A short review of recent advances in CO$_2$ hydrogenation to hydrocarbons over heterogeneous catalysts

Wenhui Li,$^a$ Haozhi Wang,$^a$ Xiao Jiang,$^c$ Jie Zhu,$^a$ Zhongmin Liu,$^b$ Xinwen Guo,$^{a,*}$ and Chunshan Song$^{a,cc}$

CO$_2$ 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 CO$_2$ emissions. Much efforts and research are aimed at the conversion of CO$_2$ via hydrogenation to various value-added hydrocarbons, such as CH$_4$, lower olefins, gasoline, or long-chain hydrocarbons catalyzed by different catalysts with various mechanisms. This review provides an overview of advances in CO$_2$ 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 CO$_2$ 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 CO$_2$ concentration in the atmosphere, and global climate change caused by greenhouse gases has become a major challenge. Mitigation of CO$_2$ concentration in the atmosphere is in urgent need due to the continuing rise in atmospheric CO$_2$ 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 CO$_2$-eq. per year in 2050 with the objective to achieve carbon neutrality in the second half of the century.

At present, CO$_2$ can be reduced in three ways: control of CO$_2$ emissions, CO$_2$ capture and storage, and chemical conversion and utilization of CO$_2$.$^4,5$ Carbon storage is important for cutting CO$_2$ emissions quickly, but has an issue of potential leakage of CO$_2$.6,7 CO$_2$ can be regarded as a carbon source to offer an alternative to products containing value-added products and feedstocks. CO$_2$ obtained by capture not only can provide a pure carbon source for hydrogenation, but also can avoid the leakage problem caused by CO$_2$ storage. In addition, the National Aeronautics and Space Administration (NASA) also regarded the Sabatier reaction (CO$_2$ methanation) as a step in reining oxygen within closed cycle life support systems.$^6,7$ Even the CO$_2$ in industrial flue gas can be used directly as a feed for hydrogenation.$^8$ Therefore, an efficient utilization of renewable carbon resources is crucial and beneficial to maintain a long-term and sustainable development of our society.

CO$_2$ conversion requires energy input, and its conjunction with renewable energy would make this strategy more promising in terms of sustainability and environmental friendliness.

CO$_2$ reduction can be catalyzed through electrocatalysis,$^9$ photocatalysis,$^{10}$ and thermal catalysis. Among them, thermal...
produce H₂ using electricity generated with solar or wind and have already made great progress in water electrolysis to been devoted to solving the former challenge, and scientists theory (DFT) calculations. This review provides an overview of preferably involved CO₂ conversion mechanisms and the selectivity is the surface H/C ratio adjusted by the use of 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.

Fig. 2 Schematic illustration of CO₂-based sustainable production of chemicals and fuels.
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.⁷⁻⁸ CO₂ methanation is exothermic with high equilibrium conversion between 25 °C and 400 °C as shown in Fig. 3.¹⁹,⁴⁰ 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,¹⁴⁻⁴⁴ Ni,⁷,⁴⁵ Ru,⁶,⁴⁷ Rh,⁶⁸ and Pd.⁹,⁵⁰ Based on previously published results, the activity performance of various metal-based catalysts decreases in the following order: Ru > Rh > Ni > Co > Pt > Pd.³⁴ 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 Al₂O₃,²¹,⁵¹ SiO₂,²²,⁵²,⁵³ ZrO₂,²⁴ TiO₂,²⁵,²⁶ and CeO₂ (ref. 19) and zeolites.⁷ There are many factors concerning supports that can influence the performance of metal catalysts,⁴⁶ such as pore size,⁵⁷ structure of supports,⁴² surface chemistry, and metal-support interaction.⁴⁵,⁵⁸⁻⁶⁰ 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, *C,H₃, and *C,H₂O₂, 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 inter-ferograms 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-favored migration led to the formation of highly dispersed Ru in the reduced form, thereby exhibiting a superior activity (Fig. 5). Lin et al. also observed a similar phenomenon on Ni/TiO2 catalysts with different TiO2 crystal phases for both CO and CH4 formation. 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>XCH₄ [%]</th>
<th>Stability tests</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiO-MgO@SiO₂</td>
<td>Co-precipitation</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>Fixed-bed quartz tube</td>
<td>40 000</td>
<td>0.1</td>
<td>300</td>
<td>88</td>
<td>99</td>
<td>Stable after 100 h</td>
<td>74</td>
</tr>
<tr>
<td>15% Ni 2% La-hydroxide</td>
<td>Co-precipitation</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>10Ni/Co-ZrO₂</td>
<td>Ammonia evaporation</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-Al₂O₃–15% ZrO₂–15% TiO₂–15% CeO₂</td>
<td>Impregnation, coated on 3DFD structures</td>
<td>Fixed-bed quartz reactor</td>
<td>20 000</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 hydroxide</td>
<td>Co-precipitation</td>
<td>Fixed-bed quartz reactor</td>
<td>20 000</td>
<td>0.1</td>
<td>380</td>
<td>96</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>Ultrasound 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>91</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>Fixed-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>76</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>Fixed-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>Fixed-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>Fixed-bed quartz 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>Fixed-bed quartz 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/CeO₂</td>
<td>Single-step flame spray pyrolysis</td>
<td>Fixed-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., 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. 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. investigated the quantitative relationship between the concentrations of isolated Rh iso 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 Rh iso 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.

