A short review of recent advances in CO₂ hydrogenation to hydrocarbons over heterogeneous catalysts

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CO₂ hydrogenation to hydrocarbons is a promising way of making waste to wealth and energy storage, which also solves the environmental and energy issues caused by CO₂ emissions. Much efforts and research are aimed at the conversion of CO₂ via hydrogenation to various value-added hydrocarbons, such as CH₄, lower olefins, gasoline, or long-chain hydrocarbons catalyzed by different catalysts with various mechanisms. This review provides an overview of advances in CO₂ hydrogenation to hydrocarbons that have been achieved recently in terms of catalyst design, catalytic performance and reaction mechanism from both experiments and density functional theory calculations. In addition, the factors influencing the performance of catalysts and the first C–C coupling mechanism through different routes are also revealed. The fundamental factor for product selectivity is the surface H/C ratio adjusted by active metals, supports and promoters. Furthermore, the technical and application challenges of CO₂ conversion into useful fuels/chemicals are also summarized. To meet these challenges, future research directions are proposed in this review.

1. Introduction

Continuing consumption of fossil fuels worldwide has led to an increasing CO₂ concentration in the atmosphere, and global climate change caused by greenhouse gases has become a major challenge. Mitigation of CO₂ concentration in the atmosphere is in urgent need due to the continuing rise in atmospheric CO₂ concentration (e.g., exceeding 400 ppm in 2016 (ref. 1)) and its negative and even possibly irreversible impact on the climate system. A recent report by UNEP (United Nations Environment Programme) estimated that if no firm global action is taken against climate change, temperatures might increase by more than 2 °C by 2050, and more than 4 °C by 2100.² In order to avoid this outcome, scientists indicate that global greenhouse gas emissions need to be reduced by at least 50% by 2050 compared to 1990, while the European Commission objective aims to achieve a reduction of 80–95% greenhouse gas emissions by 2050 compared to 1990.³ A number of Europe’s key partners from all over the world, such as China, Brazil, and Korea, are addressing these issues through concrete actions to promote the “low carbon economy”.² The oil company TOTAL has generated its climate strategy based on the International Energy Agency’s 2 °C scenario which aims to limit emissions to approximately 15 Gt CO₂-eq. per year in 2050 with the objective to achieve carbon neutrality in the second half of the century.

At present, CO₂ can be reduced in three ways: control of CO₂ emissions, CO₂ capture and storage, and chemical conversion and utilization of CO₂.⁴ Carbon storage is important for cutting CO₂ emissions quickly, but has an issue of potential leakage of CO₂.⁵ CO₂ can be regarded as a carbon source to offer an alternative to produce carbon-containing value-added products and feedstocks. CO₂ obtained by capture not only can provide a pure carbon source for hydrogenation, but also can avoid the leakage problem caused by CO₂ storage. In addition, the National Aeronautics and Space Administration (NASA) also regarded the Sabatier reaction (CO₂ methanation) as a step in reclaiming oxygen within closed cycle life support systems.⁶ Even the CO₂ in industrial flue gas can be used directly as a feed for hydrogenation.⁷ Therefore, an efficient utilization of renewable carbon resources is crucial and beneficial to maintain a long-term and sustainable development of our society. CO₂ conversion requires energy input, and its conjunction with renewable energy would make this strategy more promising in terms of sustainability and environmental friendliness.

CO₂ reduction can be catalyzed through electrocatalysis,⁸ photocatalysis,⁹ and thermal catalysis. Among them, thermal
catalysis receives significant attention due to its fast kinetics and flexible combination of active components. Carbon dioxide is a highly stable molecule, the activation and subsequent conversion of which alone are energy demanding. The addition of another substance with relatively higher Gibbs energy will make the CO₂ conversion more favorable thermodynamically. However, electrocatalysis and photocatalysis have the fatal flaw of low energy efficiency. Therefore, CO₂ hydrogenation using H₂ produced with renewable energy sources is a promising research direction to produce chemicals and fuels, which not only reduces the CO₂ emissions, but also covers the shortage of fossil fuels.

Catalytic hydrogenation of CO₂ using H₂ produced with renewable energy is considered as a potential path forward for the sustainable production of lower olefins, higher hydrocarbons, formic acid, and methanol and higher alcohols (Fig. 1). Considering the depletion of fossil fuels, CO₂ hydrogenation to hydrocarbons is a promising way to covert CO₂ into fuels among the other CO₂ hydrogenation paths. Yet, we need to confront two challenges along with it: (1) sustainable hydrogen source and (2) dispersed product distribution. Much effort has been devoted to solving the former challenge, and scientists have already made great progress in water electrolysis to produce H₂ using electricity generated with solar or wind or other renewable energy, and water splitting using photocatalytic, photoelectrochemical or other photochemical processes. There are established industrial technologies for water electrolysis with energy efficiencies of around 70%. However, the C₂ hydrocarbons have a wide distribution. For example, CH₄, C₂—C₄, and C₅, are targeted regions for production, while the selectivity is spread in a wide range, which becomes an obstruction to meet the requirement for real applications in industry. However, to date few reviews have dealt with the CO₂ conversion mechanism and hydrocarbon chain growth both experimentally and with density functional theory (DFT) calculations. This review provides an overview of advances in CO₂ hydrogenation to hydrocarbons that have been achieved recently in terms of catalyst design, catalytic performance and reaction mechanism from both experiments and DFT calculations. The review is organized based on some apparent factors which affect catalyst performance and unified to the essential reason for CO₂ hydrogenation that is the chemical state of the catalysts. The fundamental factor for product selectivity is the surface H/C ratio adjusted by the use catalysts. In addition, DFT research advances are summarized from the point of view of C-O bond cleavage and C-C bond formation which gave a deep insight into CO₂ activation and conversion. Guidance as to how to adjust the catalysts to promote hydrocarbon chain growth in CO₂ conversion is also given in this review.

2. CO₂ hydrogenation to CH₄

CO₂ also can be identified as an energy carrier for the transformation of renewable energy. As aforementioned, CO₂ hydrogenation to value-added products is one of the promising approaches to combat the CO₂-induced climate change, wherein the electrolysis of water to generate H₂ with renewable energy is a potential energy storage approach, and would definitely add more credits to the establishment of such a sustainable carbon-based cycle. However, currently uses of renewable energy sources are limited by their inherent intermittency, and require scalable means of storage. Therefore, the production of synthetic natural gas or liquid fuels is the most feasible and convenient way to store large amounts of intermittent energy produced from renewable sources for long periods. Among them, the so-called “power to gas” (PtG) concept has garnered significant attention (Fig. 2), in which CO₂ reacts with H₂ generated by water electrolysis with renewable wind or solar energy, to produce CH₄ as an alternative source of natural gas. In Copenhagen, a commercial scale operation PtG project with 1.0 MW capacity was running successfully using transformation of the energy system toward a sustainable system in 2016. From 2009 to 2013, there were five projects in Germany involving CO₂ methanation at pilot plant or commercial scale with capacity ranging from 25 kW to 6300 kW. CO₂ methanation was first reported by the French chemist Paul Sabatier in 1902. Due to the increasing demand for
mitigating global warming and storing surplus renewable energy, this ancient art has attracted renewed attention. The Sabatier reaction is an advantageous way to store renewable energy such as wind and solar power, to transfer biogas effectively to biomethane, and to convert CO2 to chemical feedstocks and fuels.37,38 CO2 methanation is exothermic with high equilibrium conversion between 25 °C and 400 °C as shown in Fig. 3.39,40 CO2 methanation can reach 99% CH4 selectivity through use of appropriate catalysts, avoid the subsequent product separation and overcome the difficulty of dispersed product distribution. Therefore, such a thermodynamic feature makes CO2 methanation more significant in terms of energy efficiency and economic viability.

2.1 Metal-based heterogeneous catalysts

CO2 methanation can be catalyzed by transition metals such as Co,41–44 Ni,41,45 Ru,46,47 Rh,48 and Pd.49,50 Based on previously published results, the activity performance of various metal-based catalysts decreases in the following order: Ru > Rh > Ni > Co > Pt > Pd.44 Co- and Ni-based catalysts are preferred because of their low cost compared with the noble metals (Ru, Rh, Pd). Ni-based catalysts are the most commonly used for industrial purposes due to their high activity, high CH4 selectivity, and easy availability. The catalytic performances of some representative catalysts are summarized in Table 1, as well as the preparation methods and reaction conditions.

2.1.1 Metal-support interaction. The traditional catalyst supports are the metal oxides Al2O3,51 SiO2,52,53 ZrO2,54 TiO2,55,56 and CeO2 (ref. 19) and zeolites.7 There are many factors concerning supports that can influence the performance of metal catalysts,56 such as pore size,57 structure of supports,42 surface chemistry, and metal-support interaction.43,58–60 Evidently, the activity and selectivity of these supported catalysts are sensitive to the interaction between the active metals and oxide supports.45,58–60 Chen et al.61 in a current perspective provide a bottom-up look at how the synergistic interactions at the metal/oxide interface can tune the reaction mechanisms and in turn the selectivity of CO2 hydrogenation. Actually, the metal sites on metal nanoparticles and the M+ or O2− sites of oxides are observed to stabilize the key reaction intermediates, e.g., *CO2, *C2H4, and *C2H6O2 species.

