The current energy crisis caused by the depletion of fossil fuels has brought about the need to develop alternative energy sources. In addition, the indirect use of fossil fuels has accelerated global climate change owing to the increase in greenhouse gas emissions. The current statistics reveal that the carbon dioxide level will increase up to 800 ppm during this century and potentially up to 2000 ppm by 2300, which will lead to not only a dramatic temperature increase but also ocean acidification. One of the methods to resolve this problem is use of solar energy as an alternative to fossil fuel. Solar light-driven fuel generation technology is highly beneficial because of its clean nature. Additionally, this method can mitigate the current energy imbalance observed in specific regions because solar light can be harvested all over the world.

Figure 1 shows the schematic of a photovoltaic-electrolysis cell (PV-EC) system converting solar energy into fuel. Unlike a photoelectrochemical cell (PEC) in which the light absorber and fuel-generating interfaces are integrated in a single electrode, a PV-EC system has separate photovoltaic and electrolysis cells, thus allowing for further optimization. However, for the industrialization of solar-to-fuel conversion systems, the production of high-quality liquid products from the cathodic CO₂ reduction reaction along with rapid oxidation of water at the anode is the most essential requirement. Long-chain hydrocarbons are more advantageous transportation fuels than short-chain hydrocarbons. For instance, n-butanol exhibits nearly 30% higher volumetric energy density (26.9 MJ L⁻¹) than ethanol (21.4 MJ L⁻¹) and methanol (15.9 MJ L⁻¹). Such a high volumetric energy density makes the driving range of a vehicle comparable to that of a vehicle running on petroleum-derived gasoline. In addition, long-chain hydrocarbon fuels are less volatile and can easily be stored in fuel tanks. Moreover, the long hydrophobic carbon chain in these hydrocarbons makes them less hydroscopic, thereby making them compatible with the existing fuel infrastructure. Therefore, the production of long-chain hydrocarbon fuels with high selectivity is expected to reduce the fuel generation price to less than the market price.

One of the methods to resolve problems with fossil fuels is to use solar energy as an alternative. This method can also mitigate the current energy imbalance observed in specific regions because solar light can be harvested all over the world.

**ABSTRACT:** Electrocatalytic conversion of CO₂ into a long-chain hydrocarbon represents an important research direction in adding value to CO₂-based chemicals and realizing its practical application. Long-chain hydrocarbons may change the current fossil fuel-based industry in that those chemicals have a similar energy density as gasoline, high compatibility with the current infrastructure, and low hydroscopicity for pipeline distribution. However, most of the electrocatalysts produce C₂, C₃, and C₄ chemicals, and methods for producing long-chain hydrocarbons are not available thus far. Interestingly, nature utilizes many enzymes to generate long-chain hydrocarbons using C₂ building blocks and suggests key mechanisms, inspiring new perspective in the design of electrocatalysts. In this Perspective, we present case studies to demonstrate how CO₂ and its reductive derivatives interact with the electrode surface during C–C bond formation and introduce how these issues are addressed in biological systems. We end this Perspective by outlining possible strategies to translate the natural mechanism into a heterogeneous electrode.
Surprisingly, a biological complex, coenzyme A (CoA), can be carefully investigated with comprehensive understanding. In this system, the C−C coupling reaction mechanism should be understood, for example, the formation of long-chain hydrocarbons by the aforementioned CO coupling reaction reported with synthetic catalysts. Because of the selectivity issue, mechanistic investigations for the C−C coupling reaction have been conducted to only a few metal electrodes. Previous studies have demonstrated that CoA electrodes inherently possess the ability to produce more reduced hydrocarbon products such as methane (CH₄), ethylene (C₂H₄), ethanol (C₂H₅OH), and n-propanol (C₃H₇OH). This unique feature of the Cu surface can be explained in terms of the binding energy of adsorbed CO (*CO), which is the key intermediate for the formation of long-chain hydrocarbons. Cu is the only pure metal positioned around the top of the volcano-type relation and satisfies the Sabatier principle. The moderate affinity of the Cu surface for *CO enables the stabilization of *CO as a precursor for further reduction reactions. Figure 2 depicts proposed reaction pathways for the electrochemical conversion of CO₂ to *CH₃ or C₂ products on a Cu surface. CO dimerization has been suggested to be the key step for C−C coupling at low overpotentials. Calle-Vallejo et al. proposed that the CO dimerization starts with electron transfer to form the *C₂O₂¹⁻ intermediate, which is later protonated to *CO−COH. The decoupling of proton and electron transfer is supported by the pH-dependent behavior of C₂H₄ formation on Cu(100) surfaces on the RHE scale. Recently, Montoya and co-workers also found that the CO dimer configuration, in which both carbon atoms are bound to the surface, can be stabilized by a charged water layer on both Cu(111) and Cu(100). In contrast, at high overpotentials and turnover rates, the hydrogenation of *CO is kinetically facile compared to the C−C coupling in *CO. The *CO first undergoes hydrogenation to formyl (*CHO) or hydroxymethylidyne (*COH) species as a rate-limiting step, which leads to methane as a major product and methanol as a minor product. The electrokinetic studies of CO reduction support that the RDS proceeds with a concerted proton−electron transfer from pH-independent behavior on the RHE scale. At high overpotentials, C−C coupling is likely to occur between the intermediates produced from hydrogenated *CHO or *COH rather than *CO. Montoya and co-workers calculated the kinetic barriers for C−C bond formation between the adsorbates derived from *CO on a Cu(211) surface. The results showed...
that the direct dimerization of $^*$CO is the most difficult process from a kinetic point of view. As the extent of hydrogenation is increased, the kinetic barrier is decreased.

