
- 10 K. T. Rommens and M. Saeys, Molecular Views on Fischer-Tropsch Synthesis, *Chem. Rev.*, 2023, **123**(9), 5798–5858.
- 11 J. E. A. -Hernández, S. L. Bertoli, H. G. Riella, C. Soares and N. Padoin, An Overview of Low-Temperature Fischer-Tropsch Synthesis: Market Conditions, Raw Materials, Reactors, Scale-Up, Process Intensification, Mechanisms, and Outlook, *Energy Fuels*, 2024, **38**(1), 1–28.
- 12 D. S. Mallapragada, N. R. Singh, V. Curteanu and R. Agrawal, Sun-to-Fuel Assessment of Routes for Fixing CO<sub>2</sub> as Liquid Fuel, *Ind. Eng. Chem. Res.*, 2013, **52**, 5136–5144.
- 13 J. Benoit, D. Perry and K. Mondal, Fischer-Tropsch Synthesis in supercritical CO<sub>2</sub> – Inhibition of CO<sub>2</sub> selectivity for enhanced hydrocarbon production, *Fuel*, 2017, **209**, 383–393.
- 14 P. Furler, J. R. Scheffe and A. Steinfeld, Syngas production by simultaneous splitting of H<sub>2</sub>O and CO<sub>2</sub> via ceria redox reactions in a high-temperature solar reactor, *Energy Environ. Sci.*, 2012, **5**, 6098–6103.
- 15 S. S. Ail and S. Dasappa, Biomass to liquid transportation fuel via Fischer-Tropsch synthesis – Technology review and current scenario, *Renew. Sustain. Energy Rev.*, 2016, **58**, 267–286.
- 16 X. Su, X. Yang, B. Zhao and Y. Huang, Designing of highly selective and high-temperature durable RWGS heterogeneous catalysts: recent advances and the future directions, *J. Energy Chem.*, 2017, **26**, 854–867.
- 17 X. Chen, Y. Chen, C. Song, P. Ji, N. Wang, W. Wang and L. Cui, Recent Advances in Supported Metal Catalysts and Oxide Catalysts for the Reverse Water-Gas Shift Reaction, *Front. Chem.*, 2020, **8**, 709.
- 18 N. A. K. Aramouni, J. G. Touma, B. A. Tarboush, J. Zeaiter and M. N. Ahmad, Catalyst design for dry reforming of methane: analysis review, *Renew. Sustain. Energy Rev.*, 2018, **82**, 2570–2585.
- 19 C. Palmer, D. C. Upham, S. Smart, M. J. Gordon, H. Metiu and E. W. McFarland, Dry reforming of methane catalysed by molten metal alloys, *Nat. Catal.*, 2020, **3**, 83–89.
- 20 K. Wittich, M. Krämer, N. Bottke and S. A. Schunk, Catalytic Dry Reforming of Methane: Insights from Model Systems, *ChemCatChem*, 2020, **12**, 2130–2147.
- 21 X. Zhu, Q. Imtiaz, F. Donat, C. R. Müller and F. Li, Chemical looping beyond combustion – a perspective, *Energy Environ. Sci.*, 2020, **13**, 772–804.
- 22 H. J. Richter and K. F. Knoche, *Efficiency and Costing*, ed. R. A. Gaggioli, ACS Publications, Washington DC, 1983, ch. 3, vol. 235, pp. 71–85.
- 23 M. Tang, L. Xu and M. Fan, Progress in oxygen carrier development of methane-based chemical-looping reforming: A review, *Appl. Energy*, 2015, **151**, 143–156.
- 24 M. Tian, C. Wang, Y. Han and X. Wang, Recent Advances of Oxygen Carriers for Chemical Looping Reforming of Methane, *ChemCatChem*, 2021, **13**, 1615–1637.
- 25 M. Najera, R. Solunke, T. Gardner and G. Vesper, Carbon capture and utilization via chemical looping dry reforming, *Chem. Eng. Res. Des.*, 2011, **89**, 1533–1543.



- 26 D. Li, R. Xu, Z. Gu, X. Zhu, S. Qing and K. Li, Chemical-Looping Conversion of Methane: A Review, *Energy Technol.*, 2019, **8**, 1900925.