Zhou et al.62 prepared a series of CeO2-supported Ni-based catalysts with various textural properties by hard-template method, soft-template method, and precipitation method, and examined their activity performance in CO2 methanation. Among them, they found that the one prepared by the hard-template method exhibited a higher CO2 methanation activity, and attributed such superiority to the mesoporous structure and high specific surface area. Furthermore, in situ FT-IR and in situ XPS results illustrate that the surface oxygen vacancies on the CeO2 support were capable of activating the chemisorbed CO2 and subsequently forming the CO intermediate.63 Martin et al.64 investigated Rh, Pd, and Ni catalysts supported on different substrates (Al2O3, CeO2, SiO2, and zeolites) for CO2 methanation. Rh/Al2O3 and Rh/CeO2 exhibited the highest CO2 conversion, but differed in mechanism. In situ DRIFTS interferograms showed that the linear Rh–CO species was evident on Rh/Al2O3, suggesting CO2 dissociation, while the CO was formed through formate and carbonate intermediate species on Rh/CeO2. These advantageous results indicate that the surface oxygen vacancies on the CeO2 substrate enabled the interaction with CO2, and promoted the CO2 hydrogenation. Li et al.65 prepared Co/ZrO2 catalysts for CO2 methanation, as well as Co/Al2O3 catalysts for comparison. The Co/ZrO2 catalysts displayed a higher CO2 methanation activity with a practically stable performance even after 300 h on stream, while the Co/Al2O3, in contrast, deactivated rapidly within the same period of time. The Co–Zr interface was observed on the samples in reduced form, which enabled the redistribution of active Co on the ZrO2 support due to the special metal-support interaction (Fig. 4). The special Co–Zr interface is crucial for the superior CO2 methanation activity. Dreyer et al.66 have investigated the influence of metal oxide support reducibility on Ru-based catalysts for CO2 methanation. They pointed out that the intermediate CO should have an appropriate coverage and strong adsorption, which ensures the occurrence of H2 dissociation. The reducible CeO2 support is the most suitable to support Ru for CO2 methanation compared with the irreducible Al2O3 which gives a quasi-saturated CO adsorption and limits the co-adsorption of H2 and reducible ZnO which has a weak CO adsorption and leads to the reverse water–gas shift (RWGS) reaction.

In addition, metal oxide supports with the same chemical composition and different crystal phase also have an influence on the chemical state of the supported metal. Kim et al.67 synthesized monodispersed 2 nm RuO2 nanoparticle colloidal suspension, and impregnated it onto TiO2 with different crystal phases for CO2 methanation. The activity and product selectivity were strongly dependent on the composition of different crystal phases of TiO2, wherein P25, with 20% of anatase and the rest of rutile, exhibited the highest CO2 conversion and CH4 selectivity. Inspired by these results, they further developed a fundamental understanding of the composition structure–
activity performance relationship. The phenomenon that RuO₂ nanoparticles tended to migrate towards rutile TiO₂ during the CO₂ methanation process when rutile and anatase TiO₂ co-existed was evidenced by the stabilization of RuO₂ on rutile TiO₂ based on characterization results. Such rutile-RuO₂-NiO co-existed was evidenced by the stabilization of RuO₂ on rutile TiO₂ during the CO₂ methanation. Chen et al. observed a similar phenomenon on Ni/TiO₂ catalysts with different TiO₂ crystal phases for both CO and CO₂ methanation. Experimentally, both *HCOO and *HOCO were identified as reaction intermediates on both PtCo/TiO₂ and PtCo/ZrO₂, whereas *CH₃O was only evidenced on PtCo/ZrO₂. DFT results illustrate that the CO desorption energy is much lower than that of its hydrogenation to *CHO on PtCo/TiO₂. Therefore, the chemisorbed CO favored desorption energetically rather than the subsequent hydrogenation, thereby leading to a selective production of CO. On the other hand, CO formation was hindered on PtCo/ZrO₂ catalyst, and CH₄ was formed. Apparently, the interaction between metal and support plays an important role in product selectivity.

### 2.1.2 Effect of metal particle size. In addition to metal-support interaction, the particle size also strongly affects the kinetic parameters of CO₂ hydrogenation. Wu et al. tested Ni/SiO₂ catalysts with different metal loadings, namely 0.5 wt% and 10 wt%, in CO₂ methanation, the loading levels of which corresponded to small Ni clusters and large Ni particles, respectively. CO formation was favored on the small Ni clusters, while more CH₄ was produced on the large Ni particles. A

### Table 1 Summary of various catalysts for CO₂ methanation

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Preparation method</th>
<th>Reactor</th>
<th>GHSV [mL h⁻¹ g⁻¹]</th>
<th>P [MPa]</th>
<th>T [°C]</th>
<th>XCO₂ [%]</th>
<th>CH₄ [%]</th>
<th>Stability tests</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiO-MgO@SiO₂</td>
<td>Co-precipitation method</td>
<td>Fixed-bed quartz reactor</td>
<td>90 000</td>
<td>0.1</td>
<td>300</td>
<td>80</td>
<td>97</td>
<td>Stable after 100 h</td>
<td>94</td>
</tr>
<tr>
<td>NiWMgO₃</td>
<td>Precipitation</td>
<td>Fix-bed quartz tube react</td>
<td>40 000</td>
<td>0.1</td>
<td>300</td>
<td>83</td>
<td>99</td>
<td>Stable after 100 h</td>
<td>74</td>
</tr>
<tr>
<td>15% Ni 2% La-hydrotalcite</td>
<td>Co-precipitation method</td>
<td>Tubular quartz reactor</td>
<td>12 000</td>
<td>—</td>
<td>250</td>
<td>46.5</td>
<td>99</td>
<td>Stable after 5 h</td>
<td>75</td>
</tr>
<tr>
<td>NiO and Co-ZrO₂</td>
<td>Ammonia evaporation method</td>
<td>Fixed-bed quartz reactor</td>
<td>20 000</td>
<td>—</td>
<td>275</td>
<td>55</td>
<td>99.8</td>
<td>Stable after 70 h</td>
<td>88</td>
</tr>
<tr>
<td>Ni/CoO₂</td>
<td>Excess impregnation</td>
<td>Fixed-bed quartz reactor</td>
<td>22 000</td>
<td>0.1</td>
<td>340</td>
<td>91.1</td>
<td>100</td>
<td>Decreased by 18% after 700 min</td>
<td>64</td>
</tr>
<tr>
<td>14% Ni 7% Ce/USY</td>
<td>Impregnation</td>
<td>Flow tubular reactor in Pyrex</td>
<td>43 000</td>
<td>0.1</td>
<td>400</td>
<td>68.3</td>
<td>95.1</td>
<td>Stable after 10 h</td>
<td>95</td>
</tr>
<tr>
<td>10% Ni/MOF-5</td>
<td>Impregnation</td>
<td>Fixed-bed quartz reactor</td>
<td>2000</td>
<td>0.1</td>
<td>320</td>
<td>75.1</td>
<td>100</td>
<td>Stable after 100 h</td>
<td>84</td>
</tr>
<tr>
<td>20% Ni/55% γ-Al₂O₃</td>
<td>Impregnation</td>
<td>Fixed-bed quartz reactor</td>
<td>15 000</td>
<td>0.1</td>
<td>300</td>
<td>85</td>
<td>98</td>
<td>Stable after 400 min</td>
<td>79</td>
</tr>
<tr>
<td>80% Ni-Al hydrotalcite</td>
<td>Co-precipitation method</td>
<td>Fixed-bed quartz reactor</td>
<td>20 000</td>
<td>0.1</td>
<td>300</td>
<td>86</td>
<td>98</td>
<td>Stable after 25 h</td>
<td>80</td>
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<tr>
<td>2.5% Ce–10% Ni/Al₂O₃</td>
<td>Ultrasonic impregnation</td>
<td>Fixed-bed quartz reactor</td>
<td>7200</td>
<td>0.1</td>
<td>400</td>
<td>74</td>
<td>98</td>
<td>—</td>
<td>17</td>
</tr>
<tr>
<td>12% Ni/Al₂O₃ (3DFD structure)</td>
<td>Impregnation, coated on 3DFD structures</td>
<td>Fixed-bed quartz reactor</td>
<td>1500</td>
<td>0.1</td>
<td>350</td>
<td>85</td>
<td>98</td>
<td>Stable after 53 h</td>
<td>90</td>
</tr>
<tr>
<td>10% Ni/TiO₂</td>
<td>Dielectric barrier discharge plasma</td>
<td>Fixed-bed quartz reactor</td>
<td>60 000</td>
<td>0.1</td>
<td>350</td>
<td>73.2</td>
<td>99</td>
<td>—</td>
<td>84</td>
</tr>
<tr>
<td>RQ Ni</td>
<td>Rapid quenching</td>
<td>Capacity hastelloy autoclave</td>
<td>—</td>
<td>3</td>
<td>200</td>
<td>60</td>
<td>99</td>
<td>Five successive cycles without reactivation</td>
<td>78</td>
</tr>
<tr>
<td>10Ni3Pr/Al₂O₃</td>
<td>Evaporation induced self-assembly</td>
<td>Fix-bed quartz reactor</td>
<td>15 000</td>
<td>0.1</td>
<td>400</td>
<td>76</td>
<td>98</td>
<td>Stable after 50 h</td>
<td>86</td>
</tr>
<tr>
<td>0.03% Pt–20% Co–80% Al₂O₃</td>
<td>Double flame spray pyrolysis</td>
<td>U-shaped tube reactor</td>
<td>36 000</td>
<td>0.1</td>
<td>400</td>
<td>70</td>
<td>98</td>
<td>—</td>
<td>89</td>
</tr>
<tr>
<td>Co(0.01)PC-600</td>
<td>ZIF-67-derived carbonization</td>
<td>Fix-bed reactor</td>
<td>72 000</td>
<td>3</td>
<td>270</td>
<td>59</td>
<td>99</td>
<td>Stable after 420 min</td>
<td>85</td>
</tr>
<tr>
<td>Pt@CSN</td>
<td>Water-soaking-assisted phase-transformation method</td>
<td>Fix-bed reactor</td>
<td>4800</td>
<td>3</td>
<td>320</td>
<td>41.8</td>
<td>95</td>
<td>—</td>
<td>87</td>
</tr>
<tr>
<td>10Co/ZrO₂</td>
<td>Impregnation</td>
<td>Fix-bed reactor</td>
<td>3600</td>
<td>3</td>
<td>400</td>
<td>92.5</td>
<td>99</td>
<td>Stable after 300 h</td>
<td>62</td>
</tr>
<tr>
<td>20% Co/KIT-6</td>
<td>Impregnation</td>
<td>Fix-bed reactor</td>
<td>22 000</td>
<td>0.1</td>
<td>260</td>
<td>46</td>
<td>99</td>
<td>—</td>
<td>42</td>
</tr>
<tr>
<td>2.5% Ru/P25</td>
<td>Impregnation</td>
<td>Continuous flow fixed-bed reactor</td>
<td>6000</td>
<td>0.1</td>
<td>200</td>
<td>27.4</td>
<td>100</td>
<td>—</td>
<td>67</td>
</tr>
<tr>
<td>Ru/CoO₂</td>
<td>Single-step flame spray pyrolysis</td>
<td>Fix-bed reactor</td>
<td>7640</td>
<td>—</td>
<td>300</td>
<td>83</td>
<td>99</td>
<td>—</td>
<td>66</td>
</tr>
</tbody>
</table>
similar phenomenon was also evidenced on Ru/Al2O3 catalysts by Kwak et al.,\textsuperscript{47} wherein 1 wt% Ru/Al2O3 with highly dispersed particles selectively produced CO, and the selectivity was gradually shifted to CH4 along with sintering degree of Ru nanoparticles with an increase of Ru loading levels. At 5% of Ru loading, the catalyst had large Ru clusters, therefore making the reaction proceed all the way to CH4 (Fig. 6). Iablokov et al.\textsuperscript{71} investigated the influence of Co particle size on the activity and selectivity of CO2 methanation. A series of near-monodisperse Co nanoparticles with size in the range 3–10 nm were prepared using oleic acid and Co2(CO)8, among which the larger Co particles exhibited a higher turnover frequency (TOF). Christopher et al.\textsuperscript{72} investigated the quantitative relationship between the concentrations of isolated Rhiso active sites and Rh nanoparticles supported on TiO2 and the product distribution for CO2 thermal reduction. Evidently, the isolated Rh sites favored CO formation, and the CH4 selectivity increased with the decrease of Rhiso fraction.

