

Exploring Carbon Recycling Opportunities in ASEAN



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Economic Research Institute
for ASEAN and East Asia

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Foreword

Climate change is reshaping the way governments, businesses, and societies approach economic development and industrial transformation. Achieving net-zero emissions will require not only reducing greenhouse gas emissions but also developing new technologies and industries that enable carbon to become part of a more circular and sustainable economy.

In this context, carbon capture and utilisation (CCU), often referred to as carbon recycling, offers a promising opportunity. Rather than viewing carbon dioxide (CO₂) solely as an emission to be reduced, carbon recycling enables captured CO₂ to be utilised as a valuable resource for producing fuels, chemicals, construction materials, and other industrial products. By keeping carbon in productive use for longer, carbon recycling can complement broader decarbonisation efforts while creating new economic opportunities and supporting industrial innovation.

Around the world, governments are beginning to establish strategies and roadmaps to advance carbon recycling technologies. Japan has been at the forefront of these efforts, demonstrating how long-term policy direction, research and innovation, supportive regulatory frameworks, and close collaboration between government, industry, and academia can accelerate technological progress. These experiences also demonstrate that advancing carbon recycling requires sustained investment, capable institutions, and deeper international co-operation.

This publication, *Exploring Carbon Recycling Opportunities in Asia*, forms part of the work of ERIA's Asia CCUS Network and the Asia Zero Emission Center, which support Asia's transition towards net-zero emissions. Guided by the vision of the Asia Zero Emission Community (AZEC), which recognises that each country will pursue its own pathway towards carbon neutrality according to its unique circumstances, ERIA invited researchers from across Asia to undertake a collaborative study on how carbon recycling could contribute to achieving net-zero emissions.

Beyond producing high-quality research, this initiative seeks to strengthen regional knowledge networks, foster collaboration amongst research institutions, and stimulate informed discussion on the opportunities and challenges associated with carbon recycling. Following a competitive selection process involving 34 research proposals, nine proposals from nine institutions were selected to undertake 6-month studies covering various aspects of carbon recycling, including techno-economic analysis, policy and regulatory frameworks, and institutional development.

These studies aim to provide policymakers, researchers, investors, and other interested readers with an overview of the current status of carbon recycling across selected countries in Asia, together with its potential and the challenges associated with scaling up its deployment. I hope this publication will encourage further research and collaboration to realise the potential of carbon recycling in Asia as part of the region's climate action efforts. By supporting diverse pathways to net-zero emissions that reflect each country's unique circumstances, carbon recycling can contribute to a more sustainable and resilient future in the spirit of the Asia Zero Emission Community.



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List of Abbreviations and Acronyms

ACRC	ASEAN Carbon Recycling Council
AEDP	Alternative Energy Development Plan
AEL	alkaline electrolysis
AEM	anion exchange membrane
ALK	alkaline
APAEC	ASEAN Plan of Action for Energy Cooperation
ASEAN	Association of Southeast Asian Nations
ASPEC	ASEAN Standards and Performance Evaluation Criteria
AWE	alkaline water electrolyser
BECCS	Bioenergy with Carbon Capture and Storage
CaCO₃	calcium carbonate
CAPEX	capital expenditure
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation, and storage
CCUT	carbon capture and utilisation testbed
CEPCI	Chemical Engineering Plant Cost Indexes
CFPP	coal-fired power plants
ChR	chemical recycling
CNT	carbon nanotube
CO₂	carbon dioxide
COP	Conference of Parties
CPC	cyclic propylene carbonate
CR	carbon recycling
CRCF	Carbon Removal Certification Framework
CTM	coal-to-methanol
CU	conventional utilisation
DAC	direct air capture
DEG	di-ethylene glycol
DFM	dual function materials
DMC	dimethyl carbonate
DME	dimethyl ether
DRE	dry reforming of ethane
DRM	dry reforming of methane
EAS	East Asia Summit

ECR	electrochemical CO ₂ reduction
EG	ethylene glycol
EGR	enhanced gas recovery
ELPM	end of life product management
EOL	end of life
EOR	enhanced oil recovery
EPR	extended producer responsibility
ERIA	Economic Research Institute for ASEAN and East Asia
ESG	environmental, social, and governance
ETO	ethanol-to-olefins
ETS	emissions trading system
EU	European Union
EVN	Vietnam Electricity
EV	electric vehicle
FT	Fischer-Tropsch
GFI	Green Finance Index
GGI	Greenhouse Gas Index
GHG	greenhouse gas
GR	government regulation
GW	gigawatt
H₂	hydrogen
HCOOH	formic acid
HDPE	high-density polyethylene
IAM	integrated assessment model
ICCU	integrated carbon capture and utilisation
IEA	International Energy Agency
IESR	Institute for Essential Services Reform
IGCC	integrated gasification combined cycle
ILCAN	Indonesian Life Cycle Assessment Network
IP	intellectual property
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power producer
ISO	International Standard Organization
IRR	internal rate of return
ITC	investment tax credits
JOGMEC	Japan Organization for Metals and Energy Security

KLHK	Kementerian Lingkungan Hidup dan Kehutanan (Ministry of Environment and Forestry of Indonesia)
Kg	kilogramme
KMI	Kaltim Metanol Industri
kW	kilowatt
Lao PDR	Lao People's Democratic Republic
LCA	life cycle assessment
LCOH	levelised cost of hydrogen
LDPE	low-density polyethylene
LEED	Leadership in Energy and Environmental Design
LTS-LCCR	low carbon and climate resilience
MEA	monoetanolamin
MEG	mono-ethylene glycol
MEMR	Ministry of Energy and Mineral Resources
MeOH	methanol
METI	Ministry of Economy, Trade and Industry
MJ	megajoule
MRV	monitoring, reporting, and verification
Mt	metric tonne
MTA	methanol-to aromatics
Mt CO_{2e}	metric tonne of carbon dioxide equivalent
MTO	methanol-to-olefins
MTP	methanol-to-propylene
MTPA	million tonnes per annum
MW	megawatt
MWh	megawatt hours
NASA	National Aeronautics and Space Administration
NDC	National Determined Contribution
NEDO	New Energy and Industrial Technology Development
NEP	National Energy Policy
NETR	National Energy Transition Roadmap
NGCC	natural gas combined cycle
NGR	natural gas reforming
NPV	net present value
NZE	net-zero emissions
ODA	official development assistance
ODHE	oxidative dehydrogenation of ethane

OPEX	operational expenditure
O&G	oil and gas
O&M	operation and maintenance
PCA	principal component analysis
PCP	polyether carbonate polyol
PD	4-amino-1-methylpiperidine
PE	polyethylene
PEF	polyethylene furanoate
PEM	proton exchange membrane
PET	polyethylene terephthalate
PFR	plug flow reactor
PLA	polylactic acid
PLI	product-linked incentive
PLN	Perusahaan Listrik Negara (State-owned Electricity Company)
PO	propylene oxide
PP	polypropylene
PPA	power purchase agreement
PPP	public-private partnership
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PS	polystyrene
PT	polyethylene terephthalate
PTA	purified terephthalic acid
PV	photovoltaic
PVN	PetroVietnam
RE	renewable energy
REC	renewable energy certificate
RED II	Renewable Energy Directive II
rPET	recycled PET
RWGS	reverse water-gas shift
R&D	research and development
SAF	sustainable aviation fuel
SDGs	Sustainable Development Goals
SLO	societal license to operate
SLR	systematic literature reviews
SMEs	small and medium-sized enterprises
SNI	Standar Nasional Indonesia (Indonesian National Standard)
SOEC	solid oxide electrolysis cell

SRN	Sistem Registrasi Nasional/National Registry System
Syngas	synthetic gas
TCDR	terrestrial carbon dioxide removal
tCO₂	tonnes of carbon dioxide
TRL	technology readiness level
TWh	terawatt-hour
UN	United Nations
US	United States
VAT	value-added tax
VPI	Vietnam Petroleum Institute
WTE	waste-to-energy

Executive Summary

Exploring Carbon Recycling Opportunities in Asia is a report of a collaborative study organised by the Asia Carbon Capture, Utilisation, and Storage (CCUS) Network of the Economic Research Institute for ASEAN and East Asia (ERIA) as part of mission to support acceleration of decarbonisation in Asia. ERIA recognised that to achieve decarbonisation and net-zero emissions (NZE), there is no single solution that fits for all countries in the region. Different natural resource endowments, different technical capacities, available funding, and other resources may lead to different pathways in meeting NZE.

The objective of this study is not only to produce a high-quality report on carbon recycling, but most importantly, it is to include research institutions from various countries and expose them to potential carbon recycling issues and inclusively provide their thoughts on how to harness the opportunity. With this approach, the region is expected to have exposure to wider options in meeting the NZE target.

Carbon recycling is part of CCUS technology. CCUS consists of two technologies: carbon dioxide (CO₂) capture and storage (CCS), which is the technology to reduce CO₂ emissions by separating, capturing, and injecting it into deep underground storage such as depleted petroleum reservoirs, saline aquifers, or carbonate rock for the permanent storage of carbon dioxide; and carbon dioxide capture and utilisation (CCU) technology, which is the use or reuse of emitted carbon dioxide as a raw material for producing chemical products and fuel. CCU is known as carbon recycling as its process keeps CO₂ in the human-made system, forming a carbon loop and preventing it from immediate release into the atmosphere, like natural systems recycle carbon.

With CCU technology, captured CO₂ can be used in various products, including direct use, chemicals, fuels, construction materials, and proteins through technologies like thermochemistry, photochemistry, electrochemistry, biochemistry, and nanotechnology.

CO₂ is directly used in beverages, food industries, welding, and greenhouses, although these applications have short retention times. Enhanced oil recovery (EOR) is a commercially established technology with potential in Asian and Association of Southeast Asian Nations (ASEAN) countries.

Utilisation of CO₂ to produce chemicals can be classified into basic substances, such as methanol and chemical products. Utilising captured CO₂ as basic substances encompasses synthesis gas and methanol. In particular, methanol is crucial owing to its function as a fundamental substance for chemical compounds (polymers, synthetic resins, synthetic fibres, agrochemicals, pharmaceuticals, adhesives, coatings, etc.) and energy sources (synthetic fuels). Numerous methodologies exist for the synthesis of essential substances, such as thermochemical processes employing catalysts, photochemical methods utilising photocatalysts, electrochemical techniques incorporating electrochemical reduction, and biomanufacturing utilising microorganisms.

Owing to its thermodynamic stability, CO₂ needs a substantial quantity of energy to engage in a reaction with hydrogen to yield methanol. Conventional technology involves presenting it in the form of energy-dense hydrogen gas. CO₂ can also be derived from biomass. There exists a procedure wherein biomass resources are gasified to generate synthesis gas (carbon monoxide, carbon dioxide, hydrogen), which is subsequently utilised for the production of methanol. The impediment to these processes lies in their elevated cost-competitiveness relative to fossil fuel-derived methodologies. Some processes under development also envisage avoiding the production of hydrogen (H₂) as an intermediate and reacting the captured carbon directly with water.

The types of chemical products that may be produced with captured CO₂ can be categorised as basic chemical, functional chemical, and biomass-derived chemicals. Basic chemicals are generated utilising the methanol-to-olefins (MTO) and ethanol-to-olefins (ETO) processes, which use chemical raw materials such as methanol and ethanol to synthesise olefins including ethylene, propylene, and butene. These processes are subject to overcoming obstacles such as improving yields, reducing production costs, enhancing durability, and scaling-up production. Forthcoming technological advancements are anticipated to result in more efficient chemical production.

Polycarbonate and polyurethane raw materials (isocyanate) and highly water-absorbent polymer raw materials (acrylic acid) are functional chemicals that can be synthesised directly from CO₂ with low energy and without the utilisation of hydrogen due to their non-reductive reactions. Currently, demand for these substances, in comparison to general-purpose plastics such as polyethylene and polypropylene, is limited; however, in the foreseeable future it is anticipated these substances will be utilised in printed circuit boards, optical lenses, and automotive components.

Biomass-derived chemicals constitute a CCU pathway that employs photosynthesis to capture and store CO₂ as organic carbon. This encompasses biological conversion methodologies such as microbial fermentation and gas fermentation. Microalgae are minuscule organisms that can flourish in elevated concentrations of CO₂. They may be cultivated in open ponds or enclosed photobioreactors. Microalgae can be utilised to generate biofuels such as biodiesel and ethanol, in addition to serving as animal feed.

Synthetic hydrocarbon fuels can easily be utilised within current infrastructure and are economically advantageous when compared to the transportation and storage of electricity or hydrogen. Nevertheless, their production necessitates a significant amount of energy, which presents challenges concerning energy efficiency and cost, particularly when derived from renewable energy sources.

Synthetic methane is generated directly from CO₂ and H₂ utilising the technologically advanced methanation procedure. In this procedure, H₂ and CO₂ are initially reacted to yield methane (CH₄). This facilitates the transportation and storage of methane using existing gas infrastructure, akin to natural gas. The primary benefit of synthetic methane is that it can be managed in an analogous manner to natural gas, thereby permitting storage at low pressure and low temperature. This enables the utilisation of existing supply chains and diminishes infrastructure expenses for transportation and distribution.

Mineralisation constitutes the procedure of reacting CO₂ with natural minerals or metal ions in solid refuse or wastewater to generate carbonates. Carbonates possess a wide range of applications, encompassing construction materials such as insulation materials and bricks, chemicals, and foodstuffs. The production of carbonates can utilise industrial refuse and minerals, thereby contributing to the sustainable management of waste. One auspicious pathway for mineralisation involves carbonate blocks as a substitute for Portland cement blocks. This enables the reduction of the quantity of cement and aggregate required as the raw materials by utilising CO₂ in the manufacturing process, which is anticipated to reduce CO₂ emissions and raw material costs. These products are likewise projected to serve as a medium-term measure for emissions reduction, as CO₂ remains sequestered for a long period of time.

CCU technologies are in various stages of development. Some technologies are already in the commercial stage, for example:

1. KH Neochem synthesises aldehydes from olefins, carbon monoxide, and hydrogen through oxo reactions, leading to alcohols, synthetic fatty acids, and esters for new materials.

2. Asahi Kasei Corporation produces polycarbonate resin using CO₂, constituting about 17% of global polycarbonate production capacity, and derives isocyanate from CO₂-derived urea.
3. Chitose Bio Evolution Pte Ltd uses microalgae to convert CO₂ into valuable substances, including functional chemicals, plastic precursors, and proteins.

Several other technologies still struggle to pass the high-risk period in development. Several factors, such as government policy, collaboration, and market creation, will determine the success of the technology entering into market and becoming part of the pathway to achieve NZE.

Various governments have taken initiatives to support CCU commercialisation, creating supportive business environments that ensure the evident reduction of CO₂ in the implementation of technology and securing revenue streams, for example:

1. Japan emphasises CCU for stable energy supply, economic growth, and decarbonisation, supported by grants and carbon pricing mechanisms.
2. Singapore's CCUS Strategy, stated in Singapore's Green Plan 2030, incorporates CCUS in its energy transition, with grants for low-carbon technologies and a gradually increasing carbon tax.
3. The European Union (EU) promotes CCU through research funding and a regulatory framework, ensuring demand-side policies encourage low-carbon options. The collaborative efforts across the region aim to reduce CO₂ emissions, encourage investment, and develop sustainable technologies.
4. The United States has recognised that CCUS is essential for deep decarbonisation by 2050, with notable tax incentives emerging from recent legislation.
5. The United Kingdom's investments in CCUS and hydrogen are emphasised for job creation and industrial decarbonisation.
6. Canada focuses on CCUS as integral to its Green Economy Strategy, promoting substantial federal incentives to support deployment.

Overall, each region tailors its CCUS strategy to its specific goals, integrating various methods for financing and regulatory mechanisms.

International directives and frameworks are emerging to guide carbon accounting, certification, and the implementation of CCUS and carbon dioxide removal (CDR) strategies. The EU Directive emphasises that emissions captured and utilised permanently do not require allowance surrender. A carbon removal certification framework is proposed to ensure reliability in carbon removal projects, outlining definitions and requirements for permanent and temporary storage. The Intergovernmental Panel on Climate Change is revising guidelines for CCUS and CDR to reflect advancements in technology, differentiating between short-term and permanent carbon storage. These frameworks underline the urgency for standardised accounting methods and the credibility of CCUS and CDR technologies in achieving climate goals.

From several comprehensive studies reported in this book, the opportunities and challenges of carbon recycling in ASEAN, with particular analysis on Indonesia, Viet Nam, and India, are outlined.

This comprehensive analysis of carbon recycling in Indonesia addresses the emerging opportunities and challenges in leveraging CO₂ utilisation technologies to bolster the sustainable production of polyethylene terephthalate (PET) and high-density polyethylene (HDPE). The initiative seeks to alleviate reliance on fossil-based imports, which currently underpin Indonesia's polymer industry. The study delves into the strategic framework to convert CO₂ emissions into valuable chemicals necessary for plastic production, amidst the country's rising demand, forecast to soar by 2034 – an environment shaped by ongoing urban development and shifting consumer preferences.

Indonesia is on the threshold of integrating CO₂ recycling technology and green methanol supply chains within its petrochemical infrastructure. This is partly driven by national commitments to reduce greenhouse gas emissions substantially by 2030. Therefore, this report reviews technical pathways – such as dimethyl carbonate-based, biochemical, electrocatalytic, and others – for synthesising PET and HDPE, emphasising the pivotal role of hydrogen. Critically, the viability and economic challenges of such transitions are linked to hydrogen costs, CO₂ capture efficiencies, and incorporating renewable energy sources.

Highlighted are numerous CO₂ capture methods with varying efficiencies and scalability – spanning post-combustion, pre-combustion, and oxy-combustion technologies, amongst others – all geared towards varying applications integral to lowering input costs and enhancing process sustainability. The evaluation also extends to the burgeoning role of electrolyser technologies (e.g. alkaline water electrolysis, protein exchange membrane, solid oxide electrolysis, anion exchange membrane) for hydrogen production, aligned with the goal of reducing emissions and enhancing energy efficiency.

Ultimately, the strategic pivot towards green methanol pathways proposes leveraging industrial clusters in Banten and East Java, enhancing mainstream industrial carbon circularity. Firmly anchored are plans for comprehensive infrastructure and policy support, encompassing power procurement mechanisms, utilising power purchase agreements and renewable energy certificates to foster stable CO₂-based polymer value chains essential for sustaining competitive landscapes against internationally volatile fossil fuel markets.

The synthesis identifies potential environmental and economic benefits, whilst heralding a need for comprehensive policy alignment and stakeholder integration to realise these ambitions. As strategic planning progresses, pilot projects aim to position Indonesia as a regional leader in low-carbon plastics production, with cross-sector co-operation – from government mandates to private sector engagements – marked as essential to achieving these transformative goals.

Furthermore, the study offers policy recommendations to accelerate the implementation of CCU and/or integrated carbon capture and utilisation (ICCU) in Indonesia, including the need for a centralised carbon management task force, the development of a national CO₂ transport and storage infrastructure plan, and facilitating collaboration between state-owned enterprises and the private sector. Finally, it is crucial for Indonesia to develop a coherent policy, an enabling regulatory framework, and targeted incentives for effective and comprehensive CCU implementation.

In a wider scope in the ASEAN context, the role of cross-border collaboration is critical in advancing carbon recycling as it addresses both technological and policy challenges. Carbon recycling, particularly through innovative CO₂ utilisation technologies for fuel and chemical production, although it aligns with ASEAN's economic growth and climate objectives, faces many challenges. The national efforts in ASEAN are fragmented by high costs and regulatory discrepancies. A regional co-operation is essential for harmonising these endeavours and mainstreaming CO₂-derived products.

ASEAN Member States exhibit varied levels of progress and potential in deploying state-of-the-art carbon recycling technologies, including methanol synthesis, CO₂-to-urea production, and mineral carbonation. Whilst Singapore leads in CO₂-to-chemical integration, countries like Indonesia and Thailand are pursuing CO₂-to-urea conversion and cement mineralisation, underscoring a need for unified frameworks to co-ordinate these scattered initiatives.

ASEAN's energy and climate goals reflect a commitment to renewable integration and CO₂ reduction, but a cohesive framework to facilitate cross-border carbon recycling is lacking. Technological challenges, infrastructure gaps, and policy fragmentation must be addressed to scale initiatives effectively. The study proposes the ASEAN Carbon Recycling Council (ACRC) to harmonise regional policies, research, and infrastructure, drawing on international best practices like the European Union's CCS network and Japan's carbon transport strategies. Key strategies include establishing cross-border CO₂ supply chains, harmonised monitoring, reporting, and verification standards, and shared licensure platforms.

Strategic partnerships with developed nations like Japan and Australia could provide the necessary technology transfer and financial mechanisms to accelerate regional efforts. The proposed roadmap outlines phased implementation from 2025 to 2040, envisioning a competitive ASEAN position in the global carbon economy by transforming CO₂ from an industrial liability into a traded resource.

For the financing mechanism, the study proposes the establishment of an ASEAN Clean Innovation Fund, supported by green bonds and multilateral institutions, with the aim of accelerating CO₂ conversion initiatives with short-term, mid-term, and long-term goals. The roadmap emphasises establishing CO₂ transport and storage infrastructure, creating innovation zones, and securing international climate finance for technology diffusion and project maturity across ASEAN Member States.

A study examining strategies for achieving carbon neutrality in the ASEAN plastic ecosystem, specifically through recycling carbon-based materials and integrating CCU, reveals substantial carbon emissions from the plastic industry. ASEAN countries contribute approximately 20% of global production and face significant plastic waste management challenges. The life cycle of plastic is broken down to reveal emissions hotspots, emphasising the need for a holistic approach to achieve carbon neutrality, which includes renewable energy use and circularity. Various chemical pathways for converting captured CO₂ into plastic precursors are discussed, including the conversion into polyols for polyurethane, PET, ethylene, and polycarbonates, with a comprehensive cost analysis of integrating plastic recycling with CCUS technologies. Economic challenges are underscored, particularly the high cost of carbon capture and the gap with existing carbon pricing mechanisms in Southeast Asia.

Different scenarios for adopting CCU in ASEAN's plastic sector, ranging from conservative to ambitious, are proposed. These scenarios explore the impact of CCU on reducing reliance on fossil feedstocks and achieving a circular, low-carbon economy. The potential for significant reductions in CO₂ emissions through CCU-based plastic production is highlighted, particularly in countries with high levels of plastic waste and CCU potential, such as Indonesia, Thailand, and Viet Nam.

Incorporating CCU in plastic production is a good policy framework, and economic incentives are necessary to facilitate the transition to a sustainable plastic economy in ASEAN, such as extended producer responsibility, deposit-refund schemes, and green finance mechanisms. In conclusion, the CCU integration in plastic production brings potential benefits for ASEAN countries by reducing their reliance on virgin plastics and moving towards a circular, low-carbon economy.

A study on carbon recycling in India revealed that CCU will play an important role in meeting India's NZE target, which is outlined in its National Determined Contributions under the Paris Agreement, including achieving 500 gigawatts of non-fossil fuel capacity by 2030 and reducing carbon intensity by 45% by 2030 (compared to 2005 levels).

India's technology on carbon recycling is considered to lag behind developed countries. Many CCS technologies are at technology readiness levels (TRL) 6 and 7 globally, whilst in India they are at TRL 4 and 5. CO₂ utilisation technologies are less developed than carbon capture and sequestration technologies. Gaps exist across the CCUS value chain, including CO₂ capture (e.g. solid adsorbents with poor efficacy), CO₂ transport (e.g. two-phase flow issues in pipelines), CO₂ utilisation (e.g. limited knowledge in CO₂ to building materials), and CO₂ storage (e.g. limited understanding of CO₂ flow).

Scaling-up CO₂ utilisation in India requires cost reduction, supportive policies, industry collaboration, and investment in infrastructure and pilot projects. Achieving a 10 metric tonne-CO₂ market requires an integrated approach focusing on technological advancements, policy support, and market readiness.

India has shown seriousness about CCU with the necessary political will and an abundance of feedstocks. The CCUS policy should be carbon credits or incentives-based in the near term, transitioning to carbon taxes over time. Regional hubs and clusters need to be established to drive economies of scale. Incentives should foster innovation for low-carbon products. The protection of communities and jobs, especially in sectors affected by clean energy regulations, is a key consideration, along with regulated emissions levels and allowances for different sectors.

Adoption of life cycle analysis is crucial for considering Scope 2 and Scope 3 emissions. Limiting CO₂ liability and ownership across the CCUS value chain is also important. Implementing a monitoring, verification, and accounting framework is essential for risk management.

Indian universities and research institutions are actively involved in CCU and carbon recycling research, with Indian institutes of technology leading the research and development efforts. Research focuses on pathways for the energy and industry sectors, with fewer universities focusing on CO₂ storage and transport.

Start-up innovations are emerging in India. UrjaNovac has developed an aqueous-based CO₂ capture technology that converts captured CO₂ into high-value minerals, creating economic opportunities. This innovation is supported by industry initiatives. Thermax, Dalmia Cement, and Hindalco have launched the 'Industry Charter for Near Zero Emissions Ambition by 2050'. Various companies are engaged in carbon recycling, producing end products like soda ash, carbon black, and calcined petroleum coke. Examples include Dalmia Cement (producing soda ash), PCBL Chemical Ltd. (producing carbon black), and Goa Carbon Ltd. (producing calcined petroleum coke).

Several companies and institutions are deploying CO₂ capture technologies, including amine-based solvents, pressure swing adsorption, and direct air capture. IFFCO, Indo Gulf Corporation Ltd., and ONGC are using amine-based solvents, whilst NETRA uses pressure swing adsorption. Novonanmek Material Sciences Pvt. Ltd. is currently developing direct air capture technology.

India requires supportive banking regulations and sustainable finance incentives to promote carbon recycling. There is a need for clarity on environmental, social, and governance norms for lenders. Tax credits and product-linked incentives can boost CCUS technology implementation.

CCU initiatives are anticipated to positively affect the gross domestic product, employment growth, energy and material security, and import substitution. These projects require significant capital investments (US\$100 billion–US\$150 billion) and are projected to add US\$100 billion to US\$150 billion to India's gross domestic product over the next 30 years.

CCU projects are estimated to create 8–10 million full-time equivalent years of employment. Construction and operation phases will generate both direct and indirect employment. Skill development programmes and incentives are required to address potential shortages of skills within the green energy sector.

CCU projects offer India a pathway to reduce import dependency, stimulate economic growth, and generate substantial employment opportunities, requiring a concerted effort in policy support, financial incentives, and international collaboration.

A study on carbon recycling in Viet Nam suggests that this technology represents a significant strategy for CO₂ reduction and the promotion of sustainable industrial growth within the country. Viet Nam demonstrates an increasing interest in utilising captured CO₂ for industrial production, particularly in the production of plastics, fertilisers, and dimethyl ether.

The plastics, dimethyl ether, and fertiliser industries should have the highest CO₂ conversion rates by 2030. Carbon nanotube technology has a low CO₂ conversion rate but valuable applications.

Although CCUS technology is mentioned in national strategies on climate change and green growth, Viet Nam still lacks specific legal regulations to manage and encourage CCUS projects. The government should create a supportive legal environment and develop policies to stimulate the carbon market.

The initial investment costs of CCUS projects are very high, and capital recovery requires a long time. Viet Nam needs to invest more in technology research and development and in-depth CCUS workforce training.

Pilot projects such as CO₂ recovery at fertiliser plants and CO₂-enhanced oil recovery trials are underway. International co-operation and human resource development are required to enable Viet Nam to effectively grasp and master CCUS technology.

The study urges the government to develop a CO₂ capture and recycling plan aligned with the Paris Agreement goals and to develop a national CO₂ data system and plan for underground storage areas. The government also needs to develop a separate legal framework for the CCUS value chain, speed up the promulgation of the National Strategy on CCUS/CCU, and implement a clear roadmap with specific goals and solutions.

The study on the East Asia Summit (EAS) countries explores the impact of green finance, green innovation, and trade in green technology on carbon emissions reduction in the EAS countries. It considers governance as a moderating factor and highlights the challenges faced by these countries in reducing emissions due to their reliance on fossil fuels and rapid industrialisation. The study introduces carbon recycling as a key concept within the circular economy for long-term decarbonisation.

Through empirical analysis using panel regression and principal component analysis, the research provides evidence on the determinants of carbon emissions reduction and offers insights into transitioning towards circular carbon practices. It underscores the importance of good governance in enhancing the effectiveness of green policies, especially after the adoption of the Sustainable Development Goals (SDGs) in 2015.

The study finds that green finance initially had a negative impact, likely due to mismanagement and greenwashing, but this impact turned positive with strong governance support. Green innovation consistently demonstrates a positive effect on emission reduction, and trade in green technology has become significant in the period following the implementation of the SDGs. EAS countries need different approaches based on development and governance.

The study suggests that Asian countries such as Indonesia, Viet Nam, and India, possess notable potential for the implementation of carbon recycling technology to achieve the NZE target. Several technologies, including methanol, fertiliser, and cement production, can be scaled-up in the near future as readily available opportunities. Alternative options, such as synthetic fuel, plastic, and HDPE, necessitate advancements in technology and government support. Materialising market potential, establishing a legal framework, the establishment of a business model, and the advancement of private investment are amongst the crucial factors.



Chapter 1

Introduction to Carbon Recycling

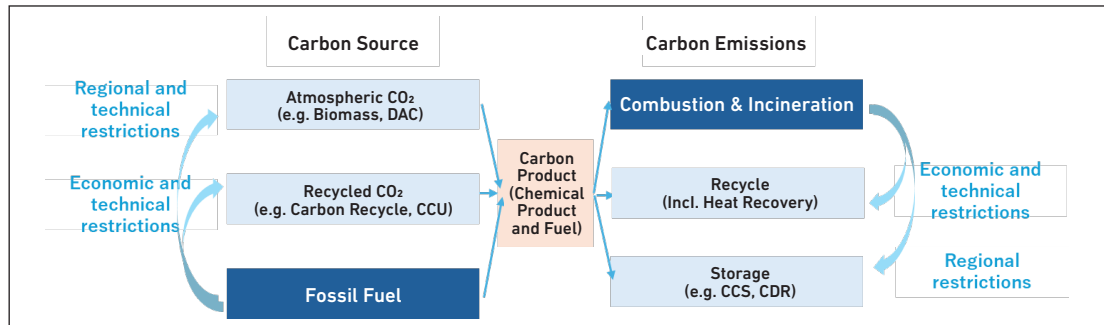
1. Defining Carbon Capture and Utilisation and Carbon Recycling

The rise of the global mean temperature subsequent to the Industrial Revolution surpassed 1.5°C in 2024 for the first time. The carbon budget, or cumulative emissions necessary to maintain this threshold at 1.5°C, is constrained, necessitating immediate climate change interventions. To achieve carbon neutrality, it is necessary that carbon capture, utilisation, and storage (CCUS), a comprehensive term for technologies devised to sequester emitted carbon dioxide (CO₂), are deployed within society at the earliest opportunity. CCUS includes carbon capture and storage (CCS), a technology that isolates and captures emitted CO₂, injects it into geological formations for permanent sequestration, as well as carbon capture and utilisation (CCU), a technology that utilises the captured CO₂ as a raw material, repurposing it in chemical production and fuel generation.

CCS is deemed as a crucial mitigation strategy within the industry sector where emissions reduction is challenging (such as cement, steel, and chemicals, which exhibit hard-to-abate emissions from industrial processes and high-temperature thermal energy) and load-following thermal-fired power plants, which will continue to be vital for a stable power supply especially with the incorporation of a significant amount of renewables into the grid. Furthermore, in the extended prognosis beyond 2040, there exists optimism regarding the societal adoption of negative emissions technologies (methods that capture and remove CO₂ that has previously been discharged into the atmosphere) that will facilitate carbon removal, which is essential for achieving global carbon neutrality, such as biomass energy with carbon capture and storage and atmospheric CO₂ direct capture and storage, which integrate CCS technology with additional technologies.

CCU is anticipated to yield a reduction in CO₂ emissions across the entire supply chain of products by treating CO₂ as a valuable asset and transforming it into a new, distinct valuable resource, in contrast to traditional manufacturing techniques. Moreover, even if decarbonisation across various sectors advances towards carbon neutrality, it is also regarded as a strategy primarily for sectors where decarbonisation through electrification and fuel switch is impractical, and CO₂ emissions are unavoidable. A comparable concept to CCU is carbon recycling, which is an approach accentuating the generation of economic value, while addressing global warming by treating CO₂ as a renewable asset and using it cyclically. For instance, numerous major industries, including chemicals, textiles, plastics, and cement, lack alternative raw materials to supplant carbon. Consequently, it is imperative to promote 'defossilisation', which entails leaving fossil resources in place and utilising alternative carbon sources. This necessitates the adoption of renewable resources such as biomass as raw materials in lieu of fossil resources. Conversely, biomass represents a resource that is unevenly distributed across various regions, and there exist challenges to securing adequate quantities. Additionally, there are concerns that an increase in biomass material availability may precipitate alterations in land use, potentially resulting in deforestation and a decline in biodiversity. As such, recycling CO₂ can contribute to alleviate such biomass resource constraints and efficient use of available resources.

Figure 1.1. Circular Carbon Economy

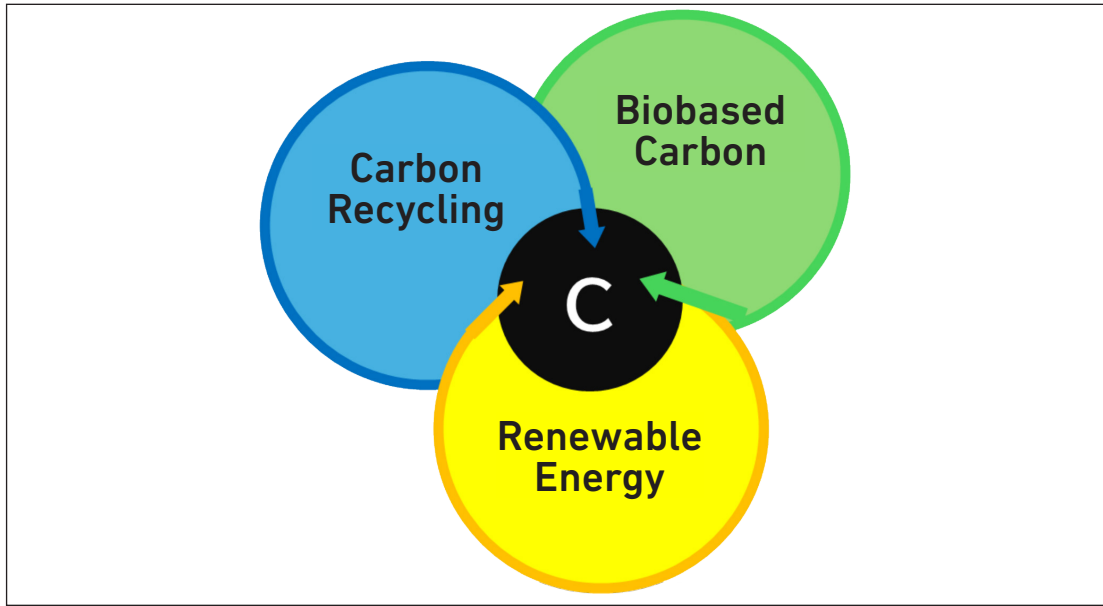


CCS = carbon capture and storage, CCU = carbon capture and utilisation, CDR = carbon dioxide removal, DAC = direct air capture.

Source: Created by Mitsubishi Research Institute based on Kanazawa et al. (2024).

Consequently, throughout the transitional phase, it is imperative to augment biomass by sequestering CO₂ from industrial emissions and solid refuse, thereby recycling the CO₂. In addition to this recycling paradigm, direct air capture (DAC) technology, which isolates CO₂ from the atmosphere, is anticipated to serve as a crucial component of the solution contingent on advancements in reducing capture costs via technological innovation. It is preferable to equilibrate the utilisation of fossil resources by capturing emitted CO₂ and permanently sequestering it; however, it is essential to establish a system in which CO₂ from alternative non-fossil resources is circulated through material cycles and the atmosphere, a concept referred to as the carbon circular economy (Figure 1.1). The circular carbon economy fundamentally represents an energy cycle, with energy-deficient CO₂ and energy-abundant methane (CH₄) at opposing poles. Therefore, energy input is essential not only for carbon recycling but also for enhancing bioresources, and it has been posited that comprehensive carbon management should be perceived as an amalgamation of the bioeconomy, carbon recycling, and renewable energy necessary for various carbon trajectories (Figure 1.2) (OECD, 2023).

Figure 1.2. Carbon Management Integrates Carbon Recycling the Bioeconomy and Sustainable Energy



Source: Authors based on OECD (2023).

2. Carbon Capture and Utilisation Applications

As a distinct application of CCU in addition to direct utilisation, the captured CO₂ is expected to be applied to various products such as chemicals, fuels, construction materials, and proteins. Numerous technologies are potentially engaged in the fabrication of these products, encompassing thermochemistry, photochemistry, electrochemistry, biochemistry, and nanotechnology. CCU technologies and products, as well as their application can be classified as follows (Table 1.1). Some of the technologies, particularly the conversion of captured CO₂ into basic substances, such as methanol as well as chemical products, such as plastic materials are elaborated below.

Table 1.1. Classification of Carbon Capture and Utilisation Applications

Category	Technology/Products	CO ₂ Utilisation Sector and Consumers
(1) Direct use	Dry ice, refrigerants, fire extinguishing agents, solvent, etc.	Chemical
	Enhanced agriculture (greenhouse)	Agriculture, food
	Carbonated beverages	Beverage
	Enhanced oil recovery (EOR)	Aquifer, oil reserve formation
(2) Basic substances	Syngas (CO + H ₂), methanol, etc.	-
(3) Chemical products	Basic chemicals: olefins (C ₂ –C ₄), BTX (C ₆ –C ₈)	Petrochemical (versatile plastics)
	Functional chemicals (including oxygen compounds), polycarbonate, etc.	Chemical and material (building materials, electrical parts, automotive parts, etc.)
	Biomass-derived chemicals	-
(4) Fuels	Methanation (e-methane)	Gas fuel (generation fuel, LPG, etc.)
	Synthetic fuel (e-methanol/e-kerosene)	Liquid fuel
	Biological conversion (biofuel)	Jet fuel
(5) Mineralisation	Construction aggregate	Building
	Carbonate products, cement, etc.	Concrete block
(6) Others	Edible protein products, carbon nanotubes, carbon black, etc.	Blue carbon, waste material, algae biomass etc.

BTX = benzene, toluene, xylene, C = carbon, CO = carbon monoxide, H₂ = hydrogen, LPG = liquefied petroleum gas.

Source: Authors.

2.1. Direct Use

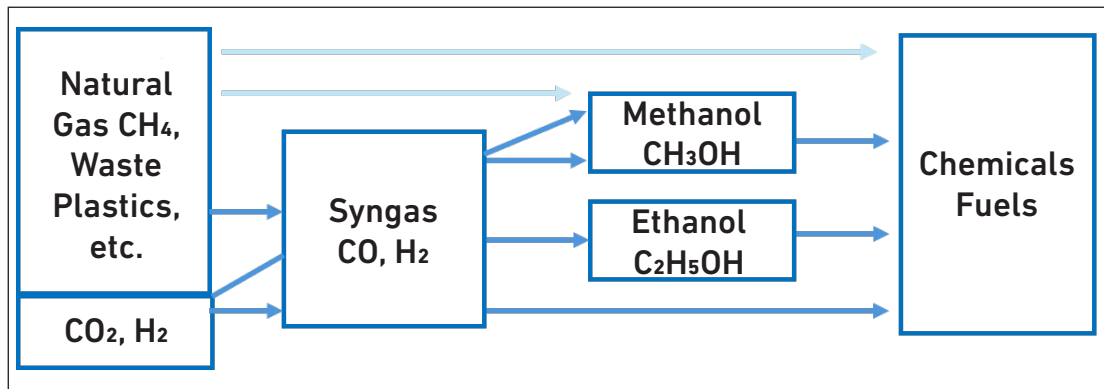
CO₂ is employed in consumer product applications within the beverage and food industries, functioning as a foaming agent for carbonated beverages and as dry ice for refrigeration. It is likewise utilised in the industry sector for the welding of metals and for promoting plant growth within greenhouses. These applications of CO₂ possess a remarkably brief retention time prior to being emitted into the atmosphere. Consequently, in order to mitigate emissions in these domains, it is imperative to transform the CO₂ source from industrial emitters to atmospheric removal through technologies such as DAC to attain carbon neutrality. On a separate note, in the resource development sector, the technique of injecting CO₂ into oil and gas reservoirs to augment the recovery rate of crude oil and natural gas (enhanced oil recovery [EOR] and enhanced gas recovery [EGR]) represents a commercially established technology that has been operational since the 1970s. As the oil and gas sectors are expected to play an important role in supply of secure and affordable energy supply in many Asian and countries, EOR and EGR have a high potential for contributing to mitigation where long-term storage of CO₂ in subsurface reservoirs is possible.

2.2. Basic Substances

Utilising captured CO₂ as basic substances encompasses synthesis gas and methanol. Particularly, methanol is crucial owing to its function as a fundamental substance for chemical compounds (polymers, synthetic resins, synthetic fibres, agrochemicals, pharmaceuticals, adhesives, coatings, etc.) and energy sources (synthetic fuels). Numerous methodologies exist for the synthesis of essential substances, such as thermochemical processes employing catalysts, photochemical methods utilising photocatalysts, electrochemical techniques incorporating electrochemical reduction, and biomanufacturing utilising microorganisms. Hydrogen, required for methanol production can be produced by water electrolysis using renewable or low-carbon electricity ('power-to-X' or approaches converting renewable electricity into a wide range of end products) or recycled from industrial processes.

Owing to its thermodynamic stability, carbon dioxide necessitates a substantial quantity of energy to engage in a reaction with hydrogen to yield methanol. A conventional technology involves presenting it in the form of energy-dense hydrogen gas. CO₂ can also be derived from biomass. There exists a procedure wherein biomass resources are gasified to generate synthesis gas (carbon monoxide, carbon dioxide, hydrogen), which is subsequently utilised for the production of methanol. The impediment to these processes lies in their elevated cost-competitiveness relative to fossil fuel-derived methodologies. Some processes currently under development are designed to avoid generating H₂ as an intermediate and instead aim to react the captured carbon directly with water. Figure 1.3 describes the process of conversion of basic substances into chemicals.

Figure 1.3. Process of Basic Substances for Carbon Capture and Utilisation



CH₄ = methane, CO = carbon monoxide, CO₂ = carbon dioxide, H₂ = hydrogen.

Source: Authors based on METI, MEXT, and MOE (2021).

2.3. Chemical Products

Types of chemical products that may be produced with captured CO₂ as well as their use-case examples are described as follows including examples of each type of chemical in Boxes 1.1 to 1.3.

Basic chemicals

Basic chemicals are generated utilising the methanol to olefins (MTO) and ethanol to olefins (ETO) processes, which use chemical raw materials such as methanol and ethanol to synthesise olefins including ethylene, propylene, and butene. These processes are subject to overcoming obstacles such as improving yields, reducing production costs, improving durability, and scaling up productions, and forthcoming technological advancements are anticipated to result in more efficient chemical production.

Box 1.1. Basic Chemical: Aldehyde synthesis by oxo reaction

Producing company:
KH NeoChem Co. Ltd.

Oxo reactions, otherwise known as hydroformylation reactions, are a reaction of olefins, carbon monoxide, and hydrogen to synthesise aldehydes. We are then able to synthesise a range of derivatives from aldehydes, including alcohols, synthetic fatty acids, and esters.

In addition, new materials are being developed based on alcohols and synthetic fatty acids synthesised via oxo reactions.

Source: KH NeoChem website.

Functional chemicals

Polycarbonate and polyurethane raw materials (isocyanate) and highly water-absorbent polymer raw materials (acrylic acid) are functional chemicals that can be synthesised directly from CO₂ with low energy and without the utilisation of hydrogen due to their non-reductive reactions. Currently, demand for these substances in comparison to general-purpose plastics such as polyethylene and polypropylene is limited; however, in the foreseeable future, they are anticipated to be utilised in printed circuit boards, optical lenses, and automotive components.

**Box 1.2. Functional Chemical:
Polycarbonate/isocyanate production**

Producing company:
Asahi Kasei Corporation

Asahi Kasei Corporation conceived the world's first polycarbonate resin manufacturing process utilising CO₂ as a fundamental material and actualised its practical application in 2002. As of 2020, it constitutes approximately 17% of the world's production capacity (approximately 890,000 tons). By substituting the traditional methodology that employs a hazardous compound (phosgene) with CO₂ as a foundational material, they have accomplished a resource- and energy-efficient approach to producing high-purity, superior-quality polycarbonate that necessitates minimal wastewater treatment. They are also advancing into the domain of manufacturing technology for high-purity ethylene carbonate and dimethyl carbonate, essential materials for lithium-ion battery electrolytes, employing CO₂ as a fundamental resource.

Asahi Kasei Corporation formulated a production methodology for isocyanate (a polyurethane precursor) as a foundational material process for urea derived from CO₂. This has also been augmented to encompass multifunctional isocyanate, which possesses attributes such as transparency, low viscosity, superior aesthetic appeal, and low-temperature curing (800C), and contributes to the mitigation of CO₂ emissions resulting from energy utilisation in the automobile painting procedure.

Source: Asahi Kasei Corporation website.

Biomass-derived chemicals

Biomass-derived chemicals constitute a CCU pathway that employs photosynthesis to capture and store CO₂ into organic carbon. This encompasses biological conversion methodologies such as microbial fermentation and gas fermentation. Microalgae are minuscule organisms that can flourish in elevated concentrations of CO₂. They may be cultivated in open ponds or enclosed photobioreactors. Microalgae can be utilised to generate biofuels such as biodiesel and ethanol, in addition to serving as animal feed.

- Microbial fermentation: The cost (land, nutrients, energy, etc.) required to produce sugar substrates for microorganisms is a challenge. To avoid competition with food production, second generation sugars derived from cellulose are necessary, however, the technology remains underdeveloped.
- Gas fermentation: Microorganisms utilise carbon gases such as CO₂ or CO as a carbon source and hydrogen gas as a hydrogen and energy source. This produces synthetic gas. CO₂ may also emanate from industrial exhaust gases. It is increasingly becoming feasible to synthesise products such as ethanol, acetone, and animal feed from industrial waste gases; nevertheless, there exists potential for enhancement. Agricultural residues, forestry waste, plastics, and municipal solid waste are likewise viable.

**Box 1.3. Biomass-derived chemicals:
Carbon dioxide resource recovery
process technology using microalgae**

Producing company:
Chitose Bio Evolution Pte. Ltd.

CO₂ is transformed into valuable substances using microalgae, which exhibit elevated photosynthetic efficiency. Through the application of microalgae cultivation technology, functional chemicals and essential compounds such as plastic precursors may be synthesised utilising solar energy and CO₂ as primary materials, while proteins can additionally be generated as by-products.

CO₂ = carbon dioxide.

Source: Chitose Journal.

2.4. Fuels

Synthetic hydrocarbon fuels can easily be used within the current infrastructure and are economically advantageous when compared to the transportation and storage of electricity or hydrogen. Nevertheless, their production necessitates a significant amount of energy, which presents challenges concerning energy efficiency and cost, particularly when derived from renewable energy sources.

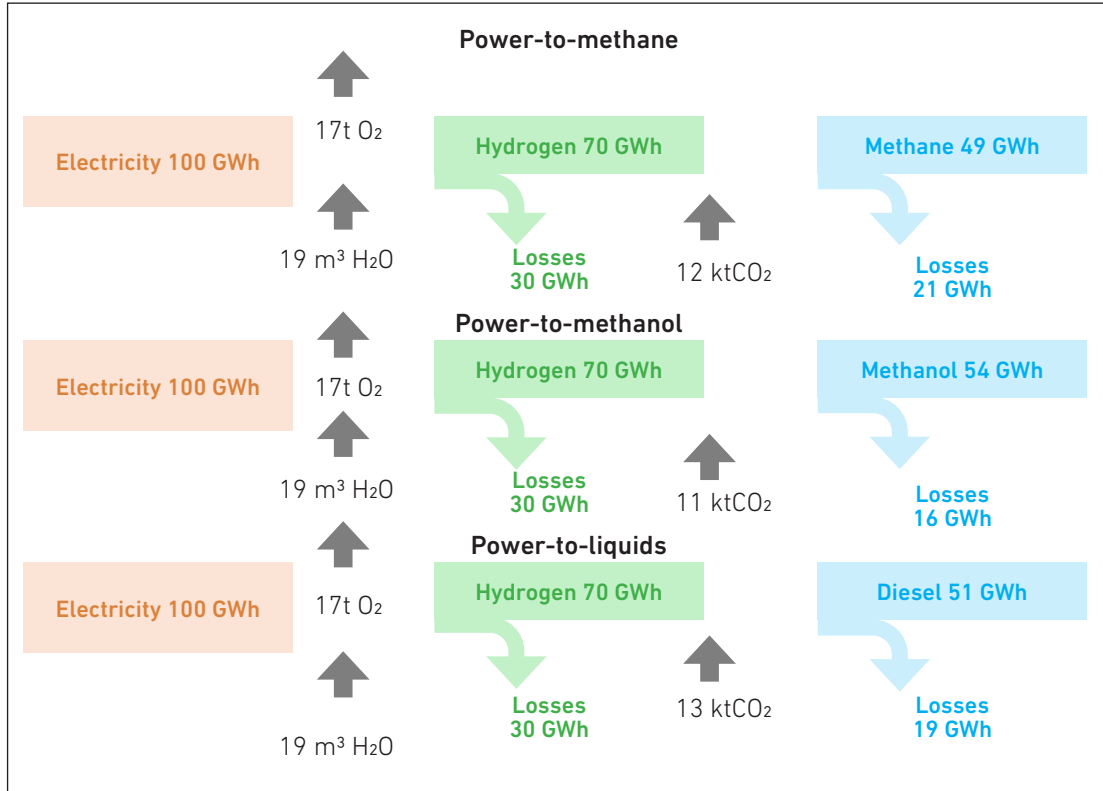
Synthetic methane is generated directly from CO₂ and hydrogen utilising the technologically advanced methanation procedure. In this procedure, hydrogen and CO₂ are initially reacted to yield CH₄. This facilitates the transportation and storage of methane using existing gas infrastructure, akin to natural gas. The primary benefit of synthetic methane is that it can be managed in an analogous manner to natural gas, thereby permitting storage at low pressure and low temperature. This enables the utilisation of existing supply chains and diminishes infrastructure expenses for transportation and distribution.

Synthetic liquid fuels are produced through a more intricate process. Initially, a reverse water-gas shift reaction converts CO₂ into CO, which is subsequently amalgamated with hydrogen to synthesise liquid fuels (such as synthetic gasoline and diesel). The synthesis process predominantly employs the Fischer-Tropsch process, and the liquid fuel produced can be further refined and utilised as diesel or kerosene. This technology has been validated on a modest scale, and the fuel synthesis process itself is technically advanced, yet challenges for mass production encompass energy efficiency and cost. A principal advantage of synthetic liquid fuels is that they can be fabricated utilising existing gas station infrastructure, thereby avoiding the necessity to alter the distribution network.

If the hydrogen is produced from electricity, the overall conversion efficiency of the production process is around 50%, but this differs per type of product. The CO₂ use rates are high, with methanol requiring 1.37 tCO₂ per tonne of product, methane 2.74 tCO₂ per tonne of product and kerosene 3.2 tCO₂ per tonne of product, assuming 100% conversion efficiency. Other chemical and biological conversion pathways, such as artificial photosynthesis, are still in the early stages of

their technological development. Significant amounts of electricity and generation capacity are required for the production of synthetic hydrocarbon fuels because of the low overall efficiency of production processes. The process of how conversion efficiency affects energy loss is described in Figure 1.4.

Figure 1.4. Conversion Losses During Production of Synthetic Hydrocarbon Fuels



CO₂ = carbon dioxide, GWh = gigawatt hour, H₂O = water, O₂ = oxygen.

Source: Authors based on IEA (2020).

As articulated above, production efficiency constitutes a significant impediment for scaling up the deployment synthetic hydrocarbon fuels. Conversely, solid oxide electrolyser cell (SOEC) technology represents a methodology that concurrently and electrochemically disassociates water vapour and CO₂, and it may assume a pivotal role in the generation of synthetic fuels. Dissimilar to the electrolysis technology employed for conventional hydrogen production, SOEC technology utilises a solid oxide electrolyser to proficiently decompose CO₂ and water vapour within a high-temperature environment through an oxidation-reduction reaction. This process facilitates the direct conversion of CO₂ into CO, which can subsequently be utilised to produce synthetic liquid fuels. Given that SOEC technology functions at elevated temperatures, it demonstrates remarkable energy efficiency, which presents substantial advantages, particularly in conjunction with renewable energy sources. The decomposition of CO₂ and water by SOEC co-electrolysis necessitates diminished energy compared to existing fuel synthesis methodologies and is anticipated to yield sustainable fuels at reduced costs.

2.5. Mineralisation

Mineralisation constitutes the process of reacting CO₂ with natural minerals or metal ions in solid refuse or wastewater to generate carbonates. Carbonates possess a wide range of applications, encompassing construction materials such as insulation materials and bricks, chemicals, and foodstuffs. The production of carbonates can utilise industrial refuse and minerals, thereby contributing to the sustainable management of waste. One auspicious pathway for mineralisation involves carbonate blocks as a substitute for Portland cement blocks. This enables the reduction of the quantity of cement and aggregate required as the raw materials by utilising CO₂ in the manufacturing process, which is anticipated to reduce CO₂ emissions and raw material costs. These products are likewise projected to serve as a medium-term measure for emissions reduction, as CO₂ remains sequestered for a long period of time.

Construction aggregate

CO₂-derived construction aggregates are primarily generated by the carbonation of waste by-products (steel slag, coal fly ash, etc.). The captured CO₂ is conveyed to a carbonation facility, where the waste particulates are enriched with CO₂. The aggregates are then generally transported to a concrete manufacturing plant. The CO₂ employed for the carbonation procedure is mineralised within the construction aggregate and is not re-emitted.

CO₂-cured concrete

CO₂-cured concrete represents an alternative to conventional concrete, which seizes CO₂ as an integral component of the carbonation procedure during mixing. This curing methodology culminates in more robust concrete, thereby permitting a reduced quantity of cement to be utilised compared to traditional methodologies. However, this concrete is generally deployed solely within the non-structural precast sector.

Box 1.4 describes the role of hydrogen and technologies that do not depend on the use of hydrogen.

Box 1.4. Carbon Recycling without Hydrogen

The majority of CCU pathways require hydrogen as a reactant and energy source. Consequently, the anticipated timeline for the commercialisation of CCU technologies fluctuates depending on the product, such as products where the alternative possesses significant added value and is readily replaceable (e.g. bio jet fuel) or products where the expense of the raw material hydrogen is reduced (e.g. synthetic fuel). Conversely, there exist carbon recycling processes that do not utilise hydrogen, and their practical implementation is advancing.

- Chemicals (polycarbonate, etc.)
 - The production of polycarbonate from alcohol and CO_2
- Liquid fuel (bio jet fuel, etc.)
 - Microalgae and other organisms grow by absorbing CO_2 through photosynthesis
 - The development of algae capable of sequestering greater oil quantities is in progress
- Carbonation (concrete products, etc.)
 - CO_2 is reacted to produce carbonates (CaCO_3 , MgCO_3 , etc.) and sequestered
 - Waste possessing elevated calcium and magnesium content is required such as coal ash, biomass ash, steel slag, etc.
 - Potential for processing additional CO_2 (concrete products, refilling antiquated coal mine sites, etc.)
- Fuel that can be amalgamated with fossil fuel-fired power plants
 - Rapidly growing trees (elite tree) that thrive by absorbing increased CO_2
 - CO_2 -free ammonia, etc.
- Utilisation of CO_2 in marine plants (blue carbon)
 - CO_2 stored by algae

CaCO_3 = calcium carbonate, CCU = carbon capture and utilisation, CO_2 = carbon dioxide, MgCO_3 = magnesium carbonate.

Source: METI, MEXT, and MOE (2021).

3. Enabling Policies

In order for CCU to be commercialised, the significance of reducing CO₂ emissions must become evident and a stream of revenue must be secured for the business. Activities towards achieving global carbon neutrality are advancing expeditiously, yet further advancement will encounter challenges if we rely solely on the market. It is anticipated that governments will take the initiative in establishing a policy-driven business environment.

Table 1.2. Key Elements for Carbon Capture and Utilisation Business Environment

Materialising market potential	The market introduction potential of carbon capture and utilisation (CCU) shall be enhanced by examining mid- to long-term energy supply and greenhouse gas emissions projections, emission forecasts, and mitigation strategies for sectors that are hard to abate, as well as the development plans and execution timelines of the hydrogen infrastructure utilised by CCU, and this shall serve as the foundation for private enterprises' market entry determinations. In recent years, the viewpoint of synergistic effects with the circular economy may emerge as a significant catalyst.
Establishment of legal framework	To render CCU a feasible business, it is imperative to institute a legal framework for the management of carbon dioxide (CO ₂) and legal accountability. It is crucial to attain public endorsement and societal consensus concerning the allocation of environmental value between CO ₂ capture businesses and users of CCU products.
Establishment of business model	The commercial framework for CCU shall be instituted by clarifying the magnitude of carbon abatement value through the concept of public-private collaboration regarding development expenditures and policy-driven carbon pricing. CCU models have been formulated thus far that are interconnected with CO ₂ capture enterprises through the aggregation of industrial facilities, and CO ₂ sequestration enterprises linked to thermal energy generation stations and hydrogen production facilities. Ensuring value chain connection including cross-border trade is essential in enabling a business model that may encompass different sectors and cover large areas.
Advancing private investment	Private investment is essential for the extensive implementation of CCU, and an approach that combines risk mitigation measures and incentives to attract private capital is necessitated. Specifically, in addition to the infusion of public resources to entice private investment, the public and private sectors ought to collaborate to formulate frameworks for technical assessment and certification as a mechanism to mitigate the distinctive business risks associated with CCU.

Source: Created by Mitsubishi Research Institute based on various sources.

International case studies of CCU enabling policy and programmes in Japan, Singapore, the European Union, the United States, the United Kingdom, Canada, and other Asian countries (i.e. Viet Nam and Indonesia) are described in Tables 1.3 to 1.8.

