CHAPTER 15

Techno-economic analysis of nanomaterials in CO_2 capture and conversion technologies

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15.1 Introduction

Climate change and global warming, caused by excessive carbon emissions and other industrial activities, nowadays is one of the most worldwide concerns and requires urgent solutions. Climate change practically cannot be mended by one individual, but requires all of us around the world to work together. This means that we as human beings need international collaboration in solving the problem. Despite having the intergovernmental panel on climate change (IPCC) set up since 1988, we are still far from success. Limitation or prevention of CO_2 emissions by improving activities that remove or abate them from the atmosphere is how we look at the CO_2 mitigation. Electrification, hydrogen, bio-based feedstock, and CO_2 capture, utilization, and storage (CCUS) will help to reduce the emissions, which is demanded to keep the global warming to be less than 1.5°C (Wigley et al., 2018). However, more than 80% of energy consumption has been based on fossil resources (January 2021 Monthly Energy Review, 2021). Hence, it is urgent to control the CO_2 emissions by taking effective measures to capture and convert CO_2, for example, into fuels and valuable chemicals, that is, methanol, ethylene, dimethyl carbonate, and many more (MacDowell et al., 2010), as CO_2 can be seen as a building block in many versatile processes.

A wide range of CO_2 capture, utilization, and storage techniques rely on the current available nanomaterials, nanoadsorbents, and nanomembranes, in which each technology has its own technical advantages and disadvantages (Lee et al., 2016). Technoeconomic analysis is also unavoidably required to compare materials, technologies, and processes in a systematic and fair manner. Compared to CO_2 storage, CO_2 conversion or CO_2 utilization seems to be a better approach in terms of cutting down the operational costs, stabilities of the systems, and maintenance complexities, although there are various challenges, that is, efficiency and conversion of the process (Ali et al., 2020; Valluri & Kawatra, 2021).

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In addition, many researchers have evaluated the CO_2 absorption/regeneration performance of nanoabsorbents at a laboratory scale (Lee et al., 2016). Most studies analyzed the performance improvement compared to the base fluid. However, the industrial CO_2 absorption system is different from the laboratory-scale systems, and it must be scaled up with energy consumption analysis. The current limitation is that no industrial system research or similarity analysis has been performed using nanoabsorbents (Elhambakhsh et al., 2020). The CO_2 capture technologies with nanomaterials as a working fluid are optimized by considering the operating power and CO_2 absorption performance, which can save a huge amount of energy consumption in industrial systems (Kim, Xu, et al., 2021).

This study focuses on the technoeconomic analyses of CO_2 capture and conversion technologies using recently developed nanomaterials, especially membranes. The technoeconomic analysis is a good method to evaluate the feasibility of a project before scaling it up from a laboratory to a pilot scale and then to a commercial facility. Also, technoeconomic analysis provides an estimation of total purchased equipment costs, total installation cost, and total capital investment.

15.2 CO_2 capture techniques

15.2.1 CO_2 capture designs

Membrane technologies offer a valid solution for a wide variety of CO_2 mitigation actions, starting from the separation of CO_2 which is considered to be a crucial step for carbon capture (Lei et al., 2020). Amongst all types of membranes, the organic membranes have inherent significant advantages such as high permeability, low cost, easy processing, and reasonable gas separation properties (Wang et al., 2016). Membranes in general exhibit excellent chemical resistance and thermal stability with high mechanical strength (Khdary & Abdelsalam, 2020). They have excellent aging resistance which is important for the actual application of CO_2 separation (Adewole et al., 2013). Wang et al. (2015) reported that an improvement in gas permeance of the membranes is more critical for reducing the technology's cost than an enhancement in the membrane's selectivity. However, nanomembranes have been recently developed for the higher efficiency of CO_2 separation.

Chemical absorption is found to be more suitable than physical absorption to achieve postcombustion CO_2 capture in power plants (Kumar et al., 2020). However, a large amount of energy is consumed in the regeneration process to break the chemical bonds. The physical absorption method captures CO_2 through solubility-based mass transfer, and its performance is inferior to that of the chemical absorption method (Kim, Xu, et al., 2021). Nanoabsorbents have thus become a new type of energy nanomaterials that can reduce CO_2 emissions. CO_2 capture by solid adsorbents offers benefits such as high adsorption capacity, easy recovery, high uptake efficiency under humid conditions, easy handling, and materials stability (Wang et al., 2011).