Empirically, highly selective C−C coupling to produce liquid carbon fuels has been realized through electrochemical reduction of CO in a basic solution. Kanan et al. have shown that the oxide-derived Cu electrodes can produce ethanol, acetate, and n-propanol with a faradaic efficiency of 57% at −0.3 V vs RHE in a CO-saturated 0.1 M KOH solution.28 Earlier studies by Hori et al. also exhibited that CO reduction on a Cu electrode can promote the formation of C$_2$H$_4$, C$_2$H$_5$OH, and C$_3$H$_7$OH over CH$_4$ at less negative overpotentials in high-pH solutions.29 This corresponds to the low-overpotential C−C coupling pathways (C$^*$O dimerization)9. In addition, Bertheussen and co-workers empirically proposed acetaldehyde (CH$_3$CHO) as the key intermediate for the formation of C$_2$H$_5$OH on oxide-derived Cu electrodes, and this was confirmed by the direct reduction of acetaldehyde.30 The reaction started with C$^*$O dimerization followed by hydrogenation and proceeded via the following pathway: $^*$OCCHO → $^*$OCHCHO → $^*$OCHCHO → $^*$OCHCH → $^*$OCH$_2$ → CH$_2$CHO on a Cu(211) surface. Therefore, C$^*$O dimerization is the most efficient pathway known to date to produce long-chain carbon fuels.

C−C coupling can be also found in reduced dinuclear metal complexes. Dinuclear copper(I) complex is the only catalyst capable of converting CO$_2$ to oxalate electrochemically in an acetonitrile solution at readily accessible potentials (0 V vs NHE).31,32 In principle, the electrochemical or chemical reduction of a dinuclear Cu(II) complex leads to the formation of a Cu(I) complex, which can produce an oxalate-bridged Cu(II) dimer in the presence of CO$_2$. Upon treatment with dilute acid or lithium perchlorate, the coordinated oxalate is detached from the coordination sphere and regenerates the starting Cu(II) complex. In addition, Saouma and co-workers developed a reactive Fe(I) complex supported by tris(phosphino)borate ligands, [PhBP$_3$CH$_2$Cy]Fe(I), that also exhibit coupling of CO$_2$ in tetrahydrofuran (THF).33 Reductive coupling of CO$_2$ to oxalate is catalyzed by an electronically saturated iron complex formed by the coordination of two THF solvent ligands and CO$_2$ to the Fe(I) center. In the coordinated complex, the unpaired electron was delocalized from the Fe center to the coordinated CO$_2$ ligand (Fe(II)$^*$−CO$_2$ species). Similarly, Horn and co-workers found that the dinuclear Ni(I) complex carries out a reductive coupling of CO$_2$ to produce an oxalate-bridged dinickel(II) complex.34 To close the synthetic cycle, KC$_8$ was employed as a reducing agent in a N$_2$ atmosphere and the original Ni(I) complex was obtained. These previous studies suggest that C−C coupling in a dinuclear complex is promoted by the
interaction between the electronically saturated coordinated CO$_2$ anions.