- 27 L. Zeng, Z. Cheng, J. A. Fan, L. S. Fan and J. Gong, Metal oxide redox chemistry for chemical looping processes, *Nat. Rev. Chem.*, 2018, **2**, 349–364.
- 28 M. M. Hossain and H. I. de Lasa, Chemical-looping combustion (CLC, for inherent CO<sub>2</sub> separations – a review, *Chem. Eng. Sci.*, 2008, **63**, 4433–4451.
- 29 J. Hu, V. V. Galvita, H. Poelman and G. B. Marin, Advanced Chemical Looping Materials for CO<sub>2</sub> utilization: A Review, *Materials*, 2018, **11**, 1187.
- 30 D. Song, Y. Lin, C. Li, S. Fang, F. He, Z. Huang, Z. Zhao, Y. Xiong and H. Huang, Review on Migration and Transformation of Lattice Oxygen during Chemical Looping Conversion: Advances and Perspectives, *Energy Fuels*, 2023, **37**, 5743–5756.
- 31 A. Lyngfelt, Chemical Looping Combustion: Status and Development Challenges, *Energy Fuels*, 2020, **34**(8), 9077–9093.
- 32 L. C. Buelens, H. Poelman, G. B. Marin and V. V. Galvita, 110th Anniversary: Carbon Dioxide and Chemical Looping: Current Research Trends, *Ind. Eng. Chem. Res.*, 2019, **58**(36), 16235–16257.
- 33 B. J. Hare, D. Maiti, Y. A. Daza, V. R. Bhethanabotla and J. N. Kuhn, Enhanced CO<sub>2</sub> Conversion to CO by Silica-Supported Perovskite Oxides at Low Temperatures, *ACS Catal.*, 2018, **8**, 3021–3029.
- 34 V. V. Galvita, H. Poelman, V. Bliznuk, C. Detavernier and G. B. Marin, CeO<sub>2</sub>-Modified Fe<sub>2</sub>O<sub>3</sub> for CO<sub>2</sub> utilization via Chemical Looping, *Ind. Eng. Chem. Res.*, 2013, **52**, 8416–8426.
- 35 Y. A. Daza, R. A. Kent, M. M. Yung and J. N. Kuhn, Carbon dioxide conversion by reverse water–gas shift chemical looping on perovskite-type oxides, *Ind. Eng. Chem. Res.*, 2014, **53**, 5828–5837.
- 36 N. V. R. A. Dharanipragada, L. C. Buelens, H. Poelman, E. De Grave, V. V. Galvita and G. B. Marin, Mg-Fe-Al-O for advanced CO<sub>2</sub> to CO conversion: carbon monoxide yield v.s. oxygen storage capacity, *J. Mater. Chem. A*, 2015, **3**, 16251–16262.
- 37 A. E. Ramos, D. Maiti, Y. A. Daza, J. N. Kuhn and V. R. Bhethanabotla, Co, Fe, and Mn in La-perovskite oxides for low temperature thermochemical CO<sub>2</sub> conversion, *Catal. Today*, 2019, **338**, 52–59.
- 38 Y. A. Daza, D. Maiti, R. A. Kent, V. R. Bhethanabotla and J. N. Kuhn, Isothermal reverse water gas shift chemical looping on La<sub>0.75</sub>Sr<sub>0.25</sub>Co<sub>(1-y)</sub>FeYO<sub>3</sub> perovskite-type oxides, *Catal. Today*, 2015, **258**, 691–698.
- 39 J. E. ten Elshof, H. J. M. Bouwmeester and H. Verweij, Oxygen transport through La<sub>1-x</sub>Sr<sub>x</sub>FeO<sub>3-δ</sub> membranes II. Permeation in air/CO, CO<sub>2</sub> gradients, *Solid State Ionics*, 1996, **89**, 81–92.
- 40 V. C. Corberán, L. G. Tejuca and A. T. Bell, Surface reactivity of reduced LaFeO<sub>3</sub> as studied by TPD and IR spectroscopies of CO, CO<sub>2</sub> and H<sub>2</sub>, *J. Mater. Sci.*, 1989, **24**, 4437–4442.