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. demonstrated that W doping can strengthen the Ni–Mg...
interaction, and enhance NiMgO$_x$ catalytic performance in terms of CO$_2$ methanation activity and stability. Furthermore, such W doping also increased the surface basic sites of NiMgO$_x$, which could improve CO$_2$ stabilization and its subsequent hydrogenation effectively. DRIFTS analysis further demonstrates that these resultant surface basic sites promoted the transfer of adsorbed CO$_2$ to monodentate formate species (m-HCOO$^-$) which was proposed as the key intermediate for the CO$_2$ methanation.

Similarly, Wierzbicki et al.$^{25}$ increased the surface basicity by adding 2 wt% lanthanum to Ni–Mg–Al hydrotalcite-derived catalysts, which remarkably enhanced the CO$_2$ 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 CO$_2$ methanation.$^{76}$ 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 CO$_2$ 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 CO$_2$ hydrogenation, such as multi-metal composite oxides, hydroxalite, 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, 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.$^{77}$ Recently, by a rapid quenching technique, Zong et al.$^{77}$ fabricated RQ Ni with peculiar UCS-abundant and tensile-strained structural characteristics. This catalyst has superior activity in the low-temperature CO$_2$ methanation and the TOF of CO$_2$ on RQ Ni is about 8 times that of the highest TOF of CO$_2$ 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 CO$_2$ methanation and more efforts should be aimed at fabricating undercoordinated catalytic materials.

Centi and co-workers have developed γ-Al$_2$O$_3$–ZrO$_2$–TiO$_2$–CeO$_2$ composite oxide-supported Ni catalysts$^{78}$ and Ni–Al hydroxalite$^{79}$ catalysts for CO$_2$ 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.$^{80-83}$ Zhen et al.$^{84}$ prepared Ni-based catalysts using MOF-5 (surface area of 2961 m$^2$ 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/SiO$_2$, and presented a superior stability after 100 h on stream for low-temperature CO$_2$ 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 Al$_2$O$_3$-supported counterpart. This catalyst even exhibited

![Fig. 6](image-url) (a) TOFs of CO and CH$_4$ formation at steady state at 300 °C over Ru/Al$_2$O$_3$ 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.41,42,86 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 mmol g⁻¹) compared with the impregnation (total H₂ uptake = 3.32 mmol g⁻¹) and deposition–precipitation (total H₂ uptake = 2.06 mmol g⁻¹) methods.88 The Ni/Co-ZrO₂ 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.89 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.90 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.91 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. Farrauto93 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.95

Duan et al.96 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⁺, 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 Ce₀.₉₅Ru₀.₀₅O₂ 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: \( \text{CO}_2 \rightarrow \text{CO} + \text{O} ightarrow \text{C} + \text{O} + 4\text{H} \rightarrow \text{CH}_2 + 2\text{H} \rightarrow \text{CH}_4 + \text{H} \rightarrow \text{CH}_3 \). Salmeron et al.⁹⁸ 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.⁹⁹ 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.⁹⁹ 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,¹⁸,⁹² 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.⁶² 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.¹⁰⁰ synthesized Ni/YSZ catalysts by different methods. On the Ni/YSZ catalyst obtained by impregnation method, graphitic filaments are formed on Ni⁹⁰ particles exposing flat surfaces, whereas thin layers of carbon are formed on Ni⁹⁰ 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 Ni⁹⁰ → 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,¹⁰¹ adding catalyst promoters,¹⁰¹ and developing advanced synthesis methods.⁹⁵ Li et al.⁸⁵ prepared MOF-derived Co-based porous carbon catalysts in which the active Co particles are separated by the graphite-like carbon avoiding metal sintering.