Seen from the results above, both noble and non-noble metal-based catalysts can be applied to CO2 methanation, and the experimental results indicate that, within a certain range of metal particle size, the atom-scale structured catalysts tend to favor the RWGS reaction, while the larger metal particles facilitate CH4 formation.\textsuperscript{50} To unveil the underlying reasons behind the size-dependent effect, Ma et al.\textsuperscript{73} prepared Ir/CeO2 catalysts with various Ir loadings using a ligand-free method, and tested them in CO2 methanation. The catalysts with low Ir loading presented partially oxidized Ir species, and displayed catalytic selectivity for CO production. On the other hand, more metallic Ir species appeared to emerge when increasing the Ir loading level, leading to a preference for desired CH4 formation. Their results suggest that the chemical state of Ir could be finely tuned by altering the loading of the metal. Actually, the particle size effect is the chemical state effect. The metal loading essentially affects the active metal state on the supports and further affects the reaction routes.

### 2.1.3 Multi-component metal catalysts.

The surface properties are also a significant factor in addition to the metal-support interaction and particle size effect. To activate CO2 molecules, it is imperative to adjust the surface basicity to improve the adsorption capability towards CO2. To achieve this goal, the effect of introducing various rare earth and other transition metals on catalytic properties in CO2 methanation has been extensively studied in past decades. Yan et al.\textsuperscript{74} demonstrated that W doping can strengthen the Ni–Mg...
interaction, and enhance NiMgOₓ catalytic performance in terms of COₓ methanation activity and stability. Furthermore, such W doping also increased the surface basic sites of NiMgOₓ, which could improve CO₂ stabilization and its subsequent hydrogenation effectively. DRIFTS analysis further demonstrates that these resultant surface basic sites promoted the transfer of adsorbed CO₂ to monodentate formate species (m-HCOO⁻) which was proposed as the key intermediate for the CO₂ methanation.

Similarly, Wierzbicki et al.⁵ increased the surface basicity by adding 2 wt% lanthanum to Ni–Mg–Al hydrotalcite-derived catalysts, which remarkably enhanced the CO₂ methanation activity. In addition, a series of rare earth-doped (La, Ce, Sm, and Pr) Ni-based mesoporous materials were facilely fabricated by the one-pot evaporation-induced self-assembly strategy for low-temperature CO₂ methanation.⁶ The rare earth-doped catalysts with enhanced surface basicity displayed two or three times higher catalytic activities than the pristine MA-10Ni catalyst in the low-temperature region (200–250 °C). Generally speaking, catalyst basicity improvement increases the CO₂ adsorption and activation by the second metal addition.

2.1.4 Novel catalysts and process integration. In addition to the traditional metal-support catalysts, more attention has been paid to the incorporation of novel materials with desired features to produce heterogeneous catalysts for CO₂ hydrogenation, such as multi-metal composite oxides, hydrotalcite, perovskite, and metal–organic framework (MOF)-based catalysts. Depending upon the knowledge and experience collected so far, specific novel materials were intentionally chosen for further modification and/or incorporation with active metals that were already identified as active sites. Preliminary results demonstrate that the tailored materials are capable of improving the catalytic performance as anticipated through strengthened metal-support interaction, generated oxygen vacancies, and improved reducibility of metals. In addition, by DFT calculations, the undercoordinated sites (UCSs) serve as the active centers for hydrogen-assisted CO dissociation and the CO dissociation barrier decreases proportionally with the expansion of the crystal lattice.⁷ Recently, by a rapid quenching technique, Zong et al.⁷ fabricated RQ Ni with peculiar UCS-abundant and tensile-strained structural characteristics. This catalyst has superior activity in the low-temperature CO₂ methanation and the TOF of CO₂ on RQ Ni is about 8 times that of the highest TOF of CO₂ ever reported at 473 K. By DFT calculations, the CO activation barrier decreases when the Ni–Ni distance expanded from 2.49 Å to 2.51 Å with tensile strain on the Ni(111) surface. The superior activity conforms to the conclusion that the UCSs are the active centers for CO₂ methanation and more efforts should be aimed at fabricating undercoordinated catalytic materials.

Centi and co-workers have developed γ-Al₂O₃–ZrO₂–TiO₂–CeO₂ composite oxide-supported Ni catalysts⁸ and Ni–Al hydrotalcite⁹ catalysts for CO₂ methanation. A better performance of the catalysts was achieved because of the improvements in the reducibility of active metal Ni.