Applications of the adsorbent materials for CO_2 capture are gathered and shown in Table 15.1. Acevedo et al. (2020) reported that the adsorption of CO_2 in the prepared activated carbons is favorable from the energy and kinetic point of view, as these, accompanied by the presence of wide micro − mesoporosity, favor the entry of CO_2 into the micropores. Wickramaratne and Jaroniec (2013) reported that activated carbon spheres possess a large fraction of fine micropores (<1 nm) and high surface area, resulting in an excellent CO_2 adsorption capacity at both ambient and low pressures.

15.2.2 CO_2 conversion and utilization

The field of nanotechnology has several advantages over traditional approaches with regard to the conversion of CO_2 to more useful materials. Nanomaterials usually have a greater degree of porosity as well as larger surface area, compared to the conventional materials of the same kind. The importance of these materials were realized when the researchers found that the size can influence the physiochemical properties of a substance (Khan et al., 2019). The benefits of nanomaterials are often ascribed to their high surface to volume ratio, high surface energy, quantum size effect, and high electron conductivity (Rezk et al., 2020). However, nanomaterials in CO_2 conversion applications are still underresearched. In addition, CO_2-to-fuels plays the more significant role in CO_2 emission management strategies than CO_2-to-chemicals as the fuels

Table 15.1 Nanomaterial of CO_2 adsorption capacity.

	Properties			
Adsorbent materials	**Surface area ($m^2 g^{-1}$)**	**Temperature (°C)**	**Pressure (kPa)**	**CO_2 adsorption capacity (Mol kg^{-1})**
Carbon-based materials				
ACCu3−1073 (Acevedo et al., 2020)	638	0	100	217 $mgCO_2\ g^{-1}$
Carbon spheres (Wickramaratne & Jaroniec, 2013)	1924	25	20	1.42
Silica/alumina/zeolites				
Zeolite-Y (Dabbawala & Ismail, 2020)	773	25	100	5.9
Zeolite geopolymer composite (Minelli et al., 2018)	791	35	100	2.5

market is globally larger than the market of organic chemicals. The emissions of CO_2 are mainly associated with the production of energy from fossil fuels.

The utilization of captured CO_2 as a feedstock in the chemical industry provides both opportunities for reducing CO_2 accumulation and increasing independence from fossil resources by replacing fossil-derived and energy-intensive materials (Otto et al., 2015). Nanotechnology has attracted researchers toward its utilization in several energy systems. CO_2 utilization is seen as a promising driver to carbon capture and storage since the production and sale of CO_2 products could provide an economic incentive to carbonization.

CO_2 conversion and utilization is an important part of CO_2 management strategy, although the amount of CO_2 that can be converted to chemicals and materials is relatively small compared to the amount of anthropogenic CO_2 emitted from fossil fuel combustion. CO_2 is a carbon source and a unique substance. CO_2 utilization represents an important aspect of greenhouse gas control and sustainable development.

Table 15.2 presents the potential CO_2 utilization processes by CO_2-based feedstock. Currently, the total global CO_2 utilization is less than 200 million tons per year (Otto et al., 2015).

15.2.3 Nanosized zeolites for CO_2 capture and conversion

Zeolites are considered feasible to act as CO_2 capture materials because of their high surface areas and adjustable pores. Zeolite's functionality enables the selective adsorption of large quantities of CO_2. The primary cost in the CO_2 capture process is to obtain the energy required to regenerate the CO_2-loaded adsorbent after it has become saturated with CO_2. In zeolites, the strength of the interaction of CO_2 with the pore surface can be tuned to minimize the energy required for capture of a given amount of CO_2 (Abdelrahman et al., 2021). The surface area and pore volume of the

Table 15.2 Current CO_2 utilization (Otto et al., 2015).