![Fig. 7 Potential energy diagram of three mechanisms of CO₂ methanation. Reprinted with permission from ref. 92. Copyright 2015 Elsevier.](image-url)
effectively. A special catalyst structure can also resist metal sintering effectively. Li et al.94 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.102,103 Substituting CO with CO2 as carbon source makes the reaction thermodynamically more difficult (see the reaction enthalpy below).104 Besides, not only will the challenge originate from the chemical inertness of CO2, but also from the competition with CO methanation.72 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.12,56,105 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 hydrocarbons106 (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>$S_{CH_{x}}$ [%]</th>
<th>$S_{C_{x}-C_{4}}$ [%]</th>
<th>$S_{C_{5+}}$ [%]</th>
<th>O/P</th>
<th>Ref.</th>
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</thead>
<tbody>
<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>300</td>
<td>350</td>
<td>73.5$^b$</td>
<td>75.5$^b$</td>
<td>22.8$^b$</td>
<td>1.9$^b$</td>
<td>4.1</td>
<td>115</td>
<td></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>116</td>
<td></td>
</tr>
<tr>
<td>10K13Fe2Co100ZrO$_2$</td>
<td>Electro-spinning</td>
<td>3600</td>
<td>3</td>
<td>400</td>
<td>21.9$^a$</td>
<td>20.5$^a$</td>
<td>36$^a$</td>
<td>34$^a$</td>
<td>18.4$^a$</td>
<td>4.2</td>
<td>117</td>
</tr>
<tr>
<td>CeO$_2$-Pt@mSiO$_2$-Co</td>
<td>Hydrothermal and impregnation</td>
<td>50 400</td>
<td>0.6</td>
<td>250</td>
<td>7.0</td>
<td>60.0$^b$</td>
<td>40.0$^b$</td>
<td>0$^b$</td>
<td>~</td>
<td>116</td>
<td></td>
</tr>
<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>32.7$^b$</td>
<td>64.9$^b$</td>
<td>7.7</td>
<td>119</td>
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<tr>
<td>0.05MnFe</td>
<td>One-step sol-gel process</td>
<td>6000</td>
<td>0.1</td>
<td>340</td>
<td>30.7</td>
<td>29.3$^a$</td>
<td>67.1$^a$</td>
<td></td>
<td>0.37</td>
<td>120</td>
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<tr>
<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>1$^b$</td>
<td>97$^b$</td>
<td>2$^b$</td>
<td>7.13</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>5.7</td>
<td>122</td>
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<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$^a$</td>
<td>1$^b$</td>
<td>13.1$^b$</td>
<td>78.6$^b$</td>
<td>~</td>
<td>105</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$^b$</td>
<td>5$^b$</td>
<td>93$^b$</td>
<td>3$^b$</td>
<td>6.1</td>
<td>123</td>
</tr>
<tr>
<td>Na-Fe$_2$O$_5$/HZSM-5</td>
<td>Granule mixin</td>
<td>4000</td>
<td>3</td>
<td>320</td>
<td>33.6</td>
<td>14.2$^b$</td>
<td>7.9$^b$</td>
<td>18.4$^b$</td>
<td>73.7$^b$</td>
<td>~</td>
<td>105</td>
</tr>
<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$^b$</td>
<td>1.5$^b$</td>
<td>71.7$^b$</td>
<td>26.8$^b$</td>
<td>~</td>
<td>124</td>
</tr>
<tr>
<td>Cu-Zn-Al/modified-HB</td>
<td>Physical mixing</td>
<td>1500</td>
<td>0.98</td>
<td>300</td>
<td>27.6</td>
<td>33.4$^b$</td>
<td>0.7$^b$</td>
<td>43.2$^b$</td>
<td>2.3$^b$</td>
<td>~</td>
<td>125</td>
</tr>
</tbody>
</table>