Metal oxides have relatively low surface areas without featuring pore structures, thereby limiting the intimate contact between reagents and active sites, and even leading to mass transfer limitation. To resolve such issues, some high BET surface supports have been explored. MOFs are a class of crystalline, nanoporous materials that offer such tailorability through large accessible surface areas, tunable pore functionalities, and reactive open metal sites.⁸¹–⁸³ Zhen et al.⁸⁴ prepared Ni-based catalysts using MOF-5 (surface area of 2961 m² g⁻¹) as support, and obtained a high Ni dispersion (41.8%). Such 10Ni/MOF-5 catalyst with highly dispersed Ni showed a higher activity than the benchmark Ni/SiO₂, and presented a superior stability after 100 h on stream for low-temperature CO₂ methanation. Li et al.⁸⁵ prepared ZIF-67-derived Co-based porous carbon catalysts, and achieved both excellent catalytic performance and good stability in comparison to the traditional Al₂O₃-supported counterpart. This catalyst even exhibited

Fig. 6 (a) TOFs of CO and CH₄ formation at steady state at 300 °C over Ru/Al₂O₃ catalysts as a function of Ru loading. (b) CO selectivity as a function of Ru loading at 300 °C. Reprinted with permission from ref. 47. Copyright 2013 ACS.
prominent activity performance in CO2 methanation at low temperatures compared with the other Co-based catalysts supported on either metal oxides or zeolites.84,85,86 Meanwhile, Zeng et al.87 have proposed a general synthesis route of ZIF-67-derived bifunctional nanoreactors via a water-soaking-assisted phase-transformation method for CO2 hydrogenation. They point out that CO2 converts to CO on the Pt active sites and CO methanation to CH4 occurs on the Co active sites. The Pt@CSN (cobalt silicate nanoparticles) bifunctional nanoreactors increase the CO2 conversion and CH4 selectivity obviously through prolonging the intermediate retention time on the catalyst surface and enhancing the probability for CO to further convert to CH4. These achievements provide insight into adapting these advancements toward the industrial utilization of CO2 in terms of economic and sustainable viability. However, MOFs are unfavorable for high-temperature reaction because of their instability under the hydrothermal reaction conditions, especially given that CO2 hydrogenation usually requires high temperature. From another point of view, developing low-temperature methanation catalysts with high activity is also a promising way for CO2 conversion from the energy conservation perspective.

In addition to the traditional homogeneous catalyst preparation methods, such as impregnation method and co-precipitation method, more and more innovation techniques have been employed to prepare catalytic materials to remedy the defects existing in traditional methods. Kawi and co-workers developed Ni/Co-ZrO2 catalysts by the ammonia evaporation (AE) method, and remarkably improved the Ni reducibility (total H2 uptake \(= 3.37 \text{ mmol g}^{-1}\)) compared with the impregnation (total H2 uptake \(= 3.32 \text{ mmol g}^{-1}\)) and deposition–precipitation (total H2 uptake \(= 2.06 \text{ mmol g}^{-1}\)) methods.88 The Ni/Co-ZrO2-89 AE possessed more oxygen vacancies, and a strengthened metal–support interaction, thereby contributing to the high activity and stability for low-temperature CO2 methanation. Schubert et al."90 used the double flame spray pyrolysis technique to control the Pt content to as low as 0.03 wt%, and improved the catalytic performance of PtCo-Al2O3 significantly. Protasova et al."91 manufactured macro-porous catalytic supports by an innovative and highly reproducible robocasting technique, three dimensional fiber deposition (3DFD), and the supports were coated with Ni/Al2O3 suspension to achieve sufficient catalytic coating. The catalysts coated on 3DFD supports had improved mass and heat transfer properties, and prevented metal sintering efficiently. These advantages were conducive to maintain the stability of the catalysts. Liu et al.92 attained a better catalytic performance of Ni/TiO2 catalysts prepared by dielectric barrier discharge plasma, depending on which more active Ni(111) facets were selectively exposed for CO2 methanation.92

To accord with practical applications, researchers have recently paid attention to the integration of carbon dioxide capture and utilization processes by incorporating together both CO2 capture system and catalytic CO2 conversion system. Farrauuto93 and co-workers devoted their effort to exploring dual functional catalysts which enable CO2 capture from an emission source, and conversion of it to synthetic natural gas in the same reactor at the same temperature (320 °C). In this process, the catalyst composition comprised 5% Ru 10% CaO/Al2O3, wherein the components of CaO and Ru were responsible for CO2 adsorption and conversion, respectively. Of note, this new approach utilized flue gas sensible heat, and needed no additional heat input, which made it more attractive in mitigating the current energy shortage. Grunwaldt et al.94 explored Ni-based catalysts under dynamic reaction conditions, especially under a fluctuating supply of renewable H2. They found the oxidation of Ni particles occurred after the removal of H2 from the gas stream, and a lower catalytic performance was observed consequently. Apparently, the Ni/CoO-Al2O3 catalyst was unadapted to the dynamic reaction conditions. Such an issue impeded its implementation in real industry, which also made the search for efficient ways for renewable H2 supply more important.

2.2 Mechanisms of CO2 methanation

CO2 methanation can be catalyzed through either CO route or formate route, which is determined by the properties of different active metals and supports. The CH4 selectivity is likely determined by the competition between the hydrogenation and C–O bond scission reactions of the *H2CO intermediates. To achieve high CH4 selectivity, the binding of *H2CO species should be strong enough to facilitate C–O bond cleavage.91

Duan et al."92 investigated the effect of oxygen vacancies on the catalytic performance of Rh/CoO2 catalysts in CO2 methanation, and developed an understanding of its role in the proposed mechanism. The existence of Ce\(^{3+}\), surface hydroxyl, and oxygen vacancies on Ru/CoO2 was evidenced from operando XANES, IR, and Raman analyses. Steady-state isotope transient kinetic analysis (SSITKA)-type in situ DRIFTS was employed to detect the surface intermediates and track their transformation during the reaction process on both Ru/CoO2 and Ru/Al2O3, wherein the latter was introduced as reference, as it barely had any oxygen vacancies. On the Ru/Al2O3 catalyst, the carbonyl species, originating from the chemisorbed CO*, was observed until 250 °C, and CH4 generation occurred within the same temperature range. In contrast, formate and methanol corresponding bands emerged for Ru/CoO2, in which the former was identified as a key intermediate via this route, and methanol-to-methane transformation was the rate-determining step at a much lower temperature (150 °C). In this work, oxygen vacancies played a crucial role in CO2 activation and formate formation. Sharma et al.97 prepared Ru-substituted Ce0.99Ru0.01O2 catalyst for CO2 methanation, and interpreted a plausible reaction mechanism by combining the characterization results (TPR and DRIFTS) and DFT calculation. In this case, surface CO* species, rather than formate, was more likely to act as a key intermediate for CH4 production, wherein the reaction proceeded through the following steps: CO2 → CO → OCH2 → OCH3 → CH4. Note that this proposed reaction pathway differed from that of the supported metal catalyst [Ru/CoO2], which proceeded via CO2 → CO → HCOO* → C → CH4.

Ren et al.98 investigated the mechanisms of CO2 methanation on Ni(111) surfaces by DFT through three routes with
and without CO formation (Fig. 7). Considering the energy barriers and reaction energies for these different routes, the CO route was more favorable energetically for CO2 methanation on Ni(111) surface: CO2 → CO + O → C + O + 4H → CH2 + 2H → CH4 + H → CH4. Salmeron et al. also concluded that the methanation reaction proceeded via CO intermediate on Ni(111) surface as evidenced by ambient pressure X-ray photoelectron spectroscopy. Meanwhile, they reported that the Ni(110) seemed to convert CO much more easily to atomic carbon than Ni(111). Henriques et al. also investigated the mechanism of USY zeolites-supported Ni catalysts for CO2 methanation, and reported results also supporting the CO route. On the other hand, Gonzalez et al. identified the surface species on Ni/ZrO2 catalysts and bare ZrO2 during CO2 methanation using DRIFTS, and they proposed a different scenario with the formate route as the favorable one, as displayed in Fig. 8. In this mechanism, chemisorbed CO2 reacted with surface hydroxyl groups of ZrO2 to give bicarbonate species that can be reversibly converted to carbonate species. H2 was dissociated on the surface of Ni particles, which may migrate to the reducible metal oxide support by a spillover process, resulting in the formation of surface hydroxyl groups, metal–H species, and formate species. Next, the formate species took part in further hydrogenation to form CH4.

In contrast to other reports, the Ni/ZrO2 catalysts barely presented vibrational bands of carbonyl species on Ni surface. Instead, carbonate and bicarbonate species were identified on both Ni/ZrO2 and bare ZrO2, and even their subsequent transition to formate species was evidenced. Clearly, the incorporation of Ni and ZrO2 was characteristic of bifunctionality for CO2 methanation, in which the former metal sites were responsible for providing hydrogen through dissociation, while the latter support accounted for the CO2 stabilization and activation. In other words, CO2 methanation can be catalyzed through the formate route rather than the CO route on ZrO2-supported Ni catalysts.

In sum, the reaction pathway of CO2 methanation varied depending on the catalytic system used, and strongly depended on the selection of active metals and supports and their interactions.

2.3 Deactivation of CO2 methanation catalysts

Deactivation of metal catalysts is a big challenge in CO2 methanation. The deactivation of methanation catalysts can be divided into two types: (a) chemical deactivation and (b) physical deactivation.