Table 1.3. Japan**Role Outlined in Strategic Documents (Decarbonisation Plan, Basic Energy Plan)**

In the 7th Basic Energy Plan announced in February 2025, carbon recycling and carbon capture and utilisation (CCU) are deemed essential for simultaneously achieving stable energy supply, economic growth, and decarbonisation by effectively utilising CO₂ from hard-to-decarbonise sectors and power plants.^[1]

Role Outlined in Nationally Determined Contribution

Sectors and scopes covered by nationally determined contributions include fuel combustion (energy industries, manufacturing, and construction), as well as the transport and storage of carbon dioxide, but there is no mention of carbon recycling or CCU.^[2]

Incentives (subsidies and tax incentives)

Grants provided by the New Energy and Industrial Technology Development Organization.^{[3], [4]}

Carbon pricing (emissions trading system, carbon tax)

An additional tax of ¥289 per ton of CO₂e is imposed on all fossil fuels as part of global warming countermeasures. Some local governments, such as Tokyo and Saitama prefectures, have introduced regional emissions trading systems. A nationwide trading system, GX-ETS is expected to be launched in 2026.^[5]

Others (valuation of green products, efforts to boost demand)

Eco Mark: a certification system operated by the Japan Environment Association, a public interest incorporated foundation. It is awarded to products and services recognised as having a low environmental impact throughout their entire life cycle.^[6]

Green Energy Certification: a certification system provided by the Japan Quality Assurance Organization, which certifies energy with a low environmental impact.^[7]

CO₂e = carbon dioxide equivalent, GX-ETS = green transformation emissions trading system.

Sources: Authors based on ^[1] METI (2025), ^[2] MOE (2025), ^[3] NEDO (2025a), ^[4] NEDO (2025b), ^[5] MOE, ^[6] EcoMark, ^[7] JQA.

Table 1.4. Singapore**Role Outlined in Strategic Documents (Decarbonisation Plan, Basic Energy Plan)**

In the environmental action plan Singapore Green Plan 2030, announced in February 2021, new low-carbon alternatives, such as carbon capture, utilisation, and storage, will be pursued as part of an energy reset.^[1]

Role Outlined in Nationally Determined Contribution (NDC)

In the Long-Term Low-Emissions Development Strategy submitted by Singapore to the United Nations Framework Convention on Climate Change in March 2020 along with its NDC, it was stated that advanced low-carbon technologies, such as carbon capture, utilisation, and storage, would be adopted to facilitate the transition to a low-carbon economy.^[2]

Incentives (subsidies and tax incentives)

Grants for the development of low-carbon energy technologies.^[3]

Carbon pricing (emissions trading system, carbon tax)

The carbon tax is raised to S\$25 per ton of CO₂e in 2024 and 2025, to \$45 per ton of CO₂e in 2026 and 2027, and to S\$50–S\$80 per ton of CO₂ by 2030.^[4]

Others (valuation of green products, efforts to boost demand)

The Singapore Green Labelling Scheme is operated by the Singapore Environment Council and provides certification for environmentally friendly products.^[5]

CO₂ = carbon dioxide, CO₂e = carbon dioxide equivalent.

Sources: ^[1] National Climate Change Secretariat (2022a), ^[2] Energy Market Authority (2021), ^[3] Bird & Bird (2024), ^[4] National Climate Change Secretariat (2022b), ^[5] Singapore Environmental Council.

Table 1.5. European Union

Role Outlined in Strategic Documents (Decarbonisation Plan, Basic Energy Plan)
The European Union (EU) positions carbon capture and utilisation (CCU) as one of the technological pathways towards decarbonisation of the industry sector. ^[1]
Role Outlined in Nationally Determined Contribution (NDC)
CCU is not mentioned in the updated NDC submitted in 2023. ^[2]
Incentives (subsidies and tax incentives)
The EU supports the development and demonstration of new CCU technologies and carbon recycling through research funding programmes such as Horizon Europe. ^[3]
Carbon pricing (emissions trading system, carbon tax)
Through the 'cap-and-trade' system, market mechanisms allow companies to choose the most cost-effective methods, leading to overall emission reductions. ^[4]
The EU has no carbon tax.
The Carbon Border Adjustment Mechanism (CBAM) has been temporarily implemented since 2023 and is planned to fully be implemented in 2026. It is a system designed to prevent products subject to strict carbon emission regulations within the EU from facing competition from countries with more lenient regulations. The CBAM imposes a carbon cost on specific imported products, calculated based on their carbon emissions. This ensures that imported goods are subject to the same environmental regulations as similar products produced within the EU. It mainly targets carbon-intensive industries such as steel, cement, chemicals, and aluminium. ^[5]
Others (valuation of green products, efforts to boost demand)
EU Ecolabel, a green product certification system, is awarded to environmentally friendly products. Established in 1992, EU Ecolabel assesses the environmental impact of products over their entire life cycle and is only awarded to products that meet stringent criteria. ^[6]

Sources: ^[1] European Commission(a), ^[2] European Union and the Member States (2023), ^[3] European Commission(b),

^[4] European Commission(c), ^[5] European Commission(d), ^[6] European Commission(e).

Table 1.6. United States

Role Outlined in Nationally Determined Contribution
United States (US) Mid-century Strategy (November 2016) points as the robust element for the transition to a low-greenhouse gas pathway to achieve deep decarbonisation that 92% of generation in 2050 coming from a diverse portfolio of clean sources, including significant contributions from solar, wind, nuclear, hydro, and carbon capture, utilisation, and storage (CCUS). Nearly all fossil fuel power plants without CCUS are phased out by 2050. ^[1]
In The Long-Term Strategy of the United States, submitted in November 2021, the strategy for energy transition in industries enabling decarbonisation includes energy efficiency, materials efficiency, electrification, the introduction of low-carbon fuels and feedstocks, and carbon capture and storage. There is no mention of carbon recycling or carbon capture and utilisation. ^[2]
Incentives (subsidies and tax incentives)
Funds for research and development carbon conversion technology and mineralisation. ^[3]
The Inflation Reduction Act (IRA) considers clean power, transportation and electric vehicles, energy efficiency, carbon capture, and clean hydrogen. ^[4]
It is noted that many incentives under the IRA have been altered in recent years under the new administration.

Table 1.6. Continued**Carbon pricing (emissions trading system, carbon tax)**

There is no carbon tax and no national-level emissions trading system. However, there is the Regional Greenhouse Gas Initiative for the power sector in the northeast (since 2009) and a multi-sector emissions trading system in California (since 2013).^[5]

Others (valuation of green products, efforts to boost demand)

ENERGY STAR label, run by the US. The Environmental Protection Agency and the Department of Energy, meets strict energy efficiency requirements, helping consumers save money and reduce greenhouse gas emissions.^[6]

Leadership in Energy and Environmental Design (LEED), administered by the US Green Building Council, is a widely used green building rating system that provides a framework for healthy, efficient, carbon-saving green buildings.^[7]

Sources: ^[1] White House (2016), ^[2] United States Department of State and the United States Executive Office of the President (2021), ^[3] US Department of Energy (n.d.a), ^[4] US Department of the Treasury, ^[5] US Environmental Protection Agency, ^[6] US Department of Energy (n.d.b), ^[7] US Green Building Council.

Table 1.7. United Kingdom**Role Outlined in Strategic Documents (Decarbonisation Plan, Basic Energy Plan)**

Net-zero Strategy: Build Back Greener (2021) describes that growing new industries in low carbon hydrogen alongside carbon capture, utilisation, and storage (CCUS) and renewable energy will put our industrial 'Super Places' at the forefront of technological development – accelerating decarbonisation in 'clusters', which account for approximately half of the United Kingdom's (UK) industrial emissions. These clusters could have the opportunity to access support under the government's CCUS programme, which includes the £1 billion CCS Infrastructure Fund and revenue supports mechanisms.^[1]

In the Ten Point Plan for a Green Industrial Revolution (2020), point 8, investing in carbon capture, utilisation, and storage could potentially deliver support for around 50,000 jobs by 2030, up to £1 billion of public investment by 2025, savings of around 40 MtCO₂e between 2023 and 2032, or 9% of 2018 UK emissions.^[2]

Role Outlined in Nationally Determined Contribution (NDC)

UK government CCUS and hydrogen industries in the Nationally Determined Contribution to achieve net zero using the pathway of the industrial processes and product use.^[3]

Incentives (subsidies and tax incentives)

In October 2024, the government announced up to £21.7bn of available funding over 25 years to launch the UK's new CCUS and hydrogen industries to make the UK an early leader in these two growing global sectors. This funding to support up to 4,000 direct jobs, with CCUS supporting up to 50,000 jobs when the sector matures into the 2030s.^[4]

Carbon pricing (emissions trading system, carbon tax)

The UK Emissions Trading Scheme (UK ETS) went live on 1 January 2021, replacing the UK's participation in the European Union ETS.^[5]

The Carbon Border Adjustment Mechanism is planned to be introduced in 2027. It is a system that imposes taxes or tariffs on carbon-intensive goods imported from countries that do not meet low-carbon standards. The purpose of this mechanism is to prevent unfair competition for companies adhering to strict emissions standards domestically and to support international carbon reduction goals.^[6]

Table 1.7. Continued**Others (valuation of green products, efforts to boost demand)**

Carbon Trust Standard is recognised for its rigorous assessment of a company's carbon footprint and efforts to reduce CO₂ emissions.^[7]

Building Research Establishment Environmental Assessment Method (BREEAM) assesses the sustainability of buildings and infrastructure projects.^[8]

MtCO₂e = metric tonnes of carbon dioxide equivalent.

Sources: ^[1] UK Government (2021); ^[2] UK Government (2020); ^[3] UK Government (2025); ^[4] UK Government (2024a); ^[5] UK Government (2024b); ^[6] UK Government (2023); ^[7] Carbon Trust; ^[8] BREEAM.

Table 1.8. Canada**Role Outlined in Strategic Documents (Decarbonisation Plan, Basic Energy Plan)**

Canada is positioning its industries to be green and competitive. This includes developing a carbon capture, utilisation, and storage (CCUS) strategy. In relation to the energy mix, CCUS technologies or switching from natural gas to hydrogen may also have the potential to help natural gas plants provide non-emitting flexible generation.^[1]

Role Outlined in Nationally Determined Contribution (NDC)

Canada is accelerating zero- and low-emissions technologies through the array of federal programmes to guide decarbonisation across industries. Canada's Clean Economy Investment Tax Credits (ITCs), representing C\$94 billion in federal incentives by 2034–2035, will play an essential role in attracting investment, creating jobs, and driving Canada's economy toward net-zero by 2050. The ITCs include CCUS.^[2]

Incentives (subsidies and tax incentives)

Canada's Clean Economy ITCs, representing C\$94 billion in federal incentives by 2034–2035, will also play an essential role in attracting investment, creating jobs, and driving Canada's economy towards net-zero by 2050. The first four ITCs, passed into law in June 2024, include the Clean Technology ITC, the CCUS ITC, the Clean Technology Manufacturing ITC, and the Clean Hydrogen ITC.^[3]

Carbon pricing (emissions trading system, carbon tax)

Since 2019, the Pan Canadian Approach to Pricing Carbon Pollution has ensured carbon pricing is in place at similar levels of stringency across the country while maintaining flexibility for provinces and territories. Provinces and territories can design their own pricing system tailored to their needs as long as it meets federal minimum national stringency standards, also known as the federal 'benchmark'.

If a province or territory decides not to price pollution or proposes a system that does not meet these standards, the federal system is put in place. The federal backstop has two parts: a regulatory charge on fossil fuels like gasoline and natural gas, known as the fuel charge and a performance-based system for industries, known as the Output-Based Pricing System.^[4]

Others (valuation of green products, efforts to boost demand)

The EcoLogo programme, also known as UL Environment's ECOLOGO Certification, established by the Government of Canada, is the environmental standard and certifies products and services that meet stringent environmental performance criteria.^[5]

Sources: ^[1] Canada, Government of (2022); ^[2] Canada, Government of (2025); ^[3] Canada, Government of (2024); ^[4] Canada, Government of (n.d.); ^[5] UL Solutions.

Viet Nam and Indonesia

- Viet Nam positions CCU and CCUS as two of the crucial technologies to enable the decarbonisation of the power and industry sectors under the National Strategy of Climate Change (2022), the National Strategy on Green Growth (2023), the National Energy Planning (2021), and the National Power Development Plan (2023). Further development is required for regulations specific to CCUS in terms of licensing for CO₂ storage, technology development and finance. Details of the state of CCUS and carbon recycling-related policies in Viet Nam are described in Chapter 7.
- Indonesia actively promotes carbon recycling as one of the crucial technologies to enable decarbonisation under the Long-Term Strategy for Low Carbon and Climate Resilience 2050 (2021) as well as circular economy policies, such as the National Waste Management Policy (2021). Financing of CCU and CCUS is promoted under the presidential decree on Economic Value of Carbon (2021). While the regulations for licensing of CO₂ storage was introduced in Presidential Decree No14/2024, Law No.59/2024 emphasises CCUS as key technology for decarbonising energy intensive industries and mandating adoption of carbon recycling technologies across sectors, integrating Indonesia's energy transition goals with Long-term national development plan. Details of the state of CCUS and carbon recycling related policies in Indonesia are described in Chapter 8.

4. Carbon Accounting

Carbon accounting constitutes a significant viewpoint in the positioning of CCU as a climate change intervention. The potential for climate change alleviation through CCU can be encapsulated as follows:

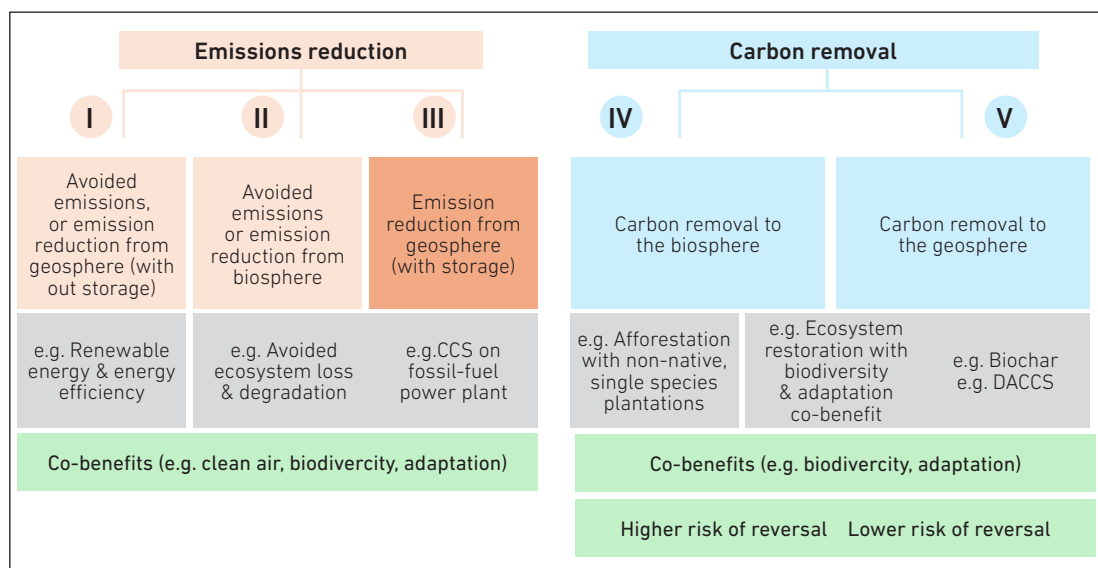
- Net-zero CO₂ emissions by producing the same end product with renewable carbon feedstocks compared to the traditional pathway (use of fossil feedstocks)
- Net zero CO₂ emissions when CO₂ emissions used as a feedstock in the production process are permanently stored in the product (e.g. mineralisation), or are re-released at the end of the product's life and then captured and recycled, or CO₂ is captured from the atmosphere and returned to the atmosphere at the end of the product's life.
- Net CO₂ removal when CO₂ captured from the atmosphere or biomass processing is permanently stored in the product through a mineralisation process.

Conversely, there exists no unequivocal international consensus regarding the positioning of CCU within carbon accounting. In the foreseeable future, it is anticipated that varied methodologies will be employed for each of the distinct CCU channels. The selection of methodology will yield disparate ramifications on the incentives for the producers of CCU products and the consumers of CCU products.

4.1. Oxford Offsetting Principle

In the discourse concerning carbon accounting, two concepts are delineated: emissions reduction and carbon removal. Carbon removal is articulated as a human-induced activity that captures CO₂ from the atmosphere and sequesters it permanently within geological, terrestrial, or marine reservoirs, or within products. A classification known as the Oxford Offsetting Principle delineates five distinct project classifications that differentiate between emissions reduction and carbon removal and elucidates the origin of the carbon extracted from the atmosphere, the manner in which the carbon is sequestered (biosphere or geosphere), as well as the risks and advantages concomitant with these varying methodologies. CCU may be categorised as carbon removal; however, a salient perspective to consider is reversal risk. In this context, the classification with minimal reversal risk pertains to subterranean storage, and it is noted that the storage duration is on the scale of centuries. This implies that even within CCU, it is confined to specific pathways such as mineralisation.

Figure 1.5. Taxonomy of Oxford Offsetting Principle



CCS = carbon capture and storage, DACCS = direct capture and storage.

Source: Authors based on Axelsson et al. (2024).

4.2. Corporate Climate Disclosure: Greenhouse Gas Protocol

In corporate climate disclosure, enterprises transparently disclose their greenhouse gas (GHG) emissions and emissions reduction targets and progress. The GHG Protocol constitutes an international framework for quantifying and reporting GHG emissions. Private enterprises report GHG emissions in three classification types: Scope 1 (direct emissions), Scope 2 (indirect emissions, electricity consumption, etc.), and Scope 3 (indirect emissions through the supply chain).

Furthermore, the GHG Protocol is considering the Land Sector and Removals Guideline, aspiring to incorporate land use and land use change and carbon removal activities within the scope of corporate reporting. The forthcoming guidelines shall formulate standards and measurement methodologies to ensure that enterprises can report meticulously how they emit or remove GHG emissions through forest management initiatives and carbon removal actions that involve land use transformation.

Presently, CCU can be positioned as product carbon storage. Product carbon storage refers to carbon stored in product carbon pools obtained from biogenic or technological CO₂ sinks. Product carbon pool pertains to the carbon contained within a product or material during the product's utilisation phase, encompassing recycling and reuse. Reporting product carbon pools is optional. Should enterprises account for and report product carbon pools in their GHG inventory, they must comply with the following accounting standards (GHG Protocol, 2024).

- Stock-change accounting approach: accounts for the annual net product carbon stock change, using the stock-change accounting approach. The net product carbon stock change shall only include biogenic and/or terrestrial carbon dioxide removal (TCDR)-based carbon in products sold by the reporting company that are in the use phase, which includes recycling and reuse.
- Data quality: accounts for and report product carbon storage using information regarding the biogenic and/or TCDR-based carbon content of their sold products, as well as data regarding product lifetime (half-life value), and conversion rates from raw material to intermediate products, final products and/or recycling and reuse.
- Product carbon storage: only reports product carbon storage if the total biogenic and/or TCDR-based product carbon stock increases in the reporting year.
- Losses of stored carbon: If the total biogenic and/or TCDR-based product carbon stock decreases in the reporting year, report negative product carbon storage, separately for biogenic and TCDR-based product carbon storage.

4.3. Carbon Pricing: Emissions Trading System, Carbon Credits

European Union Emissions Trading System (EU ETS)

The EU has been executing the EU ETS, a cap-and-trade climate change policy, since 2005. Each establishment is subject to a maximum threshold regarding the aggregate quantity of specific GHG emissions that may be released, and these establishments are mandated to allocate or purchase emission allowances. For CCU, the amended ETS Directive extends the exemption from emissions allowance requirements to encompass GHG emissions that are permanently chemically bound in the product and are not released into the atmosphere during standard usage. The revised 2023 EU ETS Directive explicitly acknowledges the permanence of carbon storage in particular categories of products. Mineralised construction materials are acknowledged as mitigation measures, provided that CO₂ is permanently fixed and that the double counting of CO₂ in alternative processes is eliminated. Conversely, other CCU products, such as chemical products, are excluded. The EU has delineated the following legislation as the criteria for acknowledging permanent storage:

Directive 2003/87/EC Article 12(3b). An obligation to surrender allowances shall not arise in respect of emissions of GHGs which are considered to have been captured and utilised in such a way that they have become permanently chemically bound in a product so that they do not enter the atmosphere under normal use, including any normal activity taking place after the end of the life of the product.

Carbon Removal Certification Framework (CRCF)

The CRCF was proposed to guarantee the dependability of carbon removal undertakings essential for the EU's ambitious objective of attaining climate neutrality by 2050, and a provisional accord was reached by the Council and the European Parliament in 2024. The framework establishes mechanisms for enduring carbon removal, carbon farming, and carbon storages in products. The permanence of carbon removal by CCU is contingent upon the life cycle of the product utilised. If the captured CO₂ is ultimately discharged into the atmosphere, it is not encompassed by the CRCF. Conversely, the CRCF permits both enduring and temporary storage for atmospheric/biogenic CCU and encompasses the following activities (Council of the EU, 2024):

- Permanent carbon removal that captures and stores atmospheric or biogenic carbon for several centuries (e.g. bioenergy with carbon capture and storage, direct air capture with storage)
- Carbon storage activities that capture and store carbon in long-lasting products for at least 35 years (such as wood-based construction products)
- Carbon farming activities that enhance carbon sequestration and storage in forests and soils, or that reduce greenhouse gas emissions from soils, carried out over a period of at least five years (e.g. reforestation, restoring peatlands or wetlands, improved fertiliser use)

4.4. International GHG Inventory: IPCC Guidelines

The Intergovernmental Panel on Climate Change (IPCC) directives have not distinctly delineated the mitigation impact of CCU. The 2006 IPCC guidelines partially show the methodology for estimating emissions stemming from carbon capture, utilisation, and storage activities when formulating national inventories; however, with the emergence of new technologies and new empirical data, it is considered imperative to reassess them, and the IPCC is presently engaged in the development of guidelines for CCUS and carbon dioxide removal, encompassing CCU (IPCC 2024).

The background paper within the directives articulates that 'The short-term use of carbon dioxide should be treated differently to carbon dioxide captured for permanent storage.' Conversely, it also asserts that 'Short-term storage is not a term that is defined by the IPCC Guidelines.'

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Quantities of CO₂ for later use and short-term storage should not be deducted from CO₂ emissions except when the CO₂ emissions are accounted for elsewhere in the inventory. The default assumption is that there is no carbon dioxide capture and storage (CCS) taking place

The IPCC intends to persist in its discussions with the objective of endorsing the guidelines in about 2027.

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Chapter 2

Carbon Dioxide
Utilisation
Technology for
Polyethylene
Terephthalate
Plastic Production
and High-density
Polyethylene
Geomembrane

1. Introduction

Indonesia's polymer industry exhibits divergent development trajectories between polyethylene terephthalate (PET) and high-density polyethylene (HDPE). PET has shown progressive advancement towards vertical integration and circular economy practices, whereas HDPE remains significantly reliant on imports to meet domestic demand. In 2023, national HDPE consumption was estimated at 700,000 tonnes, while PET consumption reached 407,000 tonnes (Badan Pusat Statistik, 2023b). Despite the presence of local HDPE producers – primarily PT Chandra Asri and PT Lotte Chemical Titan – more than 45% of domestic HDPE demand was met through imports sourced from Malaysia, China, and Thailand (Volza, 2025). This highlights an ongoing dependency on external supply chains for polyethylene resins. In contrast, the PET sector benefits from a more diversified and mature industrial ecosystem. Key manufacturers include PT Indorama Synthetics (Cilegon), PT PolyPET Karya Persada (Ciwandan), PT MC PET Film Indonesia (Cikarang), and PT Petnesia Resindo (Tangerang), all of which produce food-grade virgin PET resins to serve both domestic and export markets (Indorama Ventures, 2025; MFI, 2025; Petnesia Resindo, 2025).

A significant milestone in Indonesia's pursuit of circularity was the establishment of the nation's first food-grade recycled PET production facility by PT Amandina Bumi Nusantara. This facility supports the national circular economy agenda by introducing closed loop recycling solutions and reducing reliance on virgin raw materials (Amandina Bumi Nusantara, 2025). This context intersects with broader environmental and policy imperatives. As Indonesia needs to fulfil its broader climate commitments. As a major emitter and highly climate-vulnerable nation, Indonesia has pledged to reduce its greenhouse gas (GHG) emissions by 29% unconditionally and 41% conditionally under its Nationally Determined Contribution (NDC) by 2030 (Suroso et al., 2022; MEMR, 2015). The chemical sector, including polymer manufacturing, is energy-intensive and fossil-reliant, thus representing a key target for decarbonisation strategies. One promising approach is the deployment of CO₂ recycling technologies that convert emissions into value-added chemicals. In PET production, carbon dioxide (CO₂) can be converted into ethylene glycol or para-xylene, both essential for monomer synthesis (Damayanti et al., 2023). For HDPE, CO₂-derived methanol can be transformed into ethylene via zeolite-catalysed processes such as methanol-to-olefins (MTO) (Liu et al., 2025; Mufarrij, Navarri, Khojasteh, 2023). while technically viable, these pathways are currently constrained by economic, energy, and supply chain challenges, particularly the underdevelopment of green methanol logistics.

This chapter therefore aims to evaluate the integration of CO₂-based routes in Indonesia's polymer value chains. It also proposes a conceptual green methanol supply chain anchored in the Banten and East Java industrial clusters, addressing both technical and regional policy considerations.

2. Methodology

The method used for this study is literature review and theoretical study on the following key areas:

- CO₂ recycling technologies: evaluates CO₂ capture, conversion, and scalability;
- CO₂ in polymers: reviews its role in PET and HDPE production and hydrocarbon substitution;
- hydrogen use: compares grey, blue, and green hydrogen in polymer manufacturing;
- sustainability: assesses CO₂-based vs. conventional polymers via limited life cycle analysis;
- limited economic analysis on the cost, feasibility, and competitiveness; and
- concept of Integrated green methanol supply chain for PET and HDPE production in Banten and East Java clusters.

This study approach is expected to provide valuable insights into the feasibility and potential of CO₂ recycling technology to produce PET and HDPE, contributing to the development of sustainable and environmentally friendly practices in the plastics industry.

3. Analysis

3.1. Evaluation of CO₂ Recycling Technologies

CO₂ recycling involves three critical stages: capture, purification, and conversion, each essential for reducing atmospheric CO₂ and generating value-added products (Bocchini et al., 2017; Jo et al., 2020). The capture phase typically employs one of three primary techniques: post-combustion, pre-combustion, or oxy-combustion. Carbon separation is achieved through various methods – adsorption, absorption, membrane separation, liquid-gas extraction, biological processes, or hybrid approaches – with selection depending on the nature of the feedstock, process configuration, and operational stage (e.g. pre-, or post-exhaust) (Odunlami et al., 2022). The choice of method is guided by the physicochemical properties of the materials involved and the specific requirements of the industrial process.

Post-combustion CO₂ capturing technique

Post-combustion CO₂ capture refers to the removal of carbon dioxide from flue gas – exhaust gas produced after the combustion of fuel in the presence of air (a mixture of nitrogen and oxygen) – before it is released into the atmosphere (Shafie et al., 2021; Tomioka, Sakai, and Mano, 2021). This technique has the following key characteristics and challenges:

- High energy demand: The process is energy-intensive, particularly for solvent or adsorbent regeneration required in CO₂ separation (Zhang et al., 2018).
- Low flue gas pressure: Flue gases are typically at or near atmospheric pressure, and the presence of impurities such as sulphur oxides (SO_x) and nitrogen oxides (NO_x) can degrade capture materials (Kajama, Nwogu, and Gobina, 2021).
- Dilute CO₂ concentration: With only 13%–15% CO₂ in the flue gas, large gas volumes must be processed, increasing equipment size and operating costs (Zhang et al., 2018).

Despite these limitations, post-combustion capture is technically viable and especially suitable for retrofitting existing power plants, as it does not require major modifications to the combustion system (Shafie et al., 2021). CO₂ is typically captured through adsorption, absorption, or membrane separation technologies (Kajama, Nwogu, and Gobina, 2021). Amongst these, solvent-based absorption is the most mature and widely studied method. However, it remains both capital- and energy-intensive. Ongoing research and industrial-scale demonstrations aim to reduce these costs and improve overall system efficiency (Odunlami et al., 2022).

Pre-combustion CO₂ capturing technique

Pre-combustion CO₂ capture removes carbon dioxide before fuel combustion by converting fuels like coal or natural gas into syngas (a mix of CO and H₂) through gasification or partial oxidation. The CO is then converted to CO₂ via the water-gas shift reaction, increasing hydrogen yield. CO₂ is captured from this intermediate stream, resulting in a cleaner, hydrogen-rich fuel. Common applications include:

- Ammonia production: CO₂ and H₂ are separated before ammonia synthesis
- Coal gasification: CO₂ is removed from syngas before combustion, enabling low-carbon power generation

Although energy-intensive, especially for sorbent regeneration, pre-combustion capture is more efficient than post-combustion methods and is well-suited for large-scale hydrogen and chemical production (Odunlami et al., 2022).

Oxy-combustion CO₂ capturing technique

Oxy-combustion captures CO₂ by burning fuel with pure oxygen instead of air, resulting in a highly concentrated CO₂ stream that simplifies capture and separation. This approach combines elements of both pre- and post-combustion techniques, as the fuel undergoes gasification and oxidation, often producing steam in the process. Although it offers high CO₂ capture efficiency, oxy-combustion requires costly oxygen production systems, making it expensive to implement at industrial scale. Nevertheless, it is regarded as a promising and innovative method for addressing industrial CO₂ emissions (Odunlami et al., 2022).

Various CO₂ capture methods above offer various levels of efficiency, scalability, and energy consumption, influencing their feasibility for large-scale implementation. Amine-based absorption remains one of the most widely used capture technologies, achieving 85–95% efficiency with scalability ranging from 1 to 5 million tonnes of CO₂ per year (MtCO₂/year), although it requires 3.5–4.2 megajoules per kilogramme of CO₂ (MJ/kg CO₂), making it energy-intensive (Jhong, Ma, and Kenis, 2013; Kumari et al., 2025; Jiang et al., 2024; Soo et al., 2024). Membrane separation provides a lower energy alternative, consuming only 0.2–1.0 MJ/kg CO₂, but operates at 50%–90% efficiency and is currently scalable up to 100,000–500,000 tonnes of CO₂ per year (tCO₂/year), with challenges in maintaining gas purity (Jansen et al., 2015; Pasichnyk et al., 2023). Calcium looping, a high-efficiency method capturing 90%–95% CO₂, is suitable for large-scale operations of 500,000–1,000,000 tCO₂/year, although it demands 2.5–3.0 MJ/kg CO₂, making cost-effective deployment difficult (Madejski et al., 2022).

Pre-combustion capture, commonly applied in integrated gasification combined cycle systems, offers 85%–90% efficiency and scalability of 1–5 MtCO₂/year, but its 2.8–4.0 MJ/kg CO₂ energy requirement and high capital costs limit its broader adoption (Jansen et al., 2015). Similarly, oxy-fuel combustion achieves 90%–95% CO₂ capture, with a scalability of 1–2 MtCO₂/year, but its

reliance on pure oxygen results in high energy consumption of 3.0–5.0 MJ/kg CO₂ (Madejski et al., 2022). Direct air capture (DAC), a promising technology capable of achieving negative emissions, captures CO₂ at 75%–85% efficiency, but its 1,000–100,000 tCO₂/year scalability remains limited by an exceptionally high energy demand of 5.0–10.5 MJ/kg CO₂, making cost reductions a key challenge (An et al., 2023; Li and Yao, 2024; Bisotti et al., 2024). To enhance the feasibility of these capture technologies, ongoing research and supportive policies are crucial for improving efficiency and reducing costs, ensuring effective integration into global carbon management strategies.

Beyond capture, CO₂ purification is essential for ensuring high-quality CO₂ suitable for downstream applications. Membrane technology offers a compact and energy-efficient purification method, operating at 60%–90% purity with scalability up to 500,000 tCO₂/year, while requiring 0.5–1.2 MJ/kg CO₂. However, its effectiveness is hindered by sensitivity to contaminants such as water vapor and sulphur compounds (Pasichnyk et al., 2023). Pressure swing adsorption (PSA) and temperature swing adsorption achieve higher CO₂ purity levels of 85%–95% and can scale up to 1 MtCO₂/year, but their energy consumption ranges from 1.5–2.5 MJ/kg CO₂, and they struggle with complex gas mixtures (Das et al., 2023; Mehrotra, Ebner, and Ritter, 2008). Cryogenic distillation, one of the most effective purification methods, delivers over 99% CO₂ purity and is scalable to 1–3 MtCO₂/year, but its high energy demand of 5.0–6.5 MJ/kg CO₂ limits large-scale adoption (He et al., 2023; Font-Palma, Cann, and Udemu, 2023; Shen et al., 2022). Chemical scrubbers, which not only remove CO₂ but also eliminate sulphur oxide and nitrogen oxide contaminants, achieve 90%–98% efficiency, and can scale-up to 2 MtCO₂/year. However, their operational complexity and high energy consumption of 3.5–5.0 MJ/kg CO₂ present additional challenges (Zhao et al., 2021). To improve the economic viability of CO₂ purification, advancements in materials and process optimisation are necessary to enhance efficiency and reduce energy requirements.

The cost of carbon capture varies significantly depending on the source and concentration of CO₂. For industrial processes that emit high-purity CO₂ streams – such as ethanol production or natural gas processing – capture costs range between US\$15–25 per tonne. In contrast, dilute sources like cement production or power generation can incur costs from US\$40–120 per tonne, due to greater technical challenges and energy requirements (IEA, 2021). In the Indonesian context, the estimated cost for CO₂ capture is approximately US\$54.75 per tonne, based on techno-economic assessments by Kimura et al. (2024). The wide cost range reflects differences in technology maturity, with some capture methods already commercialised and others still under development.

3.2. CO₂ in Polymer Production: Pathways, Advantages, and Challenges

The use of CO₂ in polymerisation offers a sustainable way to reduce greenhouse gas emissions and develop eco-friendly materials (Alper and Orhan, 2017; Grignard et al., 2019). This is particularly relevant in the context of CO₂ recycling for producing PET and HDPE.

PET synthesis from CO₂

One approach to synthesising PET from CO₂ is the dimethyl carbonate (DMC)-based pathway, where CO₂ reacts with methanol to form DMC. This compound then undergoes methanolysis with p-xylene to produce dimethyl terephthalate (DMT), which is further condensed with ethylene glycol (EG) to form PET (Zhang et al., 2011). While this method is already used in industrial processes and

provides a sustainable alternative, it has certain limitations. The reaction involves multiple steps, making it complex and inefficient, and the production of DMC often depends on costly transition metal catalysts (Zhang et al., 2011).

Another pathway is CO₂ cyclisation to terephthalic acid (PTA), where CO₂ reacts with toluene or other aromatic precursors to form PTA, which is then condensed with ethylene glycol to synthesise PET (Pacheco and Davis, 2014). This method eliminates the need for intermediates like DMC, offering economic benefits as a petroleum alternative, while also contributing to the reduction of carbon emissions. However, it faces significant challenges, including low reaction selectivity, the need for extreme temperature and pressure conditions, and a lack of technological maturity, as it is still in the research phase (Zhang et al., 2011; Pacheco and Davis, 2014).

A different approach is electrocatalytic CO₂ conversion, where CO₂ is electrochemically reduced to intermediates like oxalic acid or formic acid, which are then selectively oxidised to produce PTA precursors. These can be further processed into PET. This method has the advantage of using renewable electricity to transform CO₂ and water into valuable products, making it a potentially sustainable solution. However, its current limitations include low conversion efficiency, the prohibitive cost and instability of noble metal-based catalysts, and the lack of industrial-scale applications.

A more biologically driven solution is the biocatalytic CO₂-to-PET pathway, where microorganisms or enzymes convert CO₂ into precursor compounds such as formic acid or methanol. These compounds can then be used in DMC, DMT, or PTA synthesis, which leads to PET production (Yishai et al., 2016). This pathway is environmentally friendly, allowing for direct CO₂ capture from the air while operating under mild conditions. However, it is still in its initial stages, with challenges such as slow reaction rates, highly specific conditions, and limited industrial feasibility (Bierbaumer et al., 2023).

Each of these pathways has its own strengths and limitations. The DMC-based pathway is the closest to industrial implementation but is not highly efficient in utilising CO₂. The CO₂ cyclisation pathway offers long-term potential but requires further technological advancements. The electrocatalytic pathway could become viable with improvements in catalyst efficiency, while the biocatalytic approach is the most sustainable but not yet scalable for large-scale production. If the priority is rapid industrial adoption, the DMC pathway is the best option. However, for maximum carbon emissions reduction, the electrocatalytic and biocatalytic methods hold the most promise for the future.

HDPE synthesis from CO₂

The conversion of CO₂ into HDPE involves multiple steps, including the production of methanol, syngas, or olefins. Given the stability of CO₂, researchers have explored various methods to convert it into HDPE, leveraging industrial processes while addressing challenges like high energy requirements, selectivity issues, and catalyst efficiency. Three primary pathways stand out.

One approach involves converting CO₂ into methanol, which is then processed into ethylene and polymerised into HDPE. The reduction of CO₂ to methanol requires hydrogen and a metal-based catalyst, such as copper, zinc oxide, and aluminium under 200–300°C and 20–50 bar. Methanol is then converted into ethylene via the methanol-to-olefins (MTO) process using zeolite catalysts like ZSM-5 and SAPO-34 at 300–500°C. The final polymerisation of ethylene into HDPE uses Ziegler-Natta or metallocene catalysts, producing polymers with high tensile strength and chemical resistance (Garcia et al., 2022; Ren et al., 2022; Bare, 2007; McDaniel and DesLauriers, 2015).

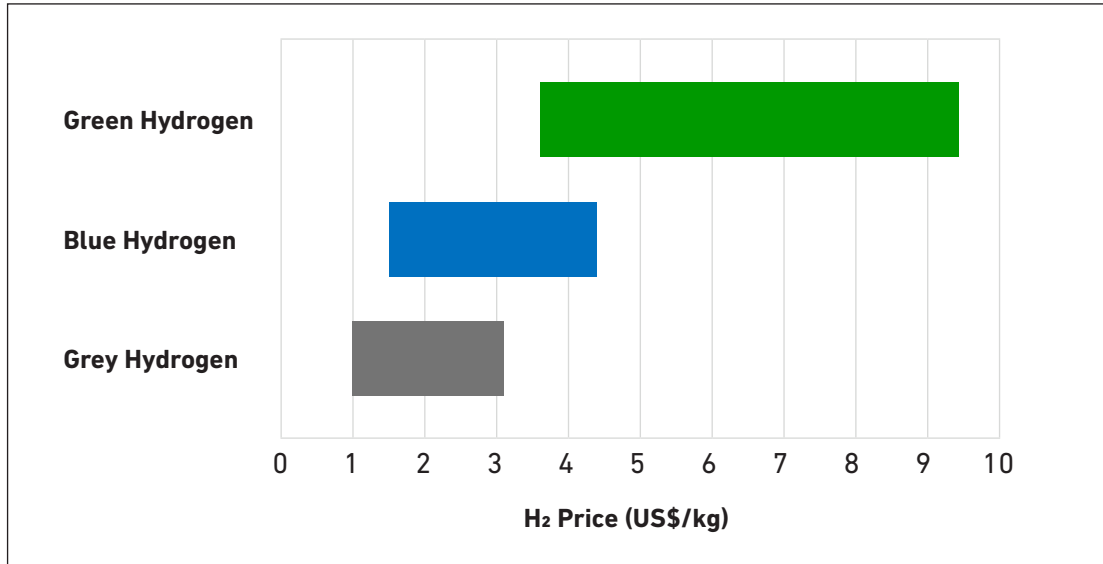
Another route converts CO₂ into syngas (CO + H₂) via the reverse water-gas shift reaction, which requires 500–900°C and metal-based catalysts like copper, iron, platinum, or ruthenium. Syngas is then processed via Fischer-Tropsch synthesis (FTS) to produce ethylene, using iron or cobalt catalysts at 250–350°C and 10–40 bar. Ethylene is subsequently polymerised into HDPE. This pathway faces challenges like low ethylene selectivity and high energy demands (Guil-López et al., 2019; Smith, Loganathan, and Shantha, 2010; Nelson and Szanyi, 2020; Weststrate et al., 2020).

A third method involves electrochemical reduction of CO₂ to acrylic acid, which is then converted to propylene, ethylene, and finally polymerised into HDPE. The process utilises transition metal-based electrodes or molecular catalysts to improve selectivity and efficiency. Acrylic acid is selectively hydrogenated into propylene using palladium or copper-based catalysts and then converted to ethylene via steam cracking at 800–900°C. This route offers a renewable alternative, but faces challenges like excessive costs and underdeveloped electrochemical catalysts (Rosen et al., 2011; Masel et al., 2018; Dessì et al., 2021; Amghizar et al., 2017; Gao et al., 2023; Pires et al., 2021; Chen et al., 2024).

3.3. Hydrogen Consumption in PET and HDPE Production

The integration of CO₂ in PET and HDPE production enhances sustainability but depends on hydrogen, whose environmental impact varies by production method. Grey hydrogen is cost-effective but emits high CO₂, blue hydrogen reduces emissions via CCS but risks leakage, and green hydrogen is emissions-free but remains costly and limited in scale (Krishnan, 2023). The success of CO₂-based polymers relies on renewable energy, economic feasibility, and carbon accounting (McLaughlin et al., 2023). A transition from grey to blue and eventually green hydrogen is necessary, supported by investments in electrolysis, renewable energy, and policy incentives (Islam et al., 2024). Future advancements in hydrogen production, catalysts, and lifecycle assessments will improve sustainability and scalability (Jeje and Shongwe, 2024).

Hydrogen is considered a clean energy carrier, producing only water when reacting with oxygen. It has a high gravimetric energy density (140 MJ/kg), storing more energy per kg than gasoline (Chi and Yu, 2018; Hassan et al., 2023). Today, 96% of hydrogen comes from fossil fuels, with only 4% produced via electrolysis using renewable energy (Karayel et al., 2022). Hydrogen is categorised by production method: blue hydrogen is derived from natural gas with CO₂ captured via CCS, grey hydrogen follows a similar process but releases CO₂, and green hydrogen is produced via electrolysis using renewable energy (Karayel, Javani, and Dincer, 2022). Green hydrogen, while the most sustainable, is expensive (IRENA, 2020). Costs vary by method and location, with grey hydrogen at US\$1–2.1/kg, blue at US\$1.5–2.9/kg, and green at US\$3.6–5.8/kg (Kumar and Lim, 2022). Electrolysis requires 50–55 kWh per kg of hydrogen, making it less energy-efficient than steam reforming. Amongst renewable sources, solar photovoltaic (PV) offers the lowest-cost hydrogen, with production costs lower than wind energy (US\$6.33/kg vs. US\$8.87/kg) (Aravindan and Praveen Kumar, 2023).

Figure 2.1. Price of Green, Blue, and Grey Hydrogen

H₂ = hydrogen, kg = kilogramme.

Source: Authors' own work based on data from Kumar and Lim (2022).

Table 2.1. Green Hydrogen from New Renewable Energy

Renewable Energy Source	Advantages	Disadvantages
Solar photovoltaic	- More flexible location^a - Close proximity for H₂ transportation^b - Low H₂ production cost^c	- Intermittent power generation^a - Small power capacity^a
Wind	- High power capacity^b - Large H₂ production^c	- Intermittent power generation^b - Remote power plant location^b - Long-distance H₂ transportation^b
Hydropower	- High power capacity^d - Large H₂ production^d - Low H₂ production cost^d	- Remote power plant location^d - Long-distance H₂ transportation^d
Geothermal	- High power capacity^e - Large H₂ production^e - Low H₂ production cost^e	- Presence of impurities (H₂S) on the opposite electrode side^e - Remote power plant location^e - Long-distance transportation^e

H₂ = hydrogen.

Sources: ^aKarayel, Javani, and Dincer (2022), ^bHassan et al. (2023), ^cKumar and Lim (2022), ^dKarayel, Javani, and Dincer (2023), ^eMahmoud et al. (2021).

Table 2.1 presents green hydrogen production from four renewable energy sources: photovoltaic (PV) solar, wind, hydro, and geothermal. Each has unique advantages and drawbacks in water electrolysis. Technical and economic analyses indicate that PV solar offers the lowest-cost hydrogen production due to its flexible installation, such as on rooftops, facilitating easier hydrogen transport.

Electrolysers are typically used to produce hydrogen through electrolysis – splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) using electricity. Four main electrolyser technologies commonly used are:

1. **Alkaline water electrolyser (AWE).** AWE uses an alkaline solution, typically potassium hydroxide (KOH), as an electrolyte. It is a mature and cost-effective technology but has relatively low efficiency and often requires elevated temperature and pressure to improve performance (IRENA and Methanol Institute, 2021).
2. **Proton exchange membrane electrolyser (PEM).** PEM employs a solid polymer membrane that conducts protons while separating hydrogen and oxygen. It offers high efficiency, rapid response to power fluctuations (ideal for solar input), and can operate at high pressures without external compressors. However, the use of expensive materials, including platinum-based catalysts, increases capital costs (IRENA and Methanol Institute, 2021).
3. **Solid oxide electrolyser cell (SOEC).** SOEC operates at high temperatures (700–850°C) using ceramic solid electrolytes (Maka and Ghalut, 2025). This enables very high efficiency by integrating external heat sources, making SOECs suitable for large-scale industrial applications. However, they have high capital costs, limited durability, and are less feasible for small-scale deployment.
4. **Anion exchange membrane electrolyser (AEM).** AEM uses a solid membrane to conduct hydroxide ions (OH^-), combining features of AWE and PEM. It eliminates the need for precious metal catalysts, potentially reducing costs and improving efficiency. As an emerging technology, AEM is still in early commercialisation stages and lacks the market maturity of AWE and PEM (IRENA and Methanol Institute, 2021).

The advantages, disadvantages, and price of each electrolyser are presented in Table 2.2.

Table 2.2. Electrolyser Comparison Matrix

No.	Electrolyser	Advantage	Disadvantage	Application	Price (US\$/kW)
1	Alkaline water electrolyser (AWE)	- Mature technology - Cost-effective - No platinum group metals (PGM)	- Low current density - Corrosive electrolyte	Industrial	760–1,000
2	Proton exchange membrane (PEM)	- Simple cell design and small footprint - High current density - Differential pressure operators - High dynamic response (suitable for variable renewable energy)	- Scale-up constrained by PGM supply and use - Perfluoro alkoxy usage - Less demonstration of long-term durability vs AWE	- Road transport - Distributed hydrogen production - Grid balancing	975–1,200

No.	Electrolyser	Advantage	Disadvantage	Application	Price (US\$/kW)
3	Solid oxide electrolyser cell (SOEC)	- Low electricity demand using steam (high efficiency) - No PGM catalyst	- Heat/steam source required - Limited dynamic response - Durability challenges with high-temperature operations	- Low purity industrial use cases - Co-location with high temperature steam	2,000–2,500
4	Anion exchange membrane (AEM)	- No PGM catalyst - High current density - Differential pressure operations - High dynamic response (suitable for variable renewable energy)	Limited performance and lifetime with current material systems	- Distributed hydrogen production - Grid balancing	New technology, estimates not available

Source: Khaerudini (2023).

A key challenge with renewable energy sources such as solar and wind is their intermittent power output, which demands careful selection of electrolyzers for hydrogen production. PEM electrolyzers are preferred in such settings due to their rapid dynamic response, making them well-suited for integration with variable sources like photovoltaic and wind power plants (Muthia et al., 2024). However, the high capital cost of PEM technology limits its broader deployment.

An emerging alternative is the AEM electrolyser, which shares PEM's fast response characteristics but operates without the need for expensive precious metal catalysts. This offers potential cost advantages. Although still in initial stages of commercialisation, AEM electrolyzers are drawing increasing interest for their potential to reduce capital expenditures in hydrogen production. Industry projections indicate that as the technology matures and manufacturing scales up, the cost of AEM systems may decline enhancing the economic feasibility of green hydrogen for industrial applications (Li and Baek, 2021).

3.4. Pathway Route Selection for Producing PET and HDPE

Table 2.3 provide features of each alternative of producing the polymer, via traditional fossil fuel, direct CO₂ conversion method and CO₂ conversion via green methanol route. Each pathway presents potential for sustainable PET and HDPE production but comes with technical and economic challenges. The methanol route though offers viable alternative from various point of views, it still requires high hydrogen input, the syngas route struggles with Fischer-Tropsch efficiency, and the acrylic acid route faces complexity in electrochemical conversion. Advances in catalyst development, process optimisation, and energy efficiency will be crucial for industrial-scale feasibility. The illustration of these routes is shown in Figure 2.2.

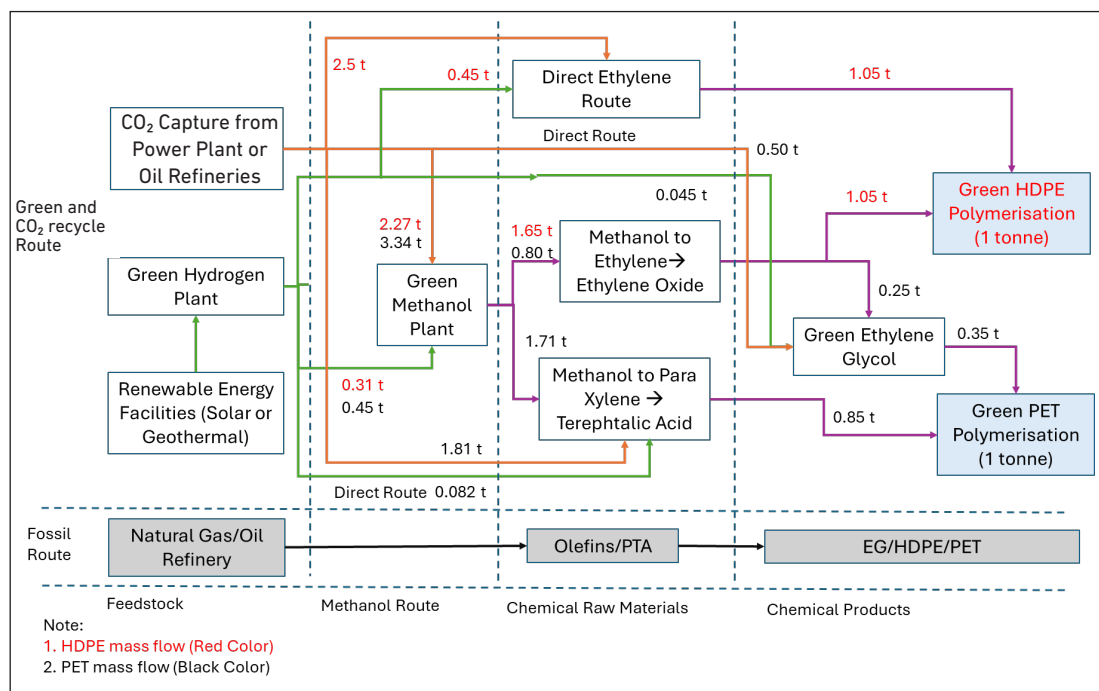
Table 2.3. Technical Comparison

Parameter	Traditional PET/HDPE	CO ₂ & H ₂ -based PET (Methanol Route)	CO ₂ & H ₂ -based PET/HDPE (Direct Route)
Process maturity	Fully commercialised	Emerging, needs optimisation	Early-stage research, not yet commercial
Technology readiness level (TRL)	TRL 9 (commercial)	TRL 4–6 (Pilot/ Demonstration)	TRL 2–4 (Laboratory/ Experimental)
Catalyst efficiency	High, well-optimised for petroleum refining	Moderate (MTA conversion still needs optimisation)	Low (electrocatalysts and biocatalysts in development)
Process complexity	Low (mature supply chain, stable processes)	Medium (additional methanol conversion step)	High (direct CO ₂ conversion is still inefficient)

CO₂ = carbon dioxide, H₂ = hydrogen, HDPE = high-density polyethylene, MTA = methanol-to-aromatics, PET = polyethylene terephthalate.

Source: Authors.

Figure 2.2. Flow Diagram of Green High-density Polyethylene via Green Methanol, Direct Route, and Fossil Route



EG = ethylene glycol, HDPE = high-density polyethylene, PET = polyethylene terephthalate, PTA = purified terephthalic acid, t = tonne.

Source: Authors.

Figure 2.2, which outlines the process flow, and Table 2.3 present technical comparisons for PET and HDPE production, suggesting future work of PET and HDPE production pathways that should be developed. For near-term deployment, the methanol route for PET & HDPE is preferred due to lower energy demand and economic feasibility. Long-term sustainability in the form of direct CO₂ conversion method requires investment in research and development to enhance efficiency and reduce costs. Policy measures like carbon pricing and green hydrogen subsidies can help to improve CO₂-based plastics' competitiveness. Technology advancements should also focus on lowering energy demand in electrocatalysis and improving catalyst efficiency.

While the integration of CO₂ recycling technologies into PET and HDPE production offers clear sustainability benefits, it must also prove economically viable to compete with conventional fossil-based methods. The process begins with the capture of CO₂ from industrial sources—a step that is often cost-intensive due to the energy demands of capture technologies, the need for high purity, and limited economies of scale. According to Rubin, Davison, and Herzog (2015), CO₂ capture costs typically range from US\$50 to US\$100 per tonne, depending on capital and operational expenditures. Specifically for Indonesia, Kimura et al. (2024) estimate the CO₂ capture cost at approximately US\$54.75 per tonne, based on regional techno-economic benchmarks.

The use of CO₂ in PET and HDPE production faces multiple cost challenges, including those associated with CO₂ capture, purification, polymerisation, infrastructure development, and integration with renewable energy systems. For instance, the amount of CO₂ required to produce one tonne of HDPE is approximately 3.137 tonnes. Based on Kimura et al. (2021), who estimate a capture cost of US\$62.80 per tonne at 70% capture efficiency, the resulting CO₂ cost component is about US\$281 per tonne of HDPE.

In terms of hydrogen input, producing 1 tonne of HDPE requires approximately 0.43 tonnes of H₂. At a green hydrogen price of US\$3.60 per kilogramme (the lowest projected cost), the hydrogen cost amounts to roughly US\$1,552 per tonne of HDPE.

A separate study by Mufarrij, Navarri, and Khojasteh (2025) found that a minimum selling price of US\$5,934 per tonne of CO₂-derived HDPE is required for financial feasibility – nearly five times higher than the current market price for naphtha-based polymers. Their analysis also concluded that a minimum carbon credit of US\$668 per tonne of CO₂ would be needed to close the cost gap.

Despite these economic barriers, improvements in catalyst performance, economies of scale, and supportive regulatory frameworks may gradually enhance the competitiveness of CO₂-based polymers. Growing interest in sustainability, along with rising carbon pricing, is already stimulating demand in sectors such as packaging and automotive. While naphtha-based polymers currently dominate due to their lower costs and established infrastructure, tightening environmental policies may eventually shift the balance. As technologies mature, costs decline, and climate incentives strengthen, CO₂-based PET and HDPE could emerge as commercially viable alternatives.

4. Integrated Concept of Green Methanol Supply Chain for Polyethylene Terephthalate and High-Density Polyethylene Production in Banten and East Java Clusters, Indonesia

Integrating Indonesia green methanol into existing and new PET and HDPE facilities presents a viable pathway towards low-carbon and circular production. This strategy leverages current infrastructure while supporting sectoral decarbonisation. The green methanol supply chain relies on carbon capture from large emitters – coal-fired power plants – and conversion to methanol via catalytic hydrogenation using green hydrogen.

4.1. Projections of HDPE and PET Consumption in 2034

Using annual import–export data from the Indonesian Statistics Agency, a projection of PET and HDPE consumption was conducted by estimating annual consumption figures for the period 2020 to 2023. Domestic production of PET during this period averaged 293,750 tonnes per year but increased to 318,750 tonnes in 2023 following the commencement of operations at PT Amandina Bumi Nusantara. In contrast, HDPE production remained constant at approximately 386,000 tonnes per year, contributed by two major producers: PT Chandra Asri and PT Lotte Chemical Titan, both located in Banten Province.

Throughout the period, as presented in Table 2.4, both PET and HDPE exhibited dynamic trade flows, characterised by substantial volumes of exports and, more significantly, imports required to meet steadily increasing domestic demand. Indonesia remained a net importer of both polymers during this period, except for 2020, when PET production exceeded domestic consumption, resulting in a temporary trade surplus. Given the fluctuating nature of production, imports, and exports, domestic consumption for each year was estimated using the formula:

$$\text{Consumption} = \text{Production} + \text{Imports} - \text{Exports}$$

This approach reflects the dynamic supply-demand balance and provides a reliable estimate of actual domestic use.

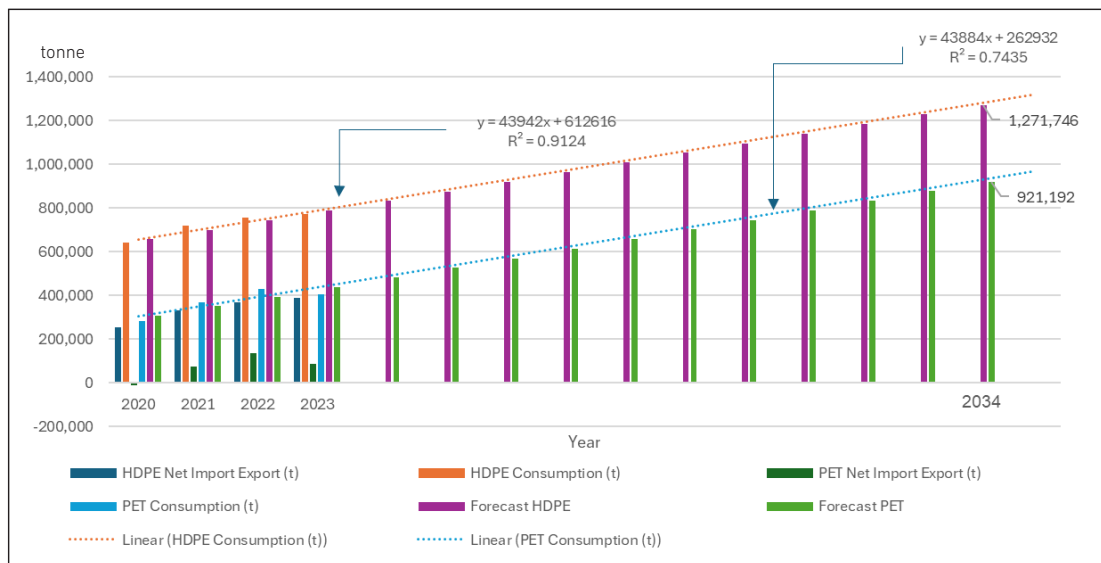
Table 2.4. Dynamic Trade Flow of High-density Polyethylene and Polyethylene Terephthalate

Year	HDPE (tonnes)		PET (tonnes)	
	Net Import-Export	Consumption	Net Import-Export	Consumption
2020	254,424	640,424	-11,863	281,887
2021	332,867	718,867	75,745	369,495
2022	370,109	756,109	138,024	431,774
2023	388,483	774,483	88,656	407,406

HDPE = high-density polyethylene, PET = polyethylene terephthalate.