The electrochemical reduction of CO$_2$ has been challenging, despite the development of many catalysts over the past few years. The challenges include the low activity, product selectivity, and stability of the catalysts, which make them unsuitable for practical applications. In addition, these catalysts seem to produce mostly C$_1$ and C$_2$ products. Although the use of preproduced CO instead of CO$_2$ yields C$_3$ products, long-chain products cannot be achieved. This implies that most of the artificial electrocatalysts are not suitable for C–C coupling. Therefore, extensive work is required to develop new catalysts capable of overcoming these challenges to produce long-chain hydrocarbon fuels.

Interestingly, nature has addressed these issues with its own active catalytic complexes. Living systems are characterized by remarkable molecular functions, which can be redesigned for in vivo synthesis of long-chain hydrocarbon fuels such as -hexanol, -octanol, and even some polymeric compounds. Because these reactions include efficient CO$_2$ fixation and its subsequent coupling, deep insight into the underlying biochemical principles can inspire us to develop synthetic catalysts capable of producing the desired value-added fuels with high selectivity and quantitative yields. Compared to the in vivo fuel production methods using enzymes and metabolites, in which the highly reversible nature of each component needs to be managed, synthetic catalysts are more adaptive to the sequestration process, and thus, the turnover rate of the catalytic system can be easily optimized. Combining these two approaches paves a new path to the utilization of CO$_2$, which is highly abundant in nature and inexpensive, and to realization of cost-effective carbon cycling. In this context, from now on, we will discuss the biological pathways and their possible applications in developing synthetic catalysts for the production of long-chain hydrocarbon fuels.

CoA and its thioester derivative, acetyl-coenzyme A (acetyl-CoA), are reported to participate in over 100 different reactions in intermediary metabolism of microorganisms. One of the most important metabolic reactions they are involved in is the C–C coupling of short-chain carbon building blocks, for example, the alcohol–acyl transferase reaction to produce various acetate esters. These acetate ester intermediates are then reduced to produce long-chain liquid fuels. Indeed, various Clostridium species can produce n-butanol (C$_4$) biochemically, where n-butanol is assembled from the direct condensation of two acetyl monomers (C$_2$) and their subsequent reduction reactions. The early stages of the CoA involved in the C–C coupling pathway of acetyl groups to n-butanol are shown in Figure 3. The acetyl groups are attached to CoA, and continuous formation of disulfide bridges between the two acetyl-CoA species brings the acetyl groups adjacent to each other, thus triggering the Claissen condensation reaction to produce a butyl group. The butyryl-CoA is then reduced to n-butanol with the help of butyryl-CoA dehydrogenase (Bcd), the electron transferring proteins A and B (EtfAB), and the bifunctional aldehyde alcohol dehydrogenase (AdhE2). However, these reactions are reversible and hence proceed only up to the equilibrium point. Therefore, many efforts have been made to enhance the yield of n-butanol through genetic engineering of key enzymes by taking into account the directionality of the reaction. Thus far, a highest n-butanol yield of 88% with a high flux production and an effective titer of up to 30 g/L of n-butanol in E. coli has been achieved by Shen et al. by using trans-enoyl-CoA reductase (Ter), which causes irreversible reduction of butyryl-CoA. Interestingly, this approach can also be applied to synthesize even longer chain hydrocarbon fuels, and Figure 3 shows the extended CoA-dependent pathways for producing C$_5$, C$_6$, and
C$_8$ species from acetyl groups. Dekishima et al. reported that the carbon chain can be elongated from butyryl-CoA (C$_4$) to hexanoyl-CoA (C$_6$) by utilizing the β-ketothiolase (BktB) enzyme. The BktB enzyme induces C–C bond formation between the β-site of butyl groups and the carbonyl site of acetyl groups to yield 3-ketohexanoyl-CoA, which is the precursor for n-hexanol, and suppresses the formation of isomers such as 2-ethyl butanol or 3-ethyl butanol. Similarly, the same β-site-directed Claisen condensation between two butyl-CoAs is reported to produce 1-octanol. More interestingly, the reaction scheme is similar to that of a polymerization process and can be applied for synthesizing polyhydroxyalkanoate, which is a representative biodegradable plastic. Sinskey et al. demonstrated the sequential chain addition of butyryl-CoA to yield C$_n$, C$_{12}$, and C$_{2n}$ species as the reaction products using phbC gene expressed E. coli. This discussion highlights that unlike the electrochemical approach, which involves the formation of long-chain hydrocarbon fuels by sequential chain addition from C$_1$ to C$_2$ to C$_n$ and so on, biological systems can effectively realize the long-chain liquid fuel formation pathways by direct coupling of short-chain carbon building blocks.