$^a$ Calculated from equation: $S_{i}(%) = \frac{m_{i,\text{out}}}{n_{i,\text{in}} - n_{i,\text{out}}} \times 100\%$, where $n_{i,\text{in}}$ and $n_{i,\text{out}}$ 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:

$$C_{i} \text{ hydrocarbon selectivity}(%) = \frac{\sum_{i=1}^{n} \text{mole of } C_{i} \text{ hydrocarbon } \times i}{100\%}.$$
dispersion increased monotonically with the increase of PZC value, while the particle size showed an opposite trend. The highest CO₂ conversion (54.4%) and selectivity of C₅⁺ hydrocarbons (31.1%) were achieved at PZC = 8.0. ZrO₂ (ref. 128) and CeO₂ (ref. 63 and 88) were used as support materials as well due to a solid grinding method. Wang et al.¹²⁹ conducted screening tests on catalysts prepared with different types of support materials, including SiO₂, Al₂O₃, TiO₂, ZrO₂, mesoporous carbon, and carbon nanotubes (CNTs), among which ZrO₂ attained the highest selectivity and yield for lower olefins. Chew et al.¹³⁰ used N-doped CNTs as a support to prepare Fe-based catalysts (Fe/NCNTs), and O-doped CNT- and SiO₂-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 SiO₂ 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 CeO₂ with various morphological properties, and examined their influence on the activity and selectivity in CO₂ hydrogenation to hydrocarbons. Results showed a strong reliance of catalytic performance on the reducibility of Fe species on the support. Among these CeO₂ 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 CeO₂.

Owing to their tailorable 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 CO₂ capture and even CO₂ activation.¹¹⁰–¹¹² Driven by their unique characteristic, researchers employed this group of materials as supports to prepare heterogeneous catalysts for CO₂ hydrogenation to hydrocarbons.¹¹³ Some metal-based MOFs and ZIFs, which were already proven to be active for hydrocarbon synthesis from either CO₂ or CO hydrogenation, were selectively chosen for activity tests in an attempt to collect first-hand data. Guo and coworkers proposed 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 α-Fe₂O₃ catalysts by a solid grinding method.¹¹³ Preliminary results indicated that ZIF-8-supported catalysts exhibited a higher CO₂ conversion than MIL-53-supported ones because the acidity on the MIL-53 impeded CO₂ 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 C₂⁺ selectivity, but also CO₂ conversion. Wang et al.¹²⁹ added alkali metal ions (with the exception of Li⁺) to Fe/ZrO₂ catalysts. Among Na⁺, K⁺, and Cs⁺, (0.5–1.0 wt%)K(10 wt%)Fe/ZrO₂ exhibited the highest CO₂ conversion. Satthawong et al.¹¹⁷° investigated the effect of K addition on light olefin production from CO₂ hydrogenation over Al₂O₃-supported Fe–Co bimetallic catalysts. When the K/Fe atomic ratio was 1, the Fe–Co bimetallic catalysts yielded the highest amount of C₂–C₄ olefins. Detailed temperature-programmed desorption (TPD) analyses demonstrate that the K₂O 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 CO₂ hydrogenation process. They reported that sodium can promote the surface basicity of catalysts, which was beneficial for CO₂ adsorption and the carbonization of Fe₂O₃, leading to more C₂–C₄ olefins (46.6%) and C₅+ hydrocarbons (30.1%). Combining the knowledge and experience accumulated, the same group made an exciting breakthrough in CO₂ conversion to gasoline fuels.¹¹⁶ Inspired by the methanol-to-gasoline process and various applications of zeolite in hydrocarbon-related¹₁⁷° oligomerization, the Na–Fe₂O₃/HZSM-5 catalyst was prepared with the characteristic of selectively producing gasoline components (78%) over methane (4%) of all hydrocarbons at 22% CO₂ conversion. Characterization results indicate the newly developed catalyst worked in a multifunctional manner, wherein Na, Fe₂O₃, Fe₃O₄, 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.¹¹⁸ prepared a series of manganese-iron oxide catalysts with different Mn contents, and found the 0.05MnFe catalyst exhibited the highest CO₂ conversion and C₂⁺–C₅ selectivity. The enhanced activity mainly resulted from the improved reducibility and the Mn-induced promotion of RWGS and FTS reactions. Choi et al.¹¹⁹ developed a new catalyst prepared by reduction of delafossite-CuFeO₂ and the catalyst can be

![Fig. 9 Reaction scheme for CO₂ hydrogenation to gasoline-range hydrocarbons through modified FTS route. Reprinted with permission from ref. 105. Copyright 2017 Nature.](image-url)
transformed in situ to active phase γ-Fe₅C₂. The CuFeO₂-derived catalyst selectively generated 65% C₅+ hydrocarbons with 16.7% CO₂ conversion, while the reference catalysts derived from bare Fe₂O₃, namely CuO–Fe₂O₃ mixture and spinel CuFe₂O₄, were much less active, and mainly produced light hydrocarbons.