The chemical deactivation of CO2 methanation catalysts is mainly directed toward the decrease of active sites caused by the formation of spinel structure. Li et al. prepared Co/ZrO2 catalysts for CO2 methanation, as well as Co/Al2O3 catalysts for comparison. The Co/ZrO2 catalysts displayed a higher CO2 methanation activity with a practically stable performance even after 300 h on stream, while the Co/Al2O3, in contrast, deactivated rapidly within the same period of time. The deactivation of the Co/Al2O3 catalyst was further studied through thermogravimetric analysis and hydrothermal (H2O) treatment verification tests. Extra H2O was pumped into the reaction system which led to a large amount of CoAl2O4 being formed and accelerated the Co/Al2O3 catalyst deactivation. Thus, the product H2O promotes the formation of the inactive phase CoAl2O4, leading to the rapid deactivation of Co/Al2O3 catalysts. Carbon deposition is one of the reasons for deactivation; however, the main reason for deactivation is the formation of inactive phase CoAl2O4 spinel structure.

Physical deactivation is caused by carbon deposition and active metal sintering. Kesavana et al. synthesized Ni/YSZ catalysts by different methods. On the Ni/YSZ catalyst obtained by impregnation method, graphitic filaments are formed on Ni0 particles exposing flat surfaces, whereas thin layers of carbon are formed on Ni0 particles with spherical shape. Ni/YSZ(EDTA) catalyst showed remarkable stability and operando XAS showed that Ni/YSZ(EDTA) catalyst did not undergo deactivation by Ni0 → Ni2+ oxidation using high CO2 : H2 ratio. Carbon deposition on the catalyst can be avoided by adding steam or increasing the H2/CO2 ratio because hydrogen reacts with the carbon deposits and prevents catalyst deactivation. To mitigate metal sintering, common strategies are increasing metal dispersion through strong metal-support interaction, adding catalyst promoters, and developing advanced synthesis methods. Li et al. prepared MOF-derived Co-based porous carbon catalysts in which the active Co particles are separated by the graphite-like carbon avoiding metal sintering.
effectively. A special catalyst structure can also resist metal sintering effectively. Li et al. prepared NiO–MgO@SiO2 core–shell structured catalysts, and activity performance was successfully retained after 100 h on stream. In summary, particles with appropriate size are beneficial for CH4 formation.

3. CO2 hydrogenation to C2+ hydrocarbons

CO2 hydrogenation to C2+, hydrocarbons is of great importance because the long-chain hydrocarbons possess higher energy density, and could be used as fuels and chemicals for a wide range of applications. Utilizing CO as the carbon source for hydrocarbon synthesis through Fischer–Tropsch synthesis has been widespread in industry, and continuing studies to further improve the activity, tune the product distribution, and develop deep understandings of catalytic composition-performance-physicochemical relationships are still ongoing worldwide. Substituting CO with CO2 as carbon source makes the reaction thermodynamically more difficult (see the reaction enthalpy below). Besides, not only will the challenge originate from the chemical inertness of CO2, but also from the competition with CO methanation. The relatively small amount of CO2 adsorbed species compared with dissociated H* on a catalyst surface leads to a low C/H ratio, which favors the fast hydrogenation of surface-adsorbed intermediates and the formation of methane and prevents chain growth. Despite the difficulties, the transformation of CO2 to value-added chemicals still receives great attention worldwide because of the significance in providing sustainable alternatives to solve urgent issues such as those of energy and the environment. This section will discuss the most recent advances in CO2 hydrogenation to hydrocarbons. Similarly, some representative catalysts for CO2 hydrogenation to C2+ hydrocarbons are presented in Table 2.

3.1 Modified Fischer–Tropsch synthesis (FTS) route

Primarily, CO2 hydrogenation to hydrocarbons could proceed through both direct and indirect pathways. The direct way is straightforward conversion of CO2 to hydrocarbons (eqn (1))
Table 2 Summary of various catalysts for CO$_2$ hydrogenation to C$_2$+ hydrocarbons

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Preparation method</th>
<th>GHSV [mL h$^{-1}$ g$^{-1}$]</th>
<th>$P$ [MPa]</th>
<th>$T$ [°C]</th>
<th>$X_{CO}$ [%]</th>
<th>$S_{CO}$ [%]</th>
<th>$S_{CH}_{4}$ [%]</th>
<th>$S_{C_{2}-C_{4}}$ [%]</th>
<th>$S_{C_{5+}}$ [%]</th>
<th>O/P</th>
<th>Ref.</th>
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<tr>
<td>Fe$_2$O$_3$-CT600</td>
<td>Precipitation method</td>
<td>1140</td>
<td>0.15</td>
<td>350</td>
<td>40.0</td>
<td>15$^a$</td>
<td>12$^a$</td>
<td>37$^a$</td>
<td>36$^a$</td>
<td>2.7</td>
<td>112</td>
</tr>
<tr>
<td>20% Fe/cube-CeO$_2$</td>
<td>Incipient wetness impregnation</td>
<td>200</td>
<td>—</td>
<td>390</td>
<td>18.9</td>
<td>73.5$^b$</td>
<td>75.5$^b$</td>
<td>22.8$^b$</td>
<td>1.9$^b$</td>
<td>—</td>
<td>115</td>
</tr>
<tr>
<td>Fe-Co(0.17)/K(1.0)/Al$_2$O$_3$</td>
<td>Incipient wetness impregnation</td>
<td>3600</td>
<td>1.1</td>
<td>300</td>
<td>31.0</td>
<td>18$^a$</td>
<td>13$^a$</td>
<td>69$^a$</td>
<td>—</td>
<td>—</td>
<td>116</td>
</tr>
<tr>
<td>10K13Fe2Co100ZrO$_2$</td>
<td>Electro-spinning method</td>
<td>3600</td>
<td>3</td>
<td>400</td>
<td>42.1</td>
<td>21.9$^b$</td>
<td>25.7$^b$</td>
<td>34$^a$</td>
<td>18.4$^a$</td>
<td>4.2</td>
<td>117</td>
</tr>
<tr>
<td>CeO$_2$/Pt@SiSIO$_3$-Co</td>
<td>Hydrothermal and impregnation</td>
<td>50 400</td>
<td>0.6</td>
<td>250</td>
<td>2.0</td>
<td>78.0</td>
<td>60.0$^b$</td>
<td>40.0$^b$</td>
<td>0$^b$</td>
<td>—</td>
<td>118</td>
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<tr>
<td>Delafossite-CuFe$_2$O$_4$</td>
<td>Hydrothermal method</td>
<td>1800</td>
<td>1</td>
<td>300</td>
<td>16.7</td>
<td>31.4$^a$</td>
<td>2.4$^b$</td>
<td>37.2$^a$</td>
<td>46.9$^b$</td>
<td>7.7</td>
<td>119</td>
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<td>0.05MnFe</td>
<td>One-step sol–gel process</td>
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<td>0.1</td>
<td>340</td>
<td>30</td>
<td>7.7$^a$</td>
<td>29.3$^a$</td>
<td>67.1$^b$</td>
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<td>ZnGa$_2$O$_4$/SAPO-34</td>
<td>Physical mixing</td>
<td>5400</td>
<td>2</td>
<td>370</td>
<td>46$^a$</td>
<td>3$^b$</td>
<td>97$^b$</td>
<td>2$^b$</td>
<td>7.7</td>
<td>121</td>
<td></td>
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<tr>
<td>ZnZrO/SAPO-34</td>
<td>Physical mixing</td>
<td>3600</td>
<td>2</td>
<td>380</td>
<td>12.6</td>
<td>47$^a$</td>
<td>3$^b$</td>
<td>94$^b$</td>
<td>5$^b$</td>
<td>5.7</td>
<td>122</td>
</tr>
<tr>
<td>In$_2$O$_3$/HZSM-5</td>
<td>Granule stacking</td>
<td>9000</td>
<td>3</td>
<td>340</td>
<td>13.1</td>
<td>45$^b$</td>
<td>3$^b$</td>
<td>13.1$^b$</td>
<td>78.6$^b$</td>
<td>—</td>
<td>26</td>
</tr>
<tr>
<td>In–Zr/SAPO-34</td>
<td>Physical mixing</td>
<td>9000</td>
<td>3</td>
<td>400</td>
<td>35</td>
<td>75$^a$</td>
<td>5$^b$</td>
<td>93$^b$</td>
<td>3$^b$</td>
<td>—</td>
<td>123</td>
</tr>
<tr>
<td>Na–Fe$_3$O$_4$/HZSM-5</td>
<td>Granule mixing</td>
<td>4000</td>
<td>3</td>
<td>320</td>
<td>33.6</td>
<td>14.2$^a$</td>
<td>7.9$^b$</td>
<td>18.4$^b$</td>
<td>73.7$^b$</td>
<td>—</td>
<td>105</td>
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<tr>
<td>Fe–Zn–Zr@HZSM-5-Hbeta</td>
<td>Cladding method</td>
<td>3000</td>
<td>8</td>
<td>340</td>
<td>14.9</td>
<td>38.6$^a$</td>
<td>1$^b$</td>
<td>71.7$^b$</td>
<td>26.6$^a$</td>
<td>—</td>
<td>124</td>
</tr>
<tr>
<td>Cu–Zn–Al/mixed-modified-HB</td>
<td>Physical mixing</td>
<td>1500</td>
<td>0.98</td>
<td>300</td>
<td>27.6</td>
<td>33.4$^a$</td>
<td>0.7$^b$</td>
<td>43.2$^a$</td>
<td>2.3$^b$</td>
<td>—</td>
<td>125</td>
</tr>
</tbody>
</table>

$^a$ Calculated from equation $S_i(\%) = \frac{m_{i,\text{out}}}{n_{\text{CO},\text{in}} - n_{\text{CO},\text{out}}} \times 100\%$, where $n_{\text{CO},\text{in}}$ and $n_{\text{CO},\text{out}}$ represent the molar concentration of CO$_2$ in the feed and effluent, respectively; $m_{i,\text{out}}$ represents the molar concentration of product $i$ in the effluent; and $m_i$ represents the number of carbon atoms in product $i$. Products include CO and hydrocarbons.