Sources: Badan Pusat Statistik (2022a; 2022b; 2023a; 2023b; 2024a; 2024b).

The figures in 2020–2023 are used for to estimate the projections of both polymers in the next 10 years. Such estimates are illustrated in Figure 2.3, which presents the estimated trajectory of PET and HDPE demand through 2034.

Figure 2.3. Projection of High-density Polyethylene and Polyethylene Terephthalate Consumption to 2034

HDPE = high-density polyethylene, PET = polyethylene terephthalate.

Source: Authors, with data from Badan Pusat Statistik (2022a; 2022b; 2023a; 2023b; 2024a; 2024b).

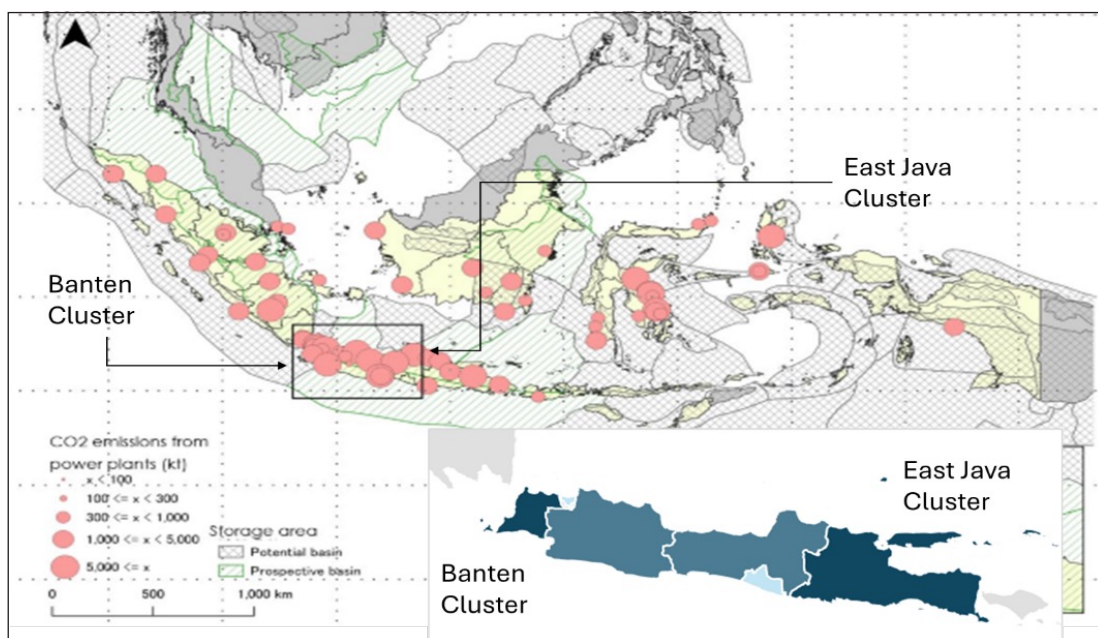
Using a linear projection, domestic consumption of polyethylene and polyester resins in Indonesia is expected to increase significantly by 2034, driven by sustained industrial expansion, rapid urbanisation, and shifting consumer behaviour. HDPE consumption is projected to reach approximately 1.27 million tonnes, while PET consumption is anticipated to rise to 921,000 tonnes. This growth reflects rising demand across key sectors, including packaging, construction, automotive, agriculture, and fast-moving consumer goods. The expansion of e-commerce, coupled with the growth of the middle-income population and increasing consumer preference for hygiene and convenience, continues to accelerate the adoption of plastic-based materials, particularly single-use and lightweight packaging (Evtriyandani et al., 2025). Moreover, ongoing infrastructure development and the modernisation of retail networks are expected to reinforce demand for durable polymer products. Indonesia's national development agenda, emphasising downstream petrochemical integration and value-added manufacturing, is also a critical driver shaping long-term consumption patterns (Hidayat, Kiranamahsa, and Zamal, 2019).

Aligned with global decarbonisation trends, the proposed integration of a green methanol supply chain for PET and HDPE production – based on captured CO₂ and renewable hydrogen – presents a viable low-carbon alternative to conventional fossil-based routes. The strategic scenario envisions substituting 30% of projected 2034 demand, equivalent to 400,000 tonnes of HDPE and 300,000 tonnes of PET. Achieving this would require approximately 1.9 million tonnes of captured CO₂ and 260,000 tonnes of green hydrogen annually, supplied through low-emissions electrolysis powered by renewable energy. These inputs are envisioned to be distributed evenly between the Banten and East Java industrial clusters, both of which possess the necessary infrastructure, logistics, and industrial integration potential. Importantly, this cluster-based strategy does not preclude the integration of clusters linked to coal-fired power plants, such as the Tanjung Jati complex, which has an installed capacity of 4,640 megawatts (MW).

This initiative aligns with Indonesia's commitments under the Paris Agreement and the country's Nationally Determined Contributions (NDCs), offering a scalable and circular approach to decarbonising the domestic plastics industry (Ramli and Kasih, 2024). By repurposing existing petrochemical assets and leveraging renewable energy pathways, the proposed transition presents a compelling model for achieving climate resilience while supporting industrial competitiveness.

4.2. Cluster Descriptions

Depicted in Figure 2.4, the Banten Cluster is located within a dense industrial corridor on the western edge of Java Island, which includes the Cilegon petrochemical complex and multiple coal-fired power generation facilities. The East Java Cluster spans the area from the Paiton power complex to Surabaya and Gresik, a well-established industrial and maritime zone that functions as both a national production hub and an international export gateway.

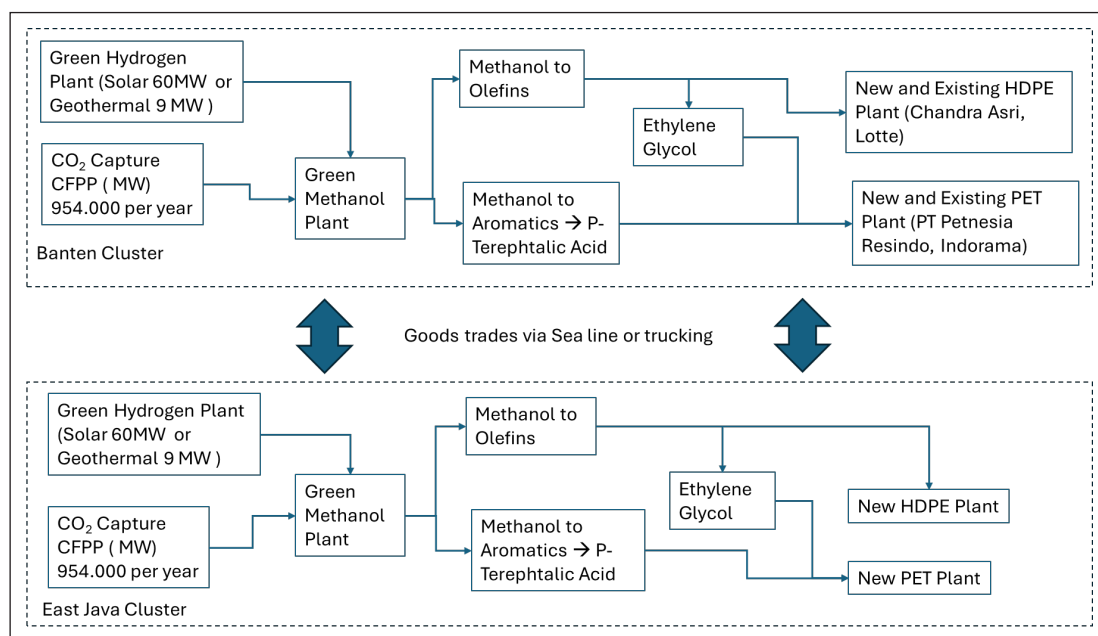
Figure 2.4. Green Methanol Clusters of Banten and East Java

CO₂ = carbon dioxide, kj = kilojoule, km = kilometre.

Source: Modified from Kimura et al. (2024a).

The flow diagram presented in Figure 2.5 illustrates the integrated supply chain for producing PET and HDPE, utilising green methanol – derived from captured CO₂ – as a key chemical intermediate. This pathway outlines the sequential transformation of CO₂ into methanol through sustainable processes, including carbon capture and the use of green hydrogen, followed by the conversion of methanol into essential monomers and the subsequent polymerisation into PET and HDPE. The figure also highlights the strategic role of green methanol as a central feedstock in supporting a more sustainable and circular plastic manufacturing ecosystem.

Furthermore, Figure 2.5 identifies potential industrial clusters in Banten and East Java, where several coal-fired power plants (CFPP) are currently operating. These sites are considered prospective sources of CO₂ emissions that could be captured and repurposed for green methanol production, particularly when combined with green hydrogen generated from renewable energy sources. Both CO₂ emitters in each region could supply 500,000 tonnes CO₂ per year for PET production of 150 thousand tonnes per year and 454,000 CO₂ per year for HDPE of 200,000 tonnes per year. Each region should also need green hydrogen of 130,000 tonnes per year which requires of 60 MW capacity generation of PV or 9 MW geothermal. Potential trading of CO₂ between two clusters could be envisioned either using sea freight or pipeline. However, such a possibility is prohibitive given the estimated transport costs are US\$17.5 per CO₂ tonnes by ship and US\$28.0 per CO₂ tonnes by pipeline (Kimura and Kunihiro, 2024).

Figure 2.5. Flow Diagram of Green Methanol Clusters of Banten and East Java

CO₂ = carbon dioxide, CFPP = coal-fired power plant, HDPE = high-density polyethylene, PET = polyethylene terephthalate, MW = megawatt,

Source: Authors.

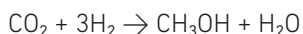
In Banten, the green methanol supply chain is anchored by CO₂ captured from the Suralaya CFPP complex, which emits approximately 20 million tonnes of CO₂ annually – well beyond the requirements for PET and HDPE production. Additional CO₂ sources include Lontar CFPP and nearby industrial facilities. Captured CO₂ will be transported via 15–25 kilometre (km) pipelines to methanol plants proposed in the Ciwandan or Bojanegara industrial zones, chosen for their proximity to petrochemical hubs, ports, and utilities. Hydrogen will be produced via water electrolysis powered by solar PV, geothermal, hydropower, and renewable electricity from the Java-Bali grid. Water for electrolysis will be sourced from industrial reuse schemes or coastal desalination. The resulting methanol will support multiple applications, including feedstock for Cilegon's petrochemical plants, marine fuel in the Sunda Strait, and export via Merak and Ciwandan ports.

In East Java, the supply chain centres on Paiton CFPP, with annual CO₂ emissions nearing 25 million tonnes, supplemented by the Pacitan CFPP and other local emitters. Methanol production is proposed in Situbondo or Probolinggo – areas offering strategic access to CO₂ sources, ports, and downstream users in Surabaya and Gresik. Hydrogen production will leverage coastal solar PV and geothermal resources from Blawan-Ijen and Arjuno. Carbon Dioxide and hydrogen will be converted into methanol via catalytic hydrogenation at 200–300°C and 50–100 bar. Water inputs will come from rivers and treated industrial wastewater. The green methanol will serve Gresik's PET and HDPE industries, marine fuel needs through Tanjung Perak Port, and exports via Probolinggo and Surabaya.

Integrating green methanol into Indonesia's petrochemical infrastructure offers substantial emissions reductions by substituting fossil feedstock. This strategy utilises existing assets through retrofitting, reduces capital investment, and aligns with Indonesia's NDCs under the Paris Agreement, enhancing the nation's role in global green supply chains. However, several challenges must be addressed for successful implementation. Technically, existing plants may require major modifications to process green methanol, demanding both engineering adaptation and innovation. Economically, green methanol must be evaluated through robust techno-economic analyses, especially against conventional feedstock that benefit from economies of scale. Additionally, a resilient supply chain – encompassing CO₂ capture, green hydrogen production, and renewable energy integration – is critical to ensure long-term viability, operational efficiency, and market competitiveness.

4.3. Process Technology

The production of green methanol is fundamentally governed by the catalytic hydrogenation of carbon dioxide, represented by the chemical reaction:



This exothermic reaction is facilitated by a copper-zinc oxide-alumina (Cu/ZnO/Al₂O₃) catalyst and typically takes place under elevated conditions – specifically at temperatures ranging from 200 to 300°C and pressures between 50 and 100 bars. The methanol synthesis process itself will utilise a Cu/ZnO/Al₂O₃ catalyst under typical reaction conditions of 50 to 70 bar pressure and 200–250°C temperature (Garcia et al., 2022).

Both the Banten and East Java clusters will incorporate a series of sequential unit operations, starting with carbon dioxide capture from major emission sources such as coal-fired power plants, followed by the production of green hydrogen through water electrolysis powered by renewable energy. The captured CO₂ and generated hydrogen will then undergo catalytic synthesis to produce methanol (Cordero-Lanzac et al., 2022). This methanol will subsequently be converted via methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) processes into key building blocks such as ethylene, propylene, and paraxylene, which are essential for the manufacture of high-value polymers, specifically PET and HDPE.

The green methanol produced in both clusters will serve several strategic applications across various sectors. Approximately 60% of the total methanol output is expected to be utilised as a petrochemical feedstock, particularly to produce olefins and aromatics that form the backbone of PET and HDPE polymer chains. In addition to its role in the petrochemical industry, green methanol presents a promising solution for the maritime sector, additive agent with gasoline – formulated in blends such as methanol-ethanol-gasoline (Agama et al., 2023) and holds significant potential as an export commodity if meets international sustainability certification standards such as the International Sustainability and Carbon Certification (ISCC), the European Union's Renewable Energy Directive II (EU RED II).

The proposed green methanol clusters are underpinned by carefully defined technical specifications that support the feasibility and scalability of the overall supply chain. Central to the system is the capture of carbon dioxide from coal-fired power plants. In the Banten cluster, the primary source will be the Suralaya CFPP, which emits approximately 34 million tonnes of CO₂ annually. Meanwhile, in the East Java cluster, the Paiton CFPP will contribute an estimated 19 million tonnes of CO₂ per year. The cost of capturing CO₂ from these sources is projected at US\$54.75 per tonne, based on techno-economic benchmarks provided by Kimura et al. (2024).

Once captured, the CO₂ will be transported via dedicated pipelines to nearby methanol synthesis facilities located within a radius of 50 km. The estimated cost for this pipeline-based transportation is US\$3.81 per tonne of CO₂ (Kimura et al., 2024). This short-range transport model ensures cost-effectiveness while minimising logistical complexities. Hydrogen, a critical reactant for methanol synthesis, will be generated through water electrolysis using renewable electricity. The Banten cluster will primarily rely on solar PV systems, including rooftop and ground-mounted installations, whereas the East Java cluster will harness geothermal energy sources – such as those in Blawan-ljen and Arjuno – to power its electrolyzers. These regionally tailored renewable energy strategies ensure alignment with local resource availability and long-term decarbonisation goals.

The methanol synthesis process itself will utilise a Cu/ZnO/Al₂O₃ catalyst under typical reaction conditions of 50–70 bar pressure and 200–250°C temperature. This process yields high-purity methanol, which will then be routed to downstream conversion units. The MTO process will transform methanol into light olefins such as ethylene and propylene, which are essential for HDPE production. Simultaneously, the MTA process will convert methanol into aromatic compounds, particularly paraxylene, a precursor for PET manufacturing.

The downstream integration of green methanol will capitalise on Indonesia's existing petrochemical infrastructure. HDPE production will be anchored by Chandra Asri Petrochemical in Cilegon, Banten and PET by PT Petnesia Resindo in Tangerang Banten, while PET production will be conducted by Polychem Indonesia in Gresik, East Java. These facilities are strategically positioned within proximity to the proposed methanol synthesis sites, reducing logistical burdens and facilitating seamless feedstock integration.

Each cluster will be designed to process between 1.5–2.5 million tonnes of CO₂ per year. To support this, an annual hydrogen requirement of 250,000–350,000 tonnes is anticipated, alongside a water demand of 4.5–6 million cubic meters – supplied via desalination, water reuse, or river extraction. Expected annual methanol production per cluster ranges between 500,000 and 1 million tonnes, with the potential to avoid 3.5–5 million tonnes of CO₂-equivalent emissions annually. To sustain electrolyser operations and other energy-intensive processes, each site will require an estimated 1.2–1.5 terawatt-hours (TWh) of electricity per year. This demand necessitates long-term renewable power purchase agreements (PPAs) or the establishment of dedicated renewable energy assets to ensure operational sustainability and compliance with low-carbon objectives. Table 2.5 shows a summary of the input resources and feedstock.

Table 2.5. Input Resources and Feedstock

Resource	Banten Cluster	East Java Cluster
CO ₂ source	Suralaya CFPP (Banten)	Paiton CFPP (Probolinggo)
Hydrogen source	Water electrolysis using solar/ photovoltaic grid	Hybrid renewable energy -grid mix and geothermal (PLTP)
Methanol catalyst	Cu/ZnO/Al ₂ O ₃ or advanced copper-based	
Methanol-to-aromatics (MTA) – for PET	Process: Methanol → BTX → Para-xylene → Terephthalic acid	
PET feedstock: Ethylene glycol (from ethylene) + terephthalic acid	Integrated with aromatic reformers or new MTA reactors in industrial estates	
Polymerisation units. Both are located near ports (Ciwandan, Gresik/ Situbondo)	HDPE Ethylene → Polymerisation PET Para-xylene + Ethylene → PET resin	Cilegon & Gresik Cilegon, Java Corridor for easy export and domestic delivery.
Supply chain integration and logistics	• CO₂ Pipelines: CFPPs → Methanol Plants • H₂ Production: Onsite electrolyzers near renewable parks • Methanol Transport: Tankers/pipelines to petrochemical clusters • Polymer Distribution: PET and HDPE to packaging, textile, and FMCG industries	

BTX = benzene, toluene, xylenes, CO₂ = carbon dioxide, CFPP = coal-fired power plant, Cu/ZnO/Al₂O₃ = copper-zinc oxide-alumina, FMCG = fast-moving consumer goods, H₂ = hydrogen, HDPE = high-density polyethylene, PET = polyethylene terephthalate.

Source: Authors.

4.4. Green Methanol Power Procurement Strategy

Green methanol, derived from renewable electricity and captured CO₂, demands a verifiable clean energy supply. Cilegon (Banten) and Paiton (East Java) are strategic sites due to their industrial capacity, port access, and integration with the Java-Bali grid, operated by Perusahaan Listrik Negara (PLN). A PPA bundled with renewable energy certificates (RECs) is proposed to ensure traceability and compliance with international sustainability standards, while supporting national renewable energy growth.

Two procurement models are available. The first is a bilateral PPA with a renewable independent power producer (IPP), where electricity from solar, hydro, wind, or geothermal sources is transmitted via PLN's grid through a wheeling agreement. The IPP issues RECs registered under global systems such as the International Renewable Energy Certificate (I-REC) Standard. The second model uses PLN's green electricity offerings, including its Green Premium Tariff and REC program. This bundled model simplifies transactions and regulatory compliance, though it may offer less pricing transparency and cost more than direct IPP agreements (PLN, 2021).

Both models must adhere to Indonesian regulations, particularly MEMR Regulation No. 50/2017 on the Utilization of Renewable Energy for Electricity Supply, which governs renewable energy procurement. For electricity delivered across regions, a wheeling agreement with PLN is required. RECs must be certified by authorised issuers such as South Pole, PT REI, or Ecohz. Commercially, PPAs should provide a balance between investment certainty and operational feasibility. Typical terms range from 10 to 25 years, with electricity prices from US\$0.05–0.10 per kWh depending on location and technology (IEA, 2023). RECs are priced around US\$2 per megawatt-hours (PLN, 2025b). Risk mitigation may involve a letter of credit and take-or-pay clauses to ensure revenue stability.

Implementation should begin with a feasibility study to assess energy needs, followed by engagement with IPPs or PLN to define the best procurement pathway. A REC acquisition strategy must also be developed. Required permits include the Electricity Supply Business License and PPA approval from the Ministry of Energy and Mineral Resources (MEMR). Sustainability reporting should follow frameworks such as the GHG Protocol and SBTi. Key stakeholders include IPPs like Pertamina NRE, Medco Power, Star Energy, and Bayu Energy. REC-related services can be sourced from South Pole and Ecohz. Grid co-ordination must be managed with PLN, under MEMR regulatory oversight.

4.5. Roadmap and Cluster Organisation

The recommended roadmap includes phases as outlined in Table 2.6.

Table 2.6. Timeline of Green Methanol towards High-density Polyethylene and Polyethylene Terephthalate Production Roadmap

Timeline	Milestone
2025	Pre-FEED, environmental assessments, MOUs with CFPPs and industry players
2026–2027	Construction of CO ₂ capture units and green hydrogen production systems
2028	Commissioning methanol synthesis and MTO/MTA plants in Banten
2029–2030	East Java replication and integration with Polychem PET line
2031+	Supply chain optimisation, further expansion to Sumatra and Kalimantan regions

CO₂ = carbon dioxide, CFPP = coal-fired power station, FEED = front end engineering design, HDPE = high-density polyethylene, MOU = memorandum of understanding, MTA = methanol-to-aromatics, MTO = methanol-to-olefins, = PET = polyethylene terephthalate.

Source: Authors.

The successful implementation of Indonesia's green methanol roadmap depends on the co-ordinated involvement of diverse stakeholders, each contributing distinct capabilities across the value chain. Industrial off-takers play a critical downstream role, ensuring demand for green methanol-derived intermediates. Chandra Asri Petrochemical, located in Cilegon, Banten, operates the country's largest integrated petrochemical complex, featuring a 900,000-tonne-per-year naphtha cracker that produces ethylene and propylene – vital for HDPE and polypropylene manufacturing (Chandra Asri Petrochemical, 2024). Their polyethylene portfolio, marketed under the brand Asrene®, offers an established market channel for green ethylene derivatives. Polychem Indonesia, based in Jakarta, is a key producer of mono-ethylene glycol (MEG) and di-ethylene glycol (DEG), essential precursors in PET manufacturing. The company also supplies a range of polyester products, including staple fibres and chips, making it a crucial node in the polyester value chain. In East Java, PT Petrokimia Gresik – while primarily focused on fertilisers – also produces a suite of chemicals with potential integration into future green petrochemical pathways. Such an integration with existing value chain actors is depicted in Table 2.7 and Table 2.8.

Table 2.7. Cluster-based Integration of New and Existing Polymer Plants

Cluster	Existing Facilities
Banten (Cilegon)	- Chandra Asri Petrochemical (CAP): Largest cracker (ethylene/propylene) + HDPE, LLDPE - Polychem Indonesia: Ethylene glycol and polyester intermediate supplier - PT Petnesia Resindo (PET Plants)
East Java (Gresik/ Tuban)	Petrokimia Gresik (limited downstream); future JIPE–Tuban complex includes olefin plants
Central Java (Batang)	Planned LG Chem complex: possible PET-grade polymer units

HDPE = high-density polyethylene, LLDPE = linear low-density polyethylene, PET = polyethylene terephthalate.

Source: Authors.

CO₂ source operators include the PLN Group, which manages major emissions sources such as the Suralaya and Paiton coal-fired power plant complexes. These facilities are pivotal for supplying the high-volume CO₂ required for methanol synthesis through carbon capture processes. Technology providers are essential for enabling both carbon capture and hydrogen generation. Leading firms such as Linde, Air Liquide, and Johnson Matthey offer proprietary methanol synthesis and CO₂ processing technologies. For hydrogen production via electrolysis, companies like Siemens and Thyssenkrupp are positioned to supply advanced electrolyser systems tailored to high-efficiency, renewable-powered operations.

Table 2.8. Green Methanol Production and Integration Points

Component	Integration Strategy
CO ₂ source	CFPPs: Suralaya (Banten), Paiton (East Java)
Hydrogen	On-site electrolyzers using hybrid renewable energy (solar + grid + geothermal in East Java)
Methanol plant	Built near CFPPs or co-located with existing petrochemical zones (e.g. Cilegon or Tuban)
Methanol-to-olefins	Retrofit or add-on to naphtha cracker units (e.g. CAP's ethylene plant) to diversify feedstock
Methanol-to-aromatics (MTA)	MTA units to complement PX production for TPA (e.g. Polychem)

CAP = Chandra Asri Petrochemical, CFPP = coal-fired power plant, PX = paraxylene, TPA = terephthalic acid.

Source: Authors.

The environmental viability of CO₂-derived plastics hinges critically on the use of renewable electricity to power the energy-intensive chemical conversion processes. Without decarbonised energy inputs, the emissions reductions promised by carbon capture and utilisation (CCU) technologies may be nullified. Therefore, to ensure genuine mitigation outcomes, Indonesia's CO₂-based polymer value chains must be underpinned by robust renewable energy procurement mechanisms – PPAs and RECs. PPAs enable industrial players to directly source electricity from renewable energy developers, offering long-term price predictability and verifiable green power usage. RECs, on the other hand, serve as market-based instruments that certify the origin of consumed electricity, thereby supporting transparent Scope 2 emissions accounting. The Java-Bali grid's demonstrated capability to integrate renewable generation, alongside the rollout of PLN's national REC program, provides a regulatory platform conducive to mainstreaming these mechanisms (PLN, 2020).

Operationalising this transition, however, requires co-ordinated participation across a broad stakeholder spectrum. The government must lead by enacting enabling regulations, expanding the REC market, offering fiscal incentives, and mandating renewable sourcing targets for hard-to-abate sectors (IESR, 2022). The private sector – including polymer manufacturers and petrochemical producers – can catalyse implementation by entering into long-term PPAs, leveraging RECs for sustainability reporting, and collaborating with CCU technology developers to scale pilot plants for CO₂-based HDPE and PET production. Academic and research institutions play an essential role in advancing catalytic and electrochemical conversion pathways, while also providing life-cycle assessments to validate environmental performance. Financial institutions – such as the Asian Development Bank, the Green Climate Fund, and PT Sarana Multi Infrastruktur – can mobilise capital through green bonds, blended finance structures, and concessional loans to de-risk early-stage projects and support infrastructure roll-out. Additionally, regulatory and scientific agencies such as the National Research and Innovation Agency (*Badan Riset dan Inovasi Nasional*), the Ministry of Energy and Mineral Resources, and the Ministry of Industry are critical in establishing governance frameworks, technical standards, and multi-sector research collaborations. Civil society actors and environmental nongovernment organisations contribute by fostering accountability, preventing greenwashing, and facilitating dialogue between stakeholders.

Finally, strategic infrastructure enhancements are necessary, including expanding renewable grid access in industrial zones like Cilegon and Gresik, establishing a national RE100-style voluntary procurement framework, and strengthening PLN's REC system via third-party verification in line with international standards (e.g. I-REC). Through an integrated, multi-stakeholder ecosystem, Indonesia can advance CO₂-based polymer innovation not only as a climate mitigation strategy but also as a cornerstone of its green industrial transformation. This approach supports national energy security, drives the development of a circular economy, and aligns with Indonesia's Enhanced Nationally Determined Contribution (NDC) and the National Medium-Term Development Plan policy goals.

5. Economics of Green Methanol Supply Chain for High-density Polyethylene and Polyethylene Terephthalate Production

5.1. Sustainability and Life Cycle Assessments

Conventional processes for both polymers rely on fossil-based feedstock and are highly energy- and emissions-intensive, as shown in Table 2.9. PET is produced from terephthalic acid and ethylene glycol, which are derived from para-xylene and ethylene, respectively. This production pathway generates approximately 3.1 kg CO₂ per kg PET, consumes 60–70 MJ/kg of energy (Nguyen et al., 2020), and requires substantial water inputs. High-temperature polymerisation and extensive global supply chains further exacerbate the associated carbon footprint. Although PET is technically recyclable, low recycling rates, downcycling, and incineration practices reduce its circularity and contribute additional emissions.

HDPE, synthesised from ethylene via steam cracking of fossil hydrocarbons, emits around 4.4 kg CO₂ per kg HDPE and requires about 66.6 MJ/kg of energy (Shen et al., 2011). Its production is also associated with volatile organic compound emissions and relies heavily on catalyst-intensive processes. While HDPE exhibits relatively higher recycling rates compared to PET, it is often downcycled into lower-value applications, with significant fractions ending up in landfill sites or being incinerated, thereby exacerbating environmental impacts.

Table 2.9. Life Cycle Assessment Results for Fossil-based High-density Polyethylene and Polyethylene Terephthalate

Impact Category	Traditional HDPE	Traditional PET
GHG emissions (kg CO ₂ -eq/tonne product)	3,100 ^a	4,400 ^c
Energy demand (GJ/tonne product)	64 ^a	68.6 ^d
Water usage (m ³ /tonne product)	8.14 ^b	7.78 ^e

GHG = greenhouse gas, GJ = gigajoule, HDPE = high-density polyethylene, kg = kilogramme, m³ = cubic metre, PET = polyethylene terephthalate.

Sources: ^aNguyen et al. (2020), ^bFranklin Associates (2020a), ^cEerhart, Faiij, and Patel (2012), ^dShen et al. (2011), ^eFranklin Associates (2020b).

Although this report does not include a full life cycle assessment (LCA), future LCAs are expected to demonstrate pathways for significant emission reductions through the conversion of captured CO₂ into value-added plastics. While this approach supports industrial decarbonisation, its high energy requirements – particularly for direct CO₂ conversion – make reliance on renewable electricity indispensable. In addition, electrolysis-based hydrogen production intensifies water demand, underscoring the need for efficiency improvements and the development of low-water alternatives. Strong policy support, including mechanisms such as carbon credits and targeted subsidies, will also be critical to ensuring the economic viability and scalability of CO₂-derived plastics.

5.2. Economic Considerations

Integrating green methanol into Indonesia's petrochemical sector presents significant environmental and economic advantages. Each tonne of green methanol can avoid approximately 1.37 tonnes of CO₂ emissions (IEA, 2023), thereby contributing to the achievement of national climate targets. Producing 400,000 tonnes of HDPE and 300,000 tonnes of PET from green methanol in the Banten and East Java industrial clusters has the potential to reduce methanol imports by 1.4 million tonnes annually, strengthening the trade balance and enhancing energy security. Furthermore, the project is projected to generate approximately 750 direct jobs, 5,200 indirect jobs, and an additional 6,000 jobs during peak construction. These combined impacts underscore the strategic role of green methanol in advancing Indonesia's sustainable industrial transition. The detailed breakdown of these benefits is presented in Table 2.10.

Table 2.10. Strategic Outlook and Benefits

Dimension	Description
Carbon reduction	1.9–2 million tonnes CO ₂ e avoided/year (combined)
Economic value	Import substitution for PET/HDPE, green premium opportunity
Jobs created	>10,000 direct and indirect jobs in construction and operation
Circular potential	Integrate with plastic recycling and pyrolysis for chemical upcycling

CO₂e = carbon dioxide equivalent, HDPE = high-density polyethylene, PET = polyethylene terephthalate.

Source: Authors

While a detailed techno-economic analysis of a green methanol plant – accounting for variations in hydrogen prices and downstream HDPE and PET facilities – is beyond the scope of this report, preliminary estimates suggest that producing 1.4 million tonnes of green methanol would require capital investments in the range of US\$1.8 billion to more than US\$7 billion (GIZ, 2024). Estimated capital costs for downstream plants are approximately US\$787.1 million for a 400,000 tonnes per annum HDPE facility and US\$260–300 million for a 300,000 tonnes per annum PET facility, based on cost data from LyondellBasell (2017) and Intratec (2024) for conventional fossil-based production.

Importantly, the capital cost for a green methanol facility is significantly higher than that of conventional fossil-based or blue methanol plants. This elevated investment burden translates into a higher levelised cost of green methanol, approaching US\$1,000 per tonne (Kausik, 2024). As a result, the production costs of HDPE and PET via green methanol pathways would be substantially higher than through conventional fossil-based routes.

Therefore, while integrating a green methanol-based supply chain into Indonesia's HDPE and PET sectors is technically feasible, it remains economically challenging under current market conditions. However, with abundant point-source CO₂, rapidly advancing electrolyser technology, and well-established industrial clusters, the Banten and East Java regions offer an attractive setting to demonstrate industrial carbon circularity. Although the required capital expenditures are considerable, a combination of supportive policies, carbon pricing mechanisms, and access to green financing could enhance both the bankability and scalability of such projects.

5.3. Alternative Supply of Hydrogen

Green hydrogen supply for the two methanol clusters is expected to be sourced from both renewable electricity producers in Java and regions outside Java. However, production outside Java is likely to be more cost-effective due to lower electricity demand and the availability of abundant renewable energy (RE) resources. These areas offer strong potential for electrolytic hydrogen generation, supported by surplus generation capacity and low opportunity costs.

Four primary criteria should guide the selection of green hydrogen production sites outside Java: (i) proximity to Java to reduce distribution and logistics costs, (ii) significant RE potential, (iii) supporting infrastructure such as roads and ports, and (iv) a high electrification ratio – ideally above 99% – to ensure reliable and continuous power supply. Based on these criteria, Lampung Province emerges as a strategic candidate. The province hosts two key RE plants: the Ulubelu geothermal power plant (55 MW, located in the Gunung Waypanas geothermal working area) and the Batu Tegi hydropower plant (28 MW, 2 × 14 MW, located in Tanggamus). Lampung's electrification ratio reached 99.99% in 2022, with 100% of villages connected to the grid (Sansuadi, Mazidah, and Nugroho, 2023), signalling its technical readiness to support hydrogen infrastructure.

Notably, the Ulubelu geothermal plant's most recent expansion – Ulubelu Gunung Tiga Unit – was inaugurated by the President of Indonesia in June 2025, alongside 55 other RE plants across 15 provinces, under a national RE acceleration programme (PLN, 2025a). These installations further strengthen Lampung's grid and RE capacity for electrolysis. In this process, renewable electricity splits water into hydrogen and oxygen, with the hydrogen stored in pressure vessels and transported by specialised trucks. For maritime distribution, hydrogen can be shipped in gaseous or liquefied form. However, liquefied hydrogen transport requires cryogenic systems capable of maintaining –253°C, infrastructure not yet available in Indonesia (Pekic, 2022). Consequently, compressed gaseous hydrogen transport remains the most viable near-term option.

Lampung's proximity to Java also provides strong logistical advantages. Maritime exports to West Java's industrial centres can be routed through Panjang Port, the largest port in Sumatra and a key inter-island logistics hub managed by Pelindo. The port features container, multipurpose, and dry bulk terminals, with a draft depth of –14 meters below low water springs and total length of roughly 6 nautical miles, accommodating mid-sized commercial vessels. The overland distance from Ulubelu to Panjang Port is about 113 km (3 hours), and from Batu Tegi about 94 km (2.5 hours), making both plants logistically feasible for hydrogen transport. Shipping rates from Panjang Port to Tanjung Priok (North Jakarta) in 2025 are projected at Rp1,275,000 (US\$79) for Class VI trucks and Rp3,305,000 (US\$206) for Class IX articulated trailers (Gautama, 2016). These rates provide a cost baseline for estimating maritime hydrogen delivery, suggesting favourable near-term economics for initial deployment.

5.4. Strategic Implication on National Oil and Petrochemical Resilience

Indonesia's continued dependence on imported fossil-based feedstock for its petrochemical industry, particularly in the production of PET and HDPE, represents a structural vulnerability that impedes national energy and industrial resilience. Both PET and HDPE are synthesised from intermediates such as ethylene, mono ethylene glycol (MEG), and paraxylene (PX), the majority of which are derived from naphtha cracking and are either insufficiently produced domestically or sourced entirely through imports (Badan Pusat Statistik, 2022b). This structural reliance not only subjects the domestic polymer sector to global crude oil price volatility but also contributes to a negative trade balance and heightens exposure to supply chain disruptions. In response to these challenges, green methanol – produced from renewable hydrogen and captured carbon dioxide or via biomass gasification – has emerged as a promising alternative feedstock capable of partially decoupling the petrochemical value chain from fossil fuel inputs. MTO and methanol-to-MEG (MTMEG) technologies, which have already been deployed at commercial scale, enable the conversion of methanol into olefins and monoethylene glycol (MEG), providing a renewable pathway for PET and HDPE production (IEA, 2023; Tian et al., 2015). While the substitution of PX remains constrained due to the limited commercial availability of renewable aromatics for purified terephthalic acid (PTA) synthesis, the replacement of ethylene and MEG alone holds significant decarbonisation and industrial resilience potential.

Assuming a policy-supported transition scenario in which 30% of Indonesia's projected 2034 consumption of PET and HDPE is met via green methanol-based pathways, the national petrochemical sector could feasibly produce approximately 400,000 tonnes of HDPE and 300,000 tonnes of PET per annum through renewable routes. This level of substitution would require replacing approximately 512,200 tonnes of fossil-derived ethylene annually, resulting in an estimated displacement of 700,000 tonnes of naphtha-based intermediates and avoidance of approximately 1.6 million tonnes of CO₂-equivalent emissions per year. To support this transition, the domestic methanol production capacity would need to be scaled to approximately 1.54 million tonnes per year. Beyond the climate benefits, this approach offers strategic advantages for Indonesia's energy security by reducing reliance on oil-linked petrochemical imports, stabilising foreign exchange flows, and mitigating exposure to international supply disruptions. The localisation of methanol production in industrial clusters such as Cilegon (Banten) and Gresik (East Java), where concentrated CO₂ point sources and renewable electricity are accessible, would further enhance integration with existing downstream polymer infrastructure and reduce logistics costs.

6. Conclusion and Recommendations

Despite not being fully quantified in this report, producing PET and HDPE from captured CO₂ and green hydrogen represents a promising low-carbon alternative to fossil-based pathways. Reference LCA studies highlight significant emission reductions: conventional PET production emits around 3.1 tonnes of CO₂-equivalent per tonne of PET, while conventional HDPE emits 1.5–4.0 tonnes per tonne of HDPE.

However, these climate benefits are constrained by major economic challenges. Producing 1 tonne of HDPE requires about 3.137 tonnes of captured CO₂. At a capture cost of US\$62.80 per tonne and an assumed 70% efficiency, CO₂ feedstock alone contributes roughly US\$281 per tonne of HDPE. Hydrogen demand is estimated at 0.43 tonnes per tonne of HDPE, and even at a low projected price of US\$3.60 per kilogramme, this adds about US\$1,552 per tonne.

Within this context, the proposed green methanol integration strategy targets substituting 30% of Indonesia's PET and HDPE demand by 2034, requiring around 1.9 million tonnes of captured CO₂ and 260,000 tonnes of green hydrogen annually. Industrial hubs in Banten and East Java are well suited for deployment, given their petrochemical infrastructure, proximity to CO₂ sources, and seaport connectivity. Conversion pathways such as MTO and MTA would allow green methanol to serve as a feedstock for ethylene and para-xylene, embedding low-carbon production into Indonesia's petrochemical chain. Additionally, future clusters may emerge around coal-fired power plants such as Tanjung Jati (4,640 MW), where CO₂ recycling could be explored through site-specific technologies.

While full substitution remains constrained by technology and cost, partial replacement, particularly for ethylene and MEG, offers meaningful climate, industrial, and economic benefits. Achieving this will require policy support, fiscal incentives, and partnerships with domestic leaders such as Chandra Asri, Polychem, and Petrokimia Gresik, alongside international collaborators like the New Energy and Industrial Technology Development Organization. Pilot projects led by the National Research and Innovation Agency and the Ministry of Energy and Mineral Resources could serve as catalysts, positioning Indonesia as a regional frontrunner in low-carbon plastics.

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Chapter 3

Cross-border Collaboration in Carbon Recycling: Transforming Carbon Dioxide Utilisation for Fuel and Chemical Production in ASEAN's Energy Sector

1. Introduction

Global carbon dioxide (CO₂) emissions surged to an all-time high of 37.4 gigatons in 2023, driven largely by continued fossil fuel use and the limitations of current mitigation strategies (IEA, 2024). Despite international commitments, less than 0.1% of global CO₂ reductions come from novel carbon dioxide removal methods. This highlights an urgent need for scalable alternatives (Geden et al., 2024). In this context, carbon recycling, the transformation of captured CO₂ into fuels, chemicals, and industrial feedstock, has gained attention as a practical, circular solution. It offers a dual benefit, i.e. reducing atmospheric carbon while producing value-added products that support energy security and economic growth. This pathway is especially relevant for the Association of Southeast Asian Nations (ASEAN), where rapid economic growth coincides with rising energy demand and emissions. However, national CO₂ utilisation initiatives remain disconnected, hindered by high capital costs, low technology readiness, and inconsistent regulations (Carbon Recycling Fund Institute, 2022; Huang and Tan, 2014; Joshi, 2014). Given the region's industrial diversity, from petrochemical hubs in Singapore to agriculture-based economies like Indonesia and Viet Nam, there is a strong case for regional collaboration to accelerate the adoption of CO₂-derived fuels, urea, polymers, and synthetic chemicals. To date, no comprehensive framework integrates cross-border carbon recycling into ASEAN's fuel and chemical strategies.

ASEAN countries exhibit differing levels of climate policy commitment and implementation readiness, as reflected in recent literature. For instance, Qiu, Seah, and Martinus (2024) highlighted that while Cambodia, Lao People's Democratic Republic (Lao PDR), and Myanmar have expanded their sectoral targets, their implementation strategies remain unclear. Furthermore, Brunei Darussalam, Singapore, and Viet Nam have made significant progress in strengthening economy-wide greenhouse gas (GHG) targets, yet overall ambition gaps persist due to public and expert concerns over implementation challenges. Moreover, Indonesia and Thailand have not significantly updated their mitigation ambitions, underscoring the need for detailed carbon utilisation strategies to attract international support. Yang and Li (2024) further identified challenges including unstable policy, weak environmental awareness, and a disconnect between technology and finance. While Nationally Determined Contributions (NDCs) outline emissions reduction goals, few ASEAN countries have integrated carbon recycling into their strategies.

Technologically, CO₂ utilisation is emerging as a cornerstone of future low-carbon industries. (Ampelli, Perathoner, and Centi, 2015). Notably, Singapore and Viet Nam have emerged as frontrunners in implementing circular economy policies that support industrial decarbonisation (Herrador and Van 2024). However, despite emerging pilot projects and growing interest, ASEAN lacks a cohesive and collaborative framework for regional carbon recycling to strengthen sustainable carbon management, especially in CO₂ utilisation. In the absence of a framework, deployment remains siloed and inefficient, with limited co-ordination and resource sharing. Consequently, cross-border collaboration presents a strategic opportunity. Defined as joint efforts amongst ASEAN member states to develop, implement, and scale CO₂ utilisation technologies, this approach is vital for addressing infrastructure gaps, policy fragmentation, and uneven technological capabilities.

A systematic understanding of these dimensions is necessary to identify scalable solutions, close implementation gaps, and discover the full potential of cross-border co-operation. However, to the best of our knowledge, a region-wide framework integrating cross-border carbon recycling for fuel and chemical production has not been systematically developed or assessed in ASEAN. Motivated

by this, this chapter aims to investigate how cross-border collaboration in CO₂ utilisation for fuel and chemical production in ASEAN's energy sector. This chapter is guided by three interlinked research questions:

- (1) What is the current state of CO₂ utilisation technologies relevant to ASEAN?
- (2) What are the main barriers and opportunities for regional co-ordination?
- (3) How feasible is it to establish a cross-border governance framework to support industrial-scale CO₂ recycling?

The analysis aims to provide actionable insights that align CO₂ utilisation with ASEAN's energy transition and climate goals, evaluates opportunities for regional co-operation, and present an implementation strategies for ASEAN-wide integration of carbon recycling.

2. State-of-the-Art Carbon Recycling Technologies

The rapid development of carbon recycling technologies presents an opportunity to decarbonise ASEAN's energy and industrial sectors. This section explores the current state of CO₂ utilisation technologies, highlighting key advancements in carbon utilisation pathways to fuel, chemicals, and building materials.

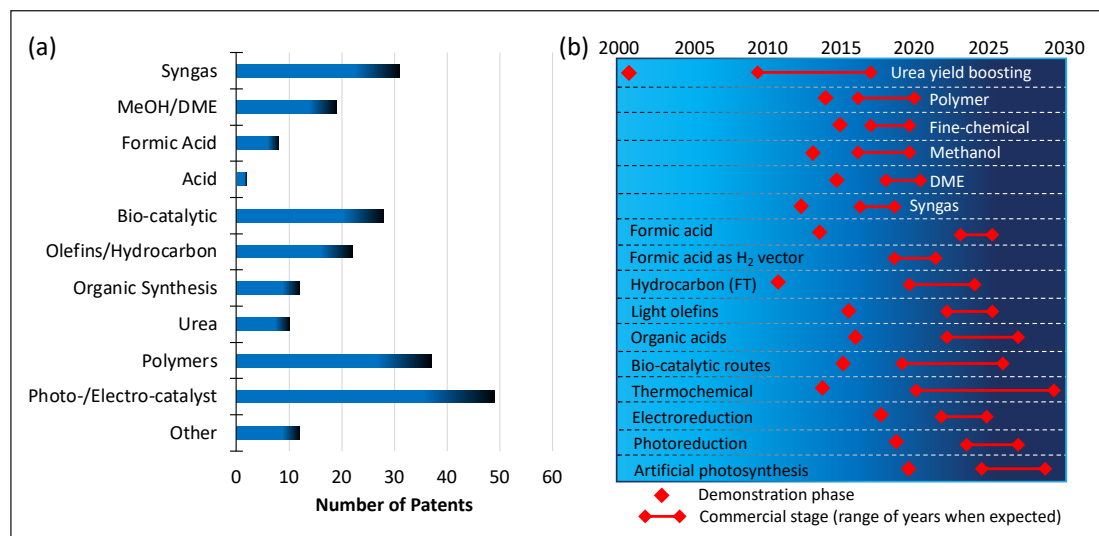
2.1. Current CO₂ Utilisation Technologies

The advancement of CO₂ utilisation technologies enable the transformation of CO₂ emissions into high-value products such as methanol, ethanol, olefins, and polymers, aligning closely with ASEAN's industrial, petrochemical, and biofuel industries. Amongst available pathways, the conversion of CO₂ into fuels and chemicals offers the greatest near-term impact, directly supporting energy diversification and circular economy goals. In agriculture-driven economies like Indonesia, Viet Nam, and Thailand, CO₂-derived urea enhances domestic fertiliser production and food security. Meanwhile, industrialised nations such as Malaysia and Singapore benefit from mature petrochemical infrastructure, making CO₂-to-methanol and syngas particularly cost-effective. Additionally, carbonated cement and aggregate products offer durable sequestration routes, relevant for urbanising economies with expanding construction demand (Ampelli, Perathoner, and Centi, 2015; ADB, 2021).

To further understand the technological landscape, Figure 3.1 presents regional patent activity alongside the commercial readiness of various CO₂ utilisation pathways. Technologies such as photo- and electrochemical conversion demonstrate high research intensity but remain years from large-scale deployment due to challenges in catalyst performance, energy efficiency, and system integration. Conversely, applications such as methanol synthesis, dimethyl ether production, and urea yield boosting exhibit higher technology readiness levels and earlier commercialisation

timelines, as many operational before 2025. Nevertheless, the region as a whole lags behind global leaders like the European Union and North America, where integrated policy support and targeted funding have significantly advanced CO₂ utilisation. To bridge this gap, ASEAN should pursue a dual-track strategy, i.e. accelerate deployment of mature technologies and foster cross-border collaboration to drive long-term innovation.

Figure 3.1. Carbon Dioxide Utilisation in ASEAN: (a) Number of Patents Filed by Category and (b) Technology Readiness vs. Commercialisation Timeline



ASEAN = Association of Southeast Asian Nations, CO₂ = carbon dioxide, DME = dimethyl ether, MeOH = methanol.

Source: Authors, data adapted from Hong (2022).

2.2. Carbon Utilisation in ASEAN: Where do we Stand?

ASEAN Member States are making incremental progress in deploying CO₂ utilisation technologies, yet these efforts remain fragmented and vary significantly in technological maturity, policy commitment, and industrial readiness. Singapore has taken the lead by embedding CO₂-to-chemical and synthetic fuel technologies into its national decarbonisation strategy. Backed by a carbon tax and robust industrial policy, projects in Jurong Island have piloted CO₂ conversion into methanol and sustainable aviation fuel, demonstrating a high level of integration between policy and technological deployment (National Climate Change Secretariat, 2022; Singapore Green Plan 2030, 2024). Meanwhile, Malaysia and Thailand have capitalised on their agricultural and biofuel industries to explore algae-based CO₂ fixation and bioethanol production. Malaysia's National Energy Policy 2022 emphasises CO₂ utilisation for chemical and fuel synthesis (Minister in the Prime Minister's Department (Economy) of Malaysia, 2022). Besides, Thailand has integrated CO₂-to-urea and CO₂-derived chemicals into its Alternative Energy Development Plan (AEDP) to enhance industrial sustainability (Ministry of Natural Resources and Environment, 2023). In parallel, Indonesia, Thailand, and Viet Nam have taken significant steps towards mineral carbonation for cement production, and synthetic methane from CO₂ conversion. Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience 2050 outlines pathways for utilising CO₂ in enhanced hydrocarbon recovery and alternative fuel synthesis (Minister for Environment

and Forestry - Indonesia, 2021). Viet Nam has initiated carbon market pilot programmes and planned to enhance their CO₂-derived polymers and synthetic fuels, leveraging its expanding petrochemical sector (UNOPS, 2023). Furthermore, the Philippines has adopted ocean-based CO₂ sequestration and direct air capture (DAC) aligned with its marine decarbonisation roadmap. Geological assessments are underway to evaluate national CO₂ storage potential, particularly for offshore energy applications (Department of Energy - Philippines, 2020).

Table 3.1. ASEAN Countries' Energy Transition, Climate Commitments, and Carbon Recycling Prospects for Cross-border Collaboration

Country	Energy Transition Goals	Climate Commitments	Carbon Recycling Initiatives	CO ₂ Utilisation Potential	Net-zero Emissions Target
Brunei Darussalam	Achieve 30% renewable energy in electricity generation by 2035.	Reduce CO ₂ emissions from vehicles during peak hours by 40% from BAU levels by 2035.	Methanol production via Brunei Methanol Company and hydrogen production and export through AHEAD project.	High potential for methanol and hydrogen production due to existing industrial infrastructure.	2050
Cambodia	By 2030, increase hydroelectric power (55%), biomass (6.5%), and solar photovoltaic (3.5%).	Target a 27% reduction in GHG emissions by 2030 with international support.	Feasibility studies on CO ₂ mineralisation in cement production.	Moderate potential for CO ₂ mineralisation in cement production due to infrastructure expansion.	2050
Indonesia	Achieve 23% renewable energy by 2025 and 31% by 2050.	Reduce GHG emissions by 41% from BAU levels by 2030 with international support.	Implementation of CO ₂ -to-urea production in fertiliser industry, methanol, and algae biofuel projects.	High potential for CO ₂ -based fuels, chemicals, and urea enhancement due to agricultural and energy sector integration.	2050
Lao PDR	Renewable energy to account for 52% of new electricity capacity (2021–2030).	Committed to CO ₂ reductions under additional conditions.	Potential for hydropowered CO ₂ electroreduction projects.	Low current utilisation, but potential for hydropower-driven CO ₂ electroreduction.	2050 (conditional)
Malaysia	Increase renewable energy share to 30% by 2025.	Reduce GHG intensity per GDP by 35% from 2005 levels (45% with international support).	Development of green methanol production in Sarawak using captured CO ₂ from natural gas processing	Strong industrial base supports CO ₂ conversion into fuels, chemicals, and polymers.	2050
Myanmar	Target 20% renewable energy share and 31% renewable capacity in electricity by 2025.	Limited national-level climate policies on CO ₂ reduction.	Potential for bioenergy-based CO ₂ capture and utilisation.	Moderate potential for biological CO ₂ conversion due to agriculture sector reliance.	2050

Country	Energy Transition Goals	Climate Commitments	Carbon Recycling Initiatives	CO ₂ Utilisation Potential	Net-zero Emissions Target
Philippines	Renewable energy installed capacity to reach 20% by 2025.	Aim to reduce GHG emissions by 70% from BAU by 2030 with international support.	Early-stage algae-based CO ₂ recycling for biofuel production.	High potential for algae cultivation and CO ₂ -to-fuel in coastal regions.	NA
Singapore	Deploy 2 GW of solar photovoltaic energy by 2030.	Cap emissions at 65 Mt CO ₂ by 2030; reduce to 33 Mt CO ₂ by 2050.	Strong investments in CO ₂ -to-chemicals, hydrogen, and industrial gas; development of ocean-based CO ₂ removal facility using Equatic process.	High potential for CO ₂ -to-methanol, synthetic fuels, and industrial gas.	2050
Thailand	Increase renewables to 30% of final energy consumption, 36% renewable capacity, and 20% of power generation by 2037.	Reduce GHG emissions by 20% from BAU by 2030 (25% with international support).	Research on green ammonia and urea production using captured CO ₂ .	High potential for CO ₂ -to-urea and industrial chemicals.	2065
Viet Nam	Renewable energy to contribute 15%–20% of primary energy by 2030 and 25%–30% by 2050.	Reduce GHG emissions by 9% (27% with international support) by 2030.	Investment and expanding CO ₂ -based biodegradable polymer and chemical production.	High potential for CO ₂ -to-methanol, synthetic fuels, and plastics.	2050

ASEAN = Association of Southeast Asian Nations, BAU = business as usual, CO₂ = carbon dioxide, GDP = gross domestic product, GHG = greenhouse gas, GW = gigawatt, NA = not available.

Source: Authors, data collected from Qiu, Seah, and Martinus (2024); (Fang and Li (2024); Herrador and Van (2024); Lidula et al. (2007); and Nurdianto and Resosudarmo (2011).

Overall, the energy transition goals across ASEAN countries exhibit a diverse spectrum of commitments towards renewable integration, reflecting the varying stages of economic development and industrial priorities, as shown in Table 3.1. From a carbon recycling perspective, ASEAN nations have initiated various CO₂ utilisation projects, with key intersections emerging in methanol production, polymer synthesis, and algae-based biofuels. Singapore stands out as a leader in CO₂-to-chemicals and synthetic fuel technologies, driven by strong industrial policies and investments in hydrogen and carbon capture. Indonesia and Thailand demonstrate high potential in CO₂-to-urea conversion and industrial chemical applications, highlighting their agricultural sectors for fertiliser production. Meanwhile, Malaysia's established petrochemical industry enables large-scale CO₂-to-methanol and hydrogenation projects, aligning with its broader decarbonisation strategy. The Philippines and Viet Nam show promising potential and advancements in CO₂-based biofuels and polymer production, capitalising on their coastal regions for algae cultivation. However, despite these developments, ASEAN still lacks a cohesive framework to co-ordinate efforts, share infrastructure, and scale CO₂ utilisation regionally.

2.3. ASEAN's Position in Global Carbon Recycling

ASEAN's role in the global carbon recycling landscape is emerging with considerable promise. As outlined in Table 3.2, the region is diversifying its CO₂ utilisation efforts across sectors ranging from agriculture to energy and materials. Urea yield enhancement stands out as the leading application, with an estimated 132 metric tons (Mt) of CO₂ utilised annually to produce 180 Mt of urea, crucial for agricultural economies like Indonesia, Viet Nam, and Thailand. This reflects a strong synergy between carbon recycling and food security, positioning ASEAN as a key player in CO₂-based fertiliser production. Moreover, several applications exhibit strong commercial viability, with industrial gas, food packaging, and beverage carbonation operating at Technology Readiness Level (TRL) 9, indicating full deployment and market acceptance. These sectors benefit from high consumer demand, particularly in Malaysia, Thailand, and Indonesia, which possess well-developed manufacturing and food industries. Additionally, methanol production (TRL 7–8) presents a strategic opportunity for Malaysia, Indonesia, and Thailand, as these countries aim to develop sustainable fuel alternatives and expand their petrochemical industries.

In contrast, emerging technologies such as algae-based biodiesel (TRL 4–7) and CO₂-derived polymers (TRL 7) remain in developmental phases, requiring further research and infrastructure investment before widespread adoption. Indonesia, Philippines, Malaysia, and Viet Nam stand out as potential leaders in these sectors, given their coastal access for algae cultivation and growing demand for biodegradable materials. To unlock these opportunities, cross-border collaboration can significantly accelerate these advancements by highlighting regional expertise, sharing infrastructure, and harmonising policies to scale up commercial applications. Ultimately, ASEAN's ability to synchronise CO₂ utilisation efforts will determine its competitiveness in the global carbon economy.

Table 3.2. Estimated Market, Technology Readiness Level of Carbon Dioxide Utilisation, and Its Potential to be Adopted in ASEAN

Application or Product	CO ₂ Utilised (MtCO ₂ /year)	Product Produced (Mt/year)	CO ₂ Storage Period	TRL	Potential for Adoption	Top Five ASEAN Countries for Adoption
Algae cultivation for biodiesel	2	1	Weeks/Months	4 to 7	High - Suitable for coastal nations with biofuel integration potential.	1. Indonesia 2. Malaysia 3. Thailand 4. Philippines 5. Viet Nam
Beverage carbonation	2.9	2.9	Days/Months	9	High - Strong demand in the beverage industry.	1. Thailand 2. Indonesia 3. Viet Nam 4. Malaysia 5. Philippines
Food packaging	8.2	8.2	Days/Months	9	High - Growing food industry and exports	1. Thailand 2. Indonesia 3. Viet Nam 4. Malaysia 5. Philippines
Industrial gas	6.3	6.3	Days/Months	9	High - Used in manufacturing and electronics	1. Malaysia 2. Thailand 3. Indonesia 4. Viet Nam 5. Singapore

Application or Product	CO ₂ Utilised (MtCO ₂ /year)	Product Produced (Mt/year)	CO ₂ Storage Period	TRL	Potential for Adoption	Top Five ASEAN Countries for Adoption
Urea yield boosting	132	180	Days/Months	9	High - Important for agriculture-based economics	1. Indonesia 2. Viet Nam 3. Thailand 4. Malaysia 5. Philippines
Carbonates	0.5	>2.0	Days/Months	7 to 8	Moderate – Demand in the construction sectors	1. Indonesia 2. Thailand 3. Viet Nam 4. Malaysia 5. Philippines
Methanol	10	60	Weeks/Months	7 to 8	High – Potential as an alternative fuel and chemical feedstock	1. Malaysia 2. Indonesia 3. Thailand 4. Viet Nam 5. Singapore
Chemicals	6.5	28	Days/Decades	6 to 8	High – ASEAN's strong chemical industry can integrate CO ₂ utilisation	1. Malaysia 2. Thailand 3. Indonesia 4. Viet Nam 5. Singapore
Polymers	1.5	15	Months/Decades	7	Moderate – Infrastructure and sustainable material demand are growing	1. Malaysia 2. Thailand 3. Indonesia 4. Viet Nam 5. Singapore

ASEAN = Association of Southeast Asian Nations CO₂ = carbon dioxide, Mt = metric ton, TRL = Technology Readiness Level.