- 41 H. Ullmann, N. Trofimenko, F. Tietz, D. Stöver and A. Ahmad-Khanlou, Correlation between thermal expansion and oxide ion transport in mixed conducting perovskite-type oxides for SOFC cathodes, *Solid State Ionics*, 2000, **138**, 79–90.
- 42 B. J. Hare, D. Maiti, S. Ramani, A. E. Ramos, V. R. Bhethanabotla and J. N. Kuhn, Thermochemical conversion of carbon dioxide by reverse water–gas shift chemical looping using supported perovskite oxides, *Catal. Today*, 2019, **323**, 225–232.
- 43 J. C. Brower, B. J. Hare, V. R. Bhethanabotla and J. N. Kuhn, Mesoporous Silica Supported Perovskite Oxides for Low Temperature Thermochemical CO<sub>2</sub> Conversion, *ChemCatChem*, 2020, **12**, 6317–6328.
- 44 A. Jo, Y. Kim, H. S. Lim, M. Lee, D. Kang and J. W. Lee, Controlled template removal from nanocast La<sub>0.8</sub>Sr<sub>0.2</sub>FeO<sub>3</sub> for enhanced CO<sub>2</sub> conversion by reverse water gas shift chemical looping, *J. CO<sub>2</sub> Util.*, 2022, **56**, 101845.
- 45 Y. A. Daza, D. Maiti, B. J. Hare, V. R. Bhethanabotla and J. N. Kuhn, More Cu, more problems: decreased CO<sub>2</sub> conversion ability by Cu-doped La<sub>0.75</sub>Sr<sub>0.25</sub>FeO<sub>3</sub> perovskite oxides, *Surf. Sci.*, 2016, **648**, 92–99.
- 46 M. Lee, Y. Kim, H. S. Lim, A. Jo, D. Kang and J. W. Lee, Reverse Water–Gas Shift Chemical Looping Using a Core–Shell Structured Perovskite Oxygen Carrier, *Energies*, 2020, **13**, 5324.
- 47 D. Maiti, B. J. Hare, Y. A. Daza, A. E. Ramos, J. N. Kuhn and V. R. Bhethanabotla, Earth abundant perovskite oxides for low temperature CO<sub>2</sub> conversion, *Energy Environ. Sci.*, 2018, **11**, 648–659.
- 48 C. J. Bartel, C. Sutton, B. R. Goldsmith, R. Ouyang, C. B. Musgrave, L. M. Ghiringhelli and M. Scheffler, New tolerance factor to predict the stability of perovskite oxides and halides, *Sci. Adv.*, 2019, **5**, eaav0693.
- 49 H. Z. Shi, V. R. Bhethanabotla and J. N. Kuhn, Role of Ba in low temperature thermochemical conversion of carbon dioxide with LaFeO<sub>3</sub> perovskite oxides, *J. CO<sub>2</sub> Util.*, 2021, **51**, 101638.
- 50 H. Shi, V. R. Bhethanabotla and J. N. Kuhn, Pelletized SiO<sub>2</sub>-supported La<sub>0.5</sub>Ba<sub>0.5</sub>FeO<sub>3</sub> for conversion of CO<sub>2</sub> to CO by a reverse water–gas shift chemical looping process, *J. Ind. Eng. Chem.*, 2023, **118**, 44–52.
- 51 H. S. Lim, Y. Kim, D. Kang, M. Lee, A. Jo and J. W. Lee, Fundamental Aspects of Enhancing Low-Temperature CO<sub>2</sub> Splitting to CO on a Double La<sub>2</sub>NiFeO<sub>6</sub> Perovskite, *ACS Catal.*, 2021, **11**, 12220–12231.
- 52 Y. Qiu, L. Ma, D. Zeng, M. Li, D. Cui, Y. Lv, S. Zhang and R. Xiao, Efficient CO<sub>2</sub> to CO conversion at moderate temperatures enabled by the cobalt and copper co-doped ferrite oxygen carrier, *J. Energy Chem.*, 2020, **46**, 123–132.
- 53 L. Ma, Y. Qiu, M. Li, D. Cui, S. Zhang, D. Zeng and R. Xiao, Spinel-Structured Ternary Ferrites as Effective Agents for Chemical Looping CO<sub>2</sub> Splitting, *Ind. Eng. Chem. Res.*, 2020, **59**, 6924–6930.