Industry	Usage ($MtCO_2$/year)
Urea	114
Methanol	8
Dimethyl ether (DME)	3
Methyl tert-butyl ether (TBME)	1.5
Formaldehyde (CH_2O)	3.5
Carbonates	0.005
Polycarbonates	0.01
Inorganic carbonates	50
Technological	28
Algea for the production of biodiesel	0.01
Total	200

synthesized nanozeolite were higher than those of zeolite, supporting its potential as an effective adsorbent for CO_2 capture. Such features would then enhance the CO_2 capture and conversion. Furthermore, decreasing the size of the crystals of zeolite to 10−15 nm results in a considerable increase in the external surface areas, which consequently enhances the associated properties such as surface charge, hydrophilicity, and external surface activity (Awala et al., 2015; Grand et al., 2020). Thi-huong et al. (2016) reported that the synthesized nanozeolite has a high adsorption capacity and good suitability for use as an adsorbent for CO_2 capture. Moreover, Rzepka et al. (2019) reported that the kinetics of the adsorption of CO_2 was affected by varying mass transfer and possibly heat transfer resistances that occurred in the nanosized zeolite. The nanosized zeolites have received much attention because of their large external surface areas and reduced diffusion limitations, compared to ordinary zeolite crystals of micrometer size, thus the nanozeolite may be useful for CO_2 capture.

15.3 The role of nanoparticles and nanomaterials in CO_2 capture

This section describes how to develop CO_2 capture technologies using nanomaterials. The researchers have brought nanotechnology into CO_2 utilization in several energy systems. The atmospheric CO_2 is increasing as a result of power plants, leading to global warming. The functionality of nanomaterials and nanoparticles is a major player in technology involving the capture of CO_2. Researchers are working with nanomaterials to enhance the efficiency of existing technologies. Wu et al. (2019) synthesized mesoporous silicates to explore their physical adsorption process with CO_2, and the raw materials came from a large number of waste coal gangue discharged from the coal mining process, which not only realized the green application of waste, but also reduced the emission of CO_2. Global CO_2 emissions are rising, and the impact of environmental pollution has greatly affected the atmosphere. However, researchers have suggested techniques and measures to prevent these types of situations. Advances in technology and processes are of critical importance in polluting environments. Valluri and Kawatra (2021) reported that chemical absorption CO_2 capture is the most competitive and economically viable method for CO_2 capture from fossil fuel-fired power plants and that the increased efficiency provided by surfactants allows even dilute sodium carbonate solutions to achieve 99.9% CO_2 capture. Thakur and Sonawane (2019) showed that nanofluids can give more absorption efficiency than conventional solvents. These nanomaterials have a high surface to volume ratio and the can be synthesized to have specific physicochemical properties (Alonso et al., 2017). Lee et al. (2016) evaluated the performance of MeOH-based nanoabsorbents using a laboratory-scale combined CO_2 absorption/regeneration system, They compared performance of two nanoparticles of Al_2O_3 and SiO_2 on the basis of cycles, and a common based fluid methanol was used. Enhancement was higher in SiO_2.

The CO_2 capture process is the extraction of CO_2 from flue gas (nitrogen, water, dust particles, and CO_2), which usually requires the capture by solvent absorption (Yingying et al., 2019). Instead of basic CO_2 storage, advances over time have led to research on the direct conversion of CO_2 into useful commodities. Nanotechnology plays an important role in reducing CO_2 around the world. Research developments show the ability of nanotech-enabled materials to provide potential solutions to energy-efficient, cost-effective, and high-volume CO_2 capture challenges. Nanotechnology is considered to be able to provide a feasible material solution to this complex technical problem. Bhoria et al. (2019) informed that the combined action of hybrid nanostructures of metal–organic frameworks and graphene oxide counterparts toward enhancing CO_2 separation performance, which was exemplified in both adsorbent and membrane modes. The solution for carbon capture uses materials from nanostructured membranes. Chen, Shi, et al. (2020) have synthesized nanostructure CaO/CuO composites by a microemulsion method to improve CO_2 capture performance. Xu et al. (2019) reported the synthesis of a nanostructured zeolite NaX sample led to a better separation performance compared with the commercial microsized zeolite NaX. The optimization results indicate that the energy consumption of the process with nanostructured zeolite is about 30% lower while achieving a higher CO_2 purity and productivity compared with a process employing a commercial microsized zeolite. Later, Ding et al. (2018) reported a hierarchical ZIF-L nanostructure with a higher specific surface area of $304\ m^2\ g^{-1}$ synthesized through a hydrothermal method and the CO_2 capture performance was enhanced ($1.56\ mmol\ g^{-1}$) as compared with the reported two-dimensional ZIF-L leaves ($0.94\ mmol\ g^{-1}$). Mesoporous nanohybrid of (3-aminopropyl) triethoxysilane (APTES)-ZnO-multiwalled carbon nanotubes were used to prepare nanocomposite materials for CO_2 capture. Metal oxide nanoparticles have been used an efficient nanomaterials due to the large surface area and quantum effects comparable to atoms and bulk materials, which makes metal nanoparticles attractive and efficient to utilize as adsorbents for CO_2 capture (Jena et al., 2019). Wahab et al. (2021) have synthesized nanoporous-graphitic CN (gNPCN) materials with an inbuilt high N content (48%) and high surface area, which is needed for enhancing the efficient CO_2 adsorption.