Notes: TRL 4: Technology validated in lab; TRL 5: Technology validated in relevant environment; TRL 6: Prototype system tested in conditions; TRL 7: Full-scale prototype tested under real operational conditions; TRL 8: System complete and qualified 9: Technology fully deployed and operational in its intended application.

Source: Authors, data collected from Hong (2022); and others Endo et al., (2023); Handoyo, Yudianto, and Dahlan (2024); Vidinopoulos, Whale, and Fuentes Hutfilter (2020).

3. Challenges in Cross-border Carbon Recycling

Carbon recycling presents an opportunity to transform CO₂ emissions into valuable fuels and chemicals, aligning with ASEAN's energy security and decarbonisation goals. However, despite scientific advancements, several barriers hinder large-scale deployment. The primary challenges include technological inefficiencies in CO₂ capture and conversion, limitations in industrial integration, and a lack of standardised regulatory frameworks across ASEAN nations.

3.1. Technical Gaps

CO₂ utilisation in ASEAN remains constrained by limited capture efficiency, low catalyst performance, and insufficient transport infrastructure (Table 3.3). Although technologies such as amine scrubbing, calcium looping, and membrane separation show potential, they are still energy-intensive and cost-prohibitive for widespread deployment. Conversion technologies, especially electrochemical and thermochemical routes, face hurdles in catalyst selectivity, scalability, and energy input requirements (Karki, Mann, and Salehfar, 2005; Vidinopoulos, Whale, and Fuentes Hutfilter, 2020).

Table 3.3. Key Technological Challenges in Carbon Dioxide Utilisation and Their Implications

Technological Challenge	Technical Perspective	Impact on Industrial Deployment
CO ₂ capture efficiency	High energy consumption and material losses hinder the viability of capture processes.	Increases operational costs, limiting feasibility for industrial emitters across ASEAN.
Limited catalyst selectivity	Poor product selectivity and conversion efficiency in CO ₂ utilisation pathways.	Reduces yield of target fuels and chemicals, impeding industrial scaling and commercialisation.
Instability of catalytic systems	Catalyst degradation under operating conditions affects long-term performance and scalability.	Raises maintenance costs and reduces operational lifespan, deterring large-scale adoption.
Lack of process integration	Difficulty in integrating CO ₂ -derived intermediates into existing industrial infrastructure.	Delays deployment within refineries, fertiliser plants, and chemical production facilities.
Infrastructure incompatibility	Absence of infrastructure for CO ₂ handling, conversion, and downstream utilisation.	Prevents cohesive industrial clustering and slows supply chain development for CO ₂ -based products.
Low technology readiness levels	Many pathways remain at laboratory or pilot scale with limited demonstration at industry scale.	Creates a disconnect between research and deployment, especially in low-innovation ecosystems.

CO₂ = carbon dioxide.

Source: Authors, data collected from Herrador and Van (2024) and Vidinopoulos, Whale, and Fuentes Hutfilter (2020).

To overcome these bottlenecks, three priority areas must be addressed. First, catalyst innovation is essential. Advanced electrocatalysts such as single-atom catalysts and metal-organic frameworks can significantly improve CO₂ conversion efficiency to methanol, formic acid, and synthetic fuels. Furthermore, photoelectrolysis offers additional potential by harnessing solar energy to drive CO₂ reduction sustainably (Zhai et al., 2023; Zhao et al., 2021; Zhu et al., 2024). Second, improving CO₂ capture and separation is critical. Low-energy solvents and hybrid adsorption–membrane systems can enhance capture rates while reducing operating costs (Khan et al., 2022; Centi and Perathoner, 2023; Raganati and Ammendola, 2024; Zhang et al., 2021). Third, cross-border infrastructure is still lacking. High-emission countries like Indonesia and Thailand must connect to conversion hubs in Singapore and Malaysia, while Brunei Darussalam, and Malaysia

could host offshore geological storage due to their favourable geology (Yang and Li, 2024). Their stable tectonic setting, well-characterised caprock integrity, and existing oil and gas infrastructure make them ideal candidates for early deployment of carbon capture and storage (CCS) and carbon capture and utilisation (CCU) hubs. Additionally, Indonesia, particularly in the South Sumatra Basin and East Natuna Basin, has also been identified as a key country with substantial geological storage potential. While these are currently less developed for CO₂ storage than Malaysia and Brunei Darussalam, they are likely to play a major role in future ASEAN-wide carbon management (IEA, 2021; Kimura et al., 2022). Strengthening these technical foundations, particularly through regional collaboration and infrastructure sharing, will enable ASEAN to scale low-carbon fuel and chemical production and position itself competitively in the global carbon economy.

3.2. Infrastructure Gaps and CO₂ Transportation to Utilisation Sites

A critical, yet often overlooked, enabler of scalable CO₂ utilisation is the development of robust cross-border transport infrastructure. In ASEAN, the lack of shared CO₂ pipelines, hubs, and harmonised regulations hinders regional integration and delays commercialisation. To address these gaps, ASEAN must prioritise infrastructure planning, regulatory harmonisation, and data transparency. As detailed in Table 3.4, co-ordinated actions such as developing an ASEAN-wide CO₂ corridor, adopting a regional monitoring, reporting, verification (MRV) framework, and creating a shared atlas of CO₂ sources and sinks, can reduce deployment costs, unlock economies of scale, and enhance investor confidence. Learning from models such as the European Union (EU) CCS network and Japan's carbon transport strategies, ASEAN has the opportunity to build a future-ready CO₂ logistics backbone that supports its low-carbon industrial transformation. Although long-distance CO₂ pipelines (over 500 kilometres) can be cost-prohibitive, ASEAN's compact geography and industrial clustering enable viable short- to mid-range corridors particularly when tied to regional hubs and bilateral transport agreements. For instance, shared pipelines connecting multiple emitters to centralised hubs can reduce unit transport costs through economies of scale, a principle demonstrated in Europe's Northern Lights CCS network. Furthermore, countries like Singapore, Thailand, and Viet Nam may lack domestic geological storage options, requiring access to nearby nations with verified offshore capacity such as Malaysia and Brunei Darussalam. In these cases, cross-border pipelines and shipping-based connections act not only as CO₂ conduits but also as critical enablers for regional industrial decarbonisation and circular economy strategies using a corridor-specific solution approach.

Table 3.4. Key Challenges and Strategic Responses for Cross-border Carbon Dioxide Network in ASEAN, with Reference to International Best Practices and Regional Feasibility Considerations

Issue in CO ₂ Transfer and Interconnection	Impact on Regional Technology	Proposed Mitigation	Implementation Strategy	Project Example	Source
Inadequate cross-border pipeline infrastructure	Limits deployment of CO ₂ capture, transport, and utilisation technologies across ASEAN borders	Develop ASEAN-wide CO ₂ corridors with shared pipelines (about 250 km) and exploring shipping-based connections (about 1,000 km)	Conduct joint feasibility studies and CO ₂ corridor mapping under APAEC Phase II, focusing on realistic cross-border routes such as Brunei-Bintulu (about 250 km by road), and exploring shipping-based connections for longer distances like Singapore-Sarawak and Java-Malaysia (about 1,000 km by sea)	European Northern Lights CCS project demonstrates scalable shared transport infrastructure	Sandhu and Kamal (2015); Ding and Beh (2022); International Energy Agency (2024)
High logistics cost for CO ₂ liquefaction and shipping	Discourages deployment of CO ₂ conversion projects located far from emission or storage hubs	Establish co-funded regional CO ₂ logistics hubs and subsidies for initial deployment	Launch public-private investment funds for CO ₂ handling terminals and liquefaction plants	Japan–Australia CO ₂ shipping pilot (HySTRA project) shows cost-effective shipping routes	Global CCS Institute (2024)
Unclear liability and monitoring, reporting, verification (MRV) protocols	Reduces confidence in long-term storage, especially offshore	Establish ASEAN-wide MRV and liability-sharing framework based on international standards	Build capacity in CO ₂ tracking, registry systems, and regional insurance protocols	North Sea basin projects (e.g. Porthos, Netherlands) offer robust MRV governance models	Geden et al. (2024); Liu, Lu, and Wang, (2023); Zhang et al. (2022)
Fragmented data on CO ₂ sources and sinks	Weakens pipeline of investment-ready CO ₂ utilisation projects	Develop a comprehensive ASEAN CO ₂ atlas with GIS-mapped emissions sources and potential sinks	Integrate into ERIA's energy information platform and national energy planning systems	Japan's JOGMEC CO ₂ storage atlas facilitates cross-sectoral project siting and planning	Global CCS Institute (2024); Handoyo, Yudianto, and Dahlan (2024); Saeki (n.d.)

ASEAN = Association of Southeast Asian Nations, APAEC = ASEAN Plan of Action for Energy Cooperation, ASEAN = Association of Southeast Asian Nations, CO₂ = carbon dioxide, ERIA = Economic Institute for ASEAN and East Asia, JOGMEC = Japan Organization for Metals and Energy Security, km = kilometre.

Source: Authors.

3.3. Policy Fragmentation and Regulatory Barriers

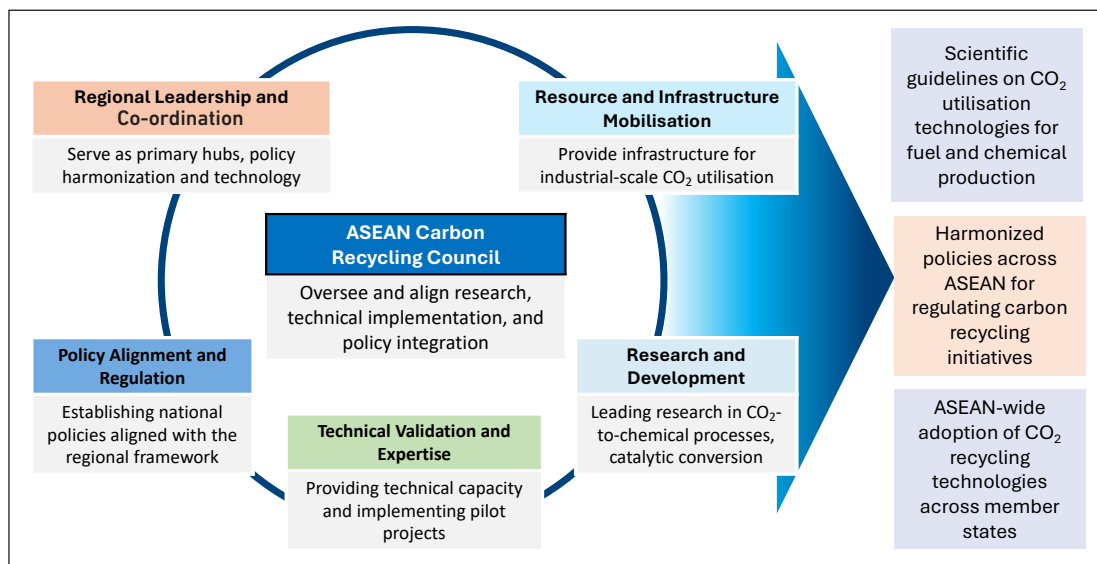
While ASEAN countries have adopted various energy transition and climate commitments, the absence of a unified policy framework for CO₂ utilisation remains a major constraint. Disparate national regulations create uncertainty for investors and complicate cross-border project development. Unlike global leaders such as the EU and China, ASEAN lacks standardised protocols for CO₂ transport, storage, and industrial application, delaying the growth of a regional carbon value chain (Nurdianto and Resosudarmo, 2011; Tongsopit et al., 2016). Addressing these regulatory gaps requires a coherent regional strategy. Establishing an ASEAN-wide carbon infrastructure and utilisation plan is a first step. This includes bilateral agreements to support CO₂ trading and regional hubs for transport, storage, and conversion. Uniform regulatory benchmarks will provide market confidence and ensure compatibility across national systems. Additionally, ASEAN must deepen its engagement with global carbon innovation networks. Participation in international research and development (R&D) consortia will help ASEAN align with best practices, attract technology transfers, and scale domestic innovation. By implementing these policy measures, ASEAN can build a cohesive framework for carbon utilisation and accelerate the deployment of CO₂-derived fuels and chemicals across borders.

4. Framework for ASEAN Collaboration for Carbon Recycling

Given the diverse industrial strengths and emission profiles across ASEAN, a cohesive cross-border collaboration framework is essential to accelerate the deployment of CO₂ utilisation technologies. Such a framework would enable shared access to technology, infrastructure, and finance, bridging the gap between CO₂ emitters and countries investing in CO₂ utilisation. Based on the challenges identified above, there is a clear need for a structured regional mechanism that can co-ordinate national efforts. The establishment of the ASEAN Carbon Recycling Council (ACRC) is proposed as a central mechanism to harmonise research, regulation, and infrastructure development across member states. This framework is designed to accelerate the transformation of CO₂ into fuels and chemicals, while promoting regional energy security and industrial competitiveness. The ACRC (Figure 3.2) will be built on five interdependent pillars:

1. Policy alignment ensures national regulations are streamlined with regional frameworks, enabling a cohesive CO₂ market across ASEAN.
2. Collaborative R&D accelerates innovation in catalytic, bio-based, and hydrogenation technologies for CO₂-to-fuel applications.
3. Technical validation supports the deployment and scale-up of utilisation pathways suited to ASEAN's industrial landscape.
4. Infrastructure mobilisation focuses on building shared facilities and logistics systems to link CO₂ sources with conversion hubs.
5. Regional co-ordination drives momentum through workforce development, institutional learning, and multilateral engagement.

Figure 3.2. ASEAN Carbon Recycling Council Framework, Illustrating the Key Pillars to Achieve Regional Carbon Recycling Integration



Association of Southeast Asian Nations, CO₂ = carbon dioxide.

Source: Authors.

4.1. Regional Innovation Hub for Carbon Recycling

To establish a competitive and sustainable CO₂ utilisation sector, ASEAN must create regional innovation hubs that facilitate a technology integration across borders, joint R&D in catalytic CO₂ conversion, shared infrastructure CO₂ supply chains that connect emitting industries with regional hubs for chemical conversion and product manufacturing. These hubs will serve as focal points for advancing catalytic CO₂ conversion technologies, scaling industrial applications, and aligning regional strategies with global best practices. Several ASEAN nations already possess strong foundations for CO₂ utilisation, making them ideal candidates for leading regional hubs, for example:

1. Singapore has positioned itself as a hub for industrial decarbonisation, highlighting its leadership in CO₂-to-chemical technologies and synthetic fuel production. The Temasek-led investment in CCU projects, alongside collaboration with the Global Centre for Maritime Decarbonisation, exemplifies Singapore's role in integrating CO₂-derived fuels into its energy transition strategy (Lau et al., 2021).
2. Malaysia has a well-established petrochemical and refinery sector, providing strong opportunities for CO₂-to-methanol conversion and hydrogenation processes. The Petronas Kasawari CCS Project, Southeast Asia's largest carbon capture and storage initiative, demonstrates Malaysia's potential to lead in industrial-scale CO₂ recycling and synthetic fuel production (Minister in the Prime Minister's Department (Economy) of Malaysia, 2022).

3. Indonesia and Thailand, as two of the region's highest CO₂ emitters, hold significant potential in CO₂-to-urea conversion (Minister for Environment and Forestry – Indonesia, 2021; Ministry of Natural Resources and Environment – Thailand, 2023). Indonesia's PT Pupuk Kalimantan Timur fertiliser plant has integrated CO₂ into urea production, setting a precedent for industrial CO₂ utilisation. Meanwhile, Thailand's SCG Cement and Chemicals Group has initiated projects exploring CO₂ mineralisation for cement production, further expanding the portfolio of carbon utilisation pathways.
4. Viet Nam is expanding its role in CO₂-to-polymer and synthetic fuel development, driven by research from the Vietnam Petroleum Institute and investments in methanol conversion (UNOPS, 2023).

By linking capabilities across member states, ASEAN can address technological gaps and create scalable, market-driven CO₂ utilisation pathways.

4.2. Harmonisation of Policies and Carbon Recycling Technologies

Policy fragmentation remains one of the greatest obstacles to regional co-operation in CO₂ utilisation. Unlike the EU's integrated carbon market, ASEAN lacks a harmonised regulatory landscape, resulting in investment uncertainty and delayed project execution. To address this, three policy priorities must be advanced:

1. Standardised CO₂ utilisation regulations to develop harmonised safety, transport, and industrial CO₂ use policies to facilitate smooth cross-border operations.
2. Unified certification and quality standards to ensure uniform guidelines for CO₂-derived fuels and chemicals to streamline regional trade and industry adoption.
3. Joint carbon utilisation investment mechanisms to establish ASEAN-wide financial incentives and public-private partnerships to promote cross-border CO₂ projects.

As detailed in Table 3.5, ASEAN's CO₂ utilisation potential varies across countries and technologies. Short-term solutions, such as CO₂-to-fuel hydrogenation and algae-based recycling, show strong bioeconomy potential but require regulatory support and infrastructure investments. In contrast, photoelectrochemical and biocatalytic pathways, while nascent, offer long-term breakthroughs if backed by co-ordinated R&D. By aligning policies with technology readiness and sectoral demand, ASEAN can unlock cost-effective carbon recycling solutions, while positioning itself as a global leader in climate-smart industrial development.

Table 3.5. Comparative Evaluation of Carbon Dioxide Utilisation Technologies in ASEAN

Commercialisation	Utilisation of CO ₂	Potential Development	Economic Viability	Energy Demand	Scalability (Mt/year)	Environment Concern	Cross-border Collaboration Potential
Already industrial	Industrial use (Concrete, Steel)	4	4	3	2	4	High (regional material trade)
	Organic synthesis (Chemicals)	4	3	2	3	3	High (ASEAN chemical industry integration)
Short term	Hydrogenation (Fuel)	3	3	2	4	3	Moderate (hydrogen availability)
	Algae-based CO ₂ utilisation	3	3	4	4	4	High (bioeconomy collaboration)
Medium term	Reforming hydrocarbons	2	ND	1	4	1	Moderate (industrial hubs required)
	Advanced algae reactor systems	2	2	4	4	4	High (regional scalability)
Long term	Mineralisation	1	1	1	3	3	Moderate (mineral availability varies)
	Thermochemical	1	2	4	4	3	Low (high infrastructure need)
	Electroreduction	1	ND	2	4	2	Low (needs advanced infrastructure)
	Photoelectro-chemical	1	ND	4	4	2	Moderate (requires solar infrastructure)
	Biocatalysts for CO ₂ conversion	1	ND	4	4	3	Moderate (biotech industry linkages)
Potential Development		: 1 (more than 10 years) to 4 (industrial)					
Economic Viability		: 1 (difficult to estimate) to 4 (available)					
Energy Demand		: 1 (difficult to decrease) to 4 (no need)					
Scalability (Mt/year)		: 1 (less than 10 Mt) to 4 (more 500 Mt)					
Environment Concern		: 1 (significant) to 4 (solvents or toxic, metal resources)					

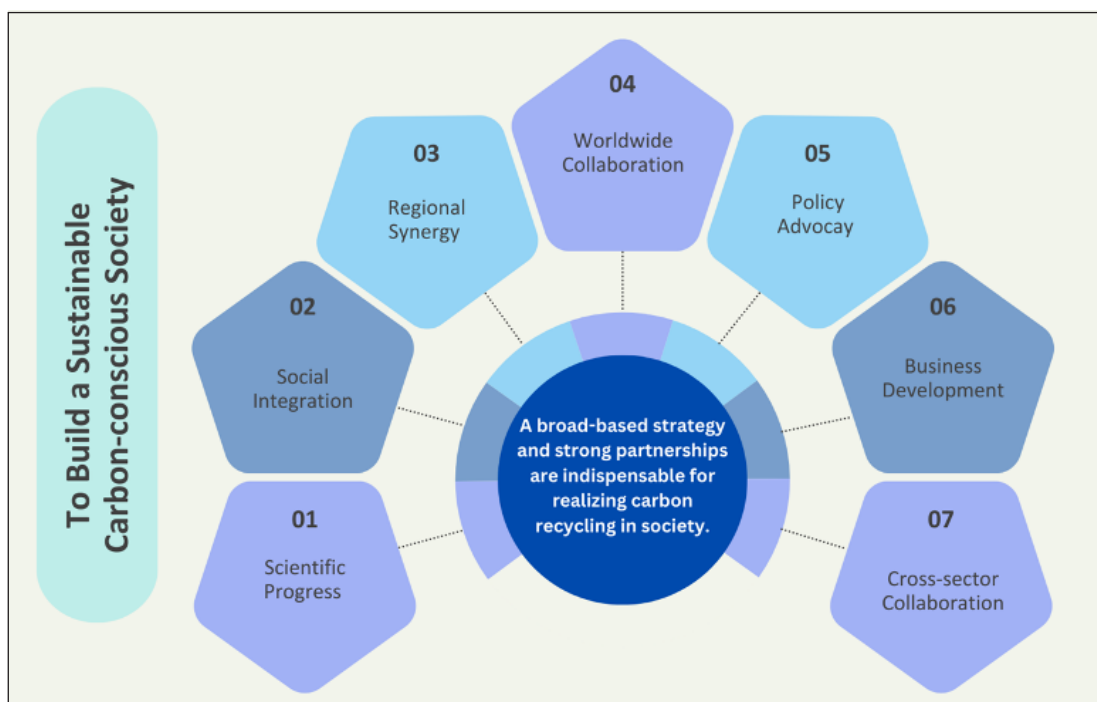
Association of Southeast Asian Nations, CO₂ = carbon dioxide, Mt = metric ton, ND = no data.

Source: Authors, data collected from Ampelli et al. (2015).

4.3. Towards a Carbon-Conscious ASEAN: Building a Holistic Ecosystem

Moving towards a carbon-conscious ASEAN requires more than deploying CO₂ technologies, it demands a well-rounded ecosystem that supports innovation, integration, and institutional alignment. As illustrated in Figure 3.3, this vision must be anchored in seven interdependent pillars: scientific progress, social integration, regional synergy, global collaboration, policy advocacy, business development, and cross-sector co-ordination. These elements complement the ACRC framework by ensuring that carbon recycling becomes embedded not only in industrial policy but also in broader social and economic systems. Moreover, to realise a carbon-conscious ASEAN, member states must cultivate trust, share knowledge, and pursue inclusive partnerships. An ecosystem-based approach can accelerate CO₂-based fuel deployment and advance ASEAN's energy security, climate resilience, and industrial competitiveness. By embedding carbon recycling within regional co-operation strategies, ASEAN can position itself as a global model for integrated, low-carbon development.

Figure 3.3. Key Strategic Pillars for Building a Sustainable Carbon-Conscious Society, Emphasising the Necessity of Cross-border Collaboration



Source: Authors.

4.4. Case Studies

The following analysis illustrates ASEAN case studies that exemplify how CO₂ can be effectively captured, transported, and utilised through regional collaboration (Figure 3.4). These examples can directly inform implementation pathways under the ASEAN Carbon Recycling Council (ACRC).

Indonesia–Singapore–Malaysia Methanol Corridor

Indonesia, as one of the region's highest CO₂ emitters, has successfully integrated CO₂ utilisation at the PT Pupuk Kalimantan Timur fertiliser plant by converting captured CO₂ into urea. Furthermore, Indonesia's substantial CO₂ storage capacity positions it to offer storage services to countries with limited capacity, facilitating cross-border CO₂ transportation and storage. Meanwhile, Singapore, with its advanced industrial infrastructure on Jurong Island, has piloted CO₂-to-methanol and synthetic aviation fuel projects, supported by Temasek-led investments and the Global Centre for Maritime Decarbonisation. Moreover, Singapore is collaborating with Indonesia and Malaysia on CO₂ transport and storage initiatives, enhancing regional CCUS capabilities. Malaysia, through Petronas's Kasawari CCS project, is developing Southeast Asia's largest carbon capture and storage (CCS) facility, making it a regional leader in synthetic fuel production. It could establish multiple CCUS hubs by 2030, with a shared storage capacity of up to 15 Mtpa (million tons per annum), supporting regional decarbonisation efforts.

Thailand's Cement Mineralisation and Regional Supply Integration

Thailand's SCG Cement and Chemicals Group has initiated projects on CO₂ mineralisation for cement production. This initiative not only utilises CO₂ from domestic emissions but could potentially absorb transported CO₂ from neighbouring countries with limited storage infrastructure, such as Cambodia or Lao PDR. Regional sharing of CO₂ supply and demand through ACRC's co-ordination would enhance the scalability of such solutions.

Viet Nam's Synthetic Fuel Development and ASEAN Energy Mix

Viet Nam is emerging as a regional leader in CO₂-based polymer and methanol production. The Vietnam Petroleum Institute is actively developing CO₂-to-methanol technologies that can integrate into the national energy mix. With existing regional gas and CO₂ transport infrastructure linking Viet Nam with Malaysia and Thailand, cross-border CO₂ sourcing and technology transfer would bolster Viet Nam's role in producing low-carbon fuels for broader ASEAN use.

Philippines' Algae-based CO₂ Utilisation for Biofuels

The Philippines has pilot initiatives using microalgae for CO₂ capture and conversion into biofuels, particularly in coastal zones. Projects like those supported by the Southeast Asian Fisheries Development Center and leading universities explore sustainable CO₂ utilisation. This positions the country as a regional R&D hub for marine-based circular bioeconomy solutions.

Brunei Darussalam's Methanol Economy and Hydrogen Export

Brunei Darussalam provides its methanol economy via the Brunei Methanol Company and its strategic role in hydrogen export through the AHEAD project, offering downstream CO₂ transformation and low-carbon fuel opportunities for regional use. Its natural gas-based hydrogen and methanol infrastructure serves as a potential anchor point for ASEAN's CO₂-derived synthetic fuel distribution.

Cambodia, Lao PDR, and Myanmar: Renewable- and Nature-based CO₂ Utilisation Cluster

Cambodia is exploring CO₂ mineralisation in its cement sector, aligned with national infrastructure growth. Lao PDR, with over 70% hydropower in its energy mix, has abundant renewable energy resources that could support future research and development in CO₂ utilisation, especially through regional partnerships. Myanmar holds moderate potential for bioenergy-based CO₂ capture and utilisation, leveraging its agriculture sector for biological CO₂ conversion.

To effectively operationalise carbon recycling across ASEAN, Table 3.6 presents a comprehensive cross-country assessment of CO₂ emissions, key industrial activities, readiness levels for carbon utilisation technologies, and potential cross-border value chains in ASEAN. It highlights strategic roles and opportunities for exporting CO₂-derived products and regional integration for low-carbon industrial transformation. This matrix not only reflects national strengths in CO₂-intensive sectors, but also presents targeted pathways for collaborative decarbonisation and trade integration. By aligning technological maturity, industrial demand, and regional infrastructure, the table identifies concrete bilateral or multilateral routes for CO₂ supply, utilisation, and conversion. These alignments are grounded in current pilot initiatives and R&D ecosystems.

Figure 3.4. ASEAN Case Studies that Exemplify on How Carbon Dioxide can be Effectively Captured, Transported, Converted, and Utilised through Regional Collaboration



ASEAN = Association of Southeast Asian Nations, CCS = carbon capture and storage, Mtpa = million tons per annum.

Source: Authors, data collected from UNOPS (2023); Department of Energy - Philippines (2020); UNDP (2021); IEA (2021); Kimura et al. (2022); Lau et al. (2021); Minister for Environment and Forestry - Indonesia, 2021; Minister in the Prime Minister's Department (Economy) of Malaysia, 2022; Ministry of Natural Resources and Environmental Conservation (Myanmar, 2021; Skocek, Zajac, and Ben Haha (2020); Vidinopoulos, Whale, and Fuentes Hutfilter (2020).

Table 3.6. Comparative Landscape of Carbon Dioxide Utilisation Readiness, Industrial Activities, and Cross-border Collaboration Potential across ASEAN Member States

Country	CO ₂ Emissions (MtCO ₂)*	Industrial Activities	CO ₂ Utilisation Readiness	Role in CO ₂ Value Chain	Main CO ₂ Use	Cross-border Collaboration
Indonesia	730	Urea, cement, methanol	Urea-grade CO ₂ reuse, capture clusters forming	Major supplier: fertiliser & cement	Urea, cement, methanol	Indonesia → Malaysia, Singapore
Viet Nam	330	Urea, cement, modular CO ₂ fuels	Pre-feasibility for cement/fuel CCU, MRV, and regional collaboration potential	Supplier and converter cluster	Cement, e-fuels	Viet Nam → Thailand, Singapore
Malaysia	290	Methanol, urea, polymers, LNG	Pilot CO ₂ -to-methanol projects	Conversion hub and maritime link	Methanol, urea, LNG	Malaysia → Singapore, Brunei
Thailand	260	Polymers, cement, refining	Semi-commercial cement and polyurethane integration; MRV, and feasibility for e-fuels	Converter and polymer end-user	Cement, e-fuels, polyols	Thailand ↔ Viet Nam, Cambodia
Philippines	150	Cement, small urea, maritime CCU	Pre-feasibility on marine and cement CCU	Niche demonstrator and logistics support	Cement, marine fuels	Philippines → Viet Nam
Singapore	50	Methanol, formic acid, CCUT	Advanced CCUT and R&D; chemical conversion, e-fuels	Tech pioneer and R&D leader	Formic acid, e-fuels	Singapore ↔ Malaysia, Viet Nam, Indonesia
Myanmar	30	Cement	Limited data post-2021; CO ₂ data gaps due to political conditions	Future supplier (cement/fertiliser)	Cement, ammonia (future)	Myanmar → Thailand (future)
Lao PDR	25	Cement	Not yet ready; minor emitters	Long-term cement integrator	Cement (low-carbon label)	Lao PDR → Viet Nam (cement)
Cambodia	20	Cement	No formal CCU projects; potential for cement CO ₂ reuse	Emerging CO ₂ cement user	Cement	Cambodia → Thailand (cement)
Brunei Darussalam	10	Fertiliser, gas-linked CO ₂ capture	Limited volume; logistics link to Sarawak/Kalimantan corridor	Logistics and fertiliser node	Ammonia fertilisers	Brunei → Malaysia (fertiliser)

ASEAN = Association of Southeast Asian Nations, CO₂ = carbon dioxide, CCU = carbon capture and utilisation, CCUT = carbon capture and utilisation testbed, LNG = liquefied natural gas, MRV = monitoring, reporting, verification, MtCO₂ = metric tonnes of carbon dioxide, R&D = research and development.

Note: * all numbers are approximate.

Source: Authors, data collected from Global Carbon Atlas (www.globalcarbonatlas.org), IEA (2021), and Endo et al. (2023).

5. Implementation Roadmap and Expected Impacts

The successful integration of CO₂ utilisation for fuel and chemical production across ASEAN requires a structured implementation roadmap backed by scientific, technological, and engineering advancements. The following sections outline the key framework, the expected climate mitigation and energy benefits, and the implementation timeline necessary for realising ASEAN's vision for cross-border CO₂ utilisation.

5.1. Implementation and Positioning Strategy

As introduced in the previous section, the ASEAN Carbon Recycling Council (ACRC) is envisioned as the governing body responsible for aligning policy, co-ordinating technology efforts, and mobilising investment across the region. It aims to facilitate multi-stakeholder engagement by connecting governments, industries, academia, and international partners to advance CO₂ utilisation initiatives. While the ACRC's central co-ordinating role is critical, its institutional design will significantly influence its effectiveness. Two foundational pathways have been assessed, such as anchoring the ACRC within the ASEAN Plan of Action for Energy Cooperation (APAEC) framework or adopting a Mission Innovation-style coalition model. Each presents unique strengths and constraints, as summarised in Table 3.7.

Table 3.7. SWOT Analysis for the ASEAN Carbon Recycling Council Positioning Strategy

Criteria	APAEC Integration (ACRC Embedded in ASEAN Energy Framework)	Mission Innovation- Inspired Model (ACRC as a Flexible Coalition)	ACRC+ (Advance Version of ACRC with External Strategic Collaboration Model)
Governance structure	Formal ASEAN intergovernmental body; high legitimacy.	Voluntary coalition, flexible engagement.	ASEAN-led with external partner councils, dual governance.
Policy alignment	Strongly aligned with APAEC pillars.	Prioritises innovation over formal policy.	Anchored in APAEC, expanded through external policy synergies.
Innovation agility	Slow due to fixed planning cycles.	Agile; supports rapid pilots and iteration.	High; enables joint R&D and fast-track scaling.
Stakeholder engagement	Limited private sector & academia inclusion.	Broad engagement across sectors.	Multi-level: public, private, academia, and partner nations.
Regional integration	Strong for structured regional energy planning.	Builds networks, but lacks enforcement.	Integrates ASEAN+ neighbours for shared infrastructure.
Funding and investment	ASEAN funds; slow access, consensus-based.	Venture and innovation funds accessible.	Blended ASEAN-partner finance, climate & technology funds.

Criteria	APAEC Integration (ACRC Embedded in ASEAN Energy Framework)	Mission Innovation-Inspired Model (ACRC as a Flexible Coalition)	ACRC+ (Advance Version of ACRC with External Strategic Collaboration Model)
International visibility	Regional profile, limited global engagement.	Global alliances, open collaboration.	High profile in Asia-Pacific; global innovation diplomacy.
Strength	Leverages ASEAN institutions and plans.	Fast-moving, innovation-centred.	Combines legitimacy with global reach and speed.
Weakness	Bureaucratic delays, rigid processes.	Uneven participation, less formal authority.	Co-ordination challenges across diverse partners.
Opportunity	Institutionalise CO ₂ reuse in energy policy.	Fast-track innovation and tech diffusion.	Bridge ASEAN needs with global solutions and funding.
Threat	Inertia and slow adaptation to emerging needs.	Fragmented outputs without formal anchor.	Misalignment risk if ASEAN and partners diverge.
Recommendation (Score out of 10)	7.0 – Strong anchor but slow innovation.	8.0 – High innovation, inclusive, fast-moving.	9.0 – Balanced model for regional leadership and outreach.

ASEAN = Association of Southeast Asian Nations, ACRC = ASEAN Carbon Recycling Council, APAEC = ASEAN Plan of Action for Energy Cooperation, R&D = research and development, SWOT = strengths, weaknesses, opportunities, threats.

Source: Authors, data from ASEAN Centre for Energy (2015) and Mission Innovation (2024).

Anchoring the ACRC under the APAEC would ensure formal alignment with ASEAN's energy policy mechanisms, enhancing regional legitimacy and institutional coherence. APAEC already prioritises multilateral energy co-operation, sustainable innovation, and regional integration, making it a natural platform to house the ACRC. However, this structure may inherit the bureaucratic inertia and slower responsiveness often associated with intergovernmental mechanisms. Conversely, adopting a mission innovation-style model (<https://mission-innovation.net>) provides greater flexibility, enabling the ACRC to operate as a voluntary, action-driven coalition focused on measurable outcomes. Furthermore, this format supports experimentation, rapid R&D mobilisation, and broader international collaboration, aligning with ASEAN's growing need for adaptive and innovation-led governance. However, based on a comprehensive evaluation of past regional co-ordination experiences, it becomes clear that a purely ASEAN-based mechanism may not be sufficient to drive the scale and pace required. While ACRC remains a crucial platform for internal alignment, its effectiveness will depend heavily on its ability to connect outward, particularly with neighbouring countries that can offer technology, funding, and strategic collaboration. To address these limitations and build on both models' complementary advantages, an enhanced framework, the ACRC+, is proposed as a potential alternative, as shown in Table 3.7. The ACRC+ represents an advanced institutional configuration that retains ASEAN's core policy alignment through APAEC, while expanding operational flexibility through structured external collaboration. This model aims to integrate external partners, such as Japan, the Republic of Korea, and Australia, to bring in technical expertise, innovation capabilities, and blended financing mechanisms. It enables ASEAN to scale up technology deployment, attract climate finance, and strengthen R&D networking by embedding global innovation diplomacy within a regional governance platform. This hybrid, outward-facing model responds to the historical inertia of ASEAN mechanisms and offers a realistic pathway to deliver timely, inclusive, and scalable solutions. In doing so, it positions ASEAN not just as a regional actor, but as a proactive contributor to global carbon circularity.

5.2. Energy and Climate Benefits

Widespread adoption of CO₂ utilisation technologies across ASEAN will yield substantial energy, industrial, and climate benefits. The conversion of CO₂ into fuels and chemicals not only reduces dependence on fossil fuels but also integrates circular carbon economy principles into industrial processes. Three key benefits were identified:

1. Energy security enhancement
 - Reduce fossil fuel imports by scaling CO₂-derived synthetic fuels and hydrogenation technologies.
 - Support the development of regional energy hubs using CO₂ as a feedstock for methanol, dimethyl ether, and synthetic fuels.
2. Climate mitigation and CO₂ reduction
 - CO₂ utilisation and storage technologies are expected to play a growing role in ASEAN's long-term decarbonisation strategy. In alignment with Paris Agreement targets, projections indicate that CO₂ capture and utilisation in Southeast Asia will need to reach at least 35 Mtpa by 2030, and over 200 Mtpa by 2050, with wide deployment across industry, power generation, and fuel transformation sectors (IEA, 2021).
 - Encouraging sector-wide adoption of carbon-neutral technologies, including CO₂-to-chemicals in refineries and cement industries.
3. Economic and industrial growth
 - Foster new job opportunities in carbon recycling and sustainable engineering.
 - Enhance ASEAN's competitiveness in the global low-carbon economy by advancing technologies for CO₂-based fuels, materials, and industrial solutions.

5.3. Timeline for Implementation

A phased approach will support the effective integration of CO₂ utilisation technologies across ASEAN. The timeline for harmonisation of policy development, technology deployment, and market adoption is outlined in Table 3.8. This implementation timeline ensures that scientific, technological, regulations, and economic considerations are integrated into ASEAN's long-term sustainable energy strategy.

Table 3.8. Roadmap for ASEAN Carbon Dioxide Utilisation and Implementation Timeline (2025–2040)

Phase	Key Milestones	Expected Outcomes
Phase 1 (2025–2030)	Establish the ASEAN Carbon Recycling Council (ACRC); develop a unified regulatory and safety framework; initiate pilot-scale CO ₂ utilisation projects in fuels, urea, and methanol.	Foundation for regional governance; policy harmonisation; early-stage R&D alignment and technology validation.
Phase 2 (2030–2035)	Expand industrial deployment of CO ₂ -to-fuel and chemical technologies; implement regional financing mechanisms and public-private partnerships.	Acceleration of commercial-scale projects; integration of CO ₂ utilisation in national energy strategies; increased investment flows.
Phase 3 (2035–2040)	Operationalise cross-border CO ₂ transport networks and shared storage/utilisation hubs; mainstream CO ₂ -derived products in ASEAN trade.	Functioning ASEAN-wide carbon recycling market; enhanced energy resilience and regional low-carbon competitiveness.

ASEAN = Association of Southeast Asian Nations, CO₂ = carbon dioxide, R&D = research and development.

Source: Authors.

5.4. Addressing Competition, Trade Secrets, and Intellectual Property

Effective cross-border co-operation in CO₂ utilisation requires not only harmonised policy and infrastructure but also mechanisms that safeguard proprietary knowledge and foster equitable technology sharing. In the context of the proposed ACRC managing risks related to competition, trade secrets, and intellectual property (IP) becomes critical for securing private sector engagement and enabling innovation diffusion. For instance, as joint R&D and pilot projects intensify across borders, concerns over technology leakage, ownership disputes, and uneven benefit-sharing could hinder collaboration. To address these challenges, Table 3.9 below presents key issues, associated risks, mitigation strategies, and precedent models, offering a practical roadmap to guide the ACRC in facilitating secure, transparent, and inclusive carbon technology co-operation across ASEAN. By adopting regionally harmonised strategies, ACRC can ensure both innovation protection and equitable benefit-sharing. Lessons from international models such as the European Research Area, the World Intellectual Property Organization's Technology Access Partnership, and Singapore's IP Hub underscore the importance of clear legal frameworks and inclusive licensing pools.

Table 3.9. Identifying Risks and its Mitigation Strategy for Competition, Trade Secrets, and Intellectual Property in the ASEAN Carbon Recycling Council

Issue	Key Risks	Mitigation Strategy	Proposed Solution	Outcomes	Reference Model or Precedent
Cross-border R&D collaboration	Risk of disclosing proprietary technologies and catalysts in joint projects	Establish cross-border confidentiality agreements and secure data protocols	Develop an ASEAN-wide NDA policy for ACRC-funded projects	Early-stage legal harmonisation builds trust and protects innovation during collaborative research	European Research Area joint programming
Technology commercialisation	Potential IP disputes in multinational pilot and demo projects	Define IP ownership and usage rights at project outset	Implement co-ownership or licensing clauses under the ACRC IP governance	Clear IP frameworks enable equitable benefit-sharing and reduce legal disputes	ASEAN COSTI bilateral R&D collaboration
Patent enforcement and regulation	Inconsistent IP enforcement across ASEAN countries	Strengthen regional IP rules and harmonise patent systems	Expand ASPEC framework; align the ACRC policy with ASEAN Action Plan	Harmonised patent governance ensures smoother technology deployment across borders	ASEAN Patent Examination Cooperation (ASPEC)
Fair access to shared technologies	Uneven access to R&D outputs amongst member states	Promote equitable licensing and capacity-building mechanisms	Create shared licensing pools (e.g. CO ₂ catalyst libraries) managed under ACRC	Inclusive innovation systems ensure balanced participation and accelerate technology diffusion	WIPO Tech Access Partnership

ASEAN = Association of Southeast Asian Nations, ACRC = ASEAN Carbon Recycling Council, COSTI = Committee on Science, Technology and Innovation, IP = Intellectual Property, NDA = non-disclosure agreement, R&D = research and development, WIPO = World Intellectual Property Organization.

Source: Authors.

5.5. Strategic Partnerships with Developed Countries

Building strategic alliances with technologically advanced partner countries is crucial for ASEAN to accelerate carbon recycling at scale. Nations such as Japan, the Republic of Korea, and Australia, have established co-operation frameworks, financial mechanisms, and innovation platforms that directly support CO₂ utilisation, transport, and market integration (Table 3.10). For instance, as shown in Table 3.11, Japan's Joint Crediting Mechanism has launched bilateral initiatives across ASEAN, providing funding and technical support for CO₂-to-fuel projects, MRV platforms, and industrial decarbonisation. Similarly, the Republic of Korea's KOICA and the ASEAN–Korea Cooperation Fund have financed green circular economy initiatives, with an emphasis on knowledge transfer and technology access. Australia has committed through the ASEAN–Australia Energy Cooperation, targeting regional clean energy transitions and hydrogen-enabling infrastructure. Embedding these best practices within ACRC's framework would safeguard proprietary knowledge, reduce duplication of efforts, and ensure equitable benefit-sharing. These partnerships offer ASEAN not only access to advanced technologies but also institutional models, intellectual property frameworks, and blended financing mechanisms that are essential for accelerating implementation.

Table 3.10. Strategic Components from Developed Partners for ASEAN Collaboration

Component Type	Area of Co-operation	ASEAN Benefits
Technology transfer	CO ₂ -to-fuel, green methanol, MRV platforms	Faster technology deployment, local upscaling
Finance and ODA	JCM (Japan), KOICA (Korea), DFAT (Australia)	De-risking investment, pilot project funding
Policy and regulation	CCU regulations, IP-sharing, carbon standards	Legal readiness, enabling regulatory frameworks
Joint R&D	Catalyst banks, CO ₂ -to-fuel and chemicals labs	Shared innovation, technical co-development
Market integration	Product trade, CO ₂ supply chain routes, certification	Access to global markets, infrastructure linking

ASEAN = Association of Southeast Asian Nations, CCU = carbon capture and utilisation, CO₂ = carbon dioxide, DFAT = Department of Foreign Affairs and Trade, IP = intellectual property, JCM = Joint Crediting Mechanism, KOICA = Korea International Cooperation Agency, MRV = monitoring, reporting, and verification, ODA = official development assistance, R&D = research and development.

Source: Authors.

Table 3.11. Strategic Partnerships for ASEAN Carbon Recycling Collaboration

Partner Country	Aligned ASEAN Priority Sector	ASEAN Impact
Japan	Carbon crediting, MRV platforms, CO ₂ -to-methanol, policy advisory	Pilot financing, MRV adoption, cross-border CO ₂ logistics
Republic of Korea	CO ₂ catalyst tech, CCUS R&D, innovation grants	R&D collaboration, CO ₂ hubs, youth training
Australia	Co-financing for clean infrastructure	Regional corridor, regulatory capacity-building

ASEAN = Association of Southeast Asian Nations, CCUS = carbon capture and utilisation, CO₂ = carbon dioxide, MRV = monitoring, reporting, and verification, R&D = research and development.

Source: Authors, data collected ADB (2015), IEA (2024), Australian Department of Prime Minister and Cabinet (www.pmc.gov.au), Carbon Pulse (www.carbon-pulse.com), and ASEAN-Korea Cooperation Fund (www.aseanrokfund.com).

6. Conclusion and Strategic Recommendations

A co-ordinated, cross-border approach to CO₂ utilisation offers ASEAN one of its most strategic pathways for achieving a low-carbon, economically resilient future. This study demonstrates that carbon recycling is not only technologically feasible, but also regionally synergistic, linking major emitters, industrial processors, and innovation leaders in a shared value chain. By aligning national capabilities with regional needs, ASEAN can transform CO₂ from an industrial liability into a traded resource that supports both climate and economic goals. The comprehensive analysis successfully suggests that ASEAN's CO₂ circular economy can be more than the sum of its parts, if co-ordinated under shared standards, infrastructure, and market frameworks. Proposed cross-border linkages are not hypothetical but grounded in existing industrial flows and emerging CO₂ utilisation pilots. Institutional innovation, through a mechanism such as the ACRC, would allow member states to align regulatory frameworks, pool resources, and engage global partners with a unified strategy. At its core, carbon recycling is not simply about emissions reduction, but also about transforming the regional economy by turning waste into value, and isolation into collaboration. This regional blueprint not only responds to ASEAN's energy and climate imperatives but also opens new frontiers for research, investment, and industrial policy. It provides a foundational basis for future work on MRV harmonisation, carbon product certification, cross-border infrastructure finance, and market design for CO₂-derived fuels and materials. While technological and regulatory disparities remain, the evidence suggests that regional action, anchored in mutual benefit, is both possible and necessary. To accelerate the regional deployment of carbon recycling, ASEAN should prioritise:

1. Establishing cross-border CO₂ supply chains that connect emitting industries with regional hubs for chemical conversion and product manufacturing.
2. Harmonising MRV, certification, and safety standards to support a regional market for CO₂-derived products.
3. Creating a shared licensing and IP platform to facilitate equitable access to carbon utilisation technologies.
4. Formalising the ASEAN Carbon Recycling Council (ACRC) to co-ordinate strategy, governance, and innovation partnerships.

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Chapter 4

Accelerating Carbon Dioxide Conversion to Chemicals in ASEAN: Opportunities and Challenges

Carbon dioxide (CO₂) levels in the atmosphere increased drastically after 1960 due to the burning of fossil fuels, including coal, petroleum, and natural gas. The accumulated CO₂ contributed to 60% of the rise in the Earth's temperature, with faster glacier melting, the rise in sea level, and floods (Sayari et al., 2011). The Association Of Southeast Asian Nations (ASEAN) Member States are vulnerable to climate change, especially sea level rise and flooding. About 23% of Ho Chi Minh City has experienced floods and this could increase to 36% in 2050. There are also various reports of flooding in major cities in Indonesia, including Jakarta, which stimulated the government to make plans to move the capital and construct a giant sea wall (Cao et al., 2021). Although Bangkok was known as a vast underground water container, there was a big flood in May 2025. In the Philippines, the government's plan to relocate residents in threatened zones is still poorly implemented since many residents earn income and food from the sea. As ASEAN intends to maintain economic growth, it should be driven by industrialisation and energy expansion that is aligned with environmental sustainability.

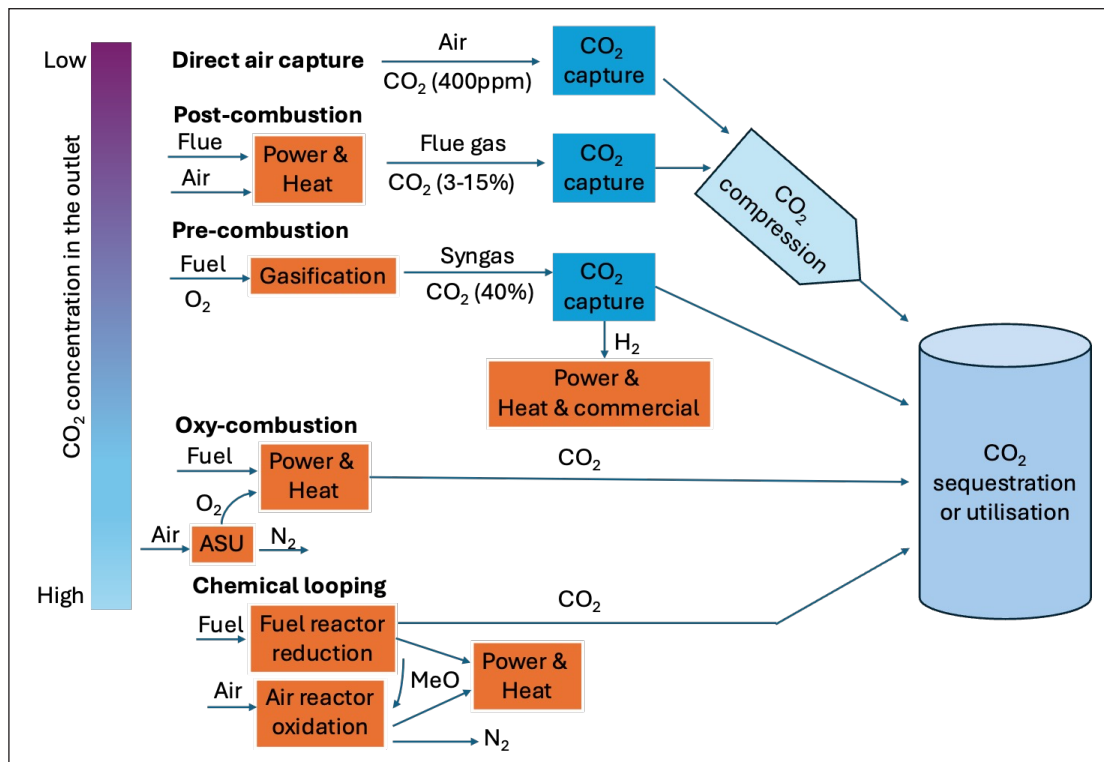
Although it is not feasible to destroy CO₂, it can either be captured or converted to more valuable chemicals (known as carbon capture utilisation and storage, CCUS). Reducing the amount of CO₂ should not only be regarded as a national obligation, but also as maintaining the socioeconomic stability of the region. The ASEAN region has committed to invest US\$6.7 trillion which is expected to create 66 million new jobs by 2050, to reduce 2.6 gigatons of CO₂ to achieve carbon neutrality (Darmawan, Ilman; Abdullah Ambiyah; Yurnaidi Zulfikar; Suryadi, 2024). At this moment, 70% of its regional energy mix is supplied by fossil fuel. Therefore, the effort for decarbonisation should be accompanied by an energy transition to clean energy. If energy resources used are not renewable, fossil fuel combustion will still emit high amounts of CO₂ pollution, and the significance of decarbonisation will not be fully realised.

This chapter highlights the strategies to accelerate the CO₂ conversion initiative in the Southeast Asian region. In some advanced technologies, ASEAN countries still lag behind several regions such as East Asia, which also includes decarbonisation. In this study, first, CO₂ capture was simulated by using coal flue gas as most energy sources in Southeast Asia to select a potential solvent that consumes less energy. Then, the captured CO₂ was converted to other chemicals to increase its value. Technologies to convert CO₂ are summarised, with a focus on the most feasible approach for commercialisation. The techno-economic analysis to understand its feasibility is also provided to convince the policymakers in the direction of the green hydrogen initiative. Finally, in the last part of this study, ASEAN collaboration was also specified to achieve a measurable goal without discriminating any country.

1. CO₂ Capture from Flue Gas

CO₂ capture is a popular topic for decarbonisation. A part of CO₂ storage in old oil reservoirs, CO₂ capture is essential, including in the ASEAN region. In 2023, half of the electricity was supplied by coal, which indicates that the economic development in the region relies on burning carbon (IEA, 2024). The largest CO₂ emissions from industry are from coal and steel manufacturing. There are several methods in the CO₂ absorption technologies, such as direct air capture (DAC), post-combustion, pre-combustion, oxy-combustion, and chemical looping as illustrated in Figure 4.1.

Figure 4.1. Technologies for Carbon Dioxide Capture



ASU = air separation unit, CO₂ = carbon dioxide, MeO = metal oxide, N₂ = nitrogen, O₂ = oxygen, ppm = parts per million.

Source: Author, adapted from Wang and Song (2020).

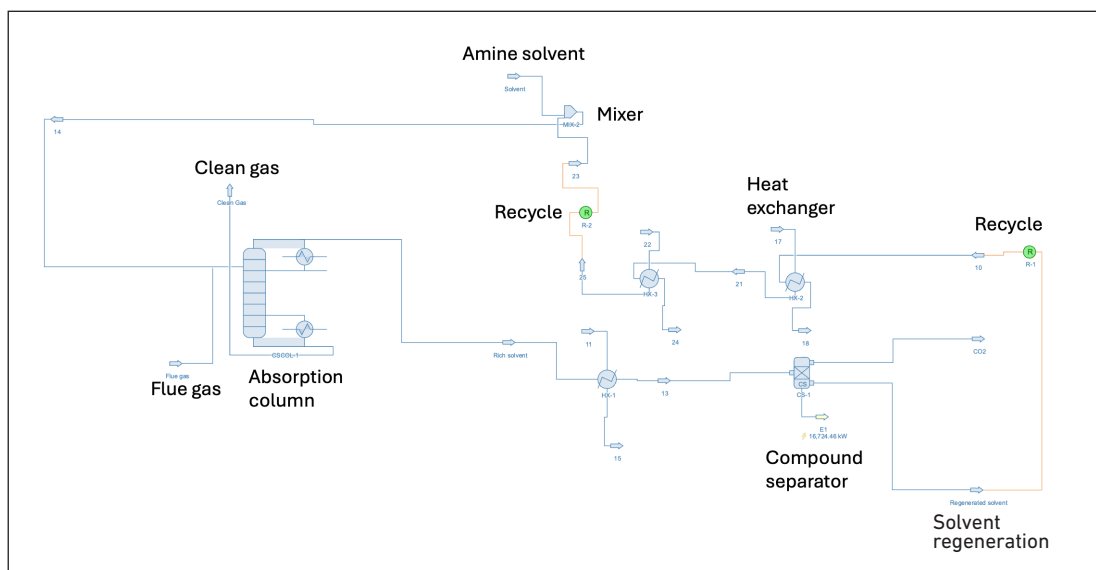
DAC is the extraction of CO₂ directly from air, which involves absorption of CO₂ into a liquid or solid absorbent, forming a CO₂-based compound, then heated to obtain high purity of CO₂. Although the aim of the process is environmentally friendly, it has a high cost. The CO₂ concentration in the air is low about 400 parts per million, hence it requires a large volume of air to capture onsite. In the pre-combustion approach, the feedstock is converted to synthetic gas (synthetic gas) that contains CO and hydrogen (H₂), then CO is further converted to CO₂ in the presence of water. The H₂-rich content is used for electricity generation. Meanwhile, oxy-combustion requires a very high concentration of oxygen for complete feedstock oxidation. Last, the post-combustion method refers to circulating flue gas into a solid or solvent to purify CO₂ in the gas streams.

Most of the existing carbon capture in power plants, cement, and steel industries is based on a post-combustion approach via amine-scrubbing, where the flue gas is adsorbed onto an amine solution to obtain high purity of CO₂ (Rochelle, 2009). However, this approach requires a significant amount of energy, especially for amine regeneration. To estimate the required energy for CO₂ absorption, the process sheet simulation as presented in Figure 4.2 is carried out using various amine compounds and the results are denoted in Table 4.1. In this study, the flue gas stream contained 81% nitrogen, 3% oxygen, and 16% carbon dioxide as a typical composition in a coal-fired powerplant with a molar flow of 69,739 kilomole per hour. From the simulation, monoethanolamine showed the lowest energy consumption compared to methylethanolamine, piperazine, triethanolamine, dimethylethanolamine, N-aminoethyl ethanolamine, and triethylamine. Then, to lower the required energy, a mixture of equimolar monoethanolamine and N-aminoethyl ethanolamine with lower water content is preferred.

Another important parameter in CO₂ absorption is amine stability in a series coupling absorption and stripping. A recent study investigated stability in three types of amines: cyclic amine, steric hindrance amine, and tertiary amines, by using oxidative and thermal stability (Wang et al., 2025). Their experiments revealed that the presence of a symmetrical heteroatom in the benzene ring and steric hindrance promoted oxidative stability. In addition, the long-branched chain outside cyclic amines also improves amine stability. In their study, piperazine and 2-amino-2-methyl-1-propanol showed better stability compared to monoethanolamine. However, the piperazine consumes more energy compared to monoethanolamine. So, it is a trade-off between amine stability and energy consumption.

To reduce further the energy consumption and increase amine stability, Li et al proposed blending tri-solvent amine (Li et al., 2024). The blending mixture consists of diethanolamine, piperazine, and 4-amino-1-methylpiperidine. This amine mixture reduced the heat regeneration duty by 44% compared to monoethanolamine with a cyclic capacity of 0.79 mol CO₂/mol amine. Swift CO₂ absorption and bicarbonate formation are expected as the potential reason for its high performance, showcasing the promising route for decarbonisation.