Inspired by these C$_2$ condensation reactions found in living systems, researchers have attempted the synthesis of C$_4$ products from ethanol (C$_2$ product) using molecular catalysts and thermally activated process. In general, the catalytic reactions for the conversion of these alcoholic substrates are surprisingly rare. One ideal example is the Guerbet reaction, a method that enables facile C–C bond formation with normally unreactive alcohols. In a typical catalytic reaction, as shown in Figure 4a, an alcohol is dehydrogenated to form an aldehyde, which then undergoes Aldol condensation followed by rehydrogenation to produce a long-chain alcohol. This condensation and reduction process is very similar to the CoA-dependent C–C coupling pathway in which both reactions are mediated by a nucleophilic molecular substrate. However, unlike Claisen condensation in the CoA-dependent pathway, this coupling reaction leaves the OH$^-$ group during the reaction. Hence, the reaction kinetics in this case highly depends on the pH and temperature. Thus, both the selectivity and conversion yield are severely limited by the experimental conditions. Some progress was made in the pioneering studies by Ishii and co-workers with a homogeneous iridium catalyst, [Ir$^{(cod)}$ (acac)] (acac = acetylacetone, cod = 1,5-cyclooctadiene), where the basic iridium center acts as an active site stabilized by phosphine ligand. In this study, they reported n-butanol selectivity of up to 67% at 12% conversion. More recently, Dowson et al. reported that the Ru- and phosphine-based molecular catalysts oxidize the ethanol and produce n-butanol with 94% selectivity at over 20% conversion.

In addition to the Guerbet reaction on molecular catalysts, a condensation reaction between the two alcohols has also been demonstrated on heterogeneous catalysts by thermally activated processes. Similar to the molecular catalyst, heterogeneous substrates also necessitate highly basic active sites. Recently, the Ca-rich hydroxyl apatite (Ca-HAP) has been reported to be a potential platform for the thermally driven selective conversion of ethanol to n-butanol. In such catalytic systems, the catalytic activity and selectivity of Ca-HAP catalysts are affected by the Ca/P molar ratios of the catalysts, and the Ca-HAP catalysts with higher Ca/P molar ratios exhibit high catalytic activity and n-butanol selectivity. Ogo et al. suggested that the surface basicity is directly related to the conversion efficiency of ethanol and demonstrated that by substituting Ca with Sr, which has higher basicity, a coupling reaction can be made to proceed even at temperatures lower than 180 °C. According to the time-dependent product analysis, they proposed that the oxygen atom of ethanol is likely to be attached on the basic sites, that is, O=Ca−O or O=Sr−O, and transformed to acetaldehyde in the same manner as that observed when molecular catalysts are used. The aldehyde adsorbs produce crotoaldehyde by Aldol condensation and then reduce to n-butanol. Taken together, controlling acid–base properties of materials and their activities in the individual reaction steps are the key parameters in C$_2$ chemical-mediated long-chain hydrocarbon synthesis. However, both the molecular catalysts and heterogeneous substrates in thermally activated processes require stepwise oxidation and rehydrogenation of the intermediates, which increase the activation energy and limit the kinetics. Hence, realizing their practical applications seems distant at the moment. The realization of these reactions in electrochemical systems may provide a new breakthrough in the field because the resulting systems will be capable of using water as a proton source, producing value-added chemicals at ambient conditions, and being easily combined with renewable energy sources. Interestingly, some ketone and aldehyde compounds, which can serve as building blocks for the synthesis of long-chain
The ultimate production of long-chain hydrocarbon fuels from abundant and inexpensive CO₂ by electrochemical reduction will provide a new approach to reduce the carbon footprint and close the carbon cycle.