Table 15.3 summarizes the CO_2 absorption performance of nanoparticles. Bahmanyar et al. (2011) reported that nanoparticles improved the mass-transfer

Table 15.3 Summary of absorption performance of nanoparticles for CO_2 capture.

Nanoparticles	Particle size	Results	References
Fe_3O_4	20 nm		–
NiNPs	43 nm	CO_2 absorption rate increased by 77%	–
CNFs	< 0.7 nm	CO_2 capture capacity retains $>95\%$	–
Fe_3O_4@SiO_2-lysine	17–20 nm	CO_2 capture up to 88%	–

performance of the system. Zhang et al. (2020) discovered that the increase of nanoparticle size led to the increase of dispersion stability of nanoparticles as well as the decrease of nanoparticle surface activity, whereas larger nanoparticles can increase the rigidity of bubbles and prevent them from coalescing. The increased dispersion stability and small bubbles made the larger nanoparticles more effective. Moreover, Ali et al. (2020) reported that CO_2 adsorption material based on the core–shell structured SnO_2 hybridized carbon nanofibers possesses high surface roughness and porous structure. Additionally, we envisage that the exceptional properties such as high flexibility and adaptability of the current material can further be extended to hybrid materials for diversity of applications in gas adsorption and separation. Therefore, based on the absorption of CO_2 by nanoparticles, several parameters are dominant, including nanoparticle type, nanoparticle morphology, nanoparticle size, nanoparticle concentration in base solvent (nanoparticle loading), CO_2 concentration in feed, gas flow rate, base solvent type, liquid flow rate, temperature, pressure, and fluid hydrodynamics (Elhambakhsh et al., 2020).

15.4 Technoeconomic analysis of CO_2 capture and conversion technologies

This section reports the critical issue of CO_2 capture and conversion costs. We begin with an overview of the many factors that affect costs and the ability to compare published estimates on a consistent basis. Different measures of CO_2 capture cost also are presented and discussed. The literature on CO_2 capture costs for currently available technologies is then reviewed, along with the outlook for future costs over the next several decades.

15.4.1 Process economic analysis of CO_2 capture

Improved technologies are needed to achieve the goals of cost-effective and energy-effective CO_2 capture. Technoeconomic analysis is a tool to estimate the feasibility of a technology (Kim, Rho, et al., 2021; Slater et al., 2019). The cost is an important parameter in determining the feasibility of a technology in the early phase of the project, and hence an integral part of a technoeconomic analysis. The calculated cost of capturing CO_2 by several researchers, using amine, monoethanol-amine (MEA), or methyl-diethanolamine (MDEA) absorption technologies for chemical plants is listed in Table 15.4, showing wide variation in the costs for homologous types of capture plants.

15.4.2 Process economic analysis of CO_2 conversion to useful fuels

This work reviews the literatures on CCU and provides insights on the motivations and potential of making use of the recovered CO_2 emissions as a commodity in the industrial production of materials and fuels. CO_2 can generally be used in many

Table 15.4 CO_2 capture cost data and parameters for the chemical industry, taken from the literature.