Figure 4.2. Process Flowsheet of Carbon Dioxide Absorption from Flue Gas



Source: Author.

Table 4.1. Required Energy for Solvent Regeneration

(condition: 70°C, 1 bar, 25,600 kmol/h)

Entry	Solvent Composition	Mole Fraction	Energy (kW)
1	Water	0.7	3,652
	Monoethanolamine	0.3	
2	Water	0.7	7,877
	Methylethanolamine	0.3	
3	Water	0.7	10,493
	Piperazine	0.3	
4	Water	0.7	8,349
	Triethanolamine	0.3	
5	Water	0.7	13,911
	Dimethylethanolamine	0.3	
6	Water	0.7	6,182
	N-aminoethyl ethanolamine	0.3	
7	Water	0.7	51,178
	Triethylamine	0.3	
8	Water	0.7	4,250
	Monoethanolamine	0.15	
	N-aminoethyl ethanolamine	0.15	
9	Water	0.60	2,855
	Monoethanolamine	0.20	
	N-aminoethyl ethanolamine	0.20	

Kmol/h = kilomole per hour, kW = kilowatt.

Source: Author.

Amine blending was also shown to increase the CO₂ absorption capacity as reported by Yan et al. (Yan et al., 2024). In their study, they used monoethanolamine, methyldiethanolamine, and 2-amino-2-methyl-1-propanol as an amine mixture. Compared to a single monoethanolamine system, the blending reduced 10% of energy consumption and increased CO₂ capture capacity by 11 tons annually. Although CO₂ absorption from flue gas, especially coal industry, is attractive from an environmental perspective, the realisation on a real scale is challenging. Less than 1% of the coal industry captures the CO₂ emissions in a commercial scale, such as Boundary Dam carbon capture and storage project in Canada. Most of the systems are still in demonstration-scale or a part of a pilot project. The reason for the lack of adoption is the economic barrier, as it requires high capital investment and no global carbon pricing agreement. Additionally, the infrastructure for storing or transporting CO₂ is still lacking and further complemented with the absence of long-term regulation or CO₂ capture mandate that discourages investment to further stimulate cleaner industry.

2. Carbon Dioxide Conversion to Chemicals

Captured CO₂ could be stored in a liquid tank or temporarily in the pipeline or buffer tanks before further conversion. There are many approaches to convert CO₂, which can be conducted by (i) hydrogenation to produce methanol or other chemicals, (ii) reaction with methane to produce synthetic gas (CO + H₂), and (iii) CO₂ fixation to produce urea, salicylic acid, polycarbonate, and others. In terms of catalyst systems, the CO₂ conversion was implemented by photocatalysis, where the reaction occurs under certain light, electrocatalysis (converting CO₂ into valuable products by using electricity), mineralisation (CO₂ is converted to mineral rocks), and thermal catalysis, where CO₂ reacts with hydrogen at high temperature and pressure. The detailed comparison of these technologies is presented in Table 4.2. These mentioned technologies depend on the catalyst and the energy input to the reaction system. For example, in photocatalysis, which uses light, the availability of intense sunlight daily is crucial to be comprehended by responsible authorities.

At present, the cement industry is the second largest CO₂ emitter after power generation. CO₂ emissions in the cement industry originate from (i) calcination, which decomposes limestone (CaCO₃) to calcium oxide (CaO) and CO₂ with the reaction as follows: $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$; (ii) fuel combustion with temperatures up to 1,450°C; and (iii) electricity for grinding and production. Reducing CO₂ in the cement industry is still challenging because it is equivalent to the amount of the CaO product. Hence, CO₂ sequestration by mineralisation is one of the potential ways to reduce and convert CO₂ into more valuable products. In this method, CO₂ was reacted with alkaline earth metals to form mineral carbonates. This mineral is stable from a thermodynamic perspective, thus prohibiting CO₂ leakage into the environment (Park et al., 2024). This approach should attract more interest to obtain more profit, while still maintaining sustainability, especially in the cement industry.

Thermal CO₂ conversion works at high temperature and pressure, where CO₂ is reacted with hydrogen to proceed through various reaction pathways. Now, the product yield is much larger compared to the photocatalysis and electrocatalysis routes. The main concern of this process is to ensure safety because of working with hydrogen at high pressure. Additionally, the initial capital cost also slows the commercialisation process.

Table 4.2. Comparison of Carbon Dioxide Conversion Technologies

Technology	Process Description	Main Products	Pros	Cons	Suitability in ASEAN	Ref
Photocatalysis	Uses sunlight and catalyst (typically semiconductor) to reduce CO ₂	Methane, methanol, formic acid	Utilise abundant solar energy and operate at low temperature	Low efficiency and catalyst degradation Still in research and development phase	Ideal for tropic countries with high solar potential	(A. Kumar et al., 2022)
Electrocatalysis	Uses electricity to reduce CO ₂ at the surface of electrode in electrochemical cell	Carbon monoxide, formic acid, ethylene	Tuneable products depend on voltage power and compatible with other renewables	Catalyst cost and stability Scale-up process	Suitable for countries investing in wind and solar such as Viet Nam and Philippines	(Alli et al., 2024)
Mineralisation	Reacting CO ₂ with minerals or industrial waste to form stable carbonates	Carbonate minerals	Permanent storage Uses industrial by-products	Slow reaction rates High transportation cost	Applicable near cement or steel industries	(Abdelshafy et al., 2025)
Thermal catalysis	Reacting CO ₂ with hydrogen at high temperature and pressure	Methanol formic acid	Faster for commercialisation	Expensive capital cost	Green hydrogen could be produced from many various renewable electricity	(Alper & Yuksel Orhan, 2017)
Urea synthesis	Involve a reaction between CO ₂ and NH ₃	Urea	Mature technology with high demand as fertiliser	Energy-intensive process and volatile to ammonia feedstock	Could be integrated with ammonia plants	(H. Wang et al., 2018)
Dry reforming of methane	Reacting CH ₄ and CO ₂	Syngas	Simultaneously reduce two major greenhouse gases	Highly endothermic and catalyst deactivation at high temperature	Strong fit near palm oil mill effluent, agro-industrial waste	(Zhu et al., 2024)

CH₄ = methane, CO₂ = carbon dioxide.

Source: Author.

Methanol is a versatile chemical that is useful in pharmaceuticals, automotive, and paints. The main demands of methanol are as a solvent in chemical manufacturing and as a fuel additive. In Indonesia, the methanol market volume was 1,350,000 tonnes in 2023 where 980,000 tonnes was imported from several countries. In 2034, the methanol demand is projected to grow to 1,900,000 tonnes (Chemanalyst, 2024). In Southeast Asia, methanol stock is still limited due to tightening supply and increased methanol cost in the region (Duffler, 2025). In Indonesia, PT. Kaltim Metanol Industri (KMI) is the only company that produces methanol with restricted capacity (0.66 million tonnes per year). With the current national interest, methanol is a crucial feedstock in the transition to energy to produce biodiesel. In addition, methanol is also considered as one of the green hydrogen vectors alongside ammonia but does not require compression to become liquid. In the Southeast Asian region, Petronas Methanol Sdn. Bhd has the largest capacity production of 2.4 million tonnes annually. Meanwhile, Brunei methanol produces 0.85 million tonnes yearly.

Methanol could be produced from several carbon-containing feedstocks such as natural gas, coal, biomass, synthetic gas (syngas), or CO₂. Although natural gas currently supplies the majority of methanol in the market, such as to KMI, the potency of CO₂ as a feedstock cannot be neglected. The reaction between CO₂ and hydrogen (or known as CO₂ hydrogenation) is the most straightforward route to produce methanol. However, there are two possible reactions in the typical conditions (220–250°C, 50–80 bar) as follows:

Methanol synthesis: $\text{CO}_2 + \text{H}_2 \leftrightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$ (Reaction 1)

Reverse water gas shift reaction (RWGS): $\text{CO}_2 + \text{H}_2 \leftrightarrow \text{CO} + \text{H}_2\text{O}$ (Reaction 2)

Figure 4.3 depicts a process sheet simulation to produce methanol through CO₂ hydrogenation. First, CO₂ was compressed in a series compressor to increase its pressure and temperature before mixing with pre-compressed H₂. CO₂ hydrogenation was conducted in a plug flow reactor (PFR) with a reactor length and diameter of 6.5 m and 1.5 m, respectively. In the simulation, the reaction was conducted at 250°C and 50 bar with a residence time of 24 minutes using copper/zinc oxide/alumina (Cu/ZnO/Al₂O₃) as a catalyst with a bulk density of 1.2 kilogrammes per cubic metre (kg/m³). The kinetic reaction is denoted as follows:

$$\text{Methanol synthesis} = \frac{k_1 P_{\text{CO}_2} P_{\text{H}_2} \left(1 - \frac{1}{K_{\text{eq}1}} \frac{P_{\text{H}_2\text{O}} P_{\text{CH}_3\text{OH}}}{P_{\text{H}_2}^3 P_{\text{CO}_2}} \right)}{\left(1 + k_2 \frac{P_{\text{H}_2\text{O}}}{P_{\text{H}_2}} + k_3 P_{\text{H}_2}^{0.5} + k_4 P_{\text{H}_2\text{O}} \right)^3} \left(\frac{\text{mol}}{\text{kg}_{\text{cat}} \text{s}} \right) \quad (3)$$

$$\text{RWGS} = \frac{k_5 P_{\text{CO}_2} \left(1 - K_{\text{eq}2} \frac{P_{\text{H}_2\text{O}} P_{\text{CO}}}{P_{\text{CO}_2} P_{\text{H}_2}} \right)}{\left(1 + k_2 \frac{P_{\text{H}_2\text{O}}}{P_{\text{H}_2}} + k_3 P_{\text{H}_2}^{0.5} + k_4 P_{\text{H}_2\text{O}} \right)} \left(\frac{\text{mol}}{\text{kg}_{\text{cat}} \text{s}} \right) \quad (4)$$

$$\text{Where } k_i = A_i \exp\left(\frac{B_i}{RT}\right) \quad (5)$$

$$\log_{10} K_{\text{eq}1} = \frac{3066}{T} - 10.592 \quad (6)$$

$$\log_{10} K_{\text{eq}2} = -\frac{2073}{T} + 2.029 \quad (7)$$

Where P_{CO_2} , P_{H_2} , $P_{\text{H}_2\text{O}}$, $P_{\text{CH}_3\text{OH}}$ correspond to the pressure of carbon dioxide, hydrogen, water, and methanol, respectively. Meanwhile, the kinetic parameters such as k_1 , k_2 , k_3 , k_4 and k_5 are based on the previous study (Van-Dal & Bouallou, 2013) and shown in Table 4.3. PFR reactors typically use a solid catalyst to convert CO_2 to methanol. Then, from PFR, liquid and gas products were separated, where the unreacted gas is recirculated to PFR. Meanwhile, the liquid fraction was distilled to obtain high purity of methanol. The reaction is exothermic, releasing 50 kilojoules/mol of methanol. To remove the heat, it requires 2 megawatts (MW) of cooling duty. Some details in the process simulation are denoted in Table 4.3.

Table 4.3. Details in the Process of Carbon Dioxide Hydrogenation to Methanol

Component	Notes	Kinetic Parameter		
p_{H_2}	0.14 tonne/hour	k_1	A_1	1.07
CO_2	1.04 tonne/hour		B_1	40,000
Methanol	6,000 tonne/year	k_2	A_2	3,453.38
H_2 price	US\$2/kg		B_2	-
CO_2 price	US\$50/tonne	k_3	A_3	0.499
Renewable methanol price	US\$770/tonne		B_3	17,197
		k_4	A_4	6.62×10^{-11}
			B_4	124,119
		k_5	A_5	1.22×10^{10}
			B_5	-98,084

CO_2 = carbon dioxide, kg = kilogramme, H_2 = hydrogen, p_{H_2} = pressure of H_2 .

Source: Authors.

To evaluate the process economically, capital expenditure (CAPEX) and operational expenditure (OPEX) were calculated. There are two categories in CAPEX, direct and indirect costs. The equipment cost was referenced to chemical engineering plant cost indexes (CEPCI), and the chemical plant was built in Southeast Asia. Design and engineering dominated the indirect costs. OPEX mainly originated from chemical feedstock (CO_2 , H_2 , catalyst), labour, and power. Labour and electricity costs are based on the Indonesian standard (Central Java). The details of CAPEX and OPEX are listed in Table 4.4. Meanwhile, the revenue of this process comes from methanol, CO_2 credits, and renewable fuel credits. Then, to reach a positive internal rate of return with a value of 8%–9%, the government must subsidise the partial cost of H_2 with a subsidy amount of US\$3.37/year and implement tax-free in the first 5 years and 20% after 5 years. In addition, securing 50% of CAPEX is also crucial to obtaining a positive internal rate of return. By these assumptions, the payback period is about 10–12 years.

In comparison to KMI, the methanol production capacity in this study is much lower. KMI produced methanol at 660,000 tonnes per year, while this study only produced an annual of 6,000 tonnes. This simulation uses PFR, while KMI utilises a multi-tubular quench reactor using natural gas as the reactant instead of CO_2 . This simulation also has a lower carbon efficiency compared to the KMI route, but it aligns with net-zero goals.

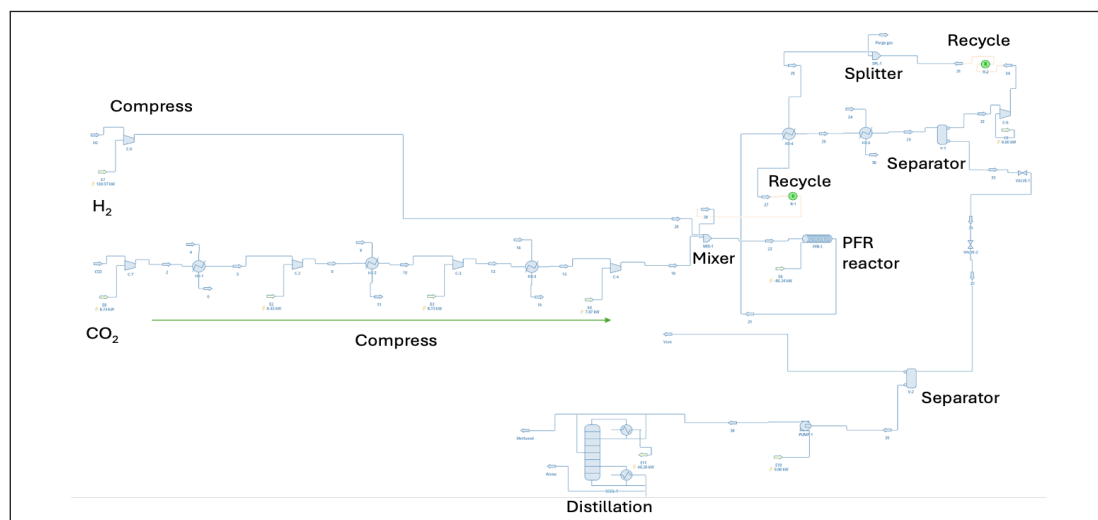
Table 4.4. Capital and Operational Expenditure of Carbon Dioxide Hydrogenation to Methanol

Capital Expenditure		Operational Expenditure	
Direct Cost	In US\$	Fixed Cost	In US\$ (per year)
Equipment	29,548,814	H ₂	22,500,000
Equipment erection	13,296,967	CO ₂	400,000
Piping	20,684,169	Catalyst and heat exchanger	2,500,000
		Labour	362,000
Instrumentation	5,909,762	Power	7,138,000
Electrical	295,488	Total	32,900,000
Utilities	4,432,322		
Storage	14,774,407		
Site preparation	4,432,322	Revenue	
Auxiliary building	1,477,439	Methanol	4,620,000
Indirect Cost		CO ₂ credits	700,000
Design & engineering	30,583,023	Renewable fuel credits	1,200,000
Contractor fee	5,097,171	Total	6,520,000
Contingency	10,194,524		
Total	143,385,808		

CO₂ = carbon dioxide, H₂ = hydrogen.

Source: Author.

Figure 4.3. Flowsheet of Carbon Dioxide Hydrogenation to Methanol



CO₂ = carbon dioxide, H₂ = hydrogen, PFR = plug flow reactor.

Source: Author.

In this study, the process simulation was conducted using Cu/ZnO/Al₂O₃ as a sample catalyst. But other catalysts were also reported in CO₂ hydrogenation to methanol, such as Pd/ZnO and In₂O₃. The comparison between the catalysts is outlined in Table 4.5.

Table 4.5. Catalyst Performance, Cost, and Lifetime in Carbon Dioxide Hydrogenation to Methanol

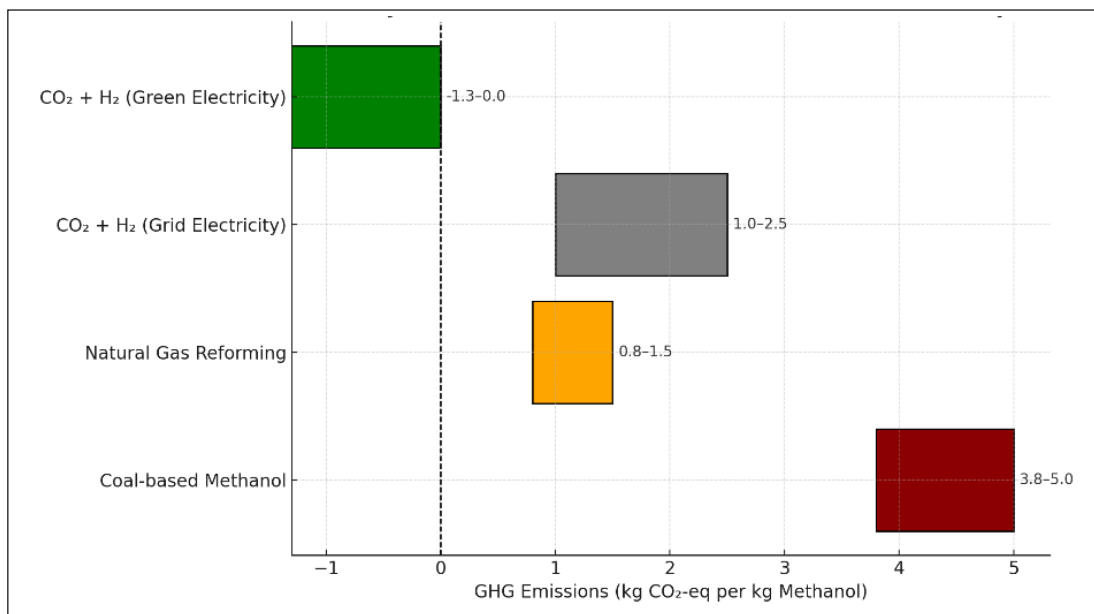
Catalyst	CO ₂ Conversion (%)	MeOH Selectivity (%)	Temperature (°C)	Pressure (bar)	Estimated Cost	Lifetime
CZA	15–25	70–90	220–70	50	Low	3–5 years
PdZn	10–20	85–95	250–300	30–50	High	<2 years
InZr	18–22	90–98	250	40	Medium	3–5 years

CO₂ = carbon dioxide, MeOH = methanol.

Sources: Jiang et al. (2020), Zhong et al. (2020).

To understand the environmental impact, especially in greenhouse gas emissions (GHG), of methanol production through CO₂ hydrogenation, a life cycle analysis (LCA) was conducted. The LCA result was then compared to other methanol production route such as coal-based methanol, natural gas reforming (Yang et al., 2025), and grid electricity H₂ as presented in Figure 4.4. This result confirmed the importance of renewable hydrogen to lower the GHG emissions significantly.

Figure 4.4. Greenhouse Gas Emissions of Several Methanol Production Routes



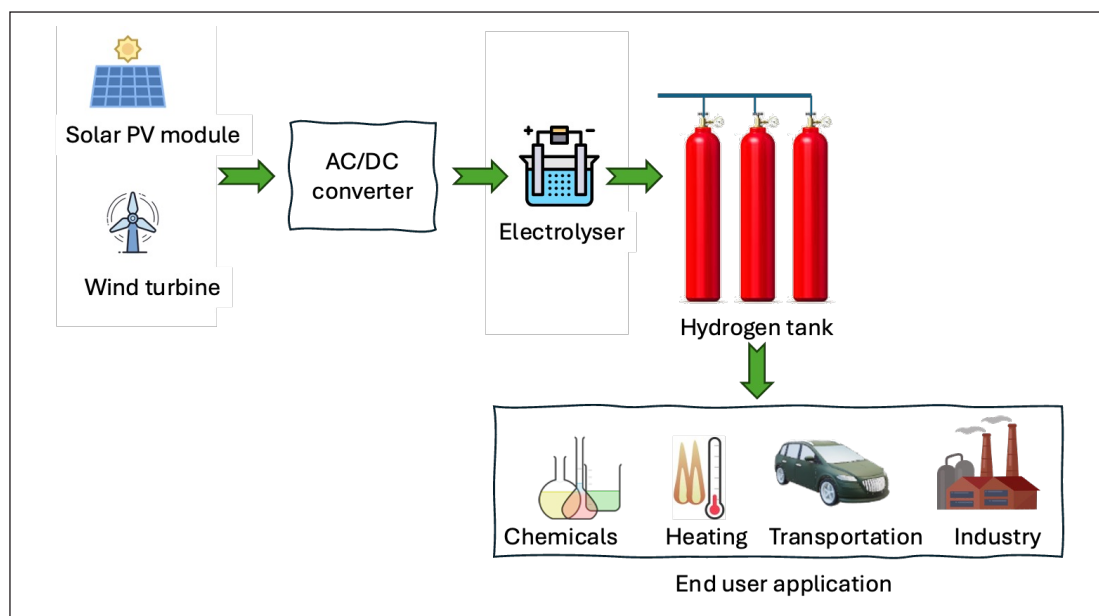
CO₂ = carbon dioxide, GHG = greenhouse gas, H₂ = hydrogen., kg = kilogramme.

Source: Author.

3. Producing Green Hydrogen

As hydrogen dominates the price of feedstock, it is important to understand the hydrogen production method to reduce the price and minimise environmental pollution. There are three categories of hydrogen production routes: grey, blue, and green hydrogen. Grey hydrogen refers to hydrogen from fossil fuel, while blue hydrogen refers to hydrogen from fossil fuel coupled with carbon capture and storage. Lastly, green hydrogen is produced from water electrolysis using renewable energy resources (Figure 4.5). The global hydrogen demand in 2020 was 87 million metric tonnes and is forecast to reach 500–680 million metric tonnes in 2050. However, only 5% of hydrogen production is considered green. Nowadays, there is an increasing interest in hydrogen as it is useful for various applications such as fuel cells, electric vehicles, ammonia production, refrigeration, and others. The capacity of the largest hydrogen production site in Indonesia, Malaysia, and Thailand is 30–70 kilotonnes per year, which is based on steam methane reforming (Y. Li et al., 2023).

Figure 4.5. Green Hydrogen Production Route



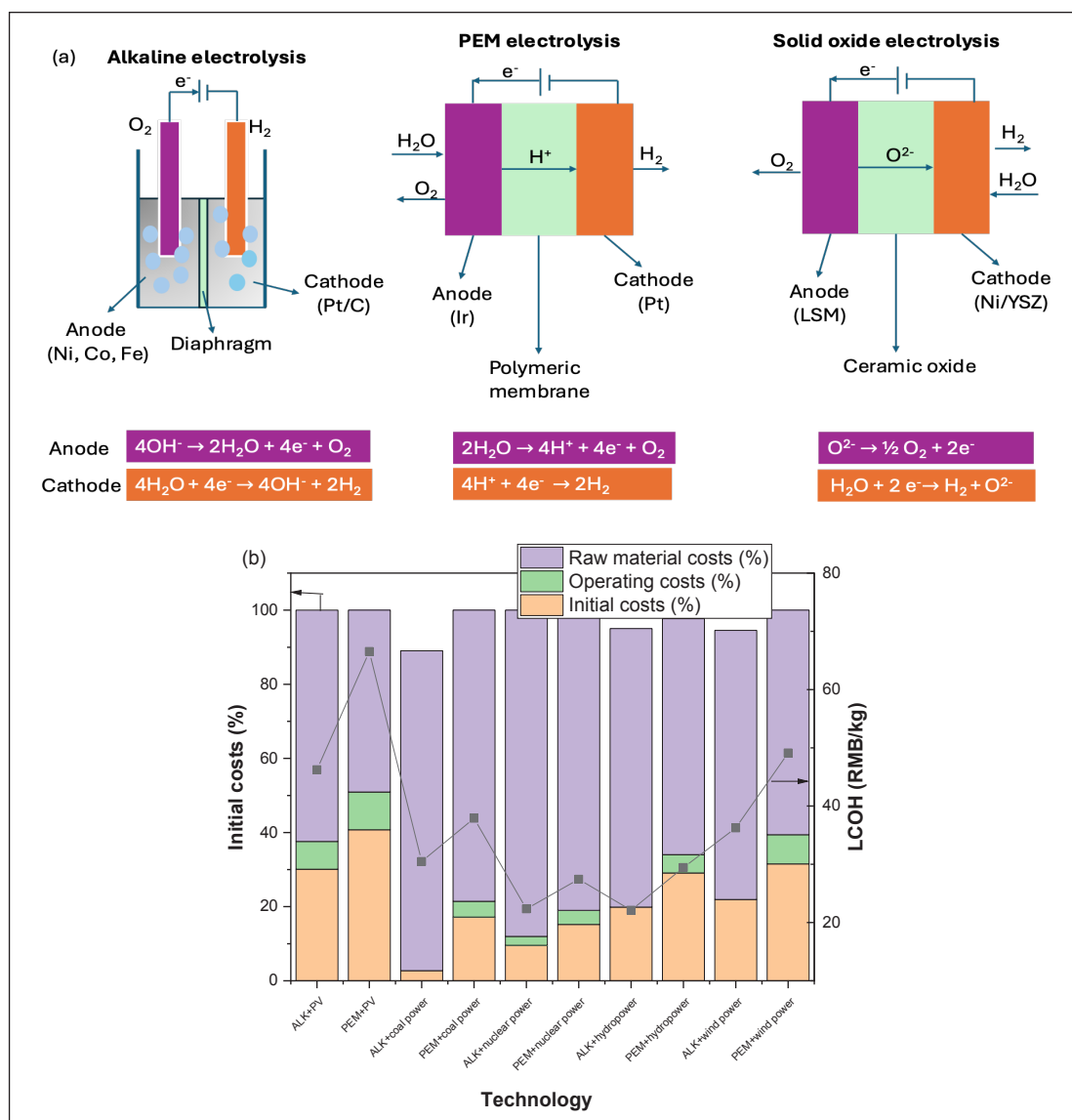
AC = alternating current, DC = direct current, PV = photovoltaic.

Source: Author, adapted from Chowdhury et al. (2025).

Generally, there are three methods for green hydrogen production: alkaline (ALK) electrolysis, proton exchange membrane (PEM), and solid oxide electrolysis (SOFC). The general difference amongst these technologies is based on the electrolyte carrier, from alkaline ions in ALK, protons in PEM, and oxide anion in SOFC. The schematic difference of these technologies is depicted in Figure 4.6 (a), and the process overview is listed in Table 4.6. A study by Li, Hao, and Zhou (2025) compared the hydrogen cost in these three production routes using a levelised cost of hydrogen (LCOH) (Y. Li et al., 2025). Additionally, they also considered two types of green hydrogen based on ALK and PEM, as shown in Figure 4.6. A lower LCOH indicates lower hydrogen production

cost, which implies higher market competitiveness and better economic viability. The initial cost, operation, and raw material cost were simplified in Figure 4.6 (b). From their study, the cheapest production cost is grey hydrogen, in which fossil fuel dominates the total prices. For green hydrogen, electricity cost is the most influential factor with ALK technologies 18%–30% cheaper than PEM electrolyser. In terms of renewable energy sources, hydropower is preferable to wind and photovoltaic. They also correlated the hydrogen cost to the CO₂ price in the market. Although ALK is the best option, it is still not economical in the current hydrogen price. However, they predicted that as the continuously increasing of CO₂ price in the future, the price of hydrogen will be steadily lower.

Figure 4.6. (a) Overview of Green Hydrogen Production (b) Initial Cost, Operating Cost, Raw Materials, and Levelised Cost of Hydrogen of Different Technologies



PEM = proton exchange membrane.

Source: Author, adapted from Li, Hao, and Zhu (2025).

Table 4.6. Overview of Green Hydrogen Production

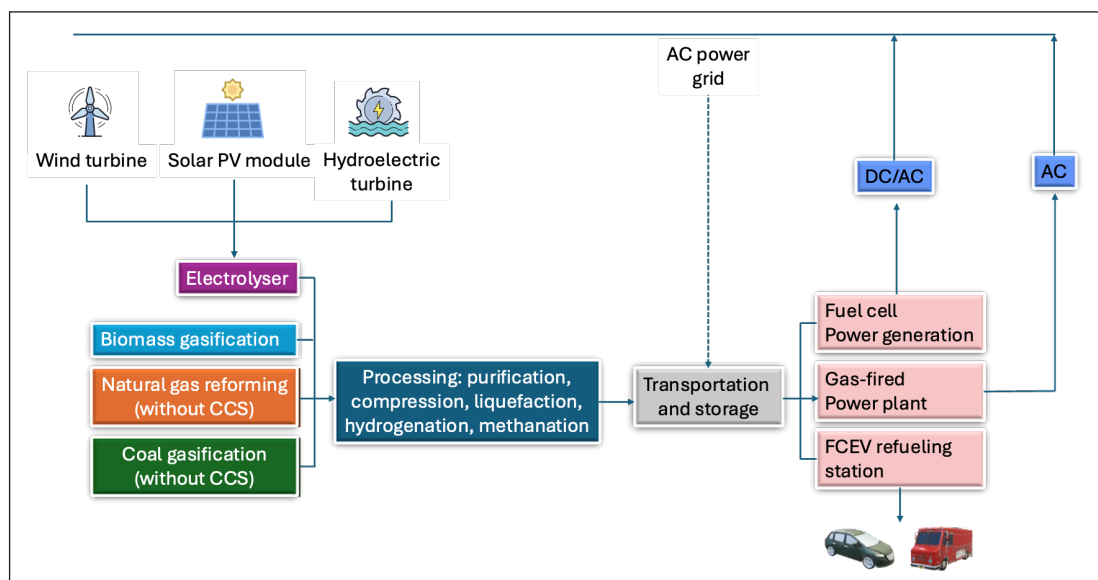
	ALK	PEM	SOFC
Temperature	70–90°C	70–80°C	600–1,000°C
Current density	<0.8 A/cm ²	1–4 A/cm ²	0.2–0.4 A/cm ²
Energy consumption	4.5–5.5 kWh/Nm ³	4–5 kWh/Nm ³	2.6–3.6 kWh/Nm ³
Efficiency	60–75%	70–90%	85–100%
Industrialisation	Yes	Yes	No
Age of system	10–20 years	10–20 years	/
Advantage	• Well industrialised • Non-noble catalyst • Relative low cost	• High current densities • Good partial load range • Rapid system range • High gas purity	• Efficiency up to 100% • Non-noble catalyst • High pressure operation
Disadvantage	• Low current density • Low partial load range • Low dynamics • Low pressure	• Component high cost • Acidic environment • Possibility low durability	• Laboratory stage • Bulky system design • Durability • No dependable cost
Reference	(Sebbahi et al., 2024)	(S. S. Kumar & Lim, 2023)	(Kamlungsua et al., 2020)

ALK = alkaline electrolysis, cm² = square centimetre, kWh = kilowatt-hour, Nm³ = normal cubic metre, PEM = proton exchange membrane, SOFC = solid oxide fuel cell.

Source: Author.

Although green hydrogen is attractive from an environmental perspective, there are still some challenges in this technology. The drawbacks of this water electrolysis are unstable (fluctuating) electricity, capacity restriction, longevity, high cost of capital and operational, and storage and safety. There are some ongoing research to tackle these limitations, especially to produce a large-scale stack of electrolyzers with high safety (due to potential mix of H₂ and O₂) and long stability (Nnabuife et al., 2025).

Besides production, hydrogen infrastructure is also crucial in defining the hydrogen price. The infrastructure includes a pipeline, storage, and refilling stations. The United States Department of Energy developed the Hydrogen Delivery Scenario Analysis Model to establish tools as follows: (i) pipeline cost (100 kilometres [km]) is US\$4.85/kilogramme (kg), (ii) compressed hydrogen tanker (283 km) is US\$3.30/kg, and (iii) liquid hydrogen (283 km) is US\$3.23/kg (Cormos and Cormos, 2019). The Asia Pacific Research Centre developed a hydrogen supply from the Asia–Pacific to Japan in the form of liquid hydrogen. The shipping costs are as follows: Russia: US\$1.76/kg, United States: US\$2.3/kg, Australia: US\$2.51/kg, and Indonesia: US\$2.23/kg (APEREC, 2018). Li et al. (2023) studied a strategic roadmap for hydrogen energy in ASEAN countries. In their study, they assumed that the distributed grey hydrogen production has a capacity of 1500 kg/day, while centralised grey hydrogen has a capacity of 200,000 kg/day, of which the centralised supply scheme is presented in Figure 4.7. They confirmed that grey hydrogen from Indonesia and Brunei Darussalam is already competitive to export at the current situation. From 2026–2030, ASEAN countries could move to blue hydrogen through the ongoing CCUS project in the region. Then, beyond 2030, the cost of green hydrogen will be lower as widespread use of renewable energy reduces the cost of non-fossil energy. It is expected that the green hydrogen from the region will dominate the overseas market, especially to East Asia.

Figure 4.7. Proposed Centralised Supply Chain of Hydrogen

CCS = carbon capture and storage, FCEV = fuel cell electric vehicle, PV = photovoltaic.

Source: Author, adapted from Li et al. (2023).

The challenge for green hydrogen production in Southeast Asia is to realise a high proportion of a renewable energy mix. Although the region is gifted with enormous renewable energy potential, it is not fully tapped by a limited power grid. The current priority of ASEAN countries is to reach an agreement in the ASEAN grid to enable system integration and cross-border electricity interconnection in the region.

Europe is a global leader in green hydrogen production in terms of technology and policy regulation. Europe has installed an electrolyser with a capacity of more than 700 MW with a target to produce 10 million tonnes of hydrogen in 2030. The key regulation to stimulate the green hydrogen production is the carbon border adjustment mechanism, which introduces an incentive to utilise low-carbon hydrogen, especially in the fertiliser and steel sectors. In addition, the current European Emission Trading System also includes free allowance and direct funding for low-carbon hydrogen projects with an innovation fund support to relieve the CAPEX and OPEX. Meanwhile, the installed electrolyser capacity in the Southeast Asian region is less than 50 MW, which is much smaller compared to Europe (700 MW) and East Asia (500 MW). In addition, from a policy perspective, it is still an absence of a strong, binding target and a limited incentive framework in either innovation fund, subsidies, tax, or clean power mandate. Therefore, it is crucial to establish the proper regulatory incentive to attract more interest from both domestic and foreign companies.

The actionable steps for green hydrogen advancement in the ASEAN region are:

- Support pilot projects and demonstration hubs. The pilot project could be located near renewable energy power plants or an industrial user.
- Build hydrogen infrastructure such as pipelines, storage, and port infrastructure.
- Establish a regional policy and regulatory framework.
- Encourage private partnership. Once regulation, infrastructure, and a pilot project are in place, it will be easier to attract private company participation and partnership.

4. Current Status of Carbon Dioxide Utilisation in ASEAN

CO₂ utilisation in Southeast Asia is emerging, but it is fragmented. There are some ongoing projects as denoted in Table 4.7, but in some countries, such as Lao People's Democratic Republic (Lao PDR), Cambodia, and Timor Leste, there is still untapped potential. The product of CO₂ conversion varies depending on the country's uniqueness. Singapore prioritises methanol as it vector for the chemical industry, while the Philippines focuses on increasing crop productivity. Besides that, the CO₂ utilisation initiative was constrained by the absence of dedicated CO₂ storage and a limited CO₂ transport network.

Table 4.7. Carbon Dioxide Utilisation Projects in Southeast Asia

Country	Project	Technology	CO ₂ Use	Partner	Status
Singapore	Keppel-MHI	Amine absorption and the photobioreactor of algae	Algae fuel, synthetic fuel	MHI Japan, Temasek, Economic Development Board	Feasibility
	CO ₂ to Methanol	Catalytic hydrogenation	Methanol	Japan	Pilot
Indonesia	Pertamina-JOGMEC	CO ₂ compression and EOR	EOR	Japan	Demonstration
	CO ₂ to DME	Coal gasification and CO ₂ hydrogenation	Substitute to LPG	Own initiative	Feasibility
Malaysia	Petronas	Reforming and methanol synthesis	Methanol, urea	Japan, Shell	Feasibility
Thailand	SCG	Carbonation curing	Carbon-cured cement	Thai Government	Pilot
Viet Nam	CO ₂ Hydrogenation	Catalytic hydrogenation	Methanol	Denmark, Asian Development Bank	Lab-scale
Philippines	PhilRice	CO ₂ fertigation	Crop productivity	Domestic	Pilot

CO₂ = carbon dioxide, DME = dimethyl ether, EOR = enhanced oil recovery, JOGMEC = Japan Organization for Metals and Energy Security, LPG = liquid petroleum gas, SCG = Siam Cement Group.

Sources: ASEAN Centre for Energy (2024), JOGMEC (2025), Media Keppel (2023), ADB (2017).

5. Carbon Dioxide Conversion Technology Readiness and Commercial Landscape

The advancement of CO₂ conversion is viewed as a critical pathway for the circular carbon economy. The assessment of technology readiness level (TRL) as an indicator of fundamental research (TRL 1–3) or commercial scale (TRL 9). Table 4.8 represents the commercial landscape of CO₂ conversion and its feasibility in the ASEAN region. It could be inferred from Table 4.7 and Table 4.8 that dry reforming of methane is underdeveloped in ASEAN countries, where it saves huge reserves of palm oil mill effluent and agricultural waste. Until now, the project in ASEAN has focused on tapping the potential of compressed biomethane and methane mitigation.

Table 4.8. Technology Readiness Level of Carbon Dioxide Conversion and Feasibility in ASEAN

Technology	Main Product	TRL	Current Pilot	Key Limitation	ASEAN Fit
Mineralisation	Carbonate for cement	8–9	Australia, Singapore	Energy-intensive, logistic of mineral feedstock	Good fit near mining waste or the cement industry
Urea synthesis from CO ₂	Fertiliser	9	Widely commercial	Required NH ₃ as feedstock	Strong fit in agricultural economies such as Indonesia, Viet Nam
Methanol synthesis	Methanol	7–9	China, Iceland	Dependent on H ₂ supply	Preferably with green H ₂ integration and a versatile chemical product
Dry reforming of methane	Syngas	6–8	Australia, Middle East	Catalyst coking at high temperature	Good for countries with biogas or methane-rich waste stream
CO ₂ to concrete	Enhanced concrete	8–9	Canada, Singapore	Need to develop infrastructure	Fit for high urbanisation and climate co-benefits

ASEAN = Association of Southeast Asian Nations, CO₂ = carbon dioxide, H₂ = hydrogen, NH₃ = ammonia, TRL = technology readiness level.

Source: Author.

6. ASEAN Collaboration for Equitable Technology Transfer

ASEAN could become one of the global leaders in co-operative climate innovation. The region, which consists of developed economies such as Singapore to emerging economies such as Lao PDR and Myanmar, avoids both possibilities and vulnerabilities in cross-border collaboration, especially in technology transfer. Therefore, ASEAN must pursue a systemic, trust-fostering, and inclusive approach to trigger CO₂ conversion technologies for all member countries.

6.1. Equitable Technology Collaboration Principles

To avoid making any member state feel aggrieved, ASEAN co-operation must be based on:

- Shared but differentiated responsibilities based on Nationally Determined Contributions (NDCs)
- Mutual benefit: Technology transfer must create local economic benefits (jobs, small and medium-sized enterprises, training) in donor and recipient countries.
- Transparency and accountability: Open reporting and documentation of the terms, scope, and progress of technology transfer agreements.
- Respect for intellectual property rights and sovereignty: Protect intellectual property rights while enabling access through licensing, joint ventures, or public-private partnerships (PPPs).

Europe is an example for successful collaboration in CO₂ conversion with the technology evenly distributed amongst its collaboration members. Carbon4PUR (2017–2021) is a collaborative work led by Germany with partners from Netherlands, Belgium, France, and Austria. The partnership includes Covestro (industry), universities (TU Berlin and RWTH Aachen), the port of Rotterdam for logistics, and small and medium-sized enterprises. The goal of the project is converting waste CO and CO₂ from steel production into polyether carbonate polyols. They reduced fossil fuel feedstock by 20% and saved 1.2 kg CO₂ per kg of polyol product. Their study demonstrated that the circular economy is economically feasible and competitive to the market. The research achievement reveals that through multi-country and multi-sector partnership advanced industrial CO₂ utilisation can be realised. This successful project could be replicated in ASEAN region and expected to bring emerging countries such as Cambodia and Lao PDR to the centre of decarbonisation.

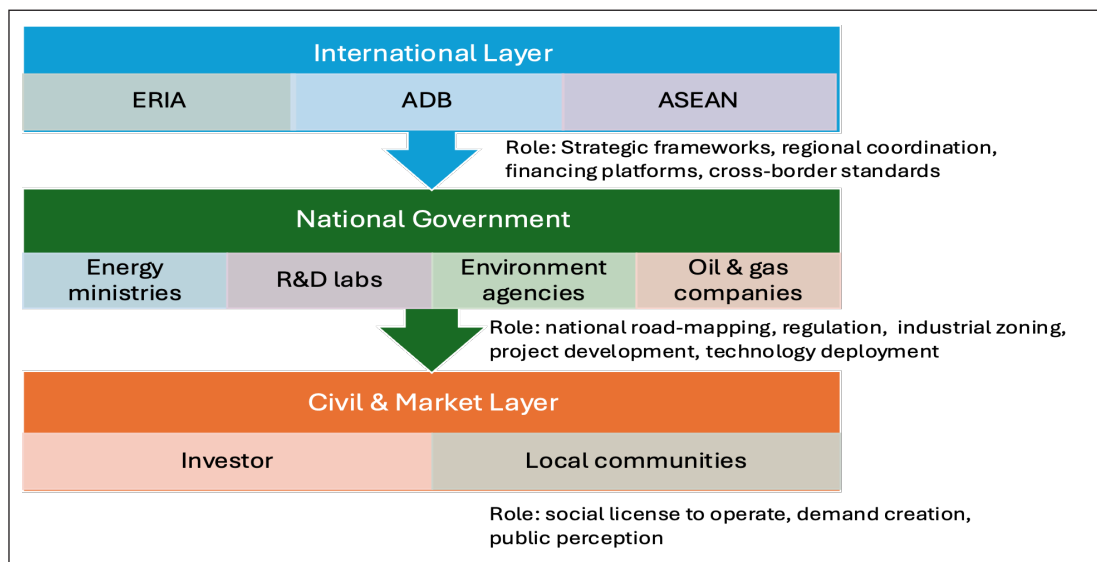
6.2. Institutional Structures for ASEAN-Led Co-ordination

Southeast Asian countries have established long-term co-operation as ASEAN. In terms of CO₂ conversion, it is still fragmented and seems to make progress with limited alignment with its neighbouring countries. Innovation and funding are two primary hindrances to the advancement of technologies such as CO₂ conversion. The suggested platforms are as follows:

- Map each country's capabilities (e.g. Singapore's research and development (R&D), Viet Nam's solar capabilities, Indonesia's biomass potential).
- Identify complementary pilot project sites.
- Match institutions, start-ups, and government agencies with innovation collaboration.
- Align regional funds to support early deployment in less developing countries.

A central clearinghouse approach can moderate direct bilateral sensitivities. For example, Singaporean or Thai technologies can be deployed in Cambodia or Lao PDR through an ASEAN-sponsored project with the Economic Research Institute for ASEAN and East Asia (ERIA) or the Asian Development Bank (ADB), monitoring equity and compliance. The institutional co-ordination and role are provided in Figure 4.8.

Figure 4.8. Institutional Co-ordination and Role in the Carbon Dioxide Conversion Initiative



ADB = Asian Development Bank, ASEAN = Association of Southeast Asian Nations, ERIA = Economic Institute for ASEAN and East Asia, R&D = research and development.

Source: Author.

6.3. Fair Technology Transfer Models

Technology transfer is a critical consideration for deploying low-carbon technologies. Despite the technological importance, licensing and transparency are key enablers to accelerate the CO₂ conversion initiatives. Thus, we propose:

- **Licensing and joint ventures:** Owners of proprietary CO₂ conversion technology (e.g. electrocatalytic reactor) may license ASEAN start-ups or government agencies for adaptation and production.
- **Open innovation platforms:** ASEAN can introduce open-source or low-barrier intellectual property modalities for non-sensitive technologies like mineralisation or bioconversion through algae.
- **Public-private pilots:** Governments and companies co-finance pilot facilities in less-developed ASEAN countries. Profit or carbon credits can be shared based on agreed key performance indicators and contribution levels.

6.4. Capability Development and Talent Mobility

To faster CO₂ conversion advancement in ASEAN, high skill talents are key requirements. Researchers in a university initiated a lab-scale experiment to produce methanol as the largest chemical demand from CO₂. From methanol, it can be converted to olefins, aromatics, gasoline, or other products. There are some potential collaboration models as follows:

- Joint research centre: Launching an ASEAN CCU research hub consisting of ITB (Indonesia), UTM (Malaysia), NUS (Singapore), and Chulalongkorn University (Thailand). Governments should provide scholarships and short-term training on CO₂ conversion. One of the successful examples is the European Union's Erasmus Mundus programme (aims to enhance the quality of higher education through scholarships and academic co-operation between the EU and the rest of the world). Talent mobility is fluid to accommodate fast and transparent collaboration.
- Cross-border CO₂ transport and utilisation. The possible CO₂ transport route is denoted in Table 4.9.

Table 4.9. Cross-border Carbon Dioxide Transport and Utilisation

Route	Mode	Distance (km)	US\$/tCO ₂	Annual Volume (MtCO ₂ /year)	Status
Indonesia (Batam) – Singapore	Shipping	60	25–45	1.5–3	Proposed (part of Singapore carbon hub plan)
Thailand (eastern seaboard) – Malaysia (Johor)	Pipeline	550	13–55	3–5	Conceptual
Viet Nam (Vũng Tàu) – Brunei via South China Sea	Shipping	1,200	45–85	2–4	Exploration
Malaysia (Sarawak) – Indonesia (Kalimantan)	Pipeline	300	7–30	2–3	Early planning
Indonesia (East Java–Natuna)– Singapore	Shipping	850	35–70	1–2	Potential

km = kilometre, MtCO₂ = metric tonnes of carbon dioxide, tCO₂ = tonnes of carbon dioxide.

Sources: Dasari et al. (2022), Al Baroudi et al. (2021), McCoy and Rubin (2008).

- Public–private partnerships. To accelerate the effort of CO₂ conversion initiatives, partnerships between public and private companies are needed. For example:
 - PT. Pertamina (Indonesia): utilisation of carbon in petrochemical industries
 - PTT Global Chemical (Thailand): CO₂-based polymer and develop other chemicals from CO₂
 - ExxonMobil Asia Pacific (Singapore): Providing technologies for CO₂ conversion
 - Petronas (Malaysia): Potential industry partner for CO₂ to methanol

7. Policy Recommendations

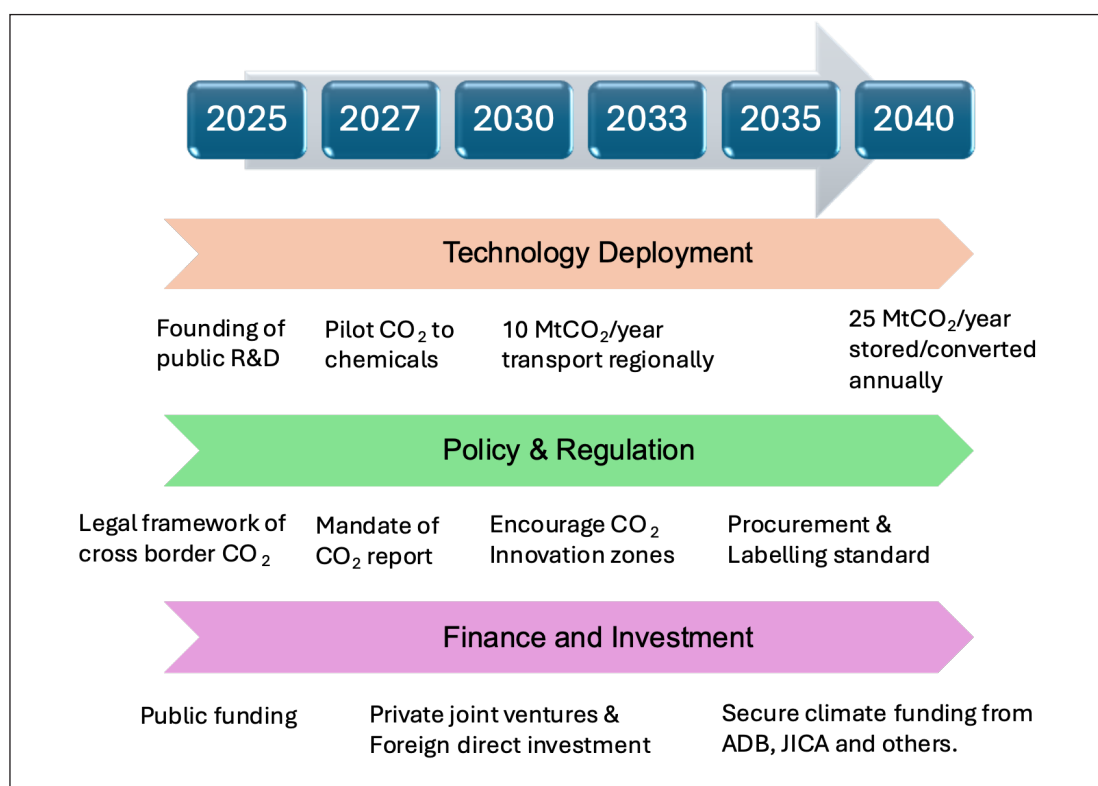
Apart from the technology perspective, policy and funding are two crucial factors governing the success path for CO₂ conversion. Besides the recent decision of United States President, Donald Trump, to leave the Paris Agreement, ASEAN countries should re-emphasise the commitment to carbon neutrality in the region. Amongst ASEAN countries, only Singapore has fully implemented carbon tax and offsets. Meanwhile, Indonesia has applied the Just Energy Transition partnership and voluntary offsets. Malaysia is currently drafting rules on tax exemptions and R&D grants, while Thailand still lacks green public procurement. Therefore, ASEAN co-ordination agencies such as the ASEAN Foundation and ASEAN Climate Change and Energy Project should make long-

term agreements for decarbonisation. There are several policy recommendations to accelerate the CO₂ conversion as follows:

- Financial and economic incentives that covers subsidy, carbon pricing and feed-in tariffs.
- Research and development support for public–private partnerships, regional innovation hubs, and start-up incubators.
- Regulatory framework that prioritises CO₂ utilisation in key sectors and green procurement policies for product from recycle CO₂ such as urea, construction materials, or minerals.
- Encourage infrastructure and market development. CO₂ storage and transport form emitters to conversion facilities should be built. In addition, establishing CO₂ certification and standard are crucial to increase consumer and investor confidence.
- To accommodate emerging economic countries, an ASEAN clean innovation fund could be established. This fund would be guaranteed by green bonds, donor countries, and multilateral institutions. In addition, hybrid finance arrangements should be encouraged that share risk between the public and private sector.

The concrete stage for policymakers with actionable steps is presented in Figure 4.9.

Figure 4.9. Roadmap to Accelerate Carbon Dioxide Conversion Initiatives in the ASEAN Region



ADB = Asian Development Bank, ASEAN = Association of Southeast Asian Nations, CO₂ = carbon dioxide, JICA = Japan International Cooperation Agency, MtCO₂ = metric tonnes of carbon dioxide, R&D = research and development.

Source: Author.

Short-term (2025–2027)

- Introduce public R&D and innovation grants. Allocate public grants for pilot projects for CO₂ to methanol in petrochemical hubs and CO₂ to urea in agricultural regions. This activity also includes university–industry collaboration with guaranteed co-funding.
- Establish regulatory clarity for CCU. The definition of CCU should be agreed amongst ASEAN members, and the permitting process for CCU facilities.
- Mandate CO₂ emissions reporting. Large industries should be required to report CO₂ emissions and the opportunity for co-shared conversion. Additionally, digital monitoring, reporting, and verification should be integrated with ASEAN carbon registries.

Mid-term (2028–2033)

- Launch carbon market pilot. Implement a voluntary carbon market that allow CCU credits with verified CO₂ conversion pathways such as CO₂ biosorption with algae, CO₂ mineralisation or CO₂ to construction minerals.
- Create ASEAN CO₂ transport and storage infrastructure. Build shared CO₂ pipelines and shipping routes between Indonesia–Singapore and Thailand–Malaysia.
- Establish CO₂ innovation zones with designated special zones that offer tax incentives, fast-track permits, and access to cheap renewable energy.
- Adopt green procurement and labelling standards. Governments should create low-carbon product certification that is recognised across ASEAN.

Long term (2034+)

- Secure international climate finance from organisations such as the Asia Development Bank (ADB), the Japan International Cooperation Agency (JICA), and others.
- Support more advanced research and global technology transfer. The regional representative should negotiate with East Asian and European countries to localise their technologies through a technology licensing agreement.

8. Conclusion and Strategic Recommendations

To build a robust CO₂ utilisation and storage economy across ASEAN, member states must collectively drive advancement in technology, legal consistency, and capital attraction. The following steps are important to achieve a significant climate mitigation outcome.

- Craft a cohesive regional CO₂ infrastructure blueprint
Integrate sovereign plans into a joint transborder transport and storage plan featuring uniform hubs and consistent regulatory benchmarks.
- Embed risk-mitigating financing structures
Mobilise blended finance, anchored by multilateral organisations like the Asian Development Bank and the Global Carbon Fund, to shield initial CCUS and utilisation projects against capital and operational uncertainties.
- Standardise legal and regulatory regimes
Create ASEAN-wide rules on CO₂ liability, purity thresholds, and measurement, reporting, and verification that draw on proven global frameworks.
- Expedite technology diffusion and domestic maturity
Leverage public procurement, targeted tax credits, and regional innovation centres to advance commercially validated conversion technologies, including scalable Carbon4PUR variants.
- Ensure open and consistent progress tracking
Establish a regional CCUS observatory or interactive dashboard that publishes live data on project advancement, emissions avoidance, and financial commitments.

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Chapter 5

Recycling Carbon-based Materials and Neutrality in ASEAN: Advancing Plastics and Carbon Capture and Utilisation Sustainability

1. Introduction and Carbon Footprint

Carbon neutrality in the plastic ecosystem has become a topic of interest due to its widespread environmental implications, as well as the challenge of making the entire plastic value chain, from feedstock sourcing to production, use, and end-of-life disposal, carbon neutral. Carbon capture and utilisation (CCU) and carbon recycling (CR) are vital in this regard as they help decarbonise carbon-based products classified into chemical products (e.g. plastics) and fuels (e.g. liquid fuels). Carbon recycling includes mechanical and chemical recycling (ChR) of carbon-based materials, biomass reuse, and CCU. Carbon recycling involves capturing carbon dioxide (CO₂) emissions from industrial processes and reusing them to produce valuable products such as plastics and fuels. However, capturing and converting CO₂ is energy-intensive, and utilisation of fossil-based energy in the process can jeopardise environmental benefits. Thus, it is imperative that renewable energy sources power carbon recycling to ensure that it contributes effectively to climate goals. The plastic industry offers multiple entry points for carbon capture, spread across its upstream, midstream, and downstream stages. A significant portion of the carbon used in producing plastics came from carbon-based fossil feedstocks, like crude oil and natural gas. A completely closed-loop plastic system is not practically achievable; however, we can replace a portion of that fossil-based carbon with captured CO₂ using carbon capture technologies. CCU is a specific approach that recycles CO₂ gas captured from industrial emissions or the atmosphere into new products like fuels, chemicals, and plastics, effectively closing the carbon loop.

The world produces 430 million tonnes of plastic waste every year, with almost half of all plastic waste (46%) ending up in landfill. According to the Organisation for Economic Co-operation and Development (2022), scientists believe just 9% of the world's plastic is recycled, and furthermore, producing one tonne of plastic generates 5 tonnes of carbon dioxide (Business Waste, n.d.), highlighting the plastic sector's significant carbon footprint. Plastics are overwhelmingly fossil-based (90.6%), with a very small share coming from recycled (8.9%) and bio-based (0.5%) sources. As of 2015, the plastic sector globally was responsible for 4.5% greenhouse gas emissions worldwide (Cabernard et al., 2021), roughly 1.7 gigatons of CO₂ equivalent. If the current trends continue, these emissions could rise to 6.5 gigatons of CO₂ equivalent by 2050 (Zheng and Suh, 2019). 63% of petrochemical output is plastics, more than one-third of which is used in packaging (Zero Carbon Analytics, 2024). This includes polyethylene, polypropylene, and polyvinyl chloride, which are integral to packaging, construction, automotive, and consumer goods. However, it has drawn growing scrutiny due to its substantial contribution to global greenhouse gas emissions. To fully decarbonise the plastic ecosystem, one can either reuse the carbon within the product through mechanical or ChR or capture and reuse the CO₂ released during disposal processes like incineration or gasification.

The Association of Southeast Asian Nations (ASEAN) region accounts for approximately 20% of global plastic production, with Indonesia, Malaysia, the Philippines, Thailand, and Viet Nam leading the sector. The average municipal solid waste generation in the ASEAN countries is 1.14 kilogrammes (kg) per capita daily, with growing demand for plastics, particularly in the packaging of food and beverages, and industrial applications. After China, several ASEAN countries account for a substantial share of global plastic waste entering the oceans. Indonesia ranks second worldwide, followed by the Philippines in third place and Viet Nam in fourth, while Thailand (sixth) and Malaysia (eighth) also appear amongst the 10 largest contributors globally (Jambeck et al., 2015; OECD, 2022). In most ASEAN nations, the recycling rate for plastics is below 50%, showing the need for better waste management, improved recycling systems, and stronger policies to support a circular economy that can help reduce plastic waste and its environmental impact.