$^b$ Calculated from equation:

$$C_1 \text{hydrocarbon selectivity}(\%) = \frac{\sum \text{mole of } C_1 \text{ hydrocarbon } \times x \text{ } i}{\sum \text{mole of } C_1 \text{ hydrocarbon } \times x \text{ } i} \times 100\%.$$

or going through the RWGS reaction and FTS reaction (eqn (2) and (3)). In addition to these proposed reaction pathways, some scientists have also attempted to use methanol as a bridge and building unit to synthesize long-chain hydrocarbons via CO$_2$ hydrogenation, and made a major breakthrough most recently. This newly developed reaction pathway is another alternative option for CO$_2$ hydrogenation to hydrocarbons through an indirect way.

$$\text{CO}_2 \text{ HYD, } n\text{CO}_2 + 3n\text{H}_2 = C_n\text{H}_{3n} + 2n\text{H}_2\text{O}, \Delta R_{H573K} = -128 \text{ kJ mol}^{-1} \text{ (1)}$$

$$\text{RWGS, } \text{CO}_2 + \text{H}_2 = \text{CO} + \text{H}_2\text{O}, \Delta R_{H573K} = +38 \text{ kJ mol}^{-1} \text{ (2)}$$

$$\text{FTS, } 2n\text{CO} + (3n + 2)\text{H}_2 = 2C_n\text{H}_{2n+2} + 2n\text{H}_2\text{O}, \Delta R_{H573K} = -166 \text{ kJ mol}^{-1} \text{ (3)}$$

Since converting CO$_2$ to hydrocarbons directly makes the reaction kinetically more difficult, some scientists have turned to the modified FTS route. This section will mainly focus on the major progress made in CO$_2$ hydrogenation to C$_2$+ hydrocarbons through the modified FTS route. Currently, FTS is mainly catalyzed by Fe-based catalysts because the metal Fe possesses the catalytic characteristic of improving C–C coupling, which was proposed as a rate-determining step. In 1978, Dwyer et al. found that the presence of CO$_2$ impacted the product distribution of FTS on Fe-based catalysts, and such an inspired finding exploited a new field for the development of active catalysts for hydrocarbon synthesis from CO$_2$, an alternative carbon source with even greater proportion in the atmosphere. Computational results demonstrate that the kinetics of FTS is not comparable to that of RWGS, which makes it another challenge other than carbon chain growth. Even so, the similarity between CO and CO$_2$ hydrogenation motivated people to apply Fe catalysts, which exhibited good performance in FTS, to CO$_2$ hydrogenation at an early stage, and more researchers then endeavored to apply modified Fe catalysts with desired features. Albrecht et al. prepared dopant-free bulk Fe$_2$O$_3$ by a cellulose-template (CT) synthesis method, and applied it in CO$_2$ hydrogenation to hydrocarbons. The catalysts selectively catalyze CO$_2$ to C$_2$–C$_4$ hydrocarbons (selectivity = 37%) with an olefin to paraffin (O/P) ratio of 2.7. Iron carbide, as high as 81 wt%, was detected on the spent Fe$_2$O$_3$-CT600 catalysts, which was considered as active sites for the FTS. In comparison to FTS, this CT-supported Fe$_2$O$_3$ catalyst yielded comparable C$_2$–C$_4$ hydrocarbons, which could be attributed to the improved reducibility and in situ formation of iron carbide promoted by the CT-synthesized catalyst precursor.

3.1.1 Selection of support materials. As is well known, the incorporation of a support is able to tune the dispersion of active sites depending on the metal–support interaction. Due to its featured surface chemistry and amphoteric property, Al$_2$O$_3$ might have a strong interaction with loaded metallic species, and was widely used as support material for the preparation of commercially available catalyst for methanol synthesis. To increase the Fe dispersion, Al$_2$O$_3$ was also employed as a support in the preparation of Fe catalysts for CO$_2$ hydrogenation to hydrocarbons. Ding et al. prepared a series of FeK/Al$_2$O$_3$ catalysts, and investigated the effect of surface hydroxyl groups of Al$_2$O$_3$ on the activity and selectivity of hydrocarbon synthesis via CO$_2$. Evidently, the variations of both Fe dispersion and particle size were strongly dependent on the point of zero charge (PZC) of the Al$_2$O$_3$ support. The Fe
dispersion increased monotonically with the increase of PZC value, while the particle size showed an opposite trend. The highest CO۲ conversion (54.4%) and selectivity of C۵+ hydrocarbons (31.1%) were achieved at PZC = 8.0. ZrO۲ (ref. 128) and CeO۲ (ref. 63 and 88) were used as support materials as well due to the basic sites and the oxygen vacancies.⁹⁶ Wang et al.¹²⁹ carried out screening tests on catalysts prepared with different types of support materials, including SiO۲, Al۲O۳, TiO۲, ZrO۲, mesoporous carbon, and carbon nanotubes (CNTs), among which ZrO۲ attained the highest selectivity and yield for lower olefins. Chew et al.¹⁰⁸ used N-doped CNTs as a support to prepare Fe-based catalysts (Fe/NCNTs), and O-doped CNT- and SiO۲-supported catalysts were also employed for comparison. Characterization results demonstrate that the incorporation of NCNTs greatly improved the Fe dispersion and reducibility, which benefited from the improved hydrophilicity and appropriate metal-support interaction. On the other hand, the O-doped SiO۲ support showed too strong an interaction with the Fe species, which, in turn, exhibited a negative impact on the reducibility of active metal. Murciano et al.¹¹⁵ prepared Fe catalysts by introducing CeO۲ with various morphological properties, and examined their influence on the activity and selectivity in CO۲ hydrogenation to hydrocarbons. Results showed a strong reliance of catalytic performance on the reducibility of Fe species on the support. Among those CeO۲ materials, the one with cubic morphology helped to improve the reducibility of Fe species as evidenced from the shift of the initial reduction temperature towards lower temperatures, thereby resulting in the obtained highest O/P ratio in comparison to rod-type and nanoparticle-type CeO۲.

Owing to their tailor able pore structure and featured physicochemical properties, MOFs and their subclass zeolitic imidazolate frameworks (ZIFs) have attracted considerable attention in a diversity of energy-related applications such as CO۲ capture and even CO۲ activation.¹¹⁰⁻¹¹² Driven by their unique characteristic, researchers employed this group of materials as supports to prepare heterogeneous catalysts for CO۲ hydrogenation to hydrocarbons.⁴⁴⁻¹¹³ Some metal-based MOFs and ZIFs, which already were proven to be active for hydrocarbon synthesis from either CO۲ or CO hydrogenation, were selectively chosen for activity tests in an attempt to collect first-hand data. Guo and coworkers prepared and carried out a series of tests using these novel catalysts, and obtained interesting results. In an early work, they employed MIL-53(Al) and ZIF-8 as supports for preparing γ-Fe۲O۳ catalysts by a solid grinding method.¹¹⁹ Preliminary results indicated that ZIF-8-supported catalysts exhibited a higher CO۲ conversion than MIL-53-supported ones because the acidity on the MIL-53 impeded CO۲ adsorption, an important step for heterogeneous catalysis.