Parameter				
Location	Norway	Australia	Finland	Romania
Capture efficiency (%)	82.2	85	90	90
Capture technology	Absorption with MEA	Absorption with MEA	Absorption in amine	Absorption with MDEA
Economic parameters				
Plant life (years)	25	25	25	25
Construction time (years)	2	2	2	3
Operating days per year	330	–	–	–
Discount rate (%)	8	7	8	–
Maintenance	2.5% of total plant cost	–	3% of total plant cost	–
Electricity cost	58.1 €/MWh	19 US$/MWh	–	50 €/MWh
Labor cost	–	–	–	40000 €/y
Capture cost per tCO2	42 €	35.0 US$	60–70 €	5 €

processes. This article focuses on potential commodity CO_2 from industrial scale and does not include biological fixation and conversion via the cultivation of crops or algae; for example, for making biofuels, when CO_2 is used directly or as feedstock for materials and fuels it will be reemitted to the atmosphere depending on the durability of the product, ranging from days to several years. As described earlier, the amounts of CO_2 used thus do not correspond to the amount of CO_2 avoided.

15.4.3 Cost-effective synthesis process of nanomaterials

The topic of nanomaterials stability is especially important, as it can affect the adsorbent lifetime and therefore the operating costs of the process. At present, the use of cost–effectiveness studies in the field of nanomaterial is still in its infancy. Indeed, the use of cost–effectiveness studies is a crucial missing link that could improve the market introduction of nanomaterials. Cost-effective capture of carbon dioxide needed technology improvements for nanomaterials. Since nanotechnology can reduce CO_2 globally, the research has shown that the ability of nanotech-enabled materials to meet the challenges of cost-effective and high-volume CO_2 capture is enormous. Thus the task is to turn this CO_2 into useful products. Nanotechnology is thought to be able to provide feasible material solutions to this complex technical dilemma.

15.4.4 Technoeconomic analysis of CO_2 electrolysis systems

The reaction to electrochemical CO_2 decrease has gained greater interest in research. The increasing use of renewables such as wind and solar energy leads to an increasingly fluctuating supply of electricity and calls for greater energy storage to prevent the reduction of excess power. The increased combustion of fossil fuels has led to an escalation of atmospheric CO_2 concentrations from the industrial revolution. These CO_2 emissions are trapping the Earth's energy in the air and contributing to the shift in the climate. The Earth would warm up to 4°C over preindustrial levels if global CO_2 emissions continue to increase (Anderson et al., 2016; Solomon et al., 2009). The anticipated impacts of global warming include increased probability of extreme weather events, decreased food safety, greater freshwater competition, and the loss of species. The anticipated impacts of global warming include an increased chance of extreme weather events, lower food safety, greater freshwater competition, and extinction of species. To restrict global warming to these levels, humanity should develop ways of reducing global CO_2 emissions (Anderson et al., 2016; Bell et al., 2018). One strategy for reducing CO_2 emissions in the atmosphere is to absorb and sequestrate or utilize CO_2. This involves converting CO_2 through the electrochemical CO_2 reduction process to value-added products. In a technoeconomic analysis of the CO_2 reduction reaction, the process of CO_2 conversion, target items which offer economic value, and performance criteria for economic viability can be estimated. The objective of a technoeconomic analysis is to find the maximum profitability of products and the performance objectives to be achieved to ensure economic viability (John et al., 2021; Sukor et al., 2020). Electrochemical CO_2 reduction reaction is changing the way we produce chemicals and fuels. A variety of products ranging from hydrocarbons to oxygenates and from C_1 to C_3 can be produced from a CO_2 reduction reaction using different catalytic materials. Na et al. (2019) have proved the technoeconomic analysis of electrochemical CO_2 reduction reaction—organic oxidation reaction coproduction via conceptual process design and thereby propose potential economic combinations, which develop a fully automated process synthesis framework to guide process simulations for predict the levelized costs of chemicals. This prospective was illustrated by the work of Verma et al. (2016), who developed a technoeconomic gross-margin model for generalized electrochemical CO_2 reduction plant to analyze the economic viability of various reduction products such as carbon monoxide, formic acid, methanol, methane, ethanol, and ethylene. The derived performance benchmarks include the maximum operating cell potential, minimum operating current density, Faradaic efficiency, and catalyst durability. Although many researchers are presently working toward the commercialization of CO_2 electroreduction by improving the performance of catalyst, device, and process, these aspects are generally examined in isolation and are rarely considered all at once.