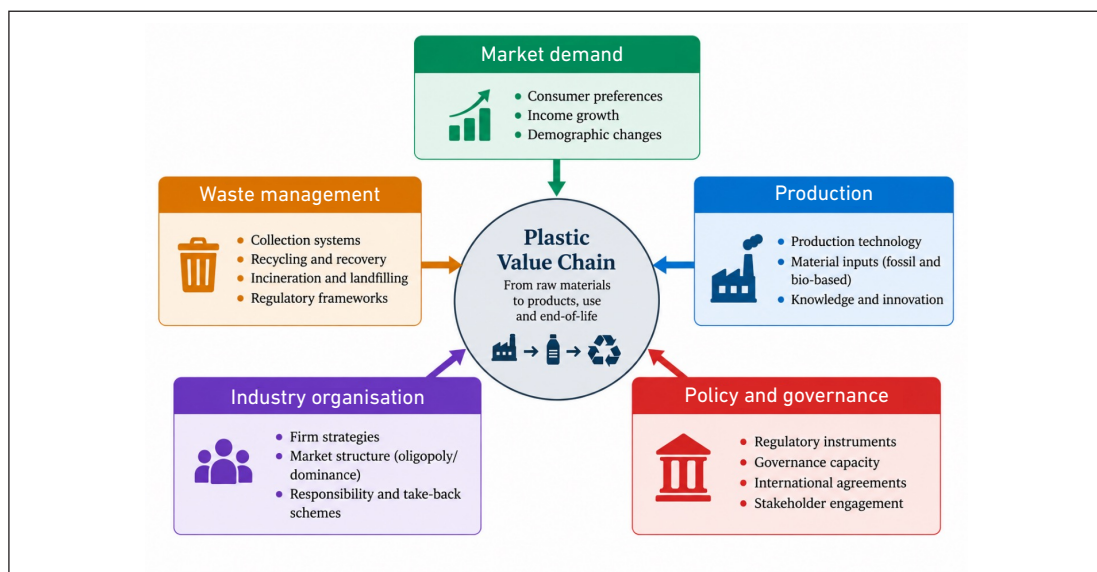
The main objective of this chapter is to provide an in-depth understanding of how the ASEAN region can recycle carbon-intensive plastics with lower carbon emissions, and the cost-effective role of CCU in decarbonisation efforts. The objective also includes exploring the possibilities of CCU in plastic production and other materials in the ASEAN region. To our knowledge, this is the first study in the ASEAN region on carbon recycling in the plastic industry. We use secondary sourced data to fulfil the objective of this study, and it does not include any specific time period.

The rest of the chapter is organised as follows: Section 2 sheds light on the carbon emissions aspect and captures opportunities across the plastic life cycle. Section 3 discusses estimating decarbonisation potential in ASEAN through plastic recycling. Section 4 highlights the cost analysis of plastic recycling and CCU integration. Section 5 gives an overview of plastic recycling efforts in ASEAN, followed by a conclusion and discussion in Section 6.

2. Carbon Emissions Hotspots and Capture Opportunities Across the Plastic Life Cycle

This section breaks down the carbon footprint across the plastic life cycle, identifying key emissions hotspots where CCU can most effectively achieve a carbon-neutral plastic ecosystem. At the upstream level, the most prominent CO₂ sources arise during the production of basic petrochemical feedstocks like ethylene, propylene, and paraxylene used to make plastic polymers like polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), etc. Upstream units (e.g. steam crackers, reformers) burn vast amounts of fossil fuel and emit concentrated CO₂ from fixed locations (stacks), making CO₂ capture more efficient because separating CO₂ is easier when its concentration is higher. Additionally, syngas and methanol plants release CO₂ as a byproduct, making all these ideal candidates for industrial CCUS. At the midstream level, CO₂ is emitted during polymerisation and plastic manufacturing, mainly due to the use of fossil energy for heat and steam using various processes and chemical reactions that contribute to indirect CO₂ emissions, although these emissions are less concentrated, CO₂ can still be captured. At the downstream stage of the plastic lifecycle, significant carbon emissions occur during both the use and end-of-life (EOL) phases. In this stage, plastic incineration and ChR release CO₂ as plastics that are burned or thermally broken down. These processes are major emissions sources since plastics are made from fossil-based carbon. The use phase in a plastic's life cycle contributes to the environmental footprint after production but before disposal, covering transportation, additives, and degradation. The EOL phase poses both direct emissions and opportunities for CO₂ capture. This includes disposal pathways such as landfilling, incineration, mechanical recycling, ChR, and pyrolysis. Amongst these, incineration and thermal conversion methods significantly contribute to CO₂ emissions. For example, Singapore's Tuas Nexus integrated waste management facility, currently under development, is exploring carbon capture integration to reduce post-incineration emissions. Capturing and reusing this CO₂ can help close the carbon loop and reduce the plastic system's climate impact. In bio-based plastic production (like polylactic acid or polyethylene furanoate), CO₂ is released during the fermentation of biomass into chemical building blocks. This CO₂ is usually high in purity, making it ideal for low-cost carbon capture. The captured CO₂ can then be reused in making polymers. Figure 5.1 shows the five identified carbon path dependencies in the plastic value chains.

Figure 5.1. Carbon Path Dependencies in Plastic Value Chains



Source: Authors, based on Bauer et al. (2022)

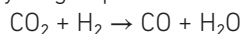
Achieving a fully carbon-neutral plastic ecosystem requires a holistic approach that addresses both inputs and outputs of carbon, energy sources, and systemic integration. This involves replacing fossil feedstocks with captured CO₂, powering all processes with renewable energy, capturing all emissions across the value chain, and circularity and system integration via recycling and reuse. Together, these four pillars form a closed-loop system where carbon remains in circulation, minimising environmental impact and aligning the plastic industry with long-term climate goals.

2.1. Key Chemical Pathways for Converting Captured CO₂ into Plastic Precursors

To decarbonise the plastic ecosystem, capturing and using CO₂ as a raw material in synthesising polymers is essential. The following section outlines the major chemical routes through which captured CO₂ is transformed into key monomers and polymers. Figure 5.2 shows the various routes for converting CO₂ into fuel linked to the discussion below:

CO₂ to syngas and olefins

Step 1: Reverse water-gas shift (RWGS) reaction: Captured CO₂ is reacted with hydrogen (preferably green hydrogen produced via renewable energy sources) to produce carbon monoxide (CO):



Step 2: Syngas formation: The CO produced from the RWGS reaction is combined with additional H₂ to form syngas (a mixture of CO and H₂).

Step 3: Fischer-Tropsch (FT) synthesis and polymerisation: Syngas undergoes FT synthesis to produce hydrocarbons, which can be further processed into olefins like ethylene and propylene. The olefins produced are polymerised to form plastics such as polyethylene (PE) and polypropylene (PP), which are widely used in plastics.

CO₂ to methanol-based routes

Methanol is a versatile platform chemical used to make olefins (ethylene, propylene) via methanol to olefins (MTO)

Step 1: Catalytic hydrogenation of CO₂ - $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$

Step 2: MTO process used for PE and PP production

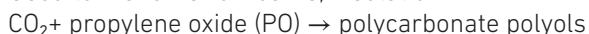


Ethylene and propylene are used to produce polyethylene (PE) and polypropylene (PP)

OR: methanol to acetic acid → polyethylene terephthalate (PET)

**CO₂ to polyols (for polyurethane [PU])**

Used to make PU for foams, insulation

**CO₂ to polyethylene terephthalate (PET)**

PET is primarily made from ethylene glycol (MEG) and terephthalic acid (PTA)

Path 1: CO₂ → methanol → ethylene glycol (MEG) → EG + PTA → PET

Path 2: CO₂ to ethylene oxide (EO) and then EO to MEG and then MEG + PTA → PET

CO₂ to ethylene (for polyethene [PE])

Path 1: Electrochemical route: $2\text{CO}_2 + 2\text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_4 \text{ (ethylene)} + 3\text{O}_2$

Ethylene is then polymerised into polyethylene (PE)

Path 2: Indirect route via methanol and MTO

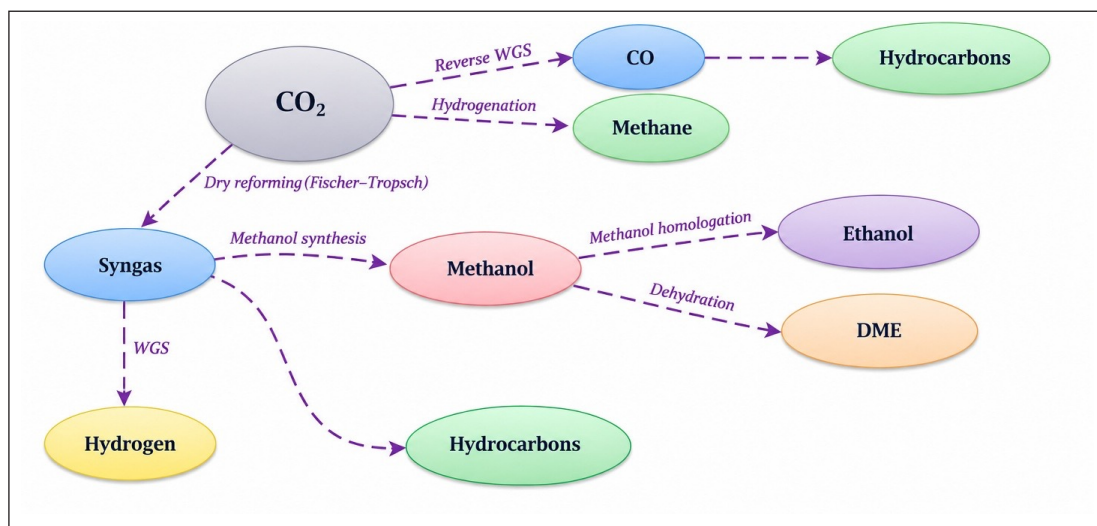
**CO₂ to polycarbonates – used in lenses, electronics, medical devices****CO₂ to formic acid derivatives (for polyamides, polyesters)**

Captured CO₂ can be converted into nylon, bio-based polymers such as polyethylene furanoate (PEF) and polyacrylamides.

CO₂ to polypropylene (PP)

Indirect route via methanol and MTO



Figure 5.2. Various Routes for Converting Carbon Dioxide into Fuel

CO₂ = carbon dioxide, DME = dimethyl ether, WGS = water-gas shift.

Source: Authors, based on Zhi et al. (2023).

CO₂ utilisation can play a supportive role by encouraging investment in capturing technologies and enabling early emissions reduction. However, it cannot substitute for CO₂ storage, which is essential for achieving large-scale and long-term climate goals. Due to its limited scale and temporary carbon retention, CO₂ use should be seen as a complement, not a substitute, to geological storage. International Energy Agency (IEA, 2019) scenarios consistently underscore the necessity of storage to meet long-term climate targets. A high-level assessment of CO₂ utilisation options indicates that while CO₂-derived fuels offer the greatest market potential, building materials provide the highest climate mitigation benefit due to low energy requirements and permanent carbon storage. However, in the near term, the market for CO₂-based products is expected to remain limited, constrained by small market sizes, geographic dependency, and regulatory barriers.

3. Estimating Decarbonisation Potential in ASEAN through Plastic Recycling

According to the Ellen MacArthur Foundation (Woolven, 2021), circular economy practices can cut plastic pollution in oceans by more than 80% and may save the world around US\$200 billion each year. Recycling plastics is crucial and a game-changer for sustainability. Recycling just 1 tonne of plastic can save about 3.8 barrels of crude oil and over 5,700 kilowatt-hours of energy. A study from 2018 also found that if we increased the global recycling rate of plastic packaging from 14% to 70%, we could cut carbon emissions by 3.5 million tonnes every year (Plastics For Change, 2024). While plastic recycling addresses post-consumer waste or reprocessing of plastic waste using mechanical or ChR, CCU focuses on capturing CO₂ emissions and converting them into raw materials for plastic production, effectively closing the carbon loop. Importantly, while CCU can be integrated with plastic recycling (e.g. by capturing CO₂ emissions from a recycling

facility) or with plastic production (by using CO₂ as a feedstock), they are fundamentally different processes. For instance, CO₂ emitted from incinerated or mismanaged plastics can be captured and reused to produce methanol, ethylene, or other plastic precursors. This offers an alternative decarbonisation pathway and also contributes to resource efficiency and climate mitigation by reducing fossil resources.

The plastic recycling efforts primarily focus on rigid plastics such as polyethylene terephthalate, (PET) high-density polyethylene, low-density polyethylene, and polypropylene (PP). In contrast, flexible plastics are either burned or dumped due to the lack of economic feasibility. A tiny fraction (1.5%) of plastics comes from renewable feedstocks, such as bio-based plastics made from sugarcane, cornstarch, or algae (Liu et al., 2024). This means recycling efforts are insufficient to replace virgin plastics. A circular economy approach, including CCU and chemical recycling, is necessary to reduce fossil fuel dependency on plastics and greenhouse emissions in the plastic sector. ChR is emerging as a key solution to address the growing plastic waste crisis in ASEAN, offering the potential to recycle plastics that are difficult to process mechanically.

Table 5.1. Plastic Recycling Rates in Selected ASEAN Member States

Member State	Plastic Recycling Rate (%)	PET Bottle Recycling Rate (%)
Indonesia	10	74
Malaysia	24*	55
Philippines	28*	35–65
Singapore	6	NA
Thailand	18*	31–62
Viet Nam	33*	45–65

ASEAN= Association of Southeast Asian Nations, NA = not available, PET = polyethylene terephthalate.

Note: * sign shows key plastic resin.

Sources: Azhar (2023); NEA (2023); World Bank (2021a, 2021b, 2021c, 2021d).

3.1. Waste-Based Estimation of Decarbonisation Potential in ASEAN’s Plastic Sector via CCU

The transition to a circular plastic economy requires innovative solutions to reduce dependency on fossil feedstocks and mitigate greenhouse gas emissions. This section evaluates the potential for CCU in ASEAN nations by analysing plastic waste generation and the feasibility of converting waste into value-added materials like PP, PE, and PET, using captured CO₂. These resins form the backbone of plastic consumption in ASEAN countries, making them ideal candidates for CCU-based interventions. Table 5.1 outlines plastic recycling rates in ASEAN Member States. Viet Nam shows the highest plastic recycling rate, followed by the Philippines, Malaysia, and Thailand. Singapore has the lowest plastic recycling rate. While in the PET bottle recycling rate, Indonesia leads followed by Malaysia, Viet Nam, and Thailand. Overall, it appears that there is a significant scope for plastic recycling and the deployment of different technologies, including CCU.

Table 5.2 provides the calculated CR/CCU potential for several ASEAN countries and their recycling potential (mechanical recycling +physical recycling) and leakage percentages (Bos, van Es, and Harmsen, 2024). The data for this are sourced from The Circulate Initiative website. The country that has the lowest plastic recycling rate (from Table 5.1) has the maximum CR and CCU potentials, Singapore (92.55%), followed by Thailand and Malaysia. However, leakage-wise, Indonesia shows the maximum leakage percentage (20%), followed by the Philippines (20%) and Viet Nam (15.4%). These numbers reveal the fact that despite plastic recycling potentials, there is an immense scope for CR and CCU, and plastic waste leakage could become a major source for CCU expansion and choice of technology. Plastic waste leakage refers to the portion of plastic generated that escapes waste management systems and channels into the environment (particularly waterways and oceans) because it is not channelled into a controlled end-of-life pathway. This leakage arises primarily from uncollected waste and mismanaged waste, such as plastics dumped in open sites, unsanitary landfills, or improperly disposed of through informal channels. While not renewable in nature, plastic recycling contributes to resource efficiency and climate mitigation by reducing fossil resources. These plastic streams do not undergo recycling, controlled incineration, or proper landfilling, and therefore have a high probability of leaking into natural ecosystems. Figure 5.3 highlights the leakage pathways of plastic waste, showing how uncollected and mismanaged waste streams contribute to environmental leakage, particularly into waterways and the ocean. The recycling rate in ASEAN countries is relatively low, so CR/CCU technologies can address a large portion of plastic waste that has not been recycled or leaked into the environment. To assess decarbonisation opportunities, we calculated the CR/CCU potential using the following equations 1 and 2.

Table 5.3 provides the leakage data for the six ASEAN countries collected from The Circulate Initiative (2025). The leakage percentage is calculated using equation 2 for countries except Indonesia and the Philippines, whose leakage percentages were already given:

$$RP_{CR+CCU}[\%]=100[\%]-Leakage[\%]-RP_{MR+PR}[\%] \quad (1)$$

$$Leakage\% = \text{plastic waste leakage} / \text{plastic waste generated} \quad (2)$$

We find that volume-wise, the maximum leakage is observed for Indonesia (2 metric tonnes per year (Mt/year), followed by the Philippines and Viet Nam. In context, it appears that the countries that have one of the highest plastic recycling rates also exhibit the maximum quantity of plastic recycling leakages. The possible explanation could be a lack of recycling technology options available. Surprisingly, these countries also offer limited CR/CCU deployment potential as compared to other nations. For instance, Singapore offers the maximum CR/CCU potential but has the lowest recycling rate and leakage. These observations are relevant because CR/CCU deployment potentials require high capital, recycling infrastructure, and energy efficiency.

In Table 5.4, we estimate the decarbonisation potential by calculating the CR/CCU percentage based on recycling infrastructure, collection efficiency, and plastic leakage. By applying the CR/CCU percentages to total national plastic waste generation (in Mt/year), we estimated the volume of plastic that could be reused or recycled using CCU technologies. This gives the CR/CCU plastic potential, the volume of plastic that could be captured or reproduced using carbon-neutral technologies. For example, Indonesia could reuse up to 5.23 Mt of plastic (67% of its total), while Thailand and Malaysia could decarbonise 4.01 Mt and 2.26 Mt, respectively. We adopt a waste-based estimation method, which focuses on the supply of available plastic waste rather than market demand. It aligns with circular economy principles by aiming to reduce plastic leakage and promote the recovery and reuse of post-consumer plastic waste into value-added products.

While mechanical recycling deals with reprocessing solid plastic waste, our model explores an indirect but circular route through CCU. In scenarios where plastic waste left after recycling and leakage is incinerated or thermally decomposed, the resulting CO₂ emissions can be captured and utilised as feedstock in CCU technologies. Captured CO₂ can then be used to produce critical monomers such as methanol, ethylene glycol, and propylene, amongst others. These monomers serve as precursors to plastics like PET, PE, and PP. Thus, plastic waste indirectly contributes to new plastic production via CCU, forming a closed-loop system that decouples production from fossil feedstocks. This approach prioritises environmental waste management over market substitution.

Table 5.2. Carbon Recycling/Carbon Capture and Utilisation Potential of ASEAN Member States

Countries	Recycling Rate%	Leakage %	CR/CCU potential
Indonesia	10%	23%	67%
Malaysia	24%	7.65%(C)	68.35%
Thailand	18%	6.32%(C)	75.68%
Singapore	6%	1.45%(C)	92.55%
Philippines	28%	20%	52%
Viet Nam	33%	15.4%(C)	51.60%

ASEAN = Association of Southeast Asian Nations, CCU = carbon capture and utilisation, CR = carbon recycling.

Note: C represents the authors' calculation.

Source: Author's analysis.

Table 5.3. Plastic Leakage Percentage in ASEAN Member States

Countries	Total Plastic Waste Generated (Mt/yr)	Plastic Leakage (Mt/yr)	Plastic Leakage (%)
Indonesia	7.75	2	23
Malaysia	3.32	0.25	7.65(C)
Thailand	5.31	0.34	6.32(C)
Singapore	0.96	0.013	1.45(C)
Philippines	2.7	0.54	20
Viet Nam	2.93	0.45	15.4(C)

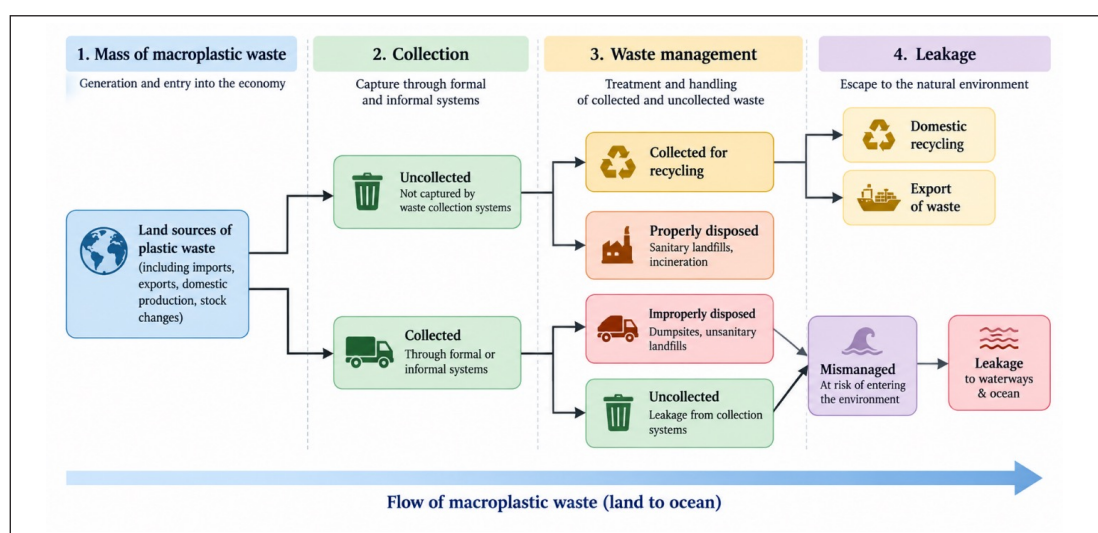
ASEAN = Association of Southeast Asian Nations, Mt/y = metric tonne per year.

Note: C represents the authors' calculation.

Source: The Circulate Initiative (2023).

Building on this, we construct a maximum substitution scenario, a modelling technique commonly used in environmental and techno-economic assessments to evaluate the theoretical maximum impact of alternative technologies. For example, in this scenario, we assume that 100% of the identified CR/CCU plastic potential is met by PP production via CO₂-based production routes rather than conventional fossil-based production. Using a conversion factor of 6.28 tonnes of captured CO₂ required per tonne of PP produced, we estimate the total CO₂ capture required. This is compared against the conventional fossil-based PP pathway, which emits approximately 4.74 tonnes of CO₂-equivalent per tonne of PP. The difference between these two values represents the net atmospheric CO₂ reduction achievable under this scenario. This provides a clear and quantifiable assessment of the climate benefits that CCU can deliver when applied to plastic production. Moreover, it demonstrates how plastic waste streams can drive demand for CO₂-based production, supporting the development of a low-carbon, circular plastic economy.

Figure 5.3. Leakage Pathway at a Glance



Source: Authors, based on IUCN, UNEP, and Life Cycle Initiative (2021).

Table 5.4. Estimated Plastic Waste Generation and Carbon Recycling/Carbon Capture and Utilisation Potential by Volume in ASEAN Member States

Country	Total Plastic Waste Generated (Mt/yr)	CR/CCU Potential (calculated)	CR/CCU Plastic Potential (Mt/yr)
Indonesia	7.8	67%	5.23
Malaysia	3.3	68.35%	2.26
Thailand	5.3	75.68%	4.01
Singapore	0.95	92.55%	0.88
Philippines	2.7	52%	1.40
Viet Nam	2.9	51.6%	1.50

ASEAN = Association of Southeast Asian Nations, CCU = carbon capture and utilisation, CR = carbon recycling, Mt/y = metric tonne per year.

Source: Authors' analysis from The Circulate Initiative (2025).

3.1. Estimating Captured CO₂ Demand and Climate Benefits of CCU-Based Plastic Production

This section assesses the climate mitigation potential of CCU-based production of three widely used plastics in ASEAN: PP, PE, and PET using country-wise plastic waste data, CR/CCU potential, and plastic-specific CO₂ conversion factors.

Estimating captured CO₂ demand for CCU-based polypropylene production

Polypropylene was selected as a reference polymer due to its widespread industrial use and relatively high carbon content. Based on stoichiometric calculations adjusted for 50% conversion efficiency, approximately 6.28 tonnes of captured CO₂ are required to produce 1 tonne of PP (Please refer to Appendix, Section A5.1). There are two ways of making plastic polypropylene:

1. Conventional fossil-based pathway – this adds CO₂ into the atmosphere
2. Transformative solution – this uses captured CO₂ and locks it inside the plastic

Table 5.5. Carbon Dioxide Impact of Using Captured Carbon for Polypropylene Production in ASEAN

Country	Total Plastic Waste Generated (Mt/yr)	CR/CCU Potential%	CR/CCU Plastic Potential (Mt/yr)	Captured CO ₂ Needed for PP Production (Mt CO ₂ e)	Fossil Emissions from PP (Mt CO ₂ e)	Net Atmospheric CO ₂ Change (Mt CO ₂ e)
Indonesia	7.8	67	5.23	32.82	24.77	-8.05
Malaysia	3.3	68.35	2.26	14.16	10.69	-3.47
Thailand	5.3	75.68	4.01	25.19	19.01	-6.18
Singapore	0.95	92.55	0.88	5.52	4.17	-1.35
Philippines	2.7	52	1.40	8.82	6.65	-2.16
Viet Nam	2.9	51	1.50	9.40	7.09	-2.30

ASEAN = Association of Southeast Asian Nations, CCU = carbon capture and utilisation, CR = carbon recycling, Mt CO₂e = metric tonne of carbon dioxide equivalent, Mt/yr = metric tonne per year, PP = polypropylene.

Note: All figures represent annual estimates, i.e. the volume of plastic waste generated, CR/CCU potential, and CO₂ demand per year. CO₂ refers to only carbon dioxide. CO₂e (carbon dioxide equivalent) includes CO₂ plus other greenhouse gases (like methane, nitrous oxide) expressed in terms of their warming potential compared to CO₂. We assumed 1 tonne of captured CO₂ ≈ 1 tonne of CO₂e, with a pure CO₂ GWP = 1, to align with fossil emissions data and ensure consistent comparison in net CO₂ impact assessment.

Source: Authors.

Table 5.5 shows the CO₂ impact of using captured carbon for PP production in ASEAN countries, and it helps compare the climate impact of PP using captured CO₂ across six Southeast Asian countries. Column 5 (captured CO₂ needed) indicates the amount of CO₂ that must be captured and utilised to produce the estimated volume of PP via CCU. This reflects the CO₂ input required per country based on a conversion factor of 6.28 tCO₂ per tonne of PP. Column 6 (fossil emissions from PP) represents the amount of CO₂e emitted into the atmosphere if the same quantity of PP were produced through conventional fossil-based pathways. This is based on the Greenhouse Gas Index (GGI) of fossil PP, 4.74 tCO₂e/t PP. Column 7 (net atmospheric CO₂ change) shows the net impact on the atmosphere by subtracting the fossil emissions (column 6) from the CO₂ captured

and used (column 5). The negative values indicate a net reduction in atmospheric CO₂, meaning more CO₂ is captured and locked into products than fossil-based production would have emitted. These inferences indicate the role of CCU in reducing emissions as we require more captured carbon compared to the traditional fossil pathway, making it attractive for plastic recycling in a decarbonised manner.

Estimating captured CO₂ demand for CCU-based polyethylene production

Polyethylene is the world's most widely produced and used plastic, making it highly relevant for decarbonisation efforts in the plastic ecosystem. The GGI for fossil-based PE production is approximately 4.83 tonnes CO₂e per tonne of PE. Assuming a process efficiency of 50%, the amount of captured CO₂ required to produce 1 tonne of PE via CCU methods increases to 6.28 tonnes of CO₂ per tonne of PE (Please refer to Appendix, Section A5.2). Table 5.6 shows the CO₂ impact of using captured carbon for PE production in ASEAN countries. It helps to understand the net reduction in atmospheric CO₂, making CCU-based PE production a climate-positive strategy. All six countries studied show negative net atmospheric CO₂ change, indicating that the amount of CO₂ captured and utilised in PE production exceeds the emissions from conventional fossil-based production. These results underscore the strong decarbonisation potential of CCU-based PE pathways, especially in nations with high plastic waste and CR/CCU potential. Compared to PP, CCU shows a positive impact with improved net atmospheric change as compared to the fossil pathway and offers a long-term decarbonisation pathway. We find that in both (PP and PE), carbon capture helps absorb more carbon and hence enhances the net atmospheric change.

Table 5.6. Carbon Dioxide Impact of Using Captured Carbon for Polyethylene Production in ASEAN

Country	Total Plastic Waste Generated (Mt/yr)	CR/CCU Potential %	CR/CCU Plastic Potential (Mt/yr)	Captured CO ₂ Needed for PE production (Mt CO ₂ e)	Fossil Emissions from PE (Mt CO ₂ e)	Net Atmospheric CO ₂ Change (Mt CO ₂ e)
Indonesia	7.8	67	5.23	32.82	25.24	-7.58
Malaysia	3.3	68.35	2.26	14.16	10.89	-3.27
Thailand	5.3	75.68	4.01	25.19	19.37	-5.82
Singapore	0.95	92.55	0.88	5.52	4.25	-1.27
Philippines	2.7	52	1.40	8.82	6.78	-2.04
Viet Nam	2.9	51.6	1.50	9.40	7.23	-2.17

ASEAN = Association of Southeast Asian Nations, CCU = carbon capture and utilisation, CR =carbon recycling, Mt CO₂e = metric tonne of carbon dioxide equivalent, Mt/yr = metric tonne per year, PE = Polyethylene.

Source: Authors' analysis.

Estimating captured CO₂ demand for CCU-based PET production

Ethylene glycol (EG) is a key monomer in PET, and its conventional production contributes significantly to PET's total GGI, approximately 1.10 tonnes of CO₂e per tonne of PET. It appears that the CO₂-derived EG requires capturing approximately 0.97 tonnes of CO₂ per tonne of PET, assuming a 50% process efficiency (Appendix, Section A5.3). Table 5.7 shows the CO₂ impact of using captured carbon for PET production in ASEAN countries. For Indonesia, if we want to produce 5.23Mt of PET, we need EG = 0.97*5.23= 5.07Mt. Total GGI for PET is 5.54 tonnes CO₂e/tonne PET. In this analysis, we applied the CO₂ capture factor to each ASEAN country's CR/CCU

plastic potential to estimate the captured CO₂ required for EG replacement. While this strategy only addresses a portion of total PET-related emissions, it represents a practical and scalable pathway for emission reduction, especially in the near term. CO₂-based EG only addresses a fraction of the total emissions. The majority of emissions (about 56%) come from p-xylene, the precursor to purified terephthalic acid (PTA) (the other building block of PET), which is still fossil-based, so it is critical to invest in decarbonising this feedstock as well, either through CO₂ conversion pathways, biomass routes, or bio-aromatics.

Table 5.7. Carbon Dioxide Impact of Using Captured Carbon for Polyethylene Terephthalate Production in ASEAN

Country	Total Plastic Waste Generated (Mt/yr)	CR/CCU Potential %	CR/CCU Plastic Potential (Mt/yr)	CO ₂ Needed for EG Replacement (Mt CO ₂ e)	Fossil Emissions Avoided due to EG Replacement (Mt CO ₂ e)	Fossil Emissions from PET (Mt CO ₂ e)	Net CO ₂ Emissions (after EG replacement) (Mt CO ₂ e)
Indonesia	7.8	67	5.23	5.07	5.58	28.95	23.37
Malaysia	3.3	68.35	2.26	2.19	2.41	12.50	10.09
Thailand	5.3	75.68	4.01	3.89	4.28	22.22	17.94
Singapore	0.95	92.55	0.88	0.85	0.94	4.87	3.93
Philippines	2.7	52	1.40	1.36	1.50	7.78	6.28
Viet Nam	2.9	51.6	1.50	1.45	1.60	8.29	6.69

ASEAN = Association of Southeast Asian Nations, CCU = carbon capture and utilisation, CO₂ = carbon dioxide, CR = carbon recycling, Mt CO₂e = metric tonne of carbon dioxide equivalent, Mt/yr = metric tonne per year, PET = polyethylene terephthalate.

Source: Authors.

CO₂-based EG helps reduce greenhouse gas emissions but does not eliminate them. The Net CO₂ Emissions column shows climate impact after replacement: the values are lower than fossil emissions, indicating a positive climate benefit (Table 5.7).

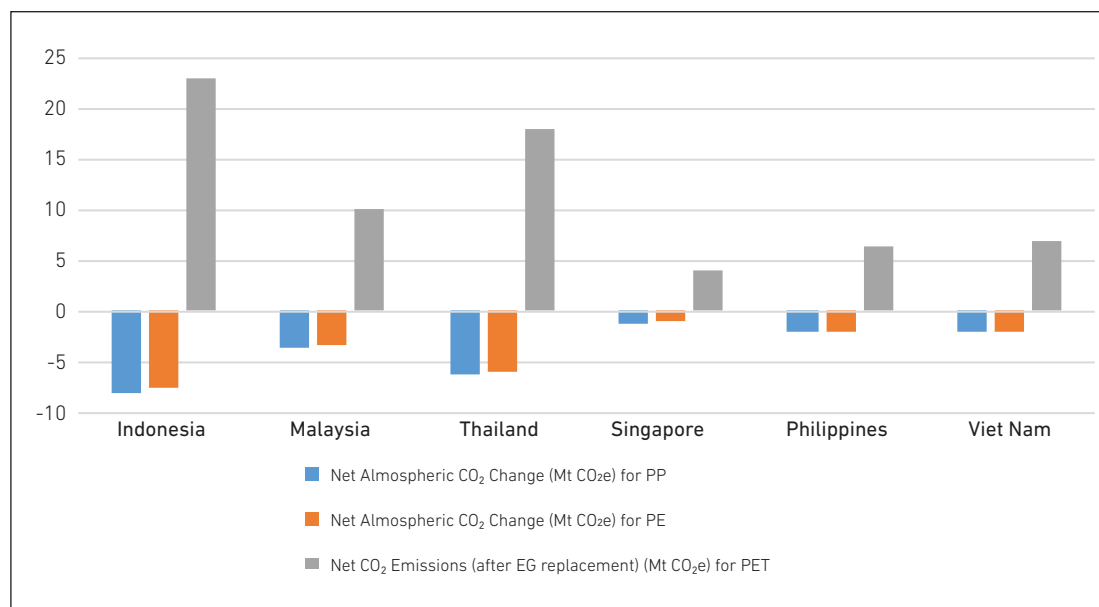
3.2. Market-based Scenarios for CCU Adoption in ASEAN's Plastic Sector (2025–2050)

To complement the CR/CCU potential analysis, this section provides an overview of plastic consumption estimates for key ASEAN Member States for 2023 (Table 5.8). Plastic consumption is used as a proxy for market demand, reflecting the total amount of plastic materials utilised within each country, including those used in packaging, consumer goods, construction, and other applications. In mature markets, consumption patterns reflect underlying economic demand. Indonesia, Thailand, and Viet Nam are the largest consumers of plastic. Since most plastics are used quickly and enter the waste stream, consumption closely reflects the real demand for plastic products in the market. While production and trade data may be used to estimate demand using the formula: *Consumption = Production + Imports – Exports*, such data are not consistently available

for all ASEAN countries due to inconsistent reporting of plastic production statistics, plastic products span multiple HS codes with varying reporting quality, re-export activities or complex trade flows, etc. Therefore, directly reported plastic consumption has been adopted here to ensure data uniformity and comparability.

Figure 5.4 illustrates the net atmospheric CO₂ impact of producing three major plastic types, PP, PE, and PET, across six ASEAN countries using CCU-based pathways. The negative values for PP and PE indicate net CO₂ reductions, where more carbon is captured and utilised than would be emitted through conventional fossil-based production. This shows the climate-positive potential of CCU technologies when applied to high-volume plastics. In contrast, PET exhibits positive residual emissions, even after replacing EG with a CO₂-derived alternative. This underscores that partial feedstock substitution is insufficient to fully decarbonise PET, given that many of its emissions originate from p-xylene (precursor to PTA). The chart shows that comprehensive feedstock decarbonisation is essential in achieving carbon neutrality in PET production.

Figure 5.4. Net Atmospheric CO₂ Impact of CCU-based Plastic Production in ASEAN (PP, PE, PET)



ASEAN = Association of Southeast Asian Nations, CCU = carbon capture and utilisation, Mt CO₂e = metric tonne of carbon dioxide equivalent, PE = polyethylene, PET = polyethylene terephthalate, PP = polypropylene.

Source: Authors.

Table 5.8. Plastic Consumption for ASEAN Countries

Country	Total Plastic Consumption (Mt/yr) for 2023
Indonesia	3.36
Malaysia	1.37
Thailand	3.35
Singapore	0.59
Philippines	0.93
Viet Nam	2.95

ASEAN = Association of Southeast Asian Nations, Mt/yr = metric tonne per year.

Data Methodology Note: The plastic waste generation figures presented in this study are sourced from the Circulate Initiative and correspond to different reporting years (ranging from 2021 to 2023), while the plastic consumption data is standardised for the year 2023, based on World Population Review estimates. This temporal mismatch may result in instances where waste generation appears higher than annual consumption. Additionally, plastic waste data may include delayed end-of-life disposal from durable goods, imported post-consumer plastic waste, and industrial residues, naturally inflating waste volumes, whereas consumption data typically captures current-year domestic usage. This explains the difference between the two figures.

Source: World Population Review (2025).

This section develops scenarios showing how CCU technology can become a viable substitute for conventional plastic production pathways. The analysis recognises that total market demand can be satisfied through three primary production routes.

1. Virgin plastic production (petroleum-based feedstock): Conventional plastic production from fossil feedstocks currently dominates the market, accounting for 85%-95% of total plastic supply across ASEAN countries.
2. Mechanical and ChR (post-consumer waste feedstock): Recycling technologies currently contribute less than 50% of the plastic supply, depending on the country.
3. CCU (CO₂ feedstock): Represents an emerging technology pathway currently in pilot and demonstration phases globally.

$$\begin{aligned}\text{Total Plastic} &= \text{Virgin} + \text{Recycled} + \text{CCU} \\ \text{Virgin} &= 100\% - \text{Recycled}\% - \text{CCU}\%\end{aligned}$$

3.3. CCU Market Penetration Scenarios (2030-2050)

Scenario 1: Conservative CCU adoption (1% market share): 2025–2030

This scenario reflects a conservative outlook for CCU integration in the plastics sector across ASEAN during the period 2025–2030 (Table 5.9). It assumes slow but emerging adoption of CO₂-based plastic technologies alongside marginal improvements in recycling systems. According to recent market projections, the global plastics market was valued at US\$712 billion in 2023 and is expected to grow to over US\$1,050 billion by 2033 (Statista, 2024). In parallel, the global CO₂-based plastics market was valued at US\$3.05 billion in 2024 and is projected to reach US\$8.80 billion by 2033 with a compound annual growth rate of 11.6% between 2025 and 2033 (IMARC Group, 2024). Based on these figures, CO₂-based plastics are projected to grow from approximately 0.5% to 0.8% of the global plastics market share by 2030. Therefore, this scenario conservatively sets the CCU-based plastic market share at 1% in ASEAN by 2030, representing a reasonable alignment with

global adoption trends under current technological and policy maturity. Virgin plastics are expected to continue dominating the market, comprising approximately 80%–90% of total plastic demand due to minimal regulatory pressure and the continued availability of low-cost fossil feedstocks. The allocation of plastic demand across virgin, recycled, and CCU-based sources is based on a realistic assessment of current trends, infrastructure limitations, and policy maturity. Recycling percentages in the conservative scenario have been increased by 2 percentage points from each country's current baseline percentages given in Table 5.2 to reflect modest improvements in waste management systems. Several barriers contribute to the conservative nature of this scenario. CO₂-derived plastics remain expensive compared to petroleum-based plastics, making them uncompetitive in price-sensitive ASEAN markets. Additionally, while the ASEAN Declaration on Plastic Circularity (2024) emphasises circular economy principles, it remains focused on traditional recycling and waste management rather than CCU-based production. Infrastructure and funding limitations also persist, with most CCU initiatives still in pilot phases and little investment flowing towards commercialisation. Overall, this scenario serves as a realistic baseline reflecting the early-stage development of CCU technologies in the region and provides a point of comparison for more progressive adoption pathways.

Table 5.9. Projected Plastic Demand Allocation under Conservative Scenario

Country	Total Plastic Consumption (Mt/yr)	Virgin (Mt/yr)	Virgin Plastic %	Recycled (Mt/yr)	Recycled Plastic %	CCU (Mt/yr)	CCU%
Indonesia	3.36	2.92	87%	0.40	12%	0.03	1%
Malaysia	1.37	1.00	73%	0.36	26%	0.01	1%
Thailand	3.35	2.65	79%	0.67	20%	0.03	1%
Singapore	0.59	0.54	91%	0.05	8%	0.01	1%
Philippines	0.93	0.64	69%	0.28	30%	0.01	1%
Viet Nam	2.95	1.89	64%	1.03	35%	0.03	1%

CCU = carbon capture and utilisation, Mt/yr = metric tonne per year.

Note: Recycling percentage for plastics is already given in Table 5.2.

Source: Authors.

Scenario 2: Moderate CCU adoption (2.5% market share) by 2040

This scenario reflects a balanced and practical outlook for improving plastic recycling across ASEAN by 2040 (Table 5.10). While ambitious environmental goals are important, this scenario focuses on setting achievable targets that consider the real-world challenges each country faces, such as available infrastructure, policy readiness, and economic conditions. It emphasises steady, measurable improvements rather than idealised outcomes. This scenario reflects a realistic yet progressively optimistic outlook for the integration of CCU technologies in the plastic sector across ASEAN by 2040, and a 2.5% CCU-based plastic market share is considered achievable under this scenario. Country-specific trajectories are outlined below to justify the moderate growth assumptions in both recycling rates and CCU integration across the region.

1. Indonesia

- Current plastic recycling baseline: 10%–15%
- Target plastic recycling by 2040: 25%
- ASEAN's largest economy with significant untapped recycling potential
- Aims for a 70% reduction in marine plastic leakage by 2025 and near-zero plastic pollution by 2040, under the National Plastic Action Partnership and National Marine Debris Action Plan.

2. Malaysia

- Current plastic recycling baseline: 24%
- Target plastic recycling by 2040: 40%
- Most comprehensive plastic sustainability roadmap in ASEAN
- 25% recycling rate for post-consumer plastic packaging by 2025, 76% plastic collection by 2030, and mandatory extended producer responsibility (EPR) by 2026

3. Thailand

- Current plastic recycling baseline: 18%
- Target plastic recycling by 2040: 33%
- Has the most ambitious plastic waste management framework in the region- 100% recycling of target plastic waste by 2027, with projected recycling and utilisation rates reaching 98.4% by 2030 under its roadmap, but only 32.3% under a business-as-usual scenario by 2030 (Kamsook et al., 2022).
- Plastic waste is required as fuel for incinerators, reducing the available recyclable volume

4. Singapore

- Current plastic recycling baseline: 6%
- Target plastic recycling by 2040: 12%
- CCU potential increases to 3.5% due to concentrated CO₂ sources from waste-to-energy (WTE) plants, its primary waste management strategy
- Land-constrained, high-density urban economy where quality-focused, technology-driven recycling takes precedence over volume-based approaches
- The Integrated Waste Management Facility, co-located with the Tuas Water Reclamation Plant, reflects Singapore's space-efficient, tech-integrated recycling model
- Singapore's land constraints and centralised CO₂ sources justify raising CCU adoption potential from 2.5% to 3.5%

5. Philippines

- Current plastic recycling baseline: 28%
- Target plastic recycling by 2040: 35%
- Dual performance: The Philippines demonstrates a 28% recycling rate for high-value plastic resins (PET, high-density polyethylene, low-density polyethylene, and PP), reflecting strong technical capability. However, the overall recycling rate remains at ~9%, highlighting systemic inefficiencies in waste collection and management. This gap indicates that a 40% recycling target by 2040 is realistic and achievable through improved infrastructure, supportive policies, and formalisation of the informal waste sector.
- The Philippines' EPR Act (2022) mandates producers to recover up to 80% of plastic by 2028, promoting circular economy practices

6. Viet Nam

- Current plastic recycling baseline: 33%
- Target plastic recycling by 2040: 45%
- Viet Nam became the first Southeast Asian country in 2022 to mandate packaging recycling and waste treatment responsibilities for producers and importers through a formal decree (Zorzi, 2023).
- The highest current baseline (33%) provides a solid foundation for recycled materials
- Targets a 50% reduction in marine plastic litter by 2025 and 75% by 2030 under the National Action Plan for Management of Marine Plastic Litter

Table 5.10. Projected Plastic Demand Allocation under Moderate Scenario

Country	Total Plastic Consumption (Mt/yr)	Virgin (Mt/yr)	Virgin Plastic %	Recycled (Mt/yr)	Recycled Plastic %	CCU (Mt/yr)	CCU%
Indonesia	3.36	2.44	72.5%	0.84	25%	0.08	2.5%
Malaysia	1.37	0.79	57.5%	0.55	40%	0.03	2.5%
Thailand	3.35	2.16	64.5%	1.11	33%	0.08	2.5%
Singapore	0.59	0.50	84.5%	0.07	12%	0.02	3.5%
Philippines	0.93	0.58	62.5%	0.33	35%	0.02	2.5%
Viet Nam	2.95	1.55	52.5%	1.33	45%	0.07	2.5%

CCU = carbon capture and utilisation, Mt/yr = metric tonne per year.

Note: Singapore was assigned a 3.5% CCU adoption rate, higher than the 2.5% baseline for other ASEAN countries

Source: Authors.

Scenario 3: Ambitious CCU adoption (5% market share)

This scenario envisions a high-level integration of CCU technologies in ASEAN's plastic sector by 2050, aligned with long-term climate goals and circular economy ambitions (Table 5.11). It assumes that significant advancements in policy, infrastructure, and industrial decarbonisation will enable CCU-based plastics to capture up to 5% of the total plastic market share across the region. We have assumed CCU adoption targets of 5% for ASEAN countries through EPR implementation, comprehensive collection system modernisation, and widespread deployment of advanced recycling technologies, including ChR for complex materials and 6% for Singapore by 2050. While most countries improve material recovery, Singapore is treated as a special case, with a lower recycling rate (20%) but greater reliance on CCU due to its WTE infrastructure and space constraints. This scenario reflects a forward-looking vision where CCU complements recycling in achieving a low-carbon, resource-efficient plastic economy in ASEAN. The 25-year development cycle from 2025–2050 provides sufficient time for CCU technology cost reduction, economies of scale through regional co-operation, and integration with expanding manufacturing infrastructure across ASEAN's petrochemical and industrial sectors. Carbon pricing mechanisms across ASEAN make CCU economically competitive with traditional disposal. This ambitious yet feasible pathway is assumed under full implementation of national roadmaps, strengthened EPR frameworks, and sustained investment in formal recycling infrastructure, including material recovery facilities and advanced recycling technologies that position ASEAN as a global model for technology-driven plastic waste management. Given that most ASEAN countries have set national roadmaps and

regional commitments targeting 100% recycling or reuse of key plastics by 2025–2030, it is reasonable to project that, with sustained policy enforcement and investment, achieving a 50% overall plastic recycling rate by 2050 is ambitious yet achievable for the region.

Figure 5.5 shows a heatmap for different scenarios to showcase the effectiveness of CCU adoption and plastic recycling. Given 1% adoption of CCU in plastic recycling, we find that by 2025–2030, Thailand and Viet Nam are the major beneficiaries of CCU integration to plastic recycling, except Singapore, due to its several advanced initiatives. By 2050, with the integration rate of 5%, Indonesia, Thailand, and Viet Nam will be more carbon neutral than Malaysia. Overall, carbon capture seems to have a positive impact on plastic recycling in a decarbonised manner.

Figure 5.5. Heatmap of Three Scenarios for Recycled Plastic and CCU in Volume

Country	Plastic Recycled (Mt/yr)			CCU (Mt/yr)		
	2025-2030	2040	2050	2025-2030	2040	2050
Indonesia						
Malaysia						
Thailand						
Singapore						
Philippines						
Viet Nam						

CCU = carbon capture and utilisation, Mt/yr = metric tonne per year.

Note: The figure shows the volume of recycled plastic and CCU in Mt/year. The heatmap is prepared using CCU adoption of 1% (scenario 1), 2.5% (scenario 2), and 5% (scenario 3) for 2025–2030, 2040, and 2050, respectively. A heatmap can be read as a transition from yellow to green colour, which shows the movement from low to high numbers. In this context, green implies a stronger impact.

Source: Authors.

Table 5.11. Projected Plastic Demand Allocation under Ambitious Scenario

Country	Total Plastic Consumption (Mt/yr)	Virgin (Mt/yr)	Virgin Plastic %	Recycled (Mt/yr)	Recycled Plastic %	CCU (Mt/yr)	CCU%
Indonesia	3.36	1.51	45%	1.68	50%	0.17	5%
Malaysia	1.37	0.55	40%	0.75	55%	0.07	5%
Thailand	3.35	1.51	45%	1.68	50%	0.17	5%
Singapore	0.59	0.44	74%	0.12	20%	0.04	6%
Philippines	0.93	0.42	45%	0.47	50%	0.05	5%
Viet Nam	2.95	1.18	40%	1.62	55%	0.15	5%

CCU = carbon capture and utilisation, Mt/yr = metric tonne per year.

Note: Singapore was assigned a 6% CCU adoption rate, higher than the 5% baseline for other ASEAN countries.

Source: Authors.

4. Cost Analysis of Plastic Recycling and CCU Integration

This section evaluates recycling methods, their economic feasibility, and integration with CCU technologies. It also examines the waste plastic recollection systems, including policy frameworks, regulations, and financial incentives that drive recycling and CCU adoption in ASEAN.

4.1. Overview of Plastic Recycling and CCU Technologies

Table 5.12 gives an overview of key plastic waste treatment and carbon capture technologies, focusing on their cost and challenges. It highlights that while mechanical recycling is cost-effective, it faces issues with contamination and quality. ChR, though capable of handling mixed plastics, is costly and energy-intensive. ChR and CCU integration could help, but we need investment to lower costs.

Table 5.12. Cost and Challenge Comparison of Plastic Waste Treatment Technologies

Process	Cost	Key Challenges
Mechanical Recycling	US\$50 to US\$200 per ton of plastic (Herrmann and Flock, 2024)	Contamination, quality degradation
Chemical Recycling	US\$300 to US\$1,000 per ton of plastic (Herrmann and Flock, 2024)	High energy demand, complex infrastructure
Direct Air Capture	US\$400– to US\$800 per tonne of CO ₂ (Mukherjee and Chatterjee, 2022)	- Energy-intensive - High capital costs
Incineration	US\$80 to US\$102 per ton (Ng et al., 2023)	CO ₂ emissions

CO₂ = carbon dioxide.

Source: Author.

4.2. Economic Challenges and the 'Cost Gap' in CCUS

Despite increasing climate awareness, the adoption of carbon capture and storage (CCS) and CCU in Southeast Asia is hindered by high costs, insufficient infrastructure, and weak carbon pricing mechanisms.

According to a McKinsey Report (2025) analysis on CCS in Southeast Asia (McKinsey & Company, 2025), The total cost of CCS in the region ranges from US\$60 to US\$120 per tonne of CO₂, depending on factors such as CO₂ purity, transportation distance, and the geological complexity of storage sites. This cost can rise as high as US\$150 per tonne in suboptimal conditions. In harder-to-abate sectors like cement, steel, and refineries, capturing CO₂ is more expensive mainly because the CO₂ is more diluted and harder to extract. So, if it costs US\$150/tonne to store CO₂ in these industries, but carbon pricing only offers US\$60/tonne as announced by Singapore, there is a 'cost gap' of

up to US\$90 per tonne. This means that companies will have to absorb those additional costs independently, making CCS less appealing unless there are subsidies or incentives to help.

One of the key barriers to adopting CCS in Southeast Asia is the mismatch between the high cost of CCS and the low regional carbon prices. While Singapore has announced plans to increase its carbon price to approximately US\$60 per tonne by 2030, other countries like Indonesia currently charge as little as US\$5 per tonne for emissions in sectors such as coal-fired power generation. According to the McKinsey Report (2025), for CCS to work without subsidies, carbon prices need to reach about US\$75 to US\$100 per tonne. This big cost difference makes it hard for industries to adopt CCS technology unless we see stronger policy support and better carbon pricing.

A major challenge in making CCS more affordable is that most of the cost, about 70%, comes from the CO₂ capture process. At present, the most common method uses amine solvents to absorb CO₂ from industrial emissions. This technology is already in its mature stage, and its deployment cost cannot be reduced further. The alternate capture technologies, like cryogenic separation (which freezes out CO₂), are available, but their deployment and operational costs are higher than amines. Indonesia and Malaysia have many depleted oil and gas fields (Kuttan and Khaing, 2025). These spaces are called 'sinks' in CCUS and are ideal for storing captured CO₂ underground for a longer duration. This gives them a unique advantage in supporting regional CCUS efforts, especially for countries like Japan, the Republic of Korea, and Singapore, which have limited storage options. However, the total cost of cross-border CCUS is currently very high (US\$141 to US\$271 per tonne of CO₂), while carbon prices in the region are much lower, only US\$2 to US\$18 in Japan, the Republic of Korea, and Singapore, and just US\$1 in Indonesia. Since many Southeast Asian countries have no carbon pricing, strong government support and funding will be needed to make these CCUS projects financially viable.

4.3. Case Study: Indonesia's Role in Cost-effective CCUS Deployment in ASEAN

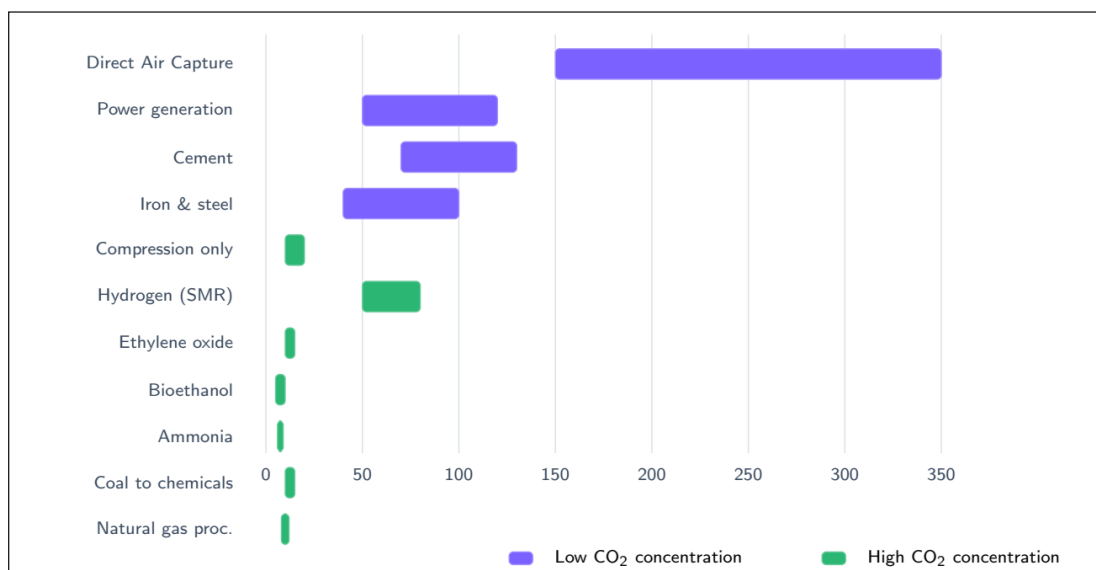
In a model CCUS project evaluated by the Economic Research Institute for ASEAN and East Asia (ERIA, 2021a), a coal-fired power plant in Central Java, Indonesia, was selected for retrofitting with CO₂ capture, with the captured emissions transported 50 kilometres via onshore pipeline to a depleted oil and gas field in Blora Regency for geological storage. The study reported that the unit cost of CCS projects in an ASEAN country is approximately US\$63/t-CO₂, with CO₂ capture accounting for 73% of the cost, storage for 25%, and transportation for only 2%, highlighted in Table 5.13. Indonesia has been identified as a strategic focal point for CCUS deployment in Southeast Asia due to its unique combination of high CO₂ emissions, dense energy infrastructure, and abundant onshore storage capacity. As the largest CO₂ emitter in the ASEAN region, Indonesia, particularly Java Island, hosts many coal-fired power plants and existing oil and gas infrastructure, making it an ideal location for cost-effective, scalable CCUS projects. However, in other ASEAN countries where cross-border shipping, offshore storage, or longer pipelines are needed, costs can rise dramatically (up to US\$270/tonne).

Table 5.13. Cost Breakdown Ratio by Component

	Capture	Transportation	Storage
US\$/per tonne CO ₂	45.92	0.95	15.93
%	73.12	1.52	25.36

Source: Kimura et al. (2022).

Figure 5.6 illustrates the wide variation in the levelised cost of CO₂ capture across sectors, largely influenced by the initial CO₂ concentration in emissions streams. Sectors with high-concentration CO₂ sources, such as ethanol production, ammonia, and natural gas processing, can capture carbon at a relatively low cost of US\$15 to US\$25 per tonne. In contrast, industries with dilute CO₂ streams, such as cement, power generation, and iron & steel, face higher capture costs of US\$40 to US\$120 per tonne. The most expensive method is DAC, ranging from US\$150 to more than US\$300 per tonne, due to the extremely low concentration of CO₂ in ambient air. These differences emphasise the importance of sector-specific strategies for cost-effective CCUS deployment.

Figure 5.6. Levelised Cost of Carbon Dioxide Capture by Sector and Initial Carbon Dioxide Concentration, 2019

 CO₂ = carbon dioxide, SMR = steam methane reforming.

Source: IEA (2020).

5. Plastic Waste Recollection Systems in ASEAN

Plastic waste in ASEAN can be classified into various streams, including municipal solid waste, single-use plastics, microplastics, recyclable plastics, marine plastics, biodegradable plastics, and emerging waste streams like healthcare and e-waste. ASEAN is one of the most significant contributors to global plastic waste, with single-use plastics making up a significant portion of the region's plastic waste stream. Microplastics, originating from degradation and specific uses, contribute significantly to environmental pollution, particularly in densely populated coastal areas. Each year, 5 to 13 million metric tonnes of plastic waste enter the oceans, harming marine ecosystems, wildlife, and coastal communities. The ASEAN-6 economies: Indonesia, Malaysia, Thailand, Singapore, the Philippines, and Brunei Darussalam, together with China contribute significantly to oceanic plastic pollution. Table 5.14 provides a comparative snapshot of waste management performance across six ASEAN countries in 2015, highlighting disparities in waste generation, collection rates, recycling, and disposal methods.