3.1.3 Other metal-based strategies. Fe and Co both display excellent performances in FTS, but Co-based catalysts selectively produce methane when replacing CO with CO₂ as carbon source. Li et al. developed a deep understanding of the difference between CO and CO₂ hydrogenation on Co- and Fe-based catalysts. They found that the different adsorption strengths of CO and CO₂ affected the H/C ratio on different catalyst surfaces, wherein CO₃ was more active than CO than Co than Fe. If CO₂ hydrogenation goes through the CO-mediated route, the abundance of chemisorbed CO* is a prerequisite and the Co-based catalysts are the ideal ones.

Yang et al. prepared CeO₂–Pt@mSiO₂–Co core–shell catalysts for converting CO₂ to C₂–C₄ hydrocarbons. The two interfaces of Pt–CeO₂ and Co–SiO₂ were intentionally created depending on the unique core–shell structure, wherein the former accounted for converting CO₂ to CO through RWGS, while the latter accounted for the subsequent hydrogenation to C₂–C₄ through FTS. Notably, this novel catalyst yielded 60% of C₂–C₄ hydrocarbons in total carbon-containing products except CO (Fig. 10).

Another promising strategy to improve the yield of higher hydrocarbons is the application of bimetallic synergy. Satthawong and coworkers conducted comprehensive screening tests over Fe–M/Al₂O₃ (M = Co, Ni, Cu, and Pd) catalysts with fixed M/(M + Fe) atomic ratios at 0.1 at per at and their K-promoted counterparts. The combination of Fe with either Co, Cu, or Pd led to a significant improvement of chain-growth possibility and bimetallic promoting effect on C₂, hydrocarbon formation, while the Fe–Ni(0.1) catalysts, on the contrary, 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. Evidently, doping Fe with appropriate amount of Co (e.g., Co/(Co + Fe) = 0.17) can maximize the promotion of C₂₂ hydrocarbon production. Inspired by such significant bimetallic synergetic effect, Li et al. 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. 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. 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. 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, Sun et al. used In₂O₃/HZSM-5 composite to selectively produce 78.6% C₇–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. Fujiwara et al. prepared composite catalysts obtained by the physical mixing of Cu–Zn–Al oxide and HB zeolite that was modified with 1,4-bis(hydroxydimethylsilyl)benzene, which were very effective for the production of C₃₂ 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 C₂₃ 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.
There are some differences between CO2 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 CO2 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 C2–C11 selectivity can reach as high as ca. 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@HMS5-M-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 C2–C4 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 ZnGa2O4/SAPO-34 for CO2 hydrogenation to C2–C4 olefins with a selectivity of 86% using the oxygen vacancies on ZnGa2O4 to activate CO2 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 C2–C4 selectivity as high as 80% at more than 35% CO2 conversion. DFT calculations revealed that In2O3 was a unique catalyst in CO2 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 In2O3 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 CO2 methanation and CO2 hydrogenation to C2+ hydrocarbons, which is the C–C coupling barrier for C2+ 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 C₂⁺ 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. 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. Different metals showed diverse catalytic performances. Co- and Fe-based catalysts are widely used to catalyze CO₂ or CO hydrogenation to hydrocarbons. Cu with unfavorable ability for C–O bond cleavage usually converted CO₂ or CO to C₂ hydrocarbons and alcohols.

### 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. studied CO activation and hydrogenation over γ-Fe₂C₁(510) surface, the most exposed one among the various facets due to its stability. The carbon chain growth was more favorable than CH₄ formation due to the high barrier of CH₃ and CH₂ hydrogenation. Compared with the CO⁺ insertion mechanism, CH₂⁺ coupling appeared to be a possible C₂ hydrocarbon synthesis route on the γ-Fe₂C₁(510) surface. The chemisorbed CO⁺ dissociated to become CO on the γ-Fe₂C₁(510) surface, and was hydrogenated to CH₂⁺ species in the following step. CH₂⁺ then to CH⁺ through subsequent hydrogenation. The intermediate CO₂⁺ 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 C₂H₄ 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. 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 restraints of the ASF distribution and the equilibrium conversion of CO₂ to methanol.