### 3.1.2 Incorporation of promoters in Fe-based catalysts

To further improve the selectivity of higher hydrocarbons, Fe-based catalysts were promoted by a variety of metals, among which K, Na, Cs, Mn, and Cu were representative ones, enabling the enhancement not only of C۵+ selectivity, but also CO۲ conversion. Wang et al.¹²⁹ added alkali metal ions (with the exception of Li⁺) to Fe/ZrO۲ catalysts. Among Na⁺, K⁺, and Cs⁺, (0.5–1.0 wt%)K(10 wt%)Fe/ZrO۲ exhibited the highest CO۲ conversion. Satthawong et al.¹¹⁶ investigated the effect of K addition on light olefin production from CO۲ hydrogenation over Al۲O۳-supported Fe–Co bimetallic catalysts. When the K/Fe atomic ratio was 1, the Fe–Co bimetallic catalysts yielded the highest amount of C۲–C۴ olefins. Detailed temperature-programed desorption (TPD) analyses demonstrate that the K۲O on the surface behaved in a manner to suppress the adsorption towards weakly bonded hydrogen which appeared to correlate with the formation of methane. Moreover, the addition of K was able to increase the basicity of the surface, through which more adsorption sites were created on the surface. In other words, the K promoter was capable of shifting the selectivity from methane to desired higher hydrocarbons by tuning the surface H/C ratios. Wei et al.¹¹⁴ studied the effect of sodium on iron-based catalysts in the CO۲ hydrogenation process. They reported that sodium can promote the surface basicity of catalysts, which was beneficial for CO۲ adsorption and the carbonization of Fe۲O۳, leading to more C۵–C۶ olefins (46.6%) and C۵+ hydrocarbons (30.1%). Combining the knowledge and experience accumulated, the same group made an exciting breakthrough in CO۲ conversion to gasoline fuels.¹⁸⁵ Inspired by the methanol-to-gasoline process and various applications of zeolite in hydrocarbon-related¹⁸⁶–¹⁸⁸ oligomerization, the Na–Fe۲O۴/HZSM-5 catalyst was prepared with the characteristic of selectively producing gasoline components (78%) over methane (4%) of all hydrocarbons at 22% CO۲ conversion. Characterization results indicate the newly developed catalyst worked in a multifunctional manner, wherein Na, Fe۲O۴, Fe۲C۲, and acid sites on zeolites were responsible for surface basicity, RWGS, FTS, and oligomerization to hydrocarbons, respectively (Fig. 9). More importantly, instead of functioning separately, granule-mixed catalysts gave a maximum gasoline component selectivity, indicating that selectivity is a function of proximity of the active species. Fierro et al.¹¹⁹ prepared a series of manganese-iron oxide catalysts with different Mn contents, and found the 0.05MnFe catalyst exhibited the highest CO۲ conversion and C۵–C۶ selectivity. The enhanced activity mainly resulted from the improved reducibility and the Mn-induced promotion of RWGS and FTS reactions. Choi et al.¹¹⁵ developed a new catalyst prepared by reduction of delafossite-CuFeO۲ and the catalyst can be

![Fig. 9 Reaction scheme for CO۲ hydrogenation to gasoline-range hydrocarbons through modified FTS route. Reprinted with permission from ref. 105. Copyright 2017 Nature.](image-url)
selectively produced undesired CH4. Interestingly, the combination of Fe and Co, Cu or Pd enhanced the catalyst activity obviously compared with their monometallic counterparts, indicating a strong synergetic effect and intimate proximity existed between the combined metal components. Also, the K addition further increased the CO2 conversion and the C2–C4 olefin production. In following work, the Fe–Co bimetallic catalysts with a wide range of Co/(Fe + Co) atomic ratios (i.e., 0.0–1.0 at per at) were selectively chosen for a systematic examination to unveil the synergetic regime of this bimetallic combination and the function of promoter in terms of adsorption properties.186,188 Evidently, doping Fe with appropriate amount of Co (e.g., Co/(Co + Fe) = 0.17 mol mol−1) can maximize the promotion of C2+ hydrocarbon production. Inspired by such significant bimetallic synergetic effect, Li et al.187 synthesized Fe–Co–Zr polymetallic fibers for CO2 hydrogenation, and obtained 27.5% C2–C4 olefins with the addition of K.

3.2 Methanol-mediated route
In addition to these proposed reaction pathways, some scientists also attempted to use methanol as a bridge and building unit to synthesize long-chain hydrocarbons via CO2 hydrogenation, and made a major breakthrough most recently.138 This newly developed reaction pathway is another alternative option for CO2 hydrogenation to hydrocarbons through an indirect way.

The products of FTS generally follow a statistical hydrocarbon distribution, which is known as the Anderson–Schulz–Flory (ASF) distribution.139 In the ideal case, the chain-growth probability (α) is independent of carbon chain length. Therefore, the product distribution is determined by the chain-growth probability (α). For example, if CO2 hydrogenation is through the modified FTS route, ASF distribution of FTS products limits the maximum selectivities of C5–C14 (gasoline range) and C12–C20 (diesel range) hydrocarbons to roughly 45% and 30%, respectively.140,141 To break the limitation of ASF distribution and get more gasoline or lower olefins, the methanol-mediated route is an ideal path. Enlightened by the superior selectivity to methanol (ca. 100%) on In2O3-based catalysts from CO2 hydrogenation,142 Sun et al.146 used In2O3/HZSM-5 composite to selectively produce 78.6% C5–C11 hydrocarbons with a high octane number through the methanol route, and broke the ASF restraint. In the proposed reaction pathway, CO2 first was converted to methanol on the In2O3 surface, which was further transformed to hydrocarbons on HZSM-5 via the hydrocarbon-pool mechanism. DFT calculation indicates that the CO2 was first chemisorbed on the oxygen vacancies on the In2O3, and the active site was not the metallic phase. Fujisawa et al.142 prepared composite catalysts obtained by the physical mixing of Cu–Zn–Al oxide and HB zeolite that was modified with 1,4-bis(hydroxymethyl)benzene, which were very effective for the production of C2+ hydrocarbons, and reached ca. 12.6% at 300 °C and 0.98 MPa. They proposed a reaction scheme of CO2 hydrogenation over the composite catalyst as illustrated in Fig. 11. The methanol was synthesized on the Cu–Zn–Al oxide catalyst, and methanol was converted to C2+ hydrocarbons on the zeolite, which proceeded simultaneously in a single catalytic bed. The preservation of the strong acid sites of the modified HB zeolite with hydrophobic surface improved the second-step CH3OH conversion activity.143

![Fig. 10](https://example.com/figure10.png)

**Fig. 10** Schematic diagram of CO2 hydrogenation on CeO2–Pt@mSiO2–Co core–shell catalysts. Reprinted with permission from ref. 118. Copyright 2017 ACS.
There are some differences between CO$_2$ hydrogenation and CO hydrogenation to hydrocarbons through the methanol-mediated route, such as the molecular polarity, number of C–O bonds and adsorption capacity of reactants. However, there are also some similarities, such as the subsequent reaction on the zeolites when methanol is formed. So, the design of bifunctional catalysts for CO$_2$ hydrogenation can be inspired by the syngas conversion catalysts. Recently, the products of syngas conversion over the bifunctional catalysts have broken through the traditional ASF distribution and giving the desired products selectively. Wang et al. prepared mesoporous H-ZSM-5-supported cobalt nanoparticles for conversion of syngas to hydrocarbons. The C$_2$–C$_4$ selectivity can reach as high as 70% which was due to the hydrocracking/isomerization of the higher hydrocarbons on the Bronsted acidic sites of H-ZSM-5. A series of core–shell catalysts (Fe–Zn–Zr@zeolites) were synthesized by Wang et al. to adjust product distribution, especially in an attempt to improve isoalkane content by the confinement effect. Over 80% isoalkanes among all hydrocarbons were produced on Fe–Zn–Zr@HZSM5-Hbeta catalyst.

Wang and co-workers also integrated the methanol synthesis and methanol-to-olefins reactions with a bifunctional catalyst, Zr–Zn (2 : 1)/SAPO-34. The C$_2$–C$_4$ olefin selectivity can reach 74% with a CO conversion of 11% at 673 K, thus breaking the limitation of ASF distribution. Furthermore, Wang et al. synthesized ZnGa$_2$O$_4$/SAPO-34 for CO$_2$ hydrogenation to C$_2$–C$_4$ olefins with a selectivity of 86% using the oxygen vacancies on ZnGa$_2$O$_4$ to activate CO$_2$ molecules. Additionally, the importance of oxygen vacancies was also evidenced by Sun and co-workers. They prepared a bifunctional catalyst composed of indium–zirconium composite oxide and SAPO-34 zeolite which offered C$_2$–C$_4$ selectivity as high as 80% at more than 35% CO$_2$ conversion. DFT calculations revealed that In$_2$O$_3$ was a unique catalyst in CO$_2$ activation and hydrogenation to methanol with its surface oxygen vacancies and that the reaction followed a mechanism comprising the cyclic creation and annihilation of oxygen vacancies. These results indicated that the incorporation of Zr into In$_2$O$_3$ created new kinds of vacancies with high concentration, which progressively enhanced the reaction rate evidenced by DFT calculations. It is worth noting that no obvious deactivation is observed over 150 h, indicating a promising potential for industrial application.