- 54 J. Rojas, E. Sun, G. Wan, J. Oh, R. Randall, V. Haribal, I.-h. Jung, R. Gupta and A. Majumdar, Iron-Poor Ferrites for Low-Temperature CO<sub>2</sub> Conversion via Reverse Water–Gas Shift Thermochemical Looping, *ACS Sustain. Chem. Eng.*, 2022, **10**, 12252–12261.



- 55 M. Wenzel, N. V. R. Aditya Dharanipragada, V. V. Galvita, H. Poelman, G. B. Marin, L. Rihko-Struckmann and K. Sundmacher, CO production from CO<sub>2</sub> via reverse water-gas shift reaction performed in a chemical looping mode: kinetics on modified iron oxide, *J. CO<sub>2</sub> Util.*, 2017, **17**, 60–68.
- 56 M. Lee, Y. Kim, H. S. Lim, A. Jo, D. Kang and J. W. Lee, Low temperature CO<sub>2</sub> conversion facilitated by the preserved morphology of metal oxide-perovskite composite, *Chem. Eng. J.*, 2022, **437**, 135151.
- 57 D. Zeng, Y. Qiu, L. Ma, M. Li, D. Cui, S. Zhang and R. Xiao, Tuning the Support Properties toward Higher CO<sub>2</sub> Conversion during a Chemical Looping Scheme, *Environ. Sci. Technol.*, 2020, **54**, 12467–12475.
- 58 J. I. Makiura, T. Higo, Y. Kurosawa, K. Murakami, S. Ogo, H. Tsuneki, Y. Hashimoto, Y. Sato and Y. Sekine, Fast oxygen ion migration in Cu-In-oxide bulk and its utilization for effective CO<sub>2</sub> conversion at lower temperature, *Chem. Sci.*, 2020, **12**, 2108–2113.
- 59 K. Kang, S. Kakihara, T. Higo, H. Sampei, K. Saegusa and Y. Sekine, Equilibrium unconstrained low-temperature CO<sub>2</sub> conversion on doped gallium oxides by chemical looping, *Chem. Commun.*, 2023, **59**, 11061–11064.
- 60 J. I. Makiura, S. Kakihara, T. Higo, N. Ito, Y. Hirano and Y. Sekine, Efficient CO<sub>2</sub> conversion to CO using chemical looping over Co-In oxide, *Chem. Commun.*, 2022, **58**, 4837–4840.
- 61 A. More, S. Bhavsar and G. Veser, Iron–Nickel Alloys for Carbon Dioxide Activation by Chemical Looping Dry Reforming of Methane, *Energy Technol.*, 2016, **4**, 1147–1157.
- 62 A. More and G. Veser, Physical mixtures as simple and efficient alternative to alloy carriers in chemical looping processes, *AIChE J.*, 2017, **63**, 51–59.
- 63 P. T. Krenzke, J. R. Fosheim and J. H. Davidson, Solar fuels via chemical-looping reforming, *Sol. Energy*, 2017, **156**, 48–72.
- 64 X. Zhang, C. Pei, X. Chang, S. Chen, R. Liu, Z. J. Zhao, R. Mu and J. Gong, FeO<sub>6</sub> Octahedral Distortion Activates Lattice Oxygen in Perovskite Ferrite for Methane Partial Oxidation Coupled with CO<sub>2</sub> Splitting, *J. Am. Chem. Soc.*, 2020, **142**, 11540–11549.
- 65 D. Sastre, D. P. Serrano, P. Pizarro and J. M. Coronado, Chemical insights on the activity of La<sub>1-x</sub>Sr<sub>x</sub>FeO<sub>3</sub> perovskites for chemical looping reforming of methane coupled with CO<sub>2</sub>-splitting, *J. CO<sub>2</sub> Util.*, 2019, **31**, 16–26.
- 66 A. Riaz, T. Tsuzuki, F. Kremer, S. Sattayaporn, M. U. Ali, W. Lipiński and A. Lowe, Structural Rearrangement in LSM Perovskites for Enhanced Syngas Production via Solar Thermochemical Redox Cycles, *ACS Catal.*, 2020, **10**, 8263–8276.