Table 5.14. Waste Management Statistics across ASEAN Countries in 2015

Indicator	Indonesia	Malaysia	Philippines	Singapore	Thailand	Viet Nam
Population (million)	259.9	30.3	100.9	5.5	67.9	91.7
Waste generation (tonnes/year)	22,500,060	10,680,000	14,400,000	7,670,000	26,850,000	12,800,000
Per capita waste generation (kg/person/day)	0.24	0.97	0.39	3.8	1.08	0.38
Source segregation (%)	<50	<51	50–70	<70	<50	<50
Collection rate (%)	56–75	>70	40–90	>90	>80	80–82
Reused or utilised (%)	7	NA	NA	NA	17.8	NA
Recycling (%)	7	5	28	47	14	8.2
Composting (%)	–	1	NA	0	10	NA
Incineration (%)	NA	NA	NA	39	5	5.4
No. of incineration plants	NA	4	NA	4	3	NA
Sanitary landfill (%)	NA	NA	NA	15	NA	NA
No. of sanitary landfills	10	8	NA	1	91	17
Controlled landfill (%)	NA	NA	NA	0	NA	NA
No. of controlled landfill sites	70	10	273	0	20	91
Solid waste disposed (%)	84	93	65	0	70	NA
Other disposal (%)	9	6	5	8	1	NA

Note: NA = not accessible.

Source: Ng et al. (2023)

5.1. Disposal Pathways and Recycling Practices

Plastic waste pathways in ASEAN typically begin with generation at household and commercial levels (import, export, production), followed by collection through formal and informal systems. However, a significant portion remains uncollected, resulting in improper disposal practices such as open dumping. Properly managed waste is either recycled or safely disposed of in sanitary landfills or incineration plants, whereas mismanaged waste often leaks into waterways and eventually the ocean, contributing to environmental pollution.

Managing this plastic waste effectively requires a combination of methods suited to the region's infrastructure and economic capacity. Mechanical recycling is cost-effective and the most common and traditional method. Advanced (chemical) recycling methods allow for the recovery of high-quality materials and fuels but are capital-intensive and energy demanding. Some ASEAN countries utilise WTE processes (incineration), where plastic waste is incinerated to generate electricity. While this method reduces the volume of waste, it faces challenges such as high capital costs (around US\$80 to US\$102 per tonne) and environmental concerns. Many ASEAN countries rely on informal waste pickers and recycling networks to collect and sell recyclable plastics, which is significant in plastic waste management. Southeast Asian countries use landfills, sanitary landfills, incineration, and composting for plastic waste disposal. Incineration and sanitary landfills are commonly used waste disposal methods in ASEAN, but both come with high costs and sustainability challenges. Sanitary landfills, which offer a more controlled disposal, are around US\$10 to US\$45 per tonne (Ng et al., 2023) and are increasingly reaching capacity limits due to the overwhelming amount of waste generated daily. Open dumping and open burning are still common in many ASEAN countries.

Singapore serves as an outlier amongst ASEAN nations, boasting a robust and systematic waste management framework. Given its severe land constraints, the city-state primarily adopts WTE incineration as its dominant waste disposal solution. According to an analysis by Bain & Company in Southeast Asian countries with high plastic demand, such as Indonesia, Thailand, and Viet Nam, only 8%–10%, 15%–20%, and 20%–25% of plastic waste in major urban areas, respectively, is captured for recycling (Bain & Company, 2024). Adding to the challenge, the total cost of collection and sorting due to multiple handling stages can be 1.5 to 2 times higher than the value of the raw plastic waste itself. This cost burden poses a major barrier, as brand owners are often reluctant to pay a premium despite setting ambitious sustainability targets. Waste collection rates in Southeast Asia range from 76% to 100%, but the system remains inefficient due to an overreliance on the informal sector. The region's PET collection landscape is split into two main areas: formal recyclers, who account for only about 2% of PET collection, and the informal sector, which is responsible for approximately 97%. There also exist high costs and competition with virgin plastic. For example, recyclers in countries like Thailand often pay a premium to import post-consumer PET from countries such as Japan, Australia, and New Zealand. This imported PET is preferred because it is cleaner and better segregated compared to domestic PET. Virgin PET (new plastic) has become cheaper because energy prices have dropped, and recycled PET is more expensive to produce; manufacturers often choose cheaper virgin PET instead, as recycled PET becomes less profitable, increasing plastic pollution. These challenges make it difficult for local recycling industries to thrive, highlighting the urgent need for improved formal collection systems, better waste segregation practices, and economic policies that level the playing field between virgin and recycled plastics.

5.2. ASEAN Policies and Regulations on Plastic and Carbon Recycling

ASEAN Member States are increasingly focused on transitioning towards a circular and low-carbon economy. They have adopted a mix of national and regional policies to tackle plastic pollution and promote carbon recycling, including CCU. Governments in ASEAN have implemented various rules, policies, and governance frameworks to address the plastic waste crisis and advance carbon recycling. While plastic waste has received significant regulatory attention, carbon recycling and CCU are gaining momentum as part of climate and industrial strategies.

Policies and governance on plastic waste

1. The ASEAN Declaration on Plastic Circularity aims to promote sustainable plastics and reduce plastic waste, particularly by reducing the use of single-use, avoidable, and problematic plastic products.
2. The ASEAN Regional Action Plan for Combating Marine Debris in the ASEAN Member States (2021–2025) addresses the issue of marine plastic pollution in ASEAN from 2021–2025.
3. Several ASEAN countries have banned single-use plastics (e.g. plastic bags, straws, and cutlery), in several cities in the Philippines, in Bali, Indonesia, amongst others.
4. Thailand's Roadmap on Plastic Waste Management 2018–2030 is a framework and direction for preventing and correcting Thailand's plastic waste problem.
5. Malaysia's Roadmap Towards Zero Single-Use Plastics 2018–2030 promotes the use of eco-friendly alternatives to single-use plastics.
6. Viet Nam's National Action Plan for Management of Marine Plastic Litter. By 2030, the plan sets targets for a 50% reduction in marine plastic litter by 2025, increasing to 75% by 2030.
7. Singapore's Zero Waste Master Plan aims to increase the national overall recycling rate to 70% and reduce waste-to-landfill per capita per day by 30% by 2030.

Advancing carbon recycling and CCU in ASEAN

ASEAN's push for carbon neutrality has brought carbon capture, utilisation, and recycling into focus. Regional strategies and national policies are now explicitly supporting the development of CCU technologies, infrastructure, and finance mechanisms.

ASEAN strategy for carbon neutrality

ASEAN has identified eight strategic pillars, each targeting a specific area critical for regional decarbonisation and sustainable development, and to operationalise its carbon neutrality vision (ASEAN, 2023).

1. Accelerate Green Value Chain Integration: Greenification of the manufacturing value chains, enable ASEAN-based biofuel feedstock pathways for global markets, support CCS/CCUS infrastructure
2. Regional Circular Economy Supply Chains: Upgrade the ASEAN Trade in Goods Agreement (ATIGA) to include circular products
3. Connect Green Infrastructure and Market: Enable multilateral power trading, standardise electric vehicles, hydrogen, and flex-fuel transport infrastructure
4. Interoperable Carbon Markets: Develop a regional monitoring, reporting, and verification system and enable seamless export of carbon credits
5. Credible and Common Standards: Develop taxonomies Carbon credits, taxonomies
6. Attracting and Deploying Green Capital: Adoption of ASEAN Sustainable Finance Taxonomy, Promote green/sustainability-linked bonds, sukuk

7. Green Talent Development and Mobility: Develop a regional green skills taxonomy
8. Green Best Practice Sharing: Share best practices on the development of sustainable infrastructure

The ASEAN Common Carbon Framework promotes a unified regional carbon market to drive high-quality carbon credit development, support Malaysia's net-zero goal, build carbon market expertise, and enable cross-border collaboration for efficient, equitable climate action (ASEAN Business Advisory Council, 2024). The November 2020 ASEAN Plan of Action for Energy Cooperation marks a significant step for Southeast Asia, as it calls for optimising the role of CCUS alongside clean coal technology in supporting a low-carbon economy.

National CCUS frameworks and projects

1. Singapore aims to achieve net-zero emissions by 2050, leveraging a rising carbon tax (up to US\$80/tCO₂e by 2030), positioning itself as a regional hub for CCUS expertise and carbon trading, and targeting 2 Mt CO₂ capture by 2030 to decarbonise Jurong Island, supported by regional storage and cross-border CO₂ transport collaborations (ERIA, 2021b).
2. Indonesia's Ministry of Energy and Mineral Resources Roadmap targets 6 Mt CO₂ captured by 2030, scaling to 190 Mt CO₂/year by 2060, and plans 16 CCUS projects operational by 2030 in Indonesia (ERIA, 2021b).
3. Indonesia's The Future is Circular initiative promotes a circular economy across five key sectors, achieving US\$30 million in cost savings, 14,270 jobs, and over 1.4 Mt CO₂e reduction, with plans to develop targeted policies based on principles like reduce, reuse, recycle, and recover (ERIA, 2021c).
4. Indonesia leads ASEAN in full-chain CCUS with flagship projects like Gundih (EGR) and Sukowati (CO₂-EOR), showcasing its technical and regulatory progress in industrial carbon capture (ASEAN Centre for Energy, 2024).
5. Indonesia leads ASEAN in full-chain CCUS with flagship projects like Gundih (EGR) and Sukowati (CO₂-EOR), showcasing its technical and regulatory progress in industrial carbon capture (ASEAN Centre for Energy, 2024).
6. Malaysia's Carbon Capture, Utilisation and Storage (CCUS) Agency, established under the CCUS Act, plays a crucial role in regulating and overseeing CCUS activities in Malaysia (ERIA, 2021b). The Green Plan 2030 pillar aims to make Singapore a leading centre for green finance, carbon services, and sustainability solutions for the region (Global Compliance News, 2025).
7. Viet Nam's 2022 circular economy plan (Decision No. 687/QD-TTg) focuses on green growth, innovation, and stronger, more resilient businesses working towards a greener economy, carbon neutrality, and fighting global warming.
8. In March 2023, Chiyoda Corporation and Pertamina signed a Joint Study Agreement to develop carbon recycling technology in Indonesia, focusing on CO₂ reforming of methane and CCU applications in high-CO₂ upstream fields to produce value-added chemicals, supporting Indonesia's net-zero emissions target by 2060 (Indian Chemical News, 2023).

5.3. Financial and Market Incentives

ASEAN's climate and recycling strategy is reinforced by a growing ecosystem of financial regulations and sustainable investment frameworks that promote recycling and carbon reduction.

1. Several ASEAN countries have introduced EPR frameworks or are in the process of developing them. It is a policy approach that holds producers accountable for the entire lifecycle of their products, including post-consumer waste management. The ASEAN Framework on Circular Economy promotes EPR as a key strategy for achieving a circular economy in the region. For example, the Philippines' Extended Producer Responsibility Act requires companies to increase their recovery rate for plastic packaging by 20% annually, reaching 80% by 2028.
2. Deposit-Refund Schemes: A system where consumers pay a small upfront deposit on beverage containers, refunded when they return empty containers for recycling. For example, Singapore's Beverage Container Return Scheme aims to increase the recycling rate of beverage containers and reduce carbon emissions (NEA, 2024a). Also, in many countries in Southeast Asia, reverse vending machines offer rewards for returning rigid plastic containers. Southeast Asia can also learn from countries like the UK, where pilot projects for flexible plastic recycling are supported by the government and businesses (Luedi, Wu, and Mekmasin, 2024).
3. Several ASEAN countries have implemented bans and taxes on waste imports. Thailand has stopped importing plastic waste to curb toxic pollution in the country. Malaysia has imposed import duties and restrictions on plastic waste to reduce imports and promote local recycling. Indonesia plans to ban plastic waste imports completely starting in 2025. For example, GTFS 2.0 also offers financial support introduced by the government to support the development of green technology in Malaysia (Malaysian Green Technology and Climate Change Centre, 2023). In 2020, Indonesia introduced a plastic bag tax, which requires retailers to charge customers a fee for plastic bags. Singapore's carbon tax is set at SG\$25 (about US\$18.5) per tonne of CO₂ equivalent for 2024 and 2025 (NEA, 2024b). Indonesia aims to give recycling industries fiscal incentives, such as lowering the value-added tax (VAT) from 10% to 5% for recycling businesses (ERIA, 2022).
4. Green bonds and sustainability-linked bonds to finance a wide range of environmental projects, and the ASEAN Green Bonds Standards, which help capital markets in the region to access green financing, supporting sustainable development

Governments can support plastic circularity by reducing capital and operating costs through grants, tax exemptions, and simplified regulations. They also boost revenue by creating demand via green procurement, offering incentives for recycled products, and discouraging single-use plastics through penalties or taxes.

5.4. CCU Deployment and Technology Readiness Levels (TRLs) in ASEAN

The pathways of TRLs in CCU deployment are seen in the following ways. First, CO₂-to-methanol/urea is at TRL (6–8) in Malaysia and Indonesia, and these projects are at pilot stage; the expected commercialisation timeline is 2028–2035. Second, CO₂-to-mineralisation (cement concrete, TRL 7–9), early deployment is scheduled in Singapore and Viet Nam. Third, CO₂-to-synthetic fuels (e-fuels, TRL, 4–6) is at the research stage in Singapore. Fourth, algae-based CO₂ utilisation (TRL 4–6) is at the demonstration stage with an expected commercialisation timeline of 2028–2038 in Thailand and Indonesia. Fifth, CO₂-to-mineral carbonation (TRL 6–7) is getting pursued in Indonesia and the Philippines, and it is at the research and pilot phase, with an expected commercialisation timeline of 2028–2035. Sixth, CO₂-to-building materials (TRL 7–9) is at the trials stage in Viet Nam and Malaysia with a full commercialisation timeline of 2025–2030.

Besides, some of the crucial CCU pathways to scale in ASEAN have the following timelines:

2025–2030	CO ₂ -to-urea/methanol, building materials, mineralisation
2030–2040	CO ₂ -to-polymers, advanced cement carbonation, algae-based CCU
2040–2050	CO ₂ -to-carbon nanotubes, CO ₂ -to-e-fuels, full-scale synthetic fuels

However, the major CCU deployment challenge appears to be sustainable fuel (hydrogen unavailability), low carbon prices, limited infrastructure (pipelines and transportation networks), and a lack of clarity in CCU deployment regulations.

CCU deployment and public perception and societal license to operate (SLO)

CCU deployment to a large extent depends upon the public perception and SLO (Kimura et al., 2022; Deonandan et al., 2024). SLO has become an industry lexicon, and in the context of CCU, public perception depends on public awareness about CCU in technology and sustainability, supported through government campaigns and media. For instance, Singapore has invested a lot in public awareness of CCU compared to other nations. The acceptance of CCU is dependent on the local conditions, such as local pollution, jobs, and construction. Some of the useful solutions could be the adoption of a co-benefit model, educational campaigns, and symmetric communication with society. In the case of plastic recycling and the CCU pathway, public outreach through campaigns and educational engagements may help increase awareness and trust and reduce the 'not in my backyard' (NIMBY) attitude of communities. On public perception, another key dimension is the perceived need for and safety of the technology, and the amount of attention given to participatory decision-making processes (Jin, Wood, and Seiler, 2015).

Key risk for investors in CCU deployment in ASEAN

Although CCU integration with plastic recycling seems viable and environmentally friendly, there are risk factors associated with CCU deployment in ASEAN:

- (i) One of the key risk factors for investors includes a lack of a clear roadmap, and in this regard, ASEAN countries, except Singapore, do not have a proper regulatory architecture to create a balance amongst various stakeholders.
- (ii) Scale-up challenge, especially in the case of CO₂-to-fuels, algae-based utilisation, and chemical conversion. Many projects are at less than TRL 7, lack performance, and have reliability issues (ASEAN Centre for Energy & Japan Carbon Frontier Organization, 2024).

(iii) Missing connection between producers and long-term buyers: CCU-based concrete or methanol faces problems with long-term buyers due to product standards and a lack of a proper business model in ASEAN countries (Kimura et al., 2022).

(iv) Carbon price risk, highly volatile carbon prices and geopolitical risk are likely to adversely impact the CCU project, as most carbon credits are not treated at par with other carbon credits in the voluntary carbon market.

(v) Some countries like Indonesia, Viet Nam, and the Philippines do not have proper carbon infrastructure to encourage carbon capture activities. Overall, there is still tremendous scope to integrate CCU with plastic recycling as the value of carbon credits will be even higher, and supply chain additions may further expand the market for carbon-based materials.

6. Conclusions and Policy Recommendations

Plastics and carbon emissions are deeply interconnected challenges that require systematic, multi-sectoral responses. This chapter highlights how carbon lock-ins in production, market demand, and waste systems inhibit progress towards sustainability in ASEAN. To effectively tackle the dual challenges of plastic waste and carbon emissions in ASEAN, multi-level policy strategies should be followed:

(i) Mandate EPR across all ASEAN member states, with clear recovery and recycling targets.

(ii) Introduce a cap-and-trade system for carbon emissions – companies either reduce emissions or purchase carbon credits from cleaner firms, driving accountability and market-driven emission reductions.

(iii) Governments can integrate a plastic credit mechanism as a market-based policy to finance plastic waste collection and recycling, allowing companies to offset their plastic footprint, complementing EPR schemes and supporting informal sector inclusion.

(iv) A hybrid EPR–plastic excise tax model can be implemented to reduce carbon emissions. Producers either participate in formal EPR or pay a tax based on plastic volume introduced to the market. Allow tax offsets for certified EPR contributions made by producers to incentivise sustainable practices.

(v) Mandate lifecycle carbon labelling on all plastic products to expose true environmental costs and drive sustainable consumption.

(vi) Provide targeted fiscal incentives for CCU and green technology adopters. Tax breaks, subsidies, and green loans for industries adopting CO₂-to-chemicals or green technologies. For example, green procurement preferences. To make CCU/CCS financially viable, ASEAN governments should progressively raise carbon pricing to reflect the true cost of mitigation, particularly in hard-to-abate sectors. Subsidise green hydrogen production linked to renewable energy for carbon recycling processes. Phasing out subsidies for fossil feedstocks used in the production of virgin plastics can increase their cost, making recycled materials more economically competitive.

(vii) Governments should mandate a minimum of 30% recycled content in plastic packaging by 2030, increasing to 50% by 2040, to drive demand for recycled materials and reduce reliance on virgin plastics.

(viii) Support CCU deployment through government-backed guarantees to incentivise private investment and standardised certification systems.

(ix) Expand waste bank systems following Indonesia's 3R model for grassroots recycling improvement and support informal sector inclusion in national targets.

(x) Invest in integrated infrastructure that simultaneously addresses plastic waste management and carbon emission reduction, creating a closed-loop system that maximises resource recovery while minimising environmental impact. For example, WTE plants with CCUS (Singapore's Tuas Nexus) capture post-incineration CO₂.

(xi) Foster public–private partnerships in carbon recycling and waste management.

(xii) Support industry–research collaboration, fund CCU pilot projects and R&D for ChR.

(xiii) Leverage shared infrastructure costs and carbon pricing for CCU economic viability.

(xiv) Establish a clear legal framework for CCU- define CO₂ management responsibilities, and environmental value allocation between stakeholders.

(xv) ASEAN should adopt differentiated national strategies as analysed through market-based scenarios for plastic and carbon recycling, recognising that a one-size-fits-all approach is ineffective. Land-scarce countries like Singapore can focus on quality-driven solutions (e.g. advanced recycling, WTE with CCU), while larger economies can scale volume-based recycling and deploy CCU in industrial hubs. This tailored approach maximises each country's comparative advantages, enhancing both environmental effectiveness and economic efficiency across the region.

(xvi) Establish mandatory digital waste flow tracking systems with harmonised characterisation standards and real-time regional plastic waste databases across ASEAN to enable evidence-based policy adjustment, performance benchmarking and cross-border opportunities for waste processing and recycling optimisation based on actual data rather than estimates.

(xvii) Address recycling infrastructure gaps by investing in strategically located facilities, as current capacity is insufficient, and urban areas lack adequate processing despite generating the most waste.

(xviii) Introduce long-term government offtake agreements for CO₂-based fuels, chemicals, and materials, offering premium pricing for 5–10 years to de-risk early investments, signal demand, and accelerate cost reductions through scale, innovation, and market confidence.

Finally, while carbon lock-ins and systemic gaps pose serious challenges, they also present a clear window of opportunity. By aligning environmental, industrial, and financial strategies through various policies, ASEAN can lead global sustainability innovation and establish itself as a model for technology-driven circular economy solutions.

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Appendix

A5.1. Composition and Carbon Content of Polypropylene (PP)

Polypropylene (PP) is derived from the monomer propylene (C_3H_6). The molar mass and carbon composition are calculated as follows:

- Molar mass of $C_3H_6 = (3 \times 12) + (6 \times 1) = 42 \text{ g/mol}$
- Carbon content per monomer unit $= 3 \times 12 = 36 \text{ g}$
- Mass fraction of carbon $= 36 / 42 = 0.857 \text{ (85.7\%)}$
- Thus, for every tonne (1000 kg) of polypropylene produced: Carbon required $= 1000 \text{ kg} \times 0.857 = 857 \text{ kg of carbon}$

Conversion from carbon requirement to CO_2 requirement

- Molar mass of $CO_2 = 44 \text{ g/mol}$
- Carbon mass in $CO_2 = 12 \text{ g}$
- Carbon fraction in $CO_2 = 12 / 44 = 0.273$

To supply 857 kg of carbon via CO_2 : $CO_2 \text{ required} = 857 \text{ kg} \div 0.273 \approx 3,139 \text{ kg}$ or 3.14 tonnes

This is the ideal value under 100% conversion efficiency.

Adjusting for Realistic Process Efficiency

Considering real-world energy losses, side reactions, and incomplete conversions, we assume a 50% overall conversion efficiency for CO_2 utilisation pathways (RWGS, syngas formation, polymerisation):

- Adjusted CO_2 required $= 3.14 \text{ tonnes} \div 0.5 = 6.28 \text{ tonnes}$

Note: While stoichiometric calculations show that about 3.14 tonnes of CO_2 are theoretically sufficient to produce 1 tonne of polypropylene (PP), real-world processes experience significant energy losses and incomplete conversions. To reflect these, an overall process efficiency of 50% is assumed, resulting in a practical CO_2 requirement of about 6.28 tonnes.

A5.2. Composition and Carbon Content of Polyethylene (PE)

Polyethylene (PE) is derived from the monomer ethylene (C_2H_4). The molar mass and carbon composition are calculated as follows:

- Molar mass of $C_2H_4 = (2 \times 12) + (4 \times 1) = 28 \text{ g/mol}$
- Carbon content per monomer unit $= 2 \times 12 = 24$
- Mass fraction of carbon $= 24 / 28 = 0.857 \text{ (85.7\%)}$

Thus, for every tonne (1000 kg) of polyethylene produced:

Carbon required $= 1000 \text{ kg} \times 0.857 = 857 \text{ kg of carbon}$

Conversion from carbon requirement to CO_2 requirement

- Molar mass of $CO_2 = 44 \text{ g/mol}$
- Carbon mass in $CO_2 = 12 \text{ g}$
- Carbon fraction in $CO_2 = 12 / 44 = 0.273$

To supply 857 kg of carbon via CO_2 :

$CO_2 \text{ required} = 857 \text{ kg} \div 0.273 \approx 3,139 \text{ kg}$ or 3.14 tonnes

This is the ideal value under 100% conversion efficiency.

Adjusting for realistic process efficiency

Considering real-world energy losses, side reactions, and incomplete conversions, we assume a *50% overall conversion efficiency* for CO₂ utilisation pathways (reverse water-gas shift reaction, syngas formation, polymerisation):

Adjusted CO₂ required = 3.14 tonnes ÷ 0.5 = 6.28 tonnes

A5.3. Captured CO₂ Requirement for PET via Ethylene Glycol Substitution

In the production of polyethylene terephthalate (PET), ethylene glycol (EG) is one of the key raw materials. This section estimates the amount of captured CO₂ required to produce the EG component of 1 tonne of PET, assuming carbon utilisation pathways.

EG requirement Per tonne of PET

- Ethylene glycol used = 0.322 tonnes per tonne of PET

The production of EG from CO₂ typically follows this simplified pathway:

- CO₂ + H₂ → CO + H₂O (reverse water-gas shift reaction)
- CO + 2H₂ → CH₃OH (methanol synthesis)
- 2CH₃OH → ethylene glycol (EG) + byproducts

The *stoichiometric ratio* for CO₂ to EG is:

- 2 moles of CO₂ → 1 mole of EG
- Molar masses:
 - CO₂: 44 g/mol
 - EG: 62 g/mol

Mass ratio: $2 \times 44 / 62 = 1.42$ tonnes CO₂ per tonne EG (theoretical minimum)

Accounting for 50% process efficiency

Real-world processes have inefficiencies (energy losses, incomplete reactions, etc.). At 50% efficiency:

Actual CO₂ needed = Theoretical CO₂ / Efficiency = $1.42 / 0.5 = 2.84$ tonnes CO₂ per tonne EG ~ 3 tonnes CO₂ per tonne EG

Captured CO₂ needed for 0.322 tonnes of EG present in 1 tonne PET

= Captured CO₂ required = $0.322 \times 3 = 0.97$ tonnes of CO₂

From the GGI breakdown for PET

The ethylene glycol contribution is:

= 0.322 tonnes EG/tonne PET × 3.42 tonnes CO₂e/tonne EG = 1.101 tonnes CO₂e/tonne PET



Chapter 6

Comprehensive Review of Socioeconomic and Environmental of Carbon Recycling in India

1. Introduction

1.1. Background

Carbon capture, utilisation, and storage (CCUS) technologies capture carbon dioxide (CO₂) from large point sources such as power generation or industrial facilities that rely on fossil fuels or biomass. The captured CO₂ can either be used on-site, compressed and transported for various applications, or injected into geological formations for permanent storage. However, certain CO₂ utilisation processes, particularly those for producing fuels and chemicals, require significant energy input, making them less-competitive compared to conventional fossil fuels. The development of adequate infrastructure for capture, transport and storage are also important concerns. Additional technical and logistical barriers to CCUS adoption include land acquisition issue, comprehensive assessment of storage sites to ensure sufficient capacity and injecting rates, and ensure the cap rock containment capacity to prevent CO₂ leakage.

As for India, data scarcity on geological storage sites poses challenge in undertaking feasibility assessments of CCUS projects. NITI Aayog (2022) mentions 'CCUS also has an important role to play in decarbonizing the power sector, given India's present reliance on coal for meeting over 70% of its electricity needs.' NITI Aayog notes that nearly two-thirds of India's 144 million tonnes per annum (MTPA) crude steel capacity and 210 gigawatts (GW) of coal-based power capacity, are relatively young, with an age of less than 15 years and cannot be disregarded or abandoned to restrict emissions. Instead, they need to be transformed into sustainable entities by retrofitting with CO₂ capture and disposition infrastructure. IEA (2021) affirms that India needs to place the industry sector on a new path through more widespread electrification, and material and energy efficiency technologies such as CCUS. Climate benefits from CO₂ use is subject to considerations like duration of carbon retention in product, source of carbon, quantity and form of energy used to convert CO₂, and the scale of project (IEA, 2019). India has committed to scaling-up renewable energy capacity and reducing greenhouse gas (GHG) emissions as part of its Nationally Determined Contributions (NDCs).

The New Energy and Industrial Technology Development (NEDO) agency in Japan has launched a development project to create the world's most advanced technology for producing industrial para-xylene from CO₂, aiming to substitute conventional fossil fuel derived chemicals. Traditionally, the production of purified terephthalic acid (PTA) generates significant emissions (ICN, 2020). As noted by METI (2021), para-xylene is a key compound in PTA production, which serves as a feedstock material for polyesters used in fibres and plastic bottles. Due to its composition, paraxylene can be produced with relatively less hydrogen, while fixing a large amount of CO₂, compared to other compounds from carbon recycling holding potential from economic and environmental perspectives. Tao (2024) emphasised that carbon capture and recycling (CCR) offer a promising solution to mitigate CO₂ emissions by capturing 90% of CO₂. By converting CO₂ and hydrogen into methane, CCR provides a low carbon alternative to natural gas, with advantages of cost efficiency, scalability, and lower risks compared to long-term CO₂ storage.

1.2. Problem Statement and Methodology

This study is based on transformative strategies of carbon recycling technologies and alternative fuels, mainly synthetic fuel as an end product of carbon recycling. By reviewing advancements in technology, policy frameworks, scalability, employability, and gross domestic product (GDP) contribution, the study aims to zero in on potential of these strategies to reshape energy systems. The body of the research is structured around:

(1) Socioeconomic impact and sustainability. The study attempts to analyse how these technologies can create jobs, drive innovation, and support equitable growth across various sectors. It also tries to assess the economic feasibility and scalability of deploying these solutions on a large scale with insights on investment optimisation.

(2) Governance and policy frameworks. The research explores policy instruments and regulatory frameworks in force.

By consolidating barriers, analysing strengths, and offering recommendations grounded in findings, the study provides a comprehensive roadmap for policymakers and stakeholders. It examines both existing and emerging strategies to reduce emissions, identifies technological gaps and research priorities across carbon capture value chain, and provides resourceful insights on CO₂ application and the potential to convert emissions into resources of economic utility value. The research employs a multidimensional approach, combining a literature review of peer reviewed papers, industry reports, government publications, and expert interviews of 10 professionals representing sectors such as small and medium-sized enterprises, agriculture, power, information technology, education, and international trade. Data were collected through a structured, open-ended questionnaire followed by descriptive analysis with relevant interpretation of information collected from all the sources.

India has made significant strides in advancing carbon recycling efforts. According to the expert interviews, the country's annual milestones for its net-zero pathway are primarily outlined in its NDCs under the Paris Agreement. Key objectives include achieving 500 gigawatts (GW) of non-fossil fuel capacity by 2030, reducing carbon intensity by 45% compared to 2005 levels, expanding forest and green cover, and accelerating clean energy solutions by promoting energy efficient technologies. Progress of these goals is monitored through annual reporting to the United Nations Framework Convention on Climate Change (UNFCCC), detailing emissions reductions, renewable energy capacity, and other targets. Data collection and monitoring are managed by national inventory systems under the Ministry of Environment, Forests and Climate Change, while independent assessments by third parties are conducted periodically to track progress and policy effectiveness.

2. Review of Literature and Carbon Recycling Status: India Focus

2.1. Storage Overview

According to the Draft 2030 Roadmap for CCUS for Upstream E&P¹ Companies by the Ministry of Petroleum and Natural Gas of India (n.d.), CO₂ storage in the major sedimentary basins in India puts forth four storage methods with sufficient potential storage through CO₂ enhanced oil recovery (EOR), enhanced coal bed methane recovery, in deep saline aquifers and basalt formations. Kearns, Liu, and Consoli (2021) stated that the major difficulty associated with ECBMR is that injection of CO₂ significantly reduces the permeability of coal due to 'plasterisation'² and swelling of the coal. Reduced permeability requires additional wells incurring additional costs and increasing operational complexity. Moreover enhanced coal bed methane recovery can only be applied to coal seams which will never be mined; otherwise the CO₂ stored in them would be released to the atmosphere. Storage of CO₂ in basalts and ultramafic rocks depends on mineral carbonation. About 90% of injected CO₂ is predicted to be mineralised within a period of a few months to decades (Kelemen et al., 2019). Basalts are a common rock type, particularly in India, and in near shore oceanic crust worldwide. The estimated storage potential of mineral carbonation is 60,000,000 gigatonnes of CO₂ (Kelemen et al., 2019). India has some of the world's largest sedimentary basins, around 29 of them (UKRI, 2022). NITI Aayog (2022) outlines theoretical CO₂ storage capacity in India as shown in Table 6.1.

Table 6.1. Estimated Carbon Dioxide Storage Capacity in India

Storage Pathway	Remarks	Capacity
EOR	Oil recovery possible to the extent of 30%–60%	3.4 Gt
ECBMR	CO ₂ injected in unmineable coal seams, further R&D required before commercial deployment	3.5–3.7 Gt
Saline Aquifers	No economic benefit but potential of large scale CO ₂ storage	291 Gt
Basic Formations	More recent developments vis-a vis saline aquifers	97–315 Gt
Total		400–600 Gt

CO₂ = carbon dioxide, EOR = enhanced oil recovery, ECBMR = enhanced coal bed methane recovery, Gt = gigatonne, R&D = research and development.

Source: NITI Aayog (2022).

¹ E&P is exploration and production.

² Plasterisation is largely an adsorption induced matrix swelling phenomenon, the effect of which is maximum near the injection well, where CO₂ concentration is the highest.

The Ministry of Petroleum and Natural Gas of India (n.d.) recommends developing a geological CO₂ storage atlas. The National Thermal Power Corporation (NTPC) is engaged in the mapping of geological storage potential of CO₂ in category I fields in India in association with the Indian Institute of Technology (IIT) Bombay. As cited in NITI Aayog (2022), the storage of CO₂ in geological storage sites requires a variety of tools to monitor the volume of CO₂ stored, as well as to prevent CO₂ leakages and releases from the storage sites. These tools are used for monitoring the CO₂ in the atmosphere, near the surface and the sub-surface. The monitoring, verification, and accounting (MVA) framework provides the tools and approaches required for ensuring the safe, effective, and permanent geological storage of CO₂. MVA plans are needed for all CO₂ geological storage projects, covering aspects of CO₂ storage, quality control, as well as verification and accounting of CO₂ volumes stored, which would be eligible for earning incentives/credits linked to carbon abatement. Pant et al. (2023) explored soil and ocean carbon sequestration together with CCUS as combating global climate challenge strategy. This strategy falls under the category of negative emissions technology, which is further divided into two subcategories: engineered solutions and natural climate solutions. Soil and carbon sequestration entail enhancing the natural process of storing carbon in the soils and oceans augmenting their potential of absorbing CO₂. Land-based negative emissions technology include afforestation, reforestation, biochar incorporation or charcoal made from biomass. Engineered solutions include direct air capture (DAC) and other techniques.

2.2. Economic Costs

Carbon capture technology allows the continuation of established and mature energy demand processes in a low carbon environment, it ameliorates economic impacts of limiting global warming to below 2°C. When integrated into existing power generation facilities, carbon capture and storage (CCS) supports the transition towards a low-carbon economy, while reducing economic repercussions of decarbonising the power sector. Typically, carbon capture technologies are installed at major emissions point sources, such as fossil-fuelled power plants and polluting factories (UNECE, 2022). However, they will not capture all emissions at these sites. Raising the proportion of captured CO₂ further increases both the capital and operational costs for power plants and industries (UNECE, 2022).

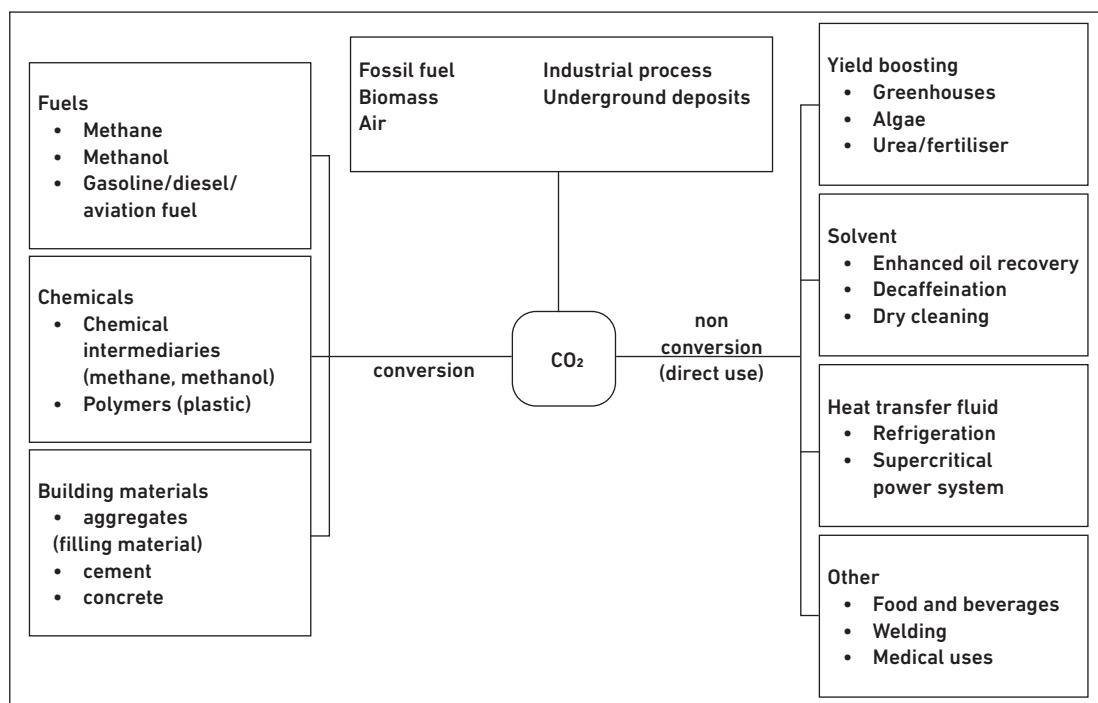
Emerging technologies such as DAC and calcium looping technologies integrate well with commercially established capture technologies for creating hybrid and highly scalable capture systems (IEA, 2019). At large scales, CO₂ is transported in its supercritical form (at pressures of 120–150 bar) through pipelines that link emissions sources to storage, utilisation, or conversion sites. Although pipeline CO₂ transport is commercially proven, it requires integration with other transport modes, such as ships and tankers, to anchoring CO₂ utilisation and disposition at scale. There is a need to develop larger CO₂ vessel designs based on lower pressures and temperatures.

Since CO₂ is a low energy molecule, converting it into other products requires massive energy input, leading to high production costs. Additional challenges include low product yields, inconsistent product quality and standards, catalyst quality and degeneration, limited feedstock availability, potential toxicity and biological impacts. These issues can be addressed through advancements in catalyst development, reactor engineering, establishing feedstock quality standards, commercial-scale production, and the development of markets for low-carbon products (IEA, 2019).

2.3. Pathways of Use

IEA (2019) affirms most commercial applications today involve direct use of CO₂. New pathways involve converting CO₂ into fuels, chemicals, and building materials. Production of CO₂ based fuels and chemical are energy intensive and requires large amounts of hydrogen. The carbon in CO₂ enables conversion of hydrogen into a fuel easier to handle and use. Less energy intensive pathways include reacting CO₂ with minerals or waste streams to form carbonates for construction material. Figure 6.1 shows the IEA (2019) model classification of pathways for CO₂ use as a guide for nations.

Figure 6.1. Simple Classification of Pathways for Carbon Dioxide Use



CO₂ = carbon dioxide.

Source: IEA (2019).

The National Academies of Sciences, Engineering, and Medicine (2019) emphasises that the scale of carbon waste utilisation will depend on the pace of technology development and future energy, market and regulatory landscapes. Carbon dioxide utilisation can be categorised into three main pathways: mineral carbonation to produce construction materials, chemical conversion to produce chemicals and fuels, and biological conversion to produce chemicals and fuels. Methane utilisation pathways include chemical and biological conversion to produce chemicals and fuels, as well as the direct use of methane as a fuel. Mineral carbonation processes transform carbon dioxide into mineral carbonates, which can be used to make concrete and cement. Because these building materials are used at enormous scale and have product lifetimes that span decades, mineral carbonation represents a significant opportunity for long term carbon sequestration in addition to being an opportunity for carbon utilisation. Chemical and biological carbon utilisation processes transform carbon dioxide and methane into carbon containing materials like fuels, polymers, commodity chemicals, and fine chemicals.

These pathways involve multiple scales of operation, are at various stages of maturity. Gaseous waste streams can contain contaminants such as hydrogen sulphide, sulphur dioxide, nitrogen oxides, and siloxanes. Often these contaminants pose barriers to the utilisation of CO₂ or methane in these waste gases. As a result, cost effective methods to separate contaminants and clean gaseous waste will be important enabling technologies for carbon utilisation. The CO₂ curing process accelerates the strength of concrete and can also be used for CCUS of CO₂ emissions from industrial sources. Known as carbonation curing, it involves the introduction of CO₂ to concrete to react with calcium oxide in the cement to form calcium carbonate (Global CO₂ Initiative, 2016).

2.4. Technology Readiness Level (TRL)

The IEAGHG (2014) defines TRL for CCS across the globe as shown in Table 6.2.

Table 6.2. Technology Readiness Level for Carbon Capture and Storage Technologies

Category	TRL	Description
Demonstration	9	Normal commercial service
	8	Commercial demonstration, full scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles, observed, initial concept

TRL = Technology Readiness Level.

Source: IEAGHG (2014).

Around the world, a large number of CCS technologies are at technology readiness levels (TRL) 6 and 7. CCS technologies are positioned at TRL 4 and 5 in India (Gupta et al., 2024). NITI Aayog (2022) affirms that while carbon capture technologies and technologies for CO₂, EOR, and sequestration are well developed and implemented at a commercial scale, technologies for the utilisation of CO₂ are relatively less developed. Even the relatively more developed technologies for CO₂ utilisation such as CO₂ to methanol and CO₂ to aggregates are at TRL levels of 4–5 and 6–7 only, respectively. Other promising technology propositions such as CO₂ to synthetic fuels, polymers, and novel materials like carbon nanotubes are even further behind. Recognising and then plugging the technology gaps is important, as compiled in Table 6.3.

Table 6.3. Summary of Technology Gaps across the Carbon Capture, Utilisation, and Storage Value Chain

Technology	Subtypes	Technology Gaps	Potential Solutions
CO₂ Capture Technologies			
Solid adsorbent	Temperature swing adsorption	Poor efficacy with lean CO ₂ concentration	Novel adsorbent architecture – it can quicken the process by 40-100 times
	Pressure swing adsorption	Slow process- cycle time in minutes/hours	Advanced metal organic framework – exponentially high surface area
Chemical solvent		- Moderate energy intensity - Solvent life - Tolerance level with industrial SO_x & other gaseous effluent	Development of new molecules and chemistry
Membrane		Poor selectivity and purity	- New polymeric membranes and electrochemical membrane - Enhancing 'countercurrent sweep' in polymeric membranes
Direct air capture		High energy and water intensity, large land requirement, and poor life of chemical media	Development of new 'chemical loop' and reagents
CO₂ Transport Technologies			
Pipe work		- Two phase flow of CO₂ - Precipitation of dry ice or hydrate	Development of 'flow model' for CO ₂ , including trans-critical, super-critical, and sub- critical phase for onshore/ offshore application
CO₂ Utilisation Technologies			
CO ₂ to building construction materials		Limited knowledge of 'process' and quality of product	Development of 'design mix' and 'process'
CO ₂ to hydrocarbon (chemicals and fuels)	Chemical process	Low 'selectivity' and 'conversion efficiency'	- Development of new mechanically-chemically stable catalysts with desired rate of action kinetics - Design of efficient reactors
	Electrochemical process	Limited knowledge on electrochemistry	- Development of co-electrolyser for direct synthesis of chemicals and liquid/ gaseous fuels - Development of electrolyser for sea water and high total dissolved solid wastewater
	Biological process	Limited knowledge on bio-species and biochemical process	- Development of biocatalyst for efficient synthesis of CO₂ and lean syngas - Development of innovative photo bio reactor for synthesis of human grade compounds

Technology	Subtypes	Technology Gaps	Potential Solutions
CO ₂ to carbon morphology (carbon black, carbon nanotubes, etc)		Shape and structural compatibility	Non-conventional and odd geometrical shaped CNT membranes require more advanced nanoscale fabrication techniques at the atomic level
		Toxicity and environmental impact	Raw carbon nanotubes are more toxic than functionalised carbon nanotubes because of the existence of metal catalysts. Thorough investigations are required on this subject
		Mechanical resilience and biofouling	Mechanical robustness to be maintained in dynamic biological environments without triggering any biological growth or degradation
CO₂ Storage Technologies			
CO ₂ injection well		Limited understanding of CO ₂ flow characteristic	Development of modelling tool for understanding multi-phase CO ₂ flow in injection well and geological formation
CO ₂ storage	Basalt and ultra-mafic rocks	Assessment of long term CO ₂ storage potential	- Advanced geological modelling alongside special conditions viz. seismic, rock fracture etc. - Smart well monitoring techniques
	Abandoned coal fields		

CO₂ = carbon storage, SO_x = sulphur oxides.

Source: Ministry of Power (2023).

2.5. Enabling Technologies and Scaling

Scaling-up calls for cost reduction, supportive policies, industry collaboration, and investment in infrastructure and pilot projects. As per IEA (2019) scaling-up to a market size of at least 10 metric tonnes CO₂ per year, calls for an integrated and multidimensional approach emphasising on technological advancements, policy support, and market readiness which can be met by targeted initiatives as building solid infrastructure for CCS, incentivising adoption, fostering a culture of novel business models, and building markets for CCU products. At full scale, CCU could open markets reaching or exceeding US\$800 billion by 2030 (METI, 2021). According to IEA (2019), commercialisation time is defined as the length of time from the project launch, to the point where annual sales are equivalent to investment in research and development (R&D) and the success rate is defined as the percentage of projects with positive return on a net present value basis, using the cost of capital with no risk adjustment.

In the case of a high degree of market and technology familiarity, the commercialisation time for established markets ranges from 2 to 5 years with a success rate ranging from 40% to 50%, while a low degree of market and technology familiarity features commercialisation times ranging from 8 to 19 years and success rates of 15%–20%. Understanding of market and societal implications of introducing new technologies will help in identifying their market opportunities and communication strategies to educate consumers and the marketplace on the societal value of developing and using these products. IEA (2019) advocates the development of databases of technical performance, financials and cost of various CO₂ utilisation technologies at different stages of maturity, as summarised in Table 6.4.

Table 6.4. Overview of Mature Carbon Dioxide Derived Products and Services

	Fuels, Chemical Intermediaries	Polymer Chemicals	Building Materials	Stabilising Waste	Yield Boosting
Mature application	Methanol, methane	Poly-carbonates	CO ₂ -cured concrete	Aggregates from waste	Greenhouses
Energy inputs	High	Low	Low, but depends on transport distances	Depends on carbonation process and transport distances	Low, but depends on transport distances
Willingness to pay for CO ₂	Low (fuels), high (chemicals)	High	High	Low	Low
Source of revenues (other than normal product sale value)	None	Cheaper feedstock	Lower cement use; extra market value of superior product	Avoided waste disposal cost	Avoided natural gas use
Main source of potential climate benefits	Displacement of fossil fuel	Displacement of fossil feedstock	Lower cement use; permanent retention of CO ₂	Permanent retention of CO ₂	Displacement of natural gas
Early opportunities	Areas with low cost CO ₂ and renewable energy	Industrial sites with excess polymer production capacity	Areas with minimum transport distances, target market segments receptive to product	Areas with minimum transport distances and high waste disposal costs	Areas with minimum transport distances and existing CO ₂ and heat infrastructure

CO₂ = carbon dioxide.

Source: IEA (2019).

2.6. Microalgae-based Carbon Capture and Alternative Fuel

Microalgae cultivation has caught the attention of researchers towards carbon sequestration and the production of alternative fuels, bio-fertilisers, and bioactive substances. This interest stems from microalgae's rapid growth rate, high oil content compared to traditional oilseed crops, and adaptability to various environments, including brackish water and seawater. Through the carbon concentrating mechanism, microalgae can utilise concentrated CO₂ of the atmosphere and thrive in saline water systems without being a threat to food crops with regard to the use of cultivable land. Their rapid growth cycle allows them to absorb 10–50 times more CO₂ than terrestrial plants, and they also help neutralise the acidity seawater or wastewater in which they grow. According to NITI Aayog (2022), a demonstration project conducted by National Aluminium Company Limited, one of India's largest integrated bauxite alumina, aluminium, and power producers, at its coal-based captive power plant in Angul, Odisha, in 2017 achieved notable results. The trial recorded algal productivity of 20 tonnes per acre per year, corresponding to a carbon sequestration capacity of 32 tonnes per acre per year, representing an exceptional outcome.

A study led by Behera, Aly, and Balasubramanian (2019) simulated the techno-economic feasibility of algal productivity for the Odisha Power Generation Corporation Limited's coal-based power plant in Jharsuguda. Singh and Gus (2010) suggested that 'the economic viability of the process in terms of minimizing the operational and maintenance cost along with maximization of oil rich microalgae production is the key factor, for successful commercialization of microalgae-based fuels'. Various companies and government organisations have explored different methodologies and designs to estimate the costs for commercial scale algae production. While technologies such as steam reforming and partial oxidation of methane for syngas production are mature commercial technologies, dry and tri-reforming of methane are still developing (Singh and Gus, 2010). The adoption of alternative fuels, as highlighted in these studies, promotes more sustainable land and resource use, while supporting biodiversity conservation.

2.7. Life Cycle Assessments of Carbon Recycling Technologies and Research Needs

Life cycle assessments (LCAs) are crucial for evaluating the environmental impact of carbon recycling technologies by analysing the emissions and resource use throughout the entire life cycle of a product, process, or service beginning from raw material extraction to disposal. According to IEA (2019), LCAs involve an intensive inventory of energy and material inputs, across the supply chain facilitating identification of the most environmentally friendly carbon recycling technologies and optimising design and implementation. For CCS, they can assess the energy requirements and emissions associated with capturing CO₂ from industrial processes and storing it underground, evaluating the environmental impact of using captured CO₂ for various applications, such as producing fuels or building materials. Compared to the LCA of conventional fuels and chemicals, carbon utilisation LCA is developing. Studies are needed to develop LCAs of waste gas generation, waste gas cleanup, waste gas transport, electricity inputs, and hydrogen inputs to facilitate consistent and transparent assessments of net GHG emissions of CCU. Further research is needed to develop transparent LCA for emerging technologies, incorporating comprehensive system boundaries that covers waste gas capture and cleanup, conversion process, use phase, and end-of-life considerations. There is also a need for advanced LCAs capable of assessing not just marginal changes in existing, static systems, but also address disruptive changes from large-scale CCU (IEA, 2019).

2.8. Integration of Alternative Fuels – The Edge

Synthetic fuel production is not confined to traditional biomass or waste materials; it extends to innovative technologies like DAC of CO₂ as a carbon neutral alternative with a scalable solution. The captured CO₂ can be used as a raw material for synthetic fuel production via catalytic and electrochemical processes. They can be used directly in existing fuel infrastructure as drop-in fuels. Janaki et. al (2024) report that the scalability of synthetic fuel production through modular processes, enabling tailored facilities to meet regional demands, highlights the adaptability of synthetic fuels to diverse energy needs and geographical contexts. Additionally, the 'drop-in' nature of synthetic fuels, seamlessly compatible with existing fuel storage, pipelines, and pumps, underscores their potential to integrate effortlessly into existing fuel infrastructure without requiring extensive modifications or investments. Rosa (2017) ratified that proven technologies and sound tested principles are available to develop an integrated energy system, relying on synthetic fuels. These would incorporate carbon capture and utilisation in a closed carbon cycle. Carbon neutral synthetic fuels are readily compatible with the existing transportation infrastructure and therefore ready for gradual deployment and replacement of natural gas and petroleum products (Rosa, 2017). Synthetic fuels produced from recovered CO₂ have a higher energy density than batteries or hydrogen, opines Horiba (n.d.). One process produces synthesis gas (hydrogen [H₂] and carbon monoxide [CO]) from CO₂ and hydrogen or water, and the other process produces synthetic fuel products from the produced synthesis gas (Horiba, n.d.). In the process of producing liquid synthetic fuels from synthesis gas, synthesis crude oil is produced from synthesis gas by Fischer-Tropsch synthesis, and the required type of liquid synthetic fuel (drop-in fuel) is produced by utilising conventional refinery production technology and refining processes for the synthesis crude oil. CO₂ is hydrogenated to methanol, which then can be converted into fuels. In the indirect route, CO₂ can be converted to CO (reverse water shift) and then combined with hydrogen to lead to gasoline, diesel, and other fuels (Styring, Dowson, and Tozer, 2021).

Styring Dowson, and Tozer (2021) studied the potential of synthetic fuel based on dimethyl ether (DME) as a future non-fossil fuel from sustainable feedstocks. Once the CO₂ has been compressed and purified to the required specification to produce DME, the CO₂ must be transported to the synthetic fuel plant. As any transportation of CO₂ will incur costs, the most economical option would be to synthesise the DME on the same site as the CO₂ is captured. This approach can also take advantage of the economies of scale of the existing plant where the CO₂ is being captured, as well as any excess heat from the plant, recycled where necessary in the DME synthesis process as per Styring, Dowson, and Tozer (2021). There are several CO₂ utilisation pathways where the technology is still developing, but should be monitored given potentially sizable markets. These include green methanol to olefins, dimethyl ether, formic acid, polymers, and CO₂-derived proteins, and CO₂ to ethanol (OGCI, 2024).

3. Analysis

This section presents a qualitative analyses based on primary information obtained from industry experts and secondary sources, including government and nongovernment documents. The analysis build upon the contents and sub contents discussed in the previous literature review section, with special emphasis on India context. The experts consulted represent organisations like the World Association of Small and Medium Enterprises, the Ministry of Petroleum and Natural Gas of India, Beroe Inc., the Indian Council of Agricultural Research, Jain Ventures, the National Council of Applied Economic Research, the Centre for Monitoring Indian Economy, Jagannath International Management School, Shree Guru Gobind Singh Tricentenary University, and KCC Institute of Technology and Management. These individuals were selected for their extensive expertise and experience in environment fields. Their valuable insights have been synthesised and integrated in this section to complement the information collected from government documents, policy briefs, and media reports.

3.1. Policy Framework

With strong political commitment and abundant feedstock availability, India has shown a serious approach about advancing CCUS. This analysis considers key elements of India's CCUS framework as outlined by NITI Aayog (2022), depicted in Table 6.5 which serves as a key reference for understanding the country's stance on CCS.

Table 6.5. Key Elements of a Carbon Capture, Utilisation, and Storage Policy Framework in India

Policy path	• In the near term, CCUS policy should be carbon credits or incentives based, to seed and promote the CCUS sector in India through tax and cash credits • Over time (probably beyond 2050), the policy should transition to carbon taxes, to enable reaching India's net-zero goals by 2070. • The policy should establish early stage financing and funding mechanisms for CCUS projects.
Hub and cluster business model	• Regional hub and cluster need to be established to drive economies of scale. • The role of emitters, aggregators, hub operator, disposers, and conversion agents needs to be defined. • Preferential procurement in government tenders for low-carbon or carbon abated products
Low carbon products	• Incentives to foster innovation for low carbon products through schemes like PLI. • Distribution of benefits of economic value added, created to communities most affected by environmental and climate change
Environmental and social justice	• Protection of communities and jobs, especially in sectors affected by clean energy regulations • Regulated emission levels and allowances for different sectors
Accounting and regulatory framework	• Adoption of life cycle analysis framework to take into account Scope 2 and Scope 3 emissions and drive effective carbon abatement • Limiting the CO₂ liability and ownership of participants across the CCUS value chain
Risk mitigation	Monitoring, verification, and accounting framework and monitoring for risk management

CCUS = carbon capture, utilisation, and storage, PLI = product-linked incentive.

Source: NITI Aayog (2022).

3.2. Academia, Public Sector Undertakings, Companies, Small and Medium-sized Enterprises, and CCUS Initiatives

Indian academia and research institutions have been actively engaged in CCU and carbon recycling initiatives. According to UK Research and Innovation (UKRI, 2022), financing CCUS could help achieve a 50%–70% reduction in GHG emissions from industrial products like cement and methanol. The report identified 29 Indian universities working in CCUS research, with seven institutes of technology across India leading the CCUS research and development work. Most of the universities are focused on CCU research targeting applications in the energy and industry sectors, while fewer are exploring CO₂ storage and transportation.

Amongst notable innovations, the startup Urjavac has developed an aqueous CO₂ capture technology comprising a new, robust, cost effective, and scalable catalyst. This system converts captured CO₂ into high-value minerals while recycling the catalyst, permanently fixing the CO₂ as stable mineral carbonates. The scalable and commercially viable solution could create multiplicative macro and microeconomic opportunities like job creation, growth of the CCUS market, and strategic alliances.

In India, CCUS projects are being implemented in sectors such as thermal power plants and the cement industry. Some leading industries like Thermax, Dalmia Cement, Hindalco, and Siemens have jointly launched the 'Industry Charter for Near Zero Emissions Ambition by 2050'. Table 6.6 is a compilation of information received from various sources: interviews, reports, data from private firms, public sector units, global firms, small and medium-sized enterprises, and startups involved in CCUS in India either independently or in partnership offering scalable models.