3.3 Mechanisms of C–C coupling

There is an essential and very large difference between CO$_2$ methanation and CO$_2$ hydrogenation to C$_2$–C$_4$ hydrocarbons, which is the C–C coupling barrier for C$_2$ hydrocarbon formation. In light of the hydrocarbon formation mechanism, the key point for producing long-chain hydrocarbons is controlling the active H/C to an appropriate ratio, wherein too much surface H* will lead to excessive hydrogenation and methane formation, while the opposite condition will offset the hydrogenation
ability and reduce the activity of CO₂ conversion. Satthawong and co-workers added different amounts of potassium to Fe–Co bimetallic catalysts to tune the product selectivity. The CO₂ adsorption was promoted and the H₂ adsorption was suppressed with increasing K content through CO₂–TPD and H₂–TPD; the C₅⁺ selectivity also increased with more potassium addition. However, when the K/Fe atomic ratio increased from 0.5 to 1, the CO₂ conversion decreased. They attributed the selectivity of the product to the type and concentration of chemisorbed hydrogen and carbon dioxide on the catalyst surface.²¹⁸ Apparently, tuning the surface H/C ratios to manipulate and optimize the product distribution appears to be decisive in the synthesis of C₂⁺ hydrocarbons via CO₂ hydrogenation.

The crucial step of hydrocarbon synthesis by CO₂ hydrogenation is first C–C bond formation and C–O bond cleavage. Many computational studies have been conducted to investigate the C–C coupling step over various catalysts.¹⁹⁹–²⁰⁷ Different metals showed diverse catalytic performances. Co- and Fe-based catalysts are widely used to catalyze CO₂ or CO hydrogenation to hydrocarbons.¹⁵⁸–¹⁶³ Cu with unfavorable ability for C–O bond cleavage usually converted CO₂ or CO to C₂. hydrocarbons²⁰⁴ or alcohols.²⁸,¹⁵⁰,¹⁶⁵–¹⁶⁸

### 3.3.1 C–C coupling over Fe-based catalysts

Fe-based catalysts are widely used in FTS for hydrocarbon production. Due to the similarity, Fe becomes one of the most important components in the catalysts for CO₂ hydrogenation to hydrocarbons. Pham et al.¹⁵⁵,¹⁵⁷ studied CO activation and hydrogenation over γ-Fe₅C₁₂(510) surface, the most exposed one among the various facets due to its stability.²¹⁷ The carbon chain growth was more favorable than CH₄ formation due to the high barrier of CH₂ and CH₃ hydrogenation.²¹⁵ Compared with the CO* insertion mechanism, CH₂* coupling appeared to be a possible C₂ hydrocarbon synthesis route on the γ-Fe₅C₁₂(510) surface. The chemisorbed CO* dissociated to become C* on the γ-Fe₅C₁₂(510) surface, and was hydrogenated to CH₂* species in the following step. C* + CH₂* and CH₂* + CH₂* were the most likely coupling pathways, and were characterized with carbide mechanism.

Recently Nie et al.²¹⁹ studied C–C coupling over Fe–Cu bimetallic catalysts (Fig. 12). CH* was proposed as the most likely monomer over both pure Fe(100) and Cu-doped Fe(100) surfaces, though CH* formation was quite different over the two surfaces. On the Fe(100) facet, CO₂ was directly dissociated to form CO* then to CH* through subsequent hydrogenation. Differently, the intermediate CO* was transformed to HCOO* then to CH* through hydrogenation and dissociation in sequence on the Cu-doped Fe(100) facet. The pure Fe(100) favored CH₄ synthesis with a low barrier of CH* hydrogenation, while Cu promoted C₂H₂ synthesis with a low barrier CH* + CH*. The CH₂* coupling pathway was also proposed as a plausible mechanism for C₂ hydrocarbon synthesis over other iron facets.²⁰⁹,²¹⁰ Clearly, the appropriate catalysts for CO₂ hydrogenation to hydrocarbons do not always go through the CO route (modified FTS route), which offers an alternative to break the restraint of the ASF distribution and the equilibrium conversion of CO₂ to methanol.

![Fig. 12 Reaction networks examined to identify energetically favorable C₁ species from CO₂ hydrogenation on (a) Fe(100) and (b) Cu–Fe(100) surface at 4/9 ML Cu coverage. Activation barriers are given in eV (the networks connected with red arrows represent the preferred path for CO₂ conversion to CH*). Reprinted with permission from ref. 109. Copyright 2017 ACS.](Image)
reaction. With the assistance of Co and the Cu$_{3}$(310) surface's special active sites, the formation of CH$_{2}^{*}$ was accelerated, and the CO* coupling mechanism was favored. Co and Ni were capable of catalyzing CO to CH$_{2}^{*}$ and further to CH$_{3}^{*}$ as the favorable monomer. Due to the low barrier of CO* insertion into CH$_{3}^{*}$ over Co(111), the Co-based catalysts favored chain growth. On the other hand, Ni-based catalysts were used for CO or CO$_{2}$ methanation with higher barrier of CO* insertion and lower barrier of CH$_{2}^{*}$ hydrogenation. Zhang et al. investigated the CO hydrogenation over Co-decorated Cu alloy catalyst, and stated that the Co–Cu(211) surface was conducive to ethanol formation rather than methane or methanol, and the C–C coupling was accomplished by interacting CO* with CH$_{2}^{*}$ and CH$_{3}^{*}$.

Zuo et al. explored ethanol synthesis by syngas over alloy-like CoCu(111) surface, and they found that CO* + CH$_{2}^{*}$ was the most likely pathway of coupling. The above computational studies demonstrate that CO*, as the main intermediate or the reactant during CO$_{2}$ hydrogenation, was able to interact with surface CO* or CH$_{2}^{*}$ species over Cu- and Co-based catalysts, through which C–C coupling was available for the formation of long-chain products.

3.4 Deactivation of catalysts for CO$_{2}$ hydrogenation to hydrocarbons

Lee et al. investigated the reasons for deactivation of Fe–K/γ-Al$_{2}$O$_{3}$ for CO$_{2}$ hydrogenation to hydrocarbons through XPS, HR-TEM, TPO, and Mössbauer spectroscopy. The reasons for deactivation are different at different positions in the reactor. As time progressed, the Fe$_{2}$O$_{3}$ was reduced to active phase γ-Fe$_{2}$C$_{3}$ and finally the γ-Fe$_{2}$C$_{3}$ was transformed to θ-FeC$_{3}$, which is not an active species for CO$_{2}$ hydrogenation. Hence, in the inlet reactor region, the deactivation pathway was phase transformation. Conversely, the main factor at the outlet part of the reactor was coke deposition.

Li et al. observed the remarkable metal sintering on supported FeCo/ZrO$_{2}$ catalysts which was responsible for the rapid deactivation of activity. In contrast, Fe–Co–Zr polymetallic fibers obtained by a one-step electrospinning technique showed stable activity over the reaction period. Co and Fe were dispersed in proximity to ZrO$_{2}$, but separately from each other, which, in turn, helped reduce the possibility of sintering. Active metals encapsulated in hollow zeolite or confined in nanotubes were also applied to resist metal sintering and increase catalyst stability, which are good references for CO$_{2}$ hydrogenation catalysts.

4. Conclusion and prospects

Environmental issues have pushed the necessity to reduce CO$_{2}$ emissions caused by the use of fossil fuels. Many efforts have been made to develop catalysts and understand the reaction mechanisms. Heterogeneous thermoautocatalysis is a promising direction for application in CO$_{2}$ conversion. The catalyst performance can be affected by many factors, such as metal–support interaction,
metal particle size and promoters. Ni-based catalysts are mainly used in CH4 production from CO2 hydrogenation. In addition, Co, Ru, Ir and Rh are also applied for CO2 methanation. Fe is an active metal for CO2 hydrogenation to C2+ hydrocarbons through modified FTS route or methanol-mediated route. Fe–metal bimetallic catalysts have shown markedly improved performance. The preparation of bifunctional catalysts combining metal oxides and zeolites is an effective way to control the product selectivity for C1 conversion. Some experiments and DFT calculations have given the encouraging result that CO2 conversion can be catalyzed through the formate intermediate route which is neither the CO route nor the methanol route, which will not be limited by the ASF distribution and the equilibrium conversion of CO2 to methanol. The crucial mechanisms of the initial C–C bond formation and C–O bond cleavage are different between Fe-based catalysts and Cu-based catalysts in DFT calculations.

In general, future research directions for CO2 hydrogenation are proposed as follows:
1. To adjust the catalyst surface H/C ratio and facilitate C–C coupling and generate high-value-added products.
2. To improve the support basicity and oxygen vacancies and increase the CO2 adsorption and activation.
3. To explore more novel catalytic materials and improve the catalyst stability.
4. To explore more active catalysts for low-temperature and energy-saving CO2 hydrogenation.

Conflicts of interest

There are no conflicts to declare.

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References

1 B. Kahn, Earth's CO2 Passes the 400 PPM Threshold—Maybe Permanently, Climate Central, 2016.
2 A Roadmap for moving to a competitive low carbon economy in 2050, European Commission, 2011.