- 67 X. Xia, W. Chang, S. Cheng, C. Huang, Y. Hu, W. Xu, L. Zhang, B. Jiang, Z. Sun, Y. Zhu and X. Wang, Oxygen Activity Tuning via FeO<sub>6</sub> Octahedral Tilting in Perovskite Ferrites for Chemical Looping Dry Reforming of Methane, *ACS Catal.*, 2022, **12**, 7326–7335.
- 68 W. Yu, X. Wang, Y. Liu, J. Wei and J. Zhang, Effect of Composition on the Redox Performance of Strontium Ferrite Nanocomposite, *Energy Fuels*, 2020, **34**, 8644–8652.
- 69 D. Sastre, C. Á. Galván, P. Pizarro and J. M. Coronado, Enhanced performance of CH<sub>4</sub> dry reforming over La<sub>0.9</sub>Sr<sub>0.1</sub>FeO<sub>3</sub>/YSZ under chemical looping conditions, *Fuel*, 2022, **309**, 122122.
- 70 Y. Zhu, N. Jin, R. Liu, X. Sun, L. Bai, H. Tian, X. Ma and X. Wang, Bimetallic BaFe<sub>2</sub>MAL<sub>3</sub>O<sub>19</sub> (M = Mn, Ni, and Co) hexaaluminates as oxygen carriers for chemical looping dry reforming of methane, *Appl. Energy*, 2020, **258**, 114070.
- 71 Y. Zhu, W. Liu, X. Sun, X. Ma, Y. Kang, X. Wang and J. Wang, La-hexaaluminate for synthesis gas generation by Chemical Looping Partial Oxidation of Methane Using CO<sub>2</sub> as Sole Oxidant, *AIChE J.*, 2018, **64**, 550–563.
- 72 Z. Cheng, L. Zhang, N. Jin, Y. Zhu, L. Chen, Q. Yang, M. Yan, X. Ma and X. Wang, Effect of calcination temperature on the performance of hexaaluminate supported CeO<sub>2</sub> for chemical looping dry reforming, *Fuel Process. Technol.*, 2021, **218**, 106873.
- 73 L. S. Fan, L. Zeng and S. Luo, Chemical-looping technology platform, *AIChE J.*, 2015, **61**, 2–22.
- 74 Y. Ge, T. He, Z. Wang, D. Han, J. Li, J. Wu and J. Wu, Chemical looping oxidation of CH<sub>4</sub> with 99.5% CO selectivity over V<sub>2</sub>O<sub>3</sub>-based redox materials using CO<sub>2</sub> for regeneration, *AIChE J.*, 2020, **66**, e16772.
- 75 J. Zhang, V. Haribal and F. Li, Perovskite nanocomposites as effective CO<sub>2</sub>-splitting agents in a cyclic redox scheme, *Sci. Adv.*, 2017, **3**, e1701184.
- 76 M. Tang, K. Liu, D. M. Roddick and M. Fan, Enhanced lattice oxygen reactivity over Fe<sub>2</sub>O<sub>3</sub>/Al<sub>2</sub>O<sub>3</sub> redox catalyst for chemical-looping dry (CO<sub>2</sub>) reforming of CH<sub>4</sub>: synergistic La-Ce effect, *J. Catal.*, 2018, **368**, 38–52.
- 77 Y. Sun, J. Li and H. Li, Core-shell-like Fe<sub>2</sub>O<sub>3</sub>/MgO oxygen carriers matched with fluidized bed reactor for chemical looping reforming, *Chem. Eng. J.*, 2022, **431**, 134173.
- 78 S. Assabumrungrat, S. Charoenseri, N. Laosiripojana, W. Kiatkittipong and P. Praserttham, Effect of oxygen addition on catalytic performance of Ni/SiO<sub>2</sub>·MgO toward carbon dioxide reforming of methane under periodic operation, *Int. J. Hydrogen Energy*, 2009, **34**, 6211–6220.
- 79 K. Otsuka, Y. Wang, E. Sunada and I. Yamanaka, Direct Partial Oxidation of Methane to Synthesis Gas by Cerium Oxide, *J. Catal.*, 1998, **175**, 152–160.
- 80 J. Wei and E. Iglesia, Structural and Mechanistic Requirements for Methane Activation and Chemical Conversion on Supported Iridium Clusters, *Angew. Chem., Int. Ed.*, 2004, **43**, 3685–3688.