### 3.3.2 C–C coupling over Cu-based catalysts

Cu-based catalysts are widely used for CO₂ hydrogenation. Ou et al. attributed the initial C–C bond formation to CO⁺ dimerization on the Cu(100) facet. The product distribution varied depending on different facets of Cu during the CO₂ hydrogenation. C₂H₂ was formed more favorably on the Cu(100) surface, and CH₄ was the main product on the Cu(111) surface under chemical conditions. CO was formed through both the direct dissociation of CO₂ over Cu(100) surface and the diatomic hydrogenation over Cu(111) surface. The CO⁺ dimerization was more favorable than CO⁺ hydrogenation to CH⁺ in terms of kinetics. The CO⁺ dimer then underwent further hydrogenation to form CH₄ on the Cu(100) surface as depicted in Fig. 13, while CO⁺ hydrogenation with CHO⁺ as the main intermediate produced CH₂. Recently Xiao et al. proposed a pH-dependent route for C₃ and C₄ product formation over Cu(111) facets. The preferred pathway for C₂H₄ formation under aqueous condition was CO → COH → COCOH → COCH₂COH → COCH₂COH → COCH₂COH → COCH₂COH → COCH₂COH → COCH₂COH, which is similar to the CO⁺ dimerization mechanism on the Cu(100) surface.

Compared with the CO⁺ dimerization mechanism, CO⁺ coupled with CH₄ also contributed to hydrocarbon formation over Cu-based catalysts. Wang et al. investigated the effect of Cu on higher alcohol and hydrocarbon formation. The higher alcohol formation was facilitated by lowering the barrier of CO⁺ coupling with CH₃⁺ using copper as the promoter over Cu-based catalysts. The C₂ oxygenate was the main product over Cu₁₅(310) surface by CO⁺ coupling with CH₃⁺ which could not occur over pure Cu(111) and Cu(100) facets. The coverage of CH₃⁺ has an essential role in this mechanism. Cu exhibited much better catalytic performance for the association reaction than Co and Ni, while Co benefited the dissociation...
reaction. With the assistance of Co and the Cu\(\text{S}_5\)\((310)\) surface’s special active sites, the formation of \(\text{CH}_2^*\) was accelerated, and the \(\text{CO}^*\) coupling mechanism was favored. Co and Ni were capable of catalyzing \(\text{CO}\) to \(\text{CH}_*\) and further to \(\text{CH}_2^*\) as the favorable monomer. Due to the low barrier of \(\text{CO}^*\) insertion into \(\text{CH}_2^*\) over Co(111), the Co-based catalysts favored chain growth. On the other hand, Ni-based catalysts were used for \(\text{CO}\) or \(\text{CO}_2\) methanation with higher barrier of \(\text{CO}^*\) insertion and lower barrier of \(\text{CH}_*\) hydrogenation.\(^{92,154,172,173}\) Zhang \textit{et al.}\(^{171}\) investigated the \(\text{CO}\) 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 \(\text{C}–\text{C}\) coupling was accomplished by interacting \(\text{CO}^*\) with \(\text{CH}_2^*\) and \(\text{CH}_3^*\).

\textit{Zuo et al.}\(^{156}\) explored ethanol synthesis by syngas over alloy-like CoCu(111) surface, and they found that \(\text{CO}^* + \text{CH}_2^*\) was the most likely pathway of coupling. The above computational studies demonstrate that \(\text{CO}^*\), as the main intermediate or the reactant during \(\text{CO}_2\) hydrogenation, was able to interact with surface \(\text{CO}^*\) or \(\text{CH}_2^*\) species over Cu- and Co-based catalysts, through which \(\text{C}–\text{C}\) coupling was available for the formation of long-chain products.

\subsection{3.4 Deactivation of catalysts for \(\text{CO}_2\) hydrogenation to hydrocarbons}

Lee \textit{et al.}\(^{174}\) investigated the reasons for deactivation of Fe–K/γ-Al\(_2\)O\(_3\) for \(\text{CO}_2\) 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 \(\text{Fe}_2\text{O}_3\) was reduced to active phase \(\gamma\text{-Fe}_5\text{C}_3\) and finally the \(\gamma\text{-Fe}_5\text{C}_3\) was transformed to \(\theta\text{-Fe}_3\text{C}\), which is not an active species for \(\text{CO}_2\) 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.

\textit{Li et al.}\(^{117}\) 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\(^{175}\) or confined in nanotubes\(^{176}\) were also applied to resist metal sintering and increase catalyst stability, which are good references for \(\text{CO}_2\) hydrogenation catalysts.

\section{4. Conclusion and prospects}

Environmental issues have pushed the necessity to reduce \(\text{CO}_2\) emissions caused by the use of fossil fuels. Many efforts have been made to develop catalysts and understand the reaction mechanisms. Heterogeneous thermo catalysis is a promising direction for application in \(\text{CO}_2\) 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


Review