In addition, Sisler et al. (2021) compared the cost of producing ethylene through CO_2 reduction in an alkaline flow cell and neutral membrane electrode assembly while incorporating losses of CO_2, using the highest efficiency values reported in the open literature for each electrolyzer, and assuming an electricity price of 2 ¢/kWh. The efficient electroreduction of CO_2 to CO was demonstrated by Chen, Wang, et al. (2020) using Ag decorated S-doped g-C_3N_4/CNT nanocomposites that were synthesized as a highly active and selective CO_2 reduction reaction catalyst. The results indicated nanocomposites exhibit excellent performance in CO_2 reduction reaction to CO, yielding a high current density of -21.3 mA cm^{-2} and maximum CO Faradaic efficiency over 90% conducted in H-type cell. Additionally, the liquid reaction environment in H-type cells also facilitates the competitive hydrogen evolution reaction against the electrochemical CO_2 reduction reaction. By contrast, more recent papers by Rumayor et al. (2019) have introduced the electrochemical reduction reactor that overcomes the above limitations for producing formic acid from CO_2. Formic acid (HCOOH) is a chemical that is widely used in textiles, food chemicals, food, pharmaceuticals, and so on. It also has potential to be a hydrogen carrier and a fuel that can be directly used for fuel cells. Formic acid is a high-value product because it has a concentrated, mature, and small market with a low risk of substitution. Many chemicals can be synthesized by electrochemical reduction of CO_2, such as carbon monoxide (CO) (Feaster et al., 2017), formic acid (HCOOH) (Ramdin et al., 2019), hydrocarbons (e.g., methane CH_4 or ethylene C_2H_4) (Peng et al., 2017; Umeda et al., 2020), and alcohols (e.g., methanol, CH_3OH) (Payra et al., 2020). Formic acid is one of the most profitable compounds manufactured with this process among these products. Formic acid may be created for metals that have a high overall potential for H_2 production with high faradaic efficiency. Formic acid is an electrochemical liquid CO_2 reduction product that is especially desirable, so can easily be stored and transported in line with current infrastructures. In the last few years the global chemical market has shown a linear trend and is predicted to rise from 620 ktons in 2012 to 1 Mton in 2030 (Global CO2, 2016). This finding is mostly driven by formic acid's potential as a hydrogen stocking medium. Formic acid is generated industrially via methyl format hydrolysis which constitutes a fossil-dependent pathway. Formic acid derived from the electronic reduction of renewable energy CO_2 is a potential alternative to a classical process by recycling CO_2 (carbon neutral cycle), providing a method of storing and using intermittent sources of renewable energy, whilst reducing the industry's dependence on fossil fuels (Rumayor et al., 2019). A technoeconomic evaluation is based on the technique used in the report, taking both the use of resources and a range of major economic process indicators as compared with the standard thermochemical pathway based on fossil fuels. The results indicated the major contributors to production costs and thus to the profitability of the utility plant by using power and process consumables (determined by the cathode lifetime). In the realistic electrochemical reduction strategy, a sensitivity analysis was carried out to examine the effect of the particular energy consumption on profitability. The results evaluated the economic competitiveness of formic acid synthesis by reducing electrochemical CO_2 in comparison with traditional manufacturing. The study showed that for their future competitiveness the electrification of such commodities generating units through low-cost renewable energy surpluses is essential (Rumayor et al., 2019).

CO_2 reduction is the conversion of CO_2 to any intermediates that could be further synthesized to fuels by using electricity to push the reaction forward, where a highly efficient catalyst is the main challenge of the technology. Chen, Wang, et al. (2020) successfully synthesized Ag decorated S-doped (graphitic carbon nitride) g-C_3N_4/CNT nanocomposites as a catalyst for the electrochemical reduction of CO_2 to CO. The results revealed that CO_2 could be converted to CO with more than 80% Faradic efficiency (FE). The FE states the number of protons that transport from anode to cathode, depending on the currency, where $200\,mA\,cm^{-2}$ was applied in this experiment. One of the outstanding advantages of the electrolysis process of CO_2 conversion is it can be performed under atmospheric pressure. Verma et al. (2016) determined the technoeconomic analysis of electrochemical reduction of CO_2 process, which also studied the efficiency of the applied catalyst. From this study, current density (j), operating cell potential (V), FE, and catalyst durability (t_{catdur}) were found to influence the overall efficiency of the catalyst. The gross-margin models, commonly used to analyze profit of the interested processes, had been utilized in this work to estimate the technoeconomic of electroreduction of CO_2 to C_1 and C_2. The gross-margin models can be applied to investigate/analyze the efficiency of the process, duration of the catalyst, and cost of the catalyst. This approach encourages an improvement of catalyst development for longer duration and for higher efficiency. Besides, the gross-margin models can be applied for analysis of different products combinations, selective ratios, and process designs. Back calculation for the product cost is also possible using the gross-margin models. In addition, this model can be applied for other electrochemical processes such as electrochemical CH_4 oxidation and NH_3 synthesis via N_2 and H_2O electrolysis.