- 81 Y. Mao, L. Zhang, X. Zheng, W. Liu, Z. Cao and H. Peng, Coke-resistance over Rh–Ni bimetallic catalyst for low temperature dry reforming of methane, *Int. J. Hydrogen Energy*, 2023, **48**, 13890–13901.
- 82 V. P. Haribal, X. Wang, R. Dudek, C. Paulus, B. Turk, R. Gupta and F. Li, Modified Ceria for “Low-Temperature” CO<sub>2</sub> utilization: A Chemical Looping Route to Exploit Industrial Waste Heat, *Adv. Energy Mater.*, 2019, **9**, 1901963.
- 83 A. Löfberg, J. Guerrero-Caballero, T. Kane, A. Rubbens and L. Jalowiecki-Duhamel, Ni/CeO<sub>2</sub> based catalysts as oxygen vectors for the chemical looping dry reforming of methane



- for syngas production, *Appl. Catal. B Environ.*, 2017, **212**, 159–174.
- 84 Y. Han, M. Tian, C. Wang, Y. Kang, L. Kang, Y. Su, C. Huang, T. Zong, J. Lin, B. Hou, X. Pan and X. Wang, Highly Active and Anticoke Ni/CeO<sub>2</sub> with Ultralow Ni Loading in Chemical Looping Dry Reforming *via* the Strong Metal–Support Interaction, *ACS Sustain. Chem. Eng.*, 2021, **9**, 17276–17288.
- 85 S. Miyazaki, Z. Li, Z. Maeno, T. Toyao, M. Ito, Y. Nakajima and K. Shimizu, Operando Ce *K*-edge XANES Study of Low-loading Ni/CeO<sub>2</sub> in Chemical Looping Dry Reforming of Methane, *Chem. Lett.*, 2022, **51**, 914–918.
- 86 J. Guerrero-Caballero, T. Kane, N. Haidar, L. Jalowiecki-Duhamel and A. Löfberg, Ni, Co, Fe supported on Ceria and Zr doped Ceria as oxygen carriers for chemical looping dry reforming of methane, *Catal. Today*, 2019, **333**, 251–258.
- 87 J. Wang, K. Li, H. Wang, Z. Li and X. Zhu, Sandwich Ni-phylosilicate@doped-ceria for moderate-temperature chemical looping dry reforming of methane, *Fuel Process. Technol.*, 2022, **232**, 107268.
- 88 S. Miyazaki, Z. Li, L. Li, T. Toyao, Y. Nakasaka, Y. Nakajima, K. Shimizu and Z. Maeno, Chemical Looping Dry Reforming of Methane over Ni-Modified WO<sub>3</sub>/ZrO<sub>2</sub>: Cooperative Work of Dispersed Tungstate Species and Ni over the ZrO<sub>2</sub> Surface, *Energy Fuels*, 2023, **37**, 7945–7957.
- 89 Z. Maeno, H. Koiso, T. Shitori, K. Hiraoka, S. Seki and N. Namiki, Syngas Production by Chemical Looping Dry Reforming of Methane over Ni-modified MoO<sub>3</sub>/ZrO<sub>2</sub>, *Chem.–Asian J.*, 2023, e202301096.
- 90 F. R. García-García and I. S. Metcalfe, Chemical looping dry reforming of methane using mixed oxides of iron and cerium: operation window, *Catal. Commun.*, 2021, **160**, 106356.
- 91 L. S. Fan, S. Luo and L. Zeng, *US Pat.*, US10501318B2, 2018.
- 92 L. S. Fan, S. Luo, L. Zeng and D. Xu, *High Quality Syngas Production Using Composite Metal Oxides*, US Provisional Patent Application, 2013.
- 93 S. Luo, L. Zeng and L. S. Fan, Chemical Looping Technology: Oxygen Carrier Characteristics, *Annu. Rev. Chem. Biomol. Eng.*, 2015, **6**, 53–75.
- 94 Y. Song, S. Teng, † D. Fang, Y. Lu, Z. Chen, R. Xiao and D. Zeng, Machine Learning for Chemical Looping: Recent Advances and Prospects, *Energy Fuels*, 2024, **38**, 11541–11561.