The technoeconomic assessment of formic acid production via electrochemical reduction of CO_2 was determined by Rumayor et al. (2019). This study focused on cathode lifetime analysis. The output indicated the benefits and challenges in terms of economy which are the key performance indicators, including total fixed cost calculation, net present value, internal rate of return, variable cost productivity, and fixed cost production. This study showed that electrochemical reduction process obviously reduced the cost of electricity, resulting in a higher profit for the manufacturing of formic acid. Another outstanding advantage is that the longer lifetime of the cathode helped to reduce the cost of the electrolyte in the electrochemical cell too. Zheng et al. (2017) compared the electrochemical conversion of CO_2 over a range of temperatures, which were low ($<200°C$), medium and high ($>800°C$). The research concluded that the low-temperature processes, including both aqueous and nonaqueous techniques, that is, transition metal electrode in electrolyte or proton exchange membrane, have more costs for the catalyst (mostly Pt-based) and complexity of the sophisticated system. On the other hand, CO_2 conversions at high temperature, such as solid oxide cells, are more demanding in terms of materials, sealants, equipment life span, and fabrication. The medium temperature processes are therefore trending as there are more possibilities in optimization and improvement of catalyst, electrode, electrolyte, and other materials. Spurgeon and Kumar (2018) investigated three electrochemical processes of CO_2 reduction: (1) to liquid fuels via Fischer-Tropsch; (2) to ethanol; and (3) to formic acid, which is very much in demand recently. The research concluded that the investment costs of these processes are still relatively high, as they require high FE for improved current densities and reduced electrolyzer costs per electrode area, to push the processes toward economic viability. Na et al. (2019) concluded that technoeconomic information offers the possibility to produce high-value products. CO_2 reduction is well-known for high investment cost, compared to other methods. This work observed cathode efficiency and cost together with that of the anodes (unlike most articles that only considered cathode-based economy as the anodes are generally not as much economically valued). In this work, CO_2 reduction reaction was integrated with an organic oxidation reaction using simulation, while the technoeconomic analysis was also involved. Such a reaction was found to be able to occur while the heat of the reactions were integrated and optimized. Possible products from such processes include syngas, methanol, and ethylene. These compounds can be utilized further to many commodities such as chemicals, plastics, and fuels. End-of-life net present value (NPV), which illustrates the added valued that could be obtained from the overall investment, of CO_2 electrolysis was calculated by Jouny et al. (2018). This work considered value of money by time and investment for money access. NPV calculated from this work was reported at 100 ton/day. Recently, NPV of CO and formic acid have been estimated at 13.5 and 39.4 million US dollars, respectively, whereas that of the alcohol-based products, that is, ethanol and propanol are likely to be higher. However, the higher efficiency of the catalyst also influences the rise in NPV.

15.5 Conclusions and future challenges

The nanotechnology in CO_2 capture and conversion processes has great potential to capture CO_2 using nanoparticles and nanomaterials in the various CO_2 capture processes. Nanomaterials are also more efficient in CO_2 capture processes due to their exceptional properties which are highlighted along with their higher thermal stability. Future research efforts must balance process feasibility with the value of the target product to maximize the economic incentive for capturing and converting CO_2.

This includes the development of efficient materials and processes that reduce the cost at the large scale. In addition to reducing the impact of other environmental harmful chemicals, future challenges need to be geared toward the production of multifunctional nanomaterials for the technoeconomic analysis of efficient CO_2 capture and conversion.

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