Table 6.6. Compilation of Establishments in India Working on Carbon Recycling

Company Name	Location	Memorandum of Understanding	End Product	Remarks
Dalmia Cement	Tuticorin, Tamil Nadu	CarbonCleanSolution	Soda ash	Amine-based solvents 50,000 t/year capacity
Tuticorin Alkali Chemicals				Amine-based solvents 6,000 t/year capacity
Carbon Clean	Mumbai (TRL 9)	United Kingdom, United States		Provides CO ₂ separation technology for industrial and gas treating applications
PCBL Chemical Ltd.			Carbon black	
Goa Carbon Ltd.			Calcined petroleum coke	Used in aluminium smelting, graphite electrodes
NETRA	NTPC power plants	Carbon Clean and Green Power	Zeolite, amine, aggregates	Amine-based solvent capture technology. 'pressure swing adsorption' for capture
My Plan 8				Environment consultant
Clime Works				Combines nature-based methods like afforestation and biochar with enhanced weathering, BECCS, and own DAC technology

Company Name	Location	Memorandum of Understanding	End Product	Remarks
Novonanmek Material Sciences Pvt. Ltd.	Delhi (TRL 4)		Novo clime	DAC product
Indian Farmers Fertilizers Cooperative (IFFCO)	Aonla, UP			Using amine solvents to capture CO ₂ . Absorber captures around 450t CO ₂ per day
IFFCO	Phulpur, UP (TRL 9)			Uses KM CDR Process® using amine solvents to capture 450 t/day CO ₂
Indo Gulf Corporation Ltd.	Jagdishpur, UP (TRL 9)			Eco amine based solvents using flour unit to capture 150t/day CO ₂ in urea manufacture
Carbon Engineering				
Aker Carbon Capture	Mumbai			CCUS projects, offers after -market support
Carbfix				Natural carbon sequestration
BASF	Mumbai			Ionic liquids for carbon capture applications
Calix Ltd				Industrial decarbonisation
Fuel Cell Energy				
Green Jams	Vishakhapatnam		Concrete, hempcrete	Converts CO ₂ into construction materials like bricks and aggregates
JSPL	Angul, Orissa		Soda ash, carbon abated steel	Capture of 2,000 tpd concentrated CO ₂ from commercial scale gasification
Fugro	Vishakhapatnam	Ecocarbon Engineering Solutions Ltd., VisakhaPharma City Ltd., Environmental Geotechnology Lab, IIT Bombay		
GAIL	artificial pond at its Pata petrochemical complex in UP			Fixing CO ₂ using microalgae for converting inorganic carbon into organic compounds
GAIL		LanzaTech		Consumer goods from fuels to packaging and clothing made from bio-recycled material
LanzaTech	Panipat	IOCL		Ethanol using refinery emissions
LanzaTech		NETRA and Mangalore Refinery & Petrochemicals Ltd.		Ethanol from agricultural residue, 4G ethanol from waste-based feedstocks

Company Name	Location	Memorandum of Understanding	End Product	Remarks
Jakson Green		LanzaTech		To provide 4G ethanol tech to NTPC
CSIR	(TRL 6)	IIT Delhi		Chemical conversion to DME
Urjanovac	Mumbai (TRL 9)	DST & IIT Bombay		Can capture CO ₂ from both industrial flue gas and ambient air in presence of water, industrial wastewater or even seawater
Carbon craft	Hubbali	AIR INK		Captures CO ₂ to make tiles
Breathe Applied Science	Bengaluru (TRL 6)	JNCASR	Methanol and other fuels	Capacity of operations 300 kg per day. National award from DST and TDB. Runner up in Startup Challenge, India Energy Week
ONGC		Equinor, Norway		EOR in key basins for developing CCUS hubs and projects
ONGC		Shell		For exploring CO ₂ storage study
ONGC	Koyali refinery, Gujarat (TRL 5)	IOCL Dastur		Capture CO ₂ emissions transported through pipelines to ONGC's Gandhar oil field where carbon will be stored
BPCL				Feasibility study for gasification of 1.2 MTPA petcoke and conversion of carbon abated chemicals
HPCL	Vishakh refinery, AP			
Tata Steel	Jamshedpur			Plant for capture of 5 tpd CO ₂ from blast furnace gases
BHEL & CSIR	Hyderabad	CIMFR		Pilot scale plants for carbon capture and conversion of high ash coal to methanol
Reliance Industries				Using bio pathways to fix CO ₂ and facilitate conversion to renewable fuels by CO ₂ capture, storage and use at competitive costs
National Aluminium Company Limited	Tamil Nadu (TRL 6)			Microalgae carbon sequestration
Hindalco				Using initial technology
Dastur & Co. Pvt. Ltd.		CRI		Marketing, business development, technology licensing, design and engineering of CO ₂ to methanol projects based on Carbon Recycling International ETL technology
Coal India	Dankuni			Coal to methanol
Coal India	Talcher			Coal to fertiliser

CCUS = carbon capture, utilisation and storage, CO₂ = carbon dioxide, BECCS = bioenergy with carbon capture and storage, DME = dimethyl ether, DST = Department of Science and Technology, EOR = enhanced oil recovery, ETL = emissions-to-liquids, IIT = Indian Institute of Technology, kg = kilogramme, MTPA = million tonnes per annum, T= tonne, TDB = Technology Development Board, tpd = tonne per day, TRL = technology readiness level, UP = Uttar Pradesh.

Source: Compiled by authors from Balakrishnan (2023), Dastur Energy (2022), FIPI (2025), Lanzatech (2023, 2024), Reliance (n.d.), and Tracxn (2025).

3.3. India's Performance with Synthetic Fuels

According to NITI Aayog (2022), CO₂ utilisation technologies are relatively less developed in India, with promising technology propositions like converting CO₂ to synthetic fuels, polymers, and novel materials like carbon nanotubes lag further. Nevertheless, India is actively exploring carbon recycling pathways to turn captured CO₂ into fuels such as blue hydrogen produced from fossil fuels with CO₂ capture, and synthetic fuels, which are liquid or gaseous hydrocarbons made by combining CO₂ and hydrogen. Over the next 5 years, India has the potential to nearly triple consumption and production.

Insights from expert interviews indicate that hydrogen demand in India currently remains concentrated in traditional sectors such as refinery, chemicals and steel, with growing scope in heavy industries, long-distance transport, and energy storage. Methanol sales are also growing rapidly and are expected to reach more than 7.5 million tonnes per year in 10 years. The government's push to promote methanol as fuel supports a higher share of domestic energy sources in national economy. Experts further noted that India is advancing efforts to convert captured CO₂ into useful chemical products, including alternative fuels such as methanol and methane, as well as feedstock for urea and polymers.

There is a growing focus on syngas as feedstock for producing synthetic fuels and chemicals such as plastics, fibres, and rubber. In addition, CO₂ is being reacted with minerals and waste materials to produce carbonates for construction material. Hydrogen is increasingly recognised as a clean energy carrier, produced primarily through ammonia and blue hydrogen from natural gas using CCS. Green ammonia is emerging as a key player in decarbonising fertilisers and energy storage, and is also being explored as a potential fuel for zero emissions shipping and power generation. Policy support for low-carbon fuels such as ammonia and synthetic kerosene is gaining ground in the aviation and maritime industry. Furthermore, sustainable feedstocks, including agricultural residues and algae, are helping reduce lifecycle emissions by 80%.

3.4. Economic Impact – Import Effects

Synthetic fuels produced from captured CO₂ offer a pathway for carbon neutral transport and the economy. These alternative fuels can buffer economies against price volatility and geopolitical disruptions. As reported by McKinsey (2022), India's petrochemical imports stood at US\$40 billion in fiscal year (FY) 2019 and were expected to reach US\$75 billion by FY 2025. India as per government reports remained the world's largest base oil importer in 2025, with imports exceeding 3 million tonnes, an 11% increase from the previous year. For FY 2026, imports are expected to remain broadly at FY 2025 levels, with public and private sector companies announcing large capacity expansion plans to reduce import dependence. India imported US\$13.407 billion of petroleum crude and products in January 2026.

Since synthetic fuels are the key products of carbon recycling, their large-scale deployment could significantly reduce India's fuel imports. Currently, the country imports 85% of its crude oil, costing about US\$115 billion annually, with a national target to reduce the dependency to 75%–80% by 2030. According to NITI Aayog (2022), scaling-up synthetic fuel production could help India lower its import bill by about US\$1 billion–US\$2 billion annually by 2030, and by as much as US\$10 billion–US\$12 billion per year by 2040. Insights from expert interviews emphasise the need

for government incentives to attract private investments in alternative fuel technologies. With policies already supporting domestic production, further innovation and improved supply chains for synthetic fuels can move India closer to being fuel independent. Experts also highlighted the importance of fostering public–private partnerships (PPP) in competitive mode.

3.5. The Finance Landscape

India requires supportive banking regulations and incentives towards sustainable finance in a scalable fashion for carbon recycling. According to the Economic Times (2023), a survey conducted by an industry body on behalf of the Reserve Bank of India, revealed that most Indian banks are not yet equipped to integrate environmental, social, and governance norms as part of their lending models due to lack of clarity on their applications. In response, the Reserve Bank of India has introduced a draft climate risk disclosure framework (XBRL, 2024), designed to strengthen the resilience of regulated entities. The framework highlights the growing imperative for robust risk management in the face of climate change challenges that are expected to have a significant impact on reporting entities and pose financial stability risks.

Expert insights indicate that incentives such as tax credits, cash credits, or product-linked incentives (PLI), on carbon-abated products could boost CCUS technology implementation. The PLI scheme, launched in India in 2020, currently applies to various manufacturing sectors and provide benefits over a period of 4 to 6 years. It envisages the creation of large-scale manufacturing capacity, promote import substitution, and generate employment.

3.6. Compliance and International Co-operation

Harmonising standards and regulations across borders is essential to remove trade and technology-sharing barriers. Expert interviews emphasised the importance of introducing a cross-border adjustment mechanism to prevent carbon leakage and the substitution of European Union (EU)-produced goods with imports from countries with lower or no carbon price or CO₂ abatement requirements. Under this mechanism, importers would be required to purchase cross-border adjustment mechanism certificates for the embedded carbon emissions in their goods, thus creating a fair competition between EU and non-EU manufacturers.

Regulatory mechanisms such as emissions trading systems, carbon taxes, and renewable energy mandates will encourage industries to prioritise low-carbon alternatives. Experts also agreed that India could enhance international collaboration by strengthening bilateral and multilateral partnerships to attract foreign investment with favourable policies, subsidies, and tax incentives. Collaborating on joint research and development with global institutions is further highlighted as a key to foster technology transfer.

3.7. India's GDP Contribution through CCUS Efforts – Export–Import Outcomes

According to NITI Aayog (2022), CCUS is expected to have a positive impact on India's GDP, employment growth, energy and material security, and import substitution. Implementing CCUS projects will require upfront capital investments of approximately US\$100–US\$150 billion (in 2022 dollars) for 750 MTPA of carbon capture, utilisation, and storage. These investments are projected to develop the domestic market for CO₂ and contribute an estimated US\$100 billion–US\$150 billion to India's GDP over the next 30 years, driven by technological advancement and localisation of CCUS solutions.

CCUS-enabled coal gasification projects will generate clean value-added products like methanol, ammonia, acetic acid, mono-ethylene glycol, etc. As highlighted by NITI Aayog (2022), coal-based chemical production at competitive costs could significantly reduce India's dependence on imports. The additional oil generated through CO₂ EOR would further substitute crude oil imports to India and, therefore will decrease the current account deficit of India.

India currently imports almost US\$13 billion worth of organic chemicals annually; with indigenous coal-based chemical production, imports worth US\$7 billion–US\$10 billion could be replaced by 2050, contributing directly to GDP growth. Furthermore, CCUS can aid in the production of low-carbon products by decarbonising hard-to-abate industries, creating export avenues for green products benefiting other manufacturing and service sectors through huge investments across CCUS and EOR carbon value chain. The resulting direct and indirect tax revenues, along with employment generated during engineering and construction phases, will have a strong multiplier effect on both social and economic development.

3.8. Employment Landscape of CCUS Projects, India and Prospects

NITI Aayog (2022) estimated that the CCUS target can create employment opportunities of 8–10 million full time equivalent years in a phased manner. During the construction stage, the generation of temporary employment for construction work (skilled, semi-skilled, and unskilled) will be one of the major impacts of CCUS projects. Additionally, high-skilled and valued resources will be required by contractors, technology suppliers, and project proponents for project management, administration, and supervision. The employment of construction workers from the nearby area will boost the regional economic conditions. As there is a multiplier effect on consumption, savings, taxes, etc. the projects will help in shaping the future economic development of the nearby areas.

The indirect employment is projected to be approximately three to five times greater than the direct employment generated. Additionally, job opportunities for operations and maintenance of the entire carbon value chain will progressively expand, primarily engaging skilled personnel and small and medium-sized enterprises in relevant fields. The total employment impact has been estimated based on the annual manpower requirement over the project's estimated operational lifespan of 25 years. As the indirect employment multiplier is a function of the salary, savings,

and domestic consumption, indirect employment could reach five to seven times of the direct employment. Consequently, CCUS projects will thus lead to significant employment generation both during the construction and operating phase, as well as create significant indirect employment and shape the future economic development of nearby areas.

According to McKinsey (2022), Indian public sector undertakings in the oil and gas sector currently employ around 100,000 workers with more than half of these jobs in refining and marketing activities. However, in the accelerated scenario, two-thirds of the 2030 refining capacity could be stranded by 2050, posing challenges for the workforce transition despite potential repurposing efforts. This scenario is expected to transform more than 30 million jobs, creating 24 million new jobs, while an existing 6 million jobs could be lost by 2050. Challenges identified by McKinsey (2022) include skill shortages as fast growth of the green energy sector has exhausted available skilled labour, lack of adequate vocational training programmes and specialised curricula, and inconsistent policies and weak incentives that hinder workforce development and scaling-up. CCUS projects can thus open jobs across diverse sectors and skill levels. The following outlines job suggestions based on insights and understandings:

- Under the 'Skill India' banner and the National Skill Development Corporation (NSDC), India can provide vocational training programmes focused on carbon management.
- A PPP model to scale-up pilot CCUS projects and synthetic fuel initiatives, undertake demonstration projects in carbon recycling that engage government, private sector, and start-ups.
- PLI-based incentives can be extended to industries producing synthetic fuels.
- Incentives and subsidies can be provided to startups developing carbon recycling technologies, providing for novel takes in product development, marketing, and scale-up. India's dynamic startup ecosystem provides a strong foundation for such start-ups with opportunities in product development and supply chain.
- Rural entrepreneurship can be promoted through bio-CCUS projects such as algae farming, biomass management towards producing fertilisers, animal feed, and bioplastics. With favourable scalability of such ventures in rural India, employability in farming, harvesting, and bio product processing can be ensured for unskilled and semiskilled workers.
- Significant employment opportunities exist in urban manufacturing industries as in retrofitting plants with carbon capture units in a range of capacities like engineers, supervisors, electricians, etc. Additionally, operation and maintenance roles in carbon recycling facilities in the capacity of plant operators, chemical engineers, safety managers, etc. CO₂ pipelines and storage sites offer avenues in maintenance and monitoring like materials researchers and quality inspectors.
- Expanding R&D funding for ideating cheaper solutions on carbon recycling and synthetic fuel generated through carbon recycling guaranteeing jobs for environment auditors, environment engineers, scientists, data analysts etc.

4. Research Implications and Roadmap

Taking into account the contents analysed in the previous section, this section focuses on practical relevance of the outcomes of research highlighted in the descriptive non-tabulated analysis.

4.1. Workable Recommendations for Policymakers and Investors Supporting Sustainable Transitions

This chapter has attempted to consolidate practical, targeted recommendations for policymakers, industry leaders, and investors stressing on creating an enabling environment for the adoption and scaling-up of alternative fuels and carbon recycling technologies. It highlights the importance of cost reduction, industry collaboration, and infrastructure investment. Rich insights and key suggestions gathered from experts interviewed, aligning with both theoretical and practical insights from India and globally, are compiled as follows:

Carbon recycling technologies

- Direct air capture (DAC): Advances in cost effective sorbents and solid adsorbents are improving the scalability of DAC. Companies like Clime works and Carbon Engineering in India are pioneering scalable models.
- Biochar production: New pyrolysis techniques are enhancing carbon sequestration through agricultural waste conversion.
- Carbon to value: Pathways like turning CO₂ to polymers, building materials (carbon infused concrete), and sustainable aviation fuels (SAF) are gaining traction.

Scaling-up

- Industrial partnerships and demand aggregation like SAF for economy of scale.
- Leveraging carbon credit markets and government subsidies under official government frameworks could accelerate adoption.

Effective instruments

- Green bonds: Particularly sovereign green bonds provide long-term, low-interest financing for climate focused infrastructure by attracting domestic and international investors. The impact of these bonds that raise significant capital could be enhanced through improvements as clearer, more transparent reporting on fund allocation and outcomes, ensuring strong oversight mechanisms, and expanding the range of eligible projects. Standardising green bond frameworks across countries and integrating robust climate risk assessments can increase investor confidence.
- Debt for climate swaps: Redirecting debt repayments into carbon recycling projects
- Concessional loans: Provided by development banks (e.g. the World Bank) with favourable terms to attract private investment
- Results-based financing: Funds disbursed upon achieving predefined performance metrics, ensuring accountability
- Public-private collaboration ensures risk mitigation for early stage technologies, complemented by venture philanthropy funds

Critical policies

- Production incentives: Subsidies similar to the United States' Inflation Reduction Act
- Infrastructure investments: Funding for pipelines, storage, and distribution networks
- Mandates and standards: Hydrogen blending mandates in natural gas and steel production; defining purity standards
- Carbon pricing: Strengthening carbon markets for competitiveness
- Export agreements: Bilateral agreements to position India as an export hub
- Pushing a culture of climate power purchase agreements that are long-term contracts between a buyer or company and developer or producer at a price fixed for a specific time period

Challenges

Constraints include lack of effective recycling infrastructure plastics, construction debris, low consumer awareness, low adoption of circular practices, and insufficient extended producer responsibility regulations.

Job creation

Carbon recycling plants and synthetic fuel facilities can generate employment in construction, operations, logistics, chemical engineering, biotechnology, and material sciences. Programmes focusing on technicians in carbon recycling plants, hydrogen fuel cell assembly, and green ammonia production can transform the workforce.

Strategies and policy reforms for accelerated transition

- Scale-up ethanol blending in fuels (targeting 20% blending by 2025, achieved successfully)
- Expand investments in carbon recycling and synthetic fuel projects
- Utilise alternative feedstocks, supported by PLI schemes
- Open method of co-ordination should address logistical issues and reduce transportation costs by promoting local ethanol production
- Import duty waivers on equipment for alternative fuels and PLI schemes
- Transparent reporting on project impacts and adopting frameworks like the Climate Bonds Standard can enhance trust and investor interest

Regulatory frameworks

- Tax incentives, enabling policies to boost private engagement
- Participation in R&D consortia for shared technology development and deployment
- Collaborating with academic institutions and global technology leaders

Upgrading of contemporary frameworks

- Satellite imaging and internet of things sensors to track project performance
- Block chain for transparent carbon credit trading
- Global standards like ISO14064 to ensure accountability
- Integration of artificial intelligence and innovation require streamlining

4.2. Fostering Public–Private Partnerships and Private Capital

Most expert respondents highlighted that private investors could provide risk capital, while governments mitigate risks through guarantees and subsidies. Effective blended financing instruments including green bonds, sustainability linked loans, concessional financing, and equity investments combine public and private capital to de-risk projects, attract investors, and scale-up initiatives in alternative fuel and carbon recycling. Leveraging global climate finance mechanisms like the Green Climate Fund and creating knowledge sharing platforms will facilitate the exchange of expertise, accelerating adoption of synthetic fuel technology in India.

Experts also emphasised that PPPs can enable technology sharing, infrastructure funding, efficient supply chain design, including collaboration on reverse logistics. There is a need to encourage collaboration between governments, industries, and research institutions to accelerate commercialisation and scaling-up. PPPs can address infrastructure gaps, technological innovation, regulatory hurdles, and favourable consumer behaviour by joint investments, developing new technologies and policies to incentivise sustainable practices. While governments can offer financial support and tax incentives, private companies bring innovation, expertise, operational efficiency, and provide necessary funds. To further encourage private sector engagement, experts underscored the importance of strengthening these regulatory frameworks:

- Incentives: Tax credits, subsidies, and risk sharing mechanisms to attract private investment
- Clear standards: Establishing uniform guidelines for green projects (e.g. green bond standards, sustainability metrics)
- Public guarantees: Providing financial guarantees to reduce risk for private investors
- Climate finance regulations: Streamlining regulations to ensure faster approval processes for green projects and investments.
- Disclosure mandates: Encouraging transparent reporting of environmental impacts and financial returns to build investor trust

The use of PPPs in low-carbon climate resilient infrastructure projects is gaining momentum. Public authorities are going for PPPs owing to budgetary constraints, thrust on innovation, and private sector participation attracted by profitability and favourable policy frameworks. These partnerships usually entail more creativity, variety of stakeholders, and focus on social acceptance and transparency. Monitoring and verification frameworks for climate financed projects are evolving to ensure accountability. Key points as compiled through responses received are:

- Third party audits: Independent auditors assess whether projects meet environmental goals and comply with green standards ensuring transparency and credibility.
- Green bond principles: These provide guidelines for issuing green bonds, emphasising the need for transparency, regular reporting and independent verification of fund usage.
- Impact assessments: Continuous monitoring of projects through data collection, including emissions reduction, energy efficiency improvements, and other environmental impacts.
- Climate disclosure standards: Adoption of frameworks like the Task Force on Climate related Financial Disclosures to enhance transparency on climate risks and project outcomes.
- Regulatory oversight: Governments and financial regulators are increasingly introducing mandates for tracking and reporting environmental impacts to align with national goals.

4.3. Support of Local Governance

Indore in Madhya Pradesh is the best example of local governance in India. In West Bengal, Basirhat Municipality has taken the initiative of registering support for green projects. Ghaziabad Municipal Council claims to be the state's first and country's second municipality after Indore to achieve the milestone of registering a carbon credit project under the Verified Carbon Standard Programme (Times of India, 2025). Another example of a blended finance model is Udaipur Municipal Corporation's PPP with Hindustan Zinc.

4.4. Public Awareness on the Role of Sustainable Practices in Energy Transitions

For CCUS technologies to be adopted, it is imperative that the public is made aware of benefits and risks associated with these technologies. Likewise, legitimate concerns of people living in the proximity of storage sites need to be addressed. Key findings should be disseminated through online platforms, webinars, and workshops targeted at educating on the benefits of carbon recycling and alternative fuels, inspiring people to be active responsible partners, and using social media to disseminate information to a wider audience like students and professionals. With enhanced public awareness, the transition becomes more inclusive, with individuals and communities contributing to the success of carbon reduction and fuel diversification efforts. Partnering with media organisations to produce content that teach the science and economics behind technologies, relating the concepts to everyday life can be done.

4.5. Technology Pathways – The Way Ahead

Identifying breakthrough technologies, innovations that enable cost reductions and efficiency improvements in CCUS and synthetic fuel production as a component of CCUS value chain is paramount. Electrolysis cost reduction is important. Expenses will decline with economies of scale, green power purchase agreements, and better electrolyser efficiency. Advanced storage also needs attention. Metal organic frameworks and hydrogen carriers are being developed for safe and voluminous storage. Recent developments have enhanced the viability of alternative fuels. Ammonia-powered tugboats are successfully deployed highlighting the potential of ammonia as a zero-carbon marine fuel. Aviation industry is increasingly using SAFs with potential to decrease life cycle CO₂ emissions to the tune of 80%. Companies are embracing renewable diesel technologies, producing gasoline blends that lessen CO₂ emissions to 40% of conventional fuels. Emerging technologies with the potential to decarbonise and disrupt the energy sector as inferred from the reference documents and information collected from industry respondents include:

- Synthetic fuels: Produced from carbon capture offer a cleaner alternative to fossil fuels and could be used in existing infrastructure, reducing reliance on oil and gas.
- Green ammonia: Used as a zero-carbon fuel for power generation and shipping, it is produced using renewable energy to split water and nitrogen.
- Advanced nuclear reactors: Small modular reactors and next generation reactors could provide a safe, reliable, and low-emissions power source.
- Energy storage solutions: Breakthroughs in battery technology and long duration storage could resolve intermittency issues of renewables enabling their widespread use.

5. Conclusion

This research offers an original synthesis of industrial practices by integrating information from multiple credible sources weaving them into a coherent narrative. It aims to create a strategic roadmap for implementing carbon recycling technologies and adopting alternative synthetic fuels to guide governments, industries, and organisations towards integrating them into their operations and energy systems. The study explores current capabilities, gaps, and technological readiness across industries and regions, while identifying key financial, regulatory, and technological barriers.

It advocates a comprehensive approach for addressing the growing challenges of carbon emissions, focusing on carbon storage, CO₂ utilisation, carbon recycling technologies, and synthetic fuels as vital components of CCU value chain. India's progress already includes CCU for fuels, chemicals, building materials, and DAC technologies. To scale-up these innovations, the study highlights the role of blended financing instruments including green bonds, sustainability linked loans, concessional financing, and equity investments that combine public and private capital to de-risk projects, attract investors, and scaling-up.

Advances in technology, materials science, and engineering will make these solutions more efficient, scalable, and affordable, while fostering innovation in capture methods, fuel production, and infrastructure integration. An innovation ecosystem that supports development of scalable solutions is needed. Effective governance regulatory frameworks and standards are essential. Governments need to establish policies that promote the use of alternative fuels and encourage private sector participation. A balanced governance model, ensuring financial incentives, accountability, and collaboration across stakeholders, is deemed essential.

Although initial investment in alternative fuel infrastructure may be high, long-term benefits include reduced energy costs, innovation-driven economic growth, and lower healthcare expenses. Such investments can reshape national economies by creating new industries and reducing energy trade deficits. Experts proposed specific financial mechanisms as tax credits, green bonds, and low interest loans, to attract both public and private investments in clean energy technologies. With the global market for green bonds projected to reach US\$1 trillion annually by 2025, these instruments can support alternative fuel adoption. It infers that clear market signals for businesses and investors are crucial suggesting flexibility of policies for emerging technologies that allow them to scale-up quickly while mitigating potential risks such as stranded assets.

Transitioning to sustainable energy systems requires investment. This study investigates financial mechanisms like public–private partnerships, green bonds, and carbon credits for their ability to simulate innovation and deployment, recommending comprehensive regulatory frameworks, fiscal incentives, global standards, and R&D investment. It also calls for channelling resources into green technologies, prioritising projects with measurable social environmental impact, and engaging in sustainable financing.

While India's carbon capture, EOR, and sequestration technologies are well developed and implemented at a commercial scale, CO₂ utilisation technologies, such as conversion to synthetic fuels, polymers, and carbon nanotubes, remain underdeveloped. Nevertheless, CCUS offers immense potential to enhance domestic production, reduce imports, and promote self-reliance, contributing to a circular economy. Realising this potential will depend on a blend of technical, economic, and policy drivers. Key policy measures include subsidies for utilisation, tax incentives for R&D, investing in infrastructure like pipelines and storage.

The research points also underscore the employment potential and economic self-reliance through CCUS, carbon recycling, and transition to alternative fuels. The transition could create a new wave of green jobs, spanning research, production, and maintenance roles. Workforce reskilling programmes and government–industry collaboration will be essential for training, certification, incentives, smooth transition, and support of India's green growth ambitions.

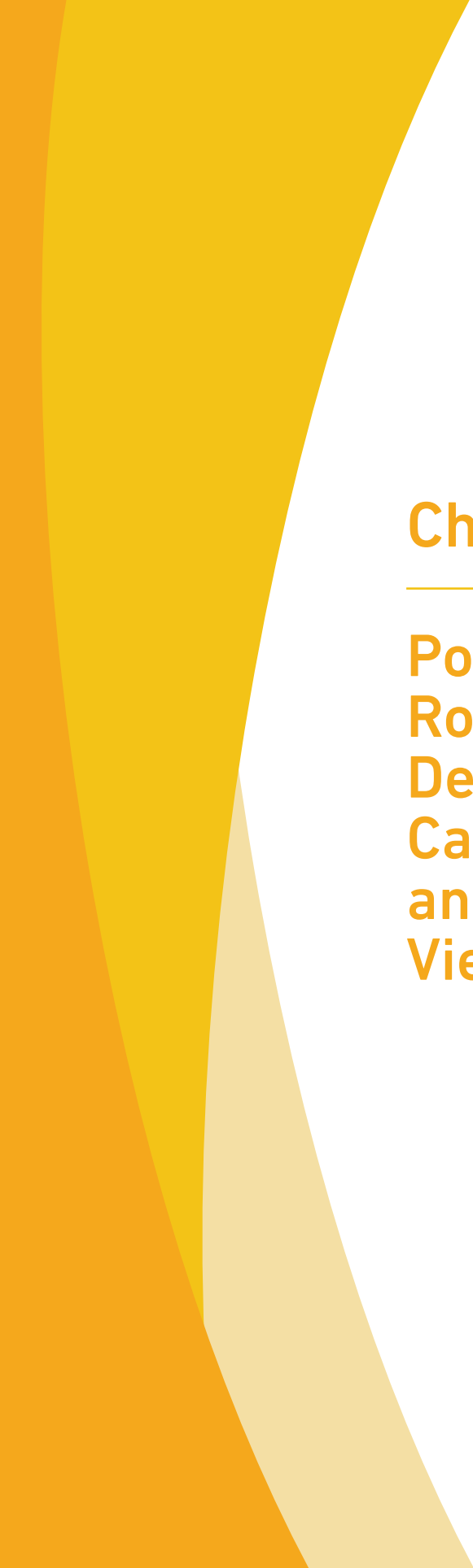
Finally, the research calls for a comprehensive research agenda to advance a diverse range of CCU technologies suitable for utilising various carbon waste streams, incorporating an enabling ecosystem and resources, and producing a variety of carbon-based products including synthetic fuel. It stresses the need to assess these technologies across maturity levels, market readiness, and environmental impact to identify gaps and find a viable pathway forwards. Achieving large-scale success in India will ultimately depend on building the necessary infrastructure, advancing technological maturity, and enacting consistent policies that reduce technology costs towards full scale deployment.

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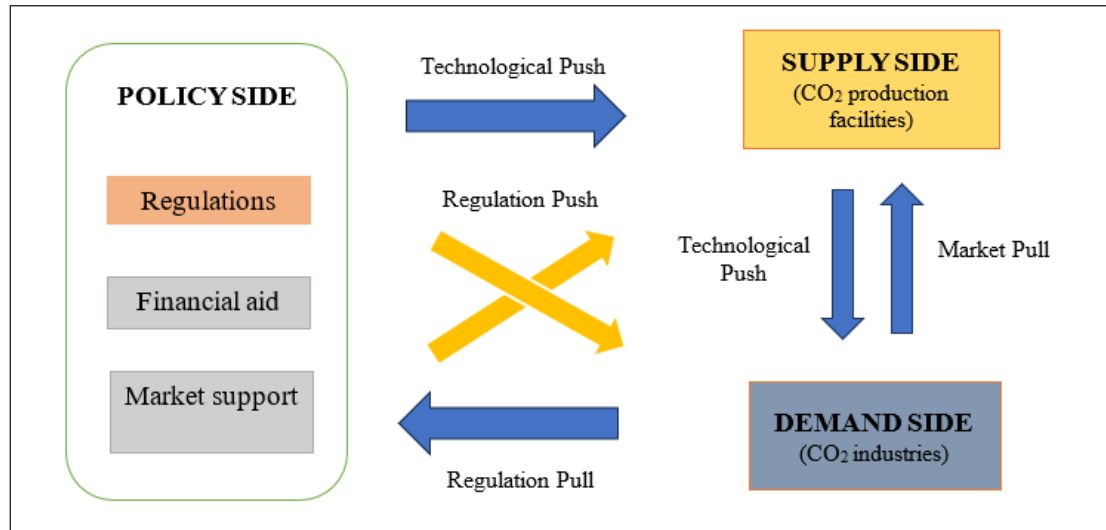
Chapter 7

Potential and Roadmap for the Development of Carbon Capture and Recycling in Viet Nam

1. Research Approaches and Methods

The United Nations (UN) Agenda for Sustainable Development has recognised that business and industry play a key role in reducing the impact on resource use and the environment through more efficient production processes, preventive strategies, and cleaner technologies and production processes (UN, 2015). In the context of environmental pollution and climate change posing many development challenges, eco-innovation can be a key catalyst to promote and implement green growth because it promotes all forms of innovation that reduce environmental impacts and increase resilience to environmental pressures. Carbon capture, utilisation, and storage (CCUS) or carbon capture and utilisation (CCU) are considered eco-innovation solutions for sustainable development and a circular economy. From a policy perspective, the government's issuance of environmental regulations that encourage new responsive technologies and financial systems is an external determinant of eco-innovation. Considering CCUS as an important tool in connecting the supply side (factories and production facilities that emit large amounts of carbon dioxide [CO₂]) with the demand side (factories that need to use CO₂) and as an important solution to reduce CO₂ emissions towards the net-zero target. By employing a market-based approach (supply-demand) and a policy-practice approach, this research aims to provide specific insights into the current state, potential, and development pathways for carbon capture and recycling in Viet Nam. This approach is presented in Figure 7.1.

Figure 7.1. Interactions amongst the Determinants of Carbon Dioxide Market-based Approach



CO₂ = carbon dioxide.

Source: Authors based on Jang et al. (2015), modified from Horbach (2008).

Government policies function in two ways: regulation push and market pull. Regulations provide an environmental technology push to the supply side by requiring it to meet environmental standards. For instance, Viet Nam's National Strategy on Climate Change to 2050 and recent amendments to its Electricity Law mandate the gradual deployment of CCUS technologies across the energy sector (Prime Minister of Viet Nam, 2022a). Financial aid, such as research and development (R&D) investments or fiscal incentives, support the development of such eco-technologies (Jang et al., 2015). For example, feasibility studies for post-combustion CO₂ capture at Vũng Áng 1 and Sông Hâm 1 power plants were co-funded through national and international co-operation (Black and Veatch, 2024). In addition, the policy side offers programs for environmental procurement and consumer awareness to create eco-innovation markets. Financial aid and market facilitation mechanisms such as extended producer responsibility (EPR) were first mentioned in the Law of Environmental Protection 2020 (National Assembly, 2020), which also contributes to forming and supporting eco-innovation markets. Therefore, as one determinant of eco-innovation, environmental policies stimulate and support the other two determinants: supply and demand. Consequently, environmental policies establish an enabling environment for eco-innovation. Technological progress facilitates creating and activating markets through products and services, whilst markets stimulate technological development. Thus, the supply and demand sides motivate each other towards eco-innovation (Jang et al., 2015). The diagram of interaction amongst determinants of eco-innovation will be applied to this study on interpreting policy instruments for CCUS/CCU in Viet Nam throughout all relevant sectors.

With that approach, the research team used a number of research methods as follows:

- Literature review: To assess the current state of carbon emissions and recycling technologies in Viet Nam, an extensive review of existing research, reports, and government documents will be conducted. This will also include a comparative analysis of international carbon recycling policies and practices from countries such as Japan, the European Union (EU), and the United States (US).
- Policy gap analysis: A systematic policy analysis will be carried out to identify gaps in Viet Nam's existing climate and environmental policies, particularly regarding carbon capture, utilisation, and recycling. This will help formulate relevant policy interventions.
- Comparative analyses: Conduct potential and prospective comparisons between electric vehicles, hydrogen, and carbon recycling to achieve the net-zero target by 2050 under the Conference of Parties (COP26) commitment (at the United Nations Climate Change Conference in Glasgow in 2021).
- Quantitative research methods: Using some indicators as internal rate of return (IRR) and net present value (NPV) calculations for financial analysis to assess the feasibility and profitability of investment projects. In the context of CCUS and carbon recycling, these methods are applied to compare upfront capital costs with projected future cash flows from carbon credit sales or operational savings. This enables policymakers and investors to make evidence-based decisions on project viability (IEA, 2021; UNIDO, 2024).
- Roadmap development and regulatory framework: Based on findings from the literature review, interviews, and considerations studies, a strategic roadmap will be developed, outlining short-term, medium-term, and long-term actions necessary for implementing an effective CCU policy in Viet Nam.

2. Overview

CCUS expands traditional carbon capture and storage (CCS) as well as carbon capture and recycling by not only storing CO₂ but also utilising it for industrial applications. This dual function enables both emissions reduction and the generation of economic value (IEA, 2020). Whilst most current CCUS projects derive revenue from selling CO₂ for enhanced oil recovery (EOR), there is growing interest in alternative uses such as synthetic fuel production, chemical manufacturing, and the creation of carbon-infused construction materials like carbonated concrete (Consoli and Kimura, 2017; IEA, 2023). These innovations support circular economy models and contribute to achieving the Sustainable Development Goals. Importantly, CCUS is considered a vital strategy in decarbonising hard-to-abate sectors, including cement, steel, and petrochemicals (Global CCS Institute, 2022). As CO₂ recycling becomes more integrated into closed-loop industrial systems, CCUS stands out as a comprehensive and scalable solution to global carbon mitigation challenges.

According to data from the World Bank, in 2022 Viet Nam ranked 21st in the world in terms of CO₂ emissions. The country accounts for about 0.8% of total global emissions (World Bank, 2022). Although not amongst the largest emitters, Viet Nam's emissions are increasing rapidly due to its high economic growth rate. According to a report by the World Bank, Viet Nam's CO₂ emissions increased fourfold from 2000 to 2018, with per capita emissions increasing from 0.79 tonnes to 3.81 tonnes. In 2022, Viet Nam emitted about 344 million tonnes of CO₂. Notably, the energy sector accounts for 63.3% of these total emissions. This increase not only contributes to pressure on the environment but also increases the impact of climate change on the country (World Bank, 2022).

With awareness of its responsibility and role in the fight against climate change, at the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change in November 2021, Viet Nam made strong commitments to reducing greenhouse gas (GHG) emissions, accordingly, with national efforts and international support, Viet Nam will bring net GHG emissions to '0' by 2050 and reduce methane emissions by 30% by 2030 compared to 2020. Recently, the National Strategy on Climate Change for the period up to 2050 submitted to the Prime Minister for promulgation (July 2022) has identified specific measures to achieve net emissions of '0' by 2050, in line with the commitments made at COP26 with the goal of proactively and effectively adapting, reducing vulnerability, loss and damage due to climate change; reduce greenhouse gas emissions towards the goal of net zero emissions by 2050; actively and responsibly contribute to the international community in protecting the Earth's climate system; take advantage of opportunities from climate change response to shift the growth model; and enhance the resilience and competitiveness of the economy (Prime Minister of Viet Nam, 2022b). This commitment not only reflects international obligations but also the need to respond to the country's increasing emissions, whilst protecting the environment and developing sustainably. This is an important basis for Viet Nam to continue to implement actions to respond to climate change more strongly in the coming period. To realise this plan, Viet Nam's updated Nationally Determined Contributions (NDC) by 2022 commits to reducing GHG emissions by 43.5% by 2030 compared to the business-as-usual scenario and achieving net-zero emissions by 2050, in line with the commitments in COP26 in 2021 (Socialist Republic of Viet Nam, 2022).

For pursuing this goal, Viet Nam needs to have appropriate strategies and policies to gradually eliminate carbon emissions from its economy. In addition to other solutions such as developing renewable energy, electrification and clean hydrogen (including blue hydrogen and green hydrogen), the process of CCUS is considered one of the important solutions in the energy transition process

towards the goal of carbon neutrality by 2050. Based on the existing potentials in capacity, the ability to store CO₂ in geological layers as well as the process of recycling CO₂ into products serving human life, CCUS is a suitable solution to reduce emissions in areas with large emissions sources such as coal-fired thermal power plants, gas-fired power plants, oil exploitation or industries that emit a lot of CO₂ such as cement, steel, etc.

Viet Nam's projected demand for CO₂ in industrial and energy sectors is expected to reach 38.6 million tonnes by 2030, driven by applications in fertilisers, methanol, plastics, and concrete. This surge presents both an opportunity and a challenge: to utilise CO₂ as a resource, whilst aligning with the nation's commitment to achieve net-zero emissions by 2050 (VPI, 2018).

Table 7.1. Forecast of Viet Nam's Carbon Dioxide Demand in 2030

Fields	CO ₂ -infused Output in 2030	Amount of CO ₂ Converted	Scale	Level
Fertiliser (urea)	1,600	2,215	Big	Commercialisation
Methanol	700	1,375	Big	Pilot
Ethanol	440	840	Medium	Commercialisation
Dimethyl ether	2,700	7,000	Big	Commercialisation
PE (plastic)	1,000	10,800	Big	Commercialisation
PP (plastic)	1,750	16,200	Big	Commercialisation
PS (plastic)	530	5,700	Big	Commercialisation
Other chemicals	150	1,500	Medium	Commercialisation
Carbon nanotubes	3.7	8	Small	Pilot
Concrete	20,000	500	Medium	Pilot

PE = polyethylene, PP = polypropylene, PS = polystyrene.

Source: Minh and Huong (2023).

By capturing CO₂ emissions from industrial processes and repurposing them for industrial use, CCUS not only supplies the necessary CO₂ for various applications but also significantly reduces greenhouse gas emissions. Table 7.1 presents a forecast of Viet Nam's CO₂ demand across various sectors by 2030. The sectors with the highest projected CO₂ conversion include plastics (polypropylene, polyethylene, polystyrene), dimethyl ether (DME), and fertiliser production. DME and PP plastics are expected to convert 7,000 and 16,200 tonnes of CO₂, respectively, indicating their significant roles in CO₂ utilisation. Most applications operate at large scale and are at the commercialisation stage, except for methanol, carbon nanotubes (CNTs), and concrete, which remain at the pilot stage. Despite the small CO₂ conversion associated with CNTs (only 8 tonnes), their high-value applications make them noteworthy. These data underscore Viet Nam's growing interest in using captured CO₂ for industrial production (Minh and Huong, 2023). Implementing CCUS and carbon recycling technologies can help Viet Nam decouple industrial growth from carbon emissions, fostering sustainable economic development. Moreover, it positions the country to capitalise on emerging carbon markets, attracting international investments, and enhancing its competitiveness in a low-carbon global economy (Mai, 2025). In this way, integrating CCUS/CCU into Viet Nam's policy framework is essential to meet the rising CO₂ demand sustainably and to fulfil its net-zero commitments. This approach not only addresses environmental concerns but also promotes economic resilience and growth in the face of global climate challenges.

3. Current Legal Document System in Viet Nam

3.1. Viet Nam's Orientation in Developing CCUS/CCU

In 2016, Viet Nam signed the 2015 Paris Agreement. The government, as well as the Ministry of Natural Resources and Environment, has taken many measures to reduce CO₂ emissions. These include building a policy and legal framework on climate change, launching tree planting campaigns, restricting the construction of factories with outdated technology that emit polluting gases, and monitoring environmental impacts in concentrated industrial zones to take measures to reduce greenhouse gas emissions. In Viet Nam, CCUS technology has received great attention from policymakers in recent years. Especially after the commitment to bring net emissions to '0' by 2050 and supporting Viet Nam's Declaration on the Global Transition from Coal to Clean Electricity at COP26 in 2021.

CCUS technology has been mentioned in many important strategies, plans, and projects of the government. Specifically, as follows:

- National Strategy on Climate Change (MONRE, 2022): Section 2.b (under Section IV - Tasks and solutions) states: '...Research and apply carbon capture and storage (CCS) technology for fossil fuel power plants and industrial production facilities'.
- National Strategy on Green Growth (Prime Minister of Viet Nam, 2021): Section 4 (Mobilising financial resources and promoting investment for green growth) states '... Establishing incentive mechanisms and incentives for green investment (application of new, clean, modern, low-emissions technologies, efficient use of resources; CCUS technology...' and Section 5.1 (Promoting green growth based on investment in science and technology, innovation) mentions 'Researching, piloting, replicating models of applying science and technology, innovation along with new technologies, advanced technologies, clean technologies serving green growth,... including carbon capture, utilisation and storage technology CCUS...'.
- Viet Nam's Hydrogen Energy Development Strategy to 2030, Vision to 2050: The strategy sets the goal of applying advanced technology in the world in capturing/using carbon associated with the process of producing hydrogen energy from different energy sources by 2030. The strategy also assigns tasks to large State-owned corporations in Viet Nam, such as Petro Vietnam and Vietnam National Coal and Mineral Industries Group, to research and apply technologies in the field of capturing/using carbon associated with the process of producing hydrogen (Prime Minister of Viet Nam, 2024).
- National energy planning: The plan has set the goal of 'Promoting the application of carbon capture, use and storage solutions in industrial production facilities and power plants to achieve the capacity to capture about 1 million tonnes by 2040 and orient about 3–6 million tonnes by 2050'. The plan also sets out the task of having mechanisms and policies to implement the capture and use of CO₂ in energy industry activities, in line with the carbon-neutral roadmap, net zero by 2050 (Prime Minister of Viet Nam, 2023a).
- Decision approving the Project on tasks and solutions to implement the results of the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change, Section 2 (under Section II - Tasks and solutions) states: '... Research, develop and use green ammonia fuel, green hydrogen; store energy and develop technology to capture, store and use carbon...' (Prime Minister of Viet Nam, 2022b).

- Additionally, in the October 2022 updated Nationally Determined Contribution (NDC), there are several sections that mention CCS technology as a solution to reduce carbon emissions from coal-fired power plants and heavy industrial plants (Section 5.1.4, Section 5.1.6 and Section 6.2.4).
- In the electricity sector, the National Power Development Plan for the 2021–2030 period, with a vision to 2050 (Prime Minister of Viet Nam, 2023b), Section VI.9. (Solutions and resources for implementing the plan) mentions the task of ‘...Focusing on developing the renewable energy equipment manufacturing industry, electricity storage equipment, carbon recovery, absorption, storage and utilisation technology... domestically to proactively exploit our country’s available potential, increase independence, reduce the cost of electricity production from renewable energy...’.

3.2. Viet Nam’s Legal Document System of CCUS/CCS

Although attention from the government, businesses, and people and has been mentioned in many strategies, plans, and projects, when going into the details of Viet Nam’s legal regulations in regulations such as the Investment Law, Environmental Protection Law, Land Law, Petroleum Law, Geology and Minerals Law, Decree on gas business, etc. there are currently no specific regulations on management, operation, exploitation, transportation, or incentive mechanisms and development incentives related to CCUS projects. This is presented in Table 7.2.

Table 7.2. Current Status of Carbon Capture, Utilisation, and Storage/Carbon Capture and Utilisation, Viet Nam

No	Aspects	Name of Laws and Regulations	Current Policy Status
A Technology			
1	Support R&D of CO ₂ capture and reuse technology	Law on Science and Technology 2013, Law on Environmental Protection 2020	National science and technology programs support environmental technology R&D but do not have specific priorities for CCUS; there is no direction in the National Science and Technology Development Strategy to 2030.
2	Clean technology transfer	Law on Technology Transfer 2017	There are policies to support the transfer of environmentally friendly technology, but there are no clear regulations on CO ₂ recovery and reuse technology.
3	Standards/ specifications for CCUS devices	Law on Technical Standards and Regulations 2006 (amended 2018)	There are no national standards or technical regulations for equipment and processes for capturing, compressing, storing, and reusing CO ₂ .
B Human Resources			
1	CCUS-related specialised training	Law on Higher Education 2018, Law on Science and Technology	There is no separate training code or specialised subject on CCUS in engineering, environmental, and chemical training programmes.
2	International co-operation in training and human resource transfer	Decree 95/2022/ND-CP on Science and Technology Cooperation	There are mechanisms for co-operation in training and exchange of experts, but CCUS is not yet the focus of international co-operation programmes.

No	Aspects	Name of Laws and Regulations	Current Policy Status
C Finance			
1	Investment incentives (tax, land, interest rate incentives)	Investment Law 2020, Environmental Protection Law 2020	CCUS may be included in the green investment portfolio, but is not specifically regulated to receive investment incentives such as tax exemption/reduction, land access
2	Green finance, green credit, green bonds	Decision 21/2025/QDD-TTg	There are definitions and guidelines for green credit, but CCUS is not yet listed in the list of industries eligible for green credit loans or green bond issuance (Prime Minister of Viet Nam, 2025b).
3	Public investment	Law on Public Investment 2019, Decree 35/2021/ND-CP on Energy Sector Planning	There is no public investment portfolio for CCUS in related sectoral plans (energy, chemicals, environment)
4	Private investment	Law on Public–Private Partnership (PPP) Investment 2020	The legal basis is available, but there has been no pilot project applying the PPP mechanism to CCUS technology due to a lack of economic efficiency and no clear carbon purchasing mechanism.
5	International sponsorship and support	Global Environment Facility, World Bank, United Nations Development Programme, Japan International Cooperation Agency	Some environmental funding programs may apply to CCUS (World Bank funds CO ₂ capture project at Ca Mau fertiliser power plant), but lack clear reception, guidance and priority mechanisms for CCUS projects.
D Infrastructure			
1	CCUS/CCU transportation and infrastructure	Law on Planning 2017, National Energy Development Strategy 2020–2045	There is no planning for CCUS/CCU, including transportation and infrastructure; CCUS content has not been integrated into energy and transport strategies.
2	Bio-industrial park, circular economy	Decision 687/QD-TTg 2022 on Circular Economy	There is a circular economy orientation but CCUS technology has not been specifically integrated into biological industrial park models or closed industry clusters.
E Market			
1	Carbon credit market	Law on Environmental Protection 2020 (Article 139), Decree 06/2022/ND-CP	CCUS has the potential to generate carbon credits, but there is no guidance for verifying and recognising credits from CO ₂ capture and reuse activities.
2	Auction/trade of recycled CO ₂	Commercial Law 2005, Chemical Law 2007	There are no specific regulations on the pricing and trading mechanism of recycled CO ₂ as a commercial product or industrial input material.

CCU = carbon capture and utilisation, CCUS = carbon capture, utilisation and storage, CO₂ = carbon dioxide, R&D = research and development.

Source: Compiled by authors.

Based on the analysis from Table 7.2, it can be seen that, in terms of overall policy documents, Viet Nam does not have laws and technical, safety, and environmental standards and regulations on CCUS. With the existing potential (to be presented Section 7.4) along with the orientations planned by the State, the development of a legal framework and regulations for CCUS/CCU is urgent and requires consideration of all aspects of the value chain. In particular, CCUS is the focus because it raises new and complex issues for regulation such as: ownership, management rights and legal responsibility for the amount of CO₂ that will be permanently stored; ensuring the selection of suitable locations and safe operation, whilst minimising and managing risks during the stages of development; legal basis for CO₂ ownership and resource management (Duc et al., 2024).

4. Potential of Carbon Capture, Utilisation, and Storage in Viet Nam

CCUS/CCU will play a role in decarbonisation in all energy transition scenarios. However, to achieve the announced net-zero emissions target, global CCUS capacity needs to increase more than 100-fold in the long term, reaching 4 to 6 gigatonnes of CO₂ by 2050, and decarbonisation is expected to reach about 15 to 20% of current energy-related emissions. According to McKinsey, along with the development and diversification of the CCUS market, average annual investment in CCUS is likely to increase sharply and could peak at nearly US\$175 billion around 2035 and surpass current gas investment as early as 2026 (McKinsey & Company, 2022). Of which, more than 70% of total global CCUS investment will be concentrated in the ASEAN region, China, India, and North America. This report will focus on analysing the potential and updating some pilot projects of CCUS in Viet Nam in heavy industrial fields such as oil and gas exploitation and energy (Biniek et al., 2024; Duc et al., 2024).

4.1. Current Status of CCUS/CCU in Viet Nam

Currently, CO₂ in Viet Nam is mainly used in the fertiliser and petrochemical sectors. Each year, the two largest fertiliser plants in Viet Nam, Phu My and Ca Mau, use about 80,000 tonnes of CO₂. This amount of CO₂ will be collected directly from the factory's exhaust gas and from exhaust gas treatment plants in the surrounding area.

The first CCU was built at Phu My Fertiliser Plant (a subsidiary of PVN) located on the premises of Phu My Fertiliser Plant, Phu My Industrial Park, Phu My Town, Ba Ria Vung Tau Province and inaugurated in 2010. The plant applies CO₂ recovery technology, the KM-CDR process¹ of Mitsubishi Heavy Industries, Ltd. (Japan) with CO₂ purity reaching 99%, with a capacity of 48,000 tonnes of liquid CO₂ per year, this amount of CO₂ will combine with the excess ammonia (NH₃) of the plant during the production process to synthesise urea fertiliser. The construction of the plant

¹ <https://www.mhi.com/business/products-services/energy-environment/co2-capture-solutions-ccus/co2-capture-technology/co2-capture-process> (accessed 11 March, 2025)

has contributed to increasing the output of urea granules from 740,000 tonnes/year to 800,000 tonnes/year, contributing to reducing CO₂ emissions equivalent to 40,000 tonnes/year. This project does not involve long-term geological storage, which is the key characteristic of full CCUS systems. Storage – such as injecting CO₂ into saline aquifers or depleted oil and gas fields – is what distinguishes CCUS from CCU. The Phu My project is a CCU system, not a full CCUS project, because it captures and reuses CO₂, but does not store it permanently underground. It contributes to emissions reduction and circular economy goals, but lacks the 'S' (storage) component of CCUS.

The second CCU being piloted in Viet Nam is the CO₂ recovery project from permeate gas at the Ca Mau fertiliser plant, in collaboration with the Ca Mau gas plant under the sponsorship of the Viet Nam Energy Efficiency for Industrial Enterprises Project of the World Bank in the period 2008–2022 (World Bank 2020). Accordingly, the project applies technology to recover and refine permeate gas (composition of 54.0% CO₂ and 43.6% methane [CH₄]) as an additional raw material for the urea fertiliser plant. During its operation, the system has recovered more than 40,000 tonnes of CO₂/year to serve urea production, helping to save more than 600,000 gigajoules per year of energy, contributing to reducing the cost of processing imported CO₂ for the factory as well as reducing total GHG emissions by about 80,000 tonnes of CO₂/year.

In addition to the projects that have produced results, a number of CCUS/CCU pilot projects are underway, including:

In coal-fired power plants, CO₂ injection project in the offshore waters of Ca Mau province, within the co-operation agreement between Vietnam National Oil and Gas Group (PVN) and Malaysia National Oil and Gas Group (Petronas) are expected to be implemented in 2027–2028, PVN's coal-fired power plants also have a roadmap to separate CO₂ from exhaust gas using the post-combustion carbon capture method, using amine solution absorption technology with a capture efficiency of 90%, and will conduct a pre-feasibility study in 2025–2026 at Vung Ang 1 plant (Duc et al., 2024).

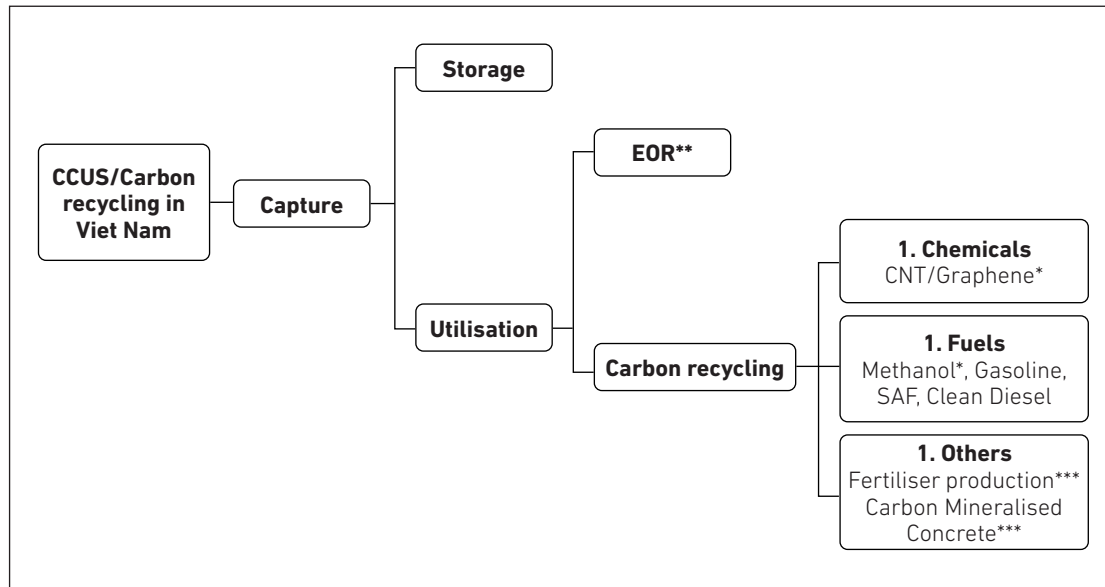
In the oil and gas sector, From October 2008 to March 2010, PVN, the Japan Organization for Metals and Energy Security (JOGMEC), and JX Nippon Oil and Gas Exploration collaborated on a feasibility study for applying CO₂-enhanced oil recovery (CO₂-EOR) at the Rang Dong oil field. Phase I included laboratory experiments and simulation studies, indicating that CO₂-EOR could increase oil recovery by over 32 million barrels, but with a cost of approximately US\$1 billion – making field-scale application unfeasible under 2010 conditions. As a result, a single-well CO₂ Huff n Puff pilot test was designed to assess technical feasibility. On 15 February 2011, the three parties signed a joint research agreement to conduct a CO₂ injection test at well N-02P targeting the Lower Miocene reservoir at Rang Dong field. This was the first offshore CO₂-EOR test in Southeast Asia. The pilot test, conducted from 19 May to 6 June 2011, yielded positive results, increasing oil production from 950 to 1,500 barrels per day. JOGMEC subsequently recommended a preliminary study for an extended test in 2012.

In chemicals production, PVN, through its research arm Vietnam Petroleum Institute (VPI), has made significant progress in developing carbon nanomaterials, particularly carbon nanotubes (CNTs) and graphene, from Viet Nam's abundant natural gas resources (VPI, 2022).

Currently, CNT production is still limited to laboratory and small-scale development. Most existing CNT production technologies use powder-form catalysts. The VPI has successfully conducted experimental synthesis of CNTs from CO₂-rich natural gas (with a composition similar to that of the Blue Whale field) using sheet-form metal catalysts. Using chemical vapour deposition (CVD) technology, the VPI has successfully synthesised CNTs from simulated gas containing CH₄ and CO₂, mimicking the composition of gas from fields like Cá Voi Xanh (Blue Whale). The estimated production cost is only US\$0.5–US\$1/gram, which is considerably lower than the domestic market price of US\$5–US\$7/gram. Furthermore, the VPI has refined a redox-based process to produce high-purity graphene from CNTs, enabling the integration of these advanced materials into practical applications. These include lubricants with enhanced anti-wear properties, anti-corrosion coatings for metal surfaces, smart fertilisers with controlled nutrient release, and reinforcement additives in rubber, cement, and concrete. The VPI has also initiated collaborations with industrial partners such as PVCFC to commercialise these technologies and is also conducting research to effectively utilise natural gas with high CO₂ content, particularly from small and marginal gas fields that are not economically viable for pipeline collection. The approach involves converting high-CO₂ natural gas into clean fuels using floating technologies such as floating gas to chemicals to produce methanol, or floating gas to liquid to generate clean gasoline, diesel, and sustainable aviation fuel (Le, Phan, and Nguyen, 2024; Nguyen et al., 2022).

In construction materials, Keppel, Singapore's largest multinational company, co-operated with Viet Nam's concrete company FiCO Pan-United and construction firm Coteccons in early May 2024 to apply carbon mineralised concrete technology in their construction. Carbon mineralised concrete involves the addition of carbon dioxide during the mixing and production procedure. This process seals carbon dioxide in the concrete and reduces the amount of needed cement simultaneously, but without compromising the structural strength. It is considered a sustainable concrete solution. FiCO Pan-United estimates that applying carbon mineralised concrete technology in the construction of the Infiniti project, along with low-carbon cement, will reduce carbon emissions by 2,803 tonnes compared to traditional materials (Recessary, 2024).

Figure 7.2. Applications of Carbon Capture, Utilisation, and Storage and Carbon Recycling in Viet Nam



CCUS = carbon capture, utilisation, and storage, CNT = carbon nanotube, EOR = enhanced oil recovery, SAF = sustainable aviation fuel.

Notes:

* Projects currently under development at the laboratory or small-scale levels.

** Projects undergoing pilot testing.

*** Projects that have been commercialised and have delivered results.

Source: Authors based on Petrovietnam (2024) and Reccessary (2024).

4.2. CCUS Potential in Viet Nam

CCUS is known as one of the few solutions to decarbonise heavy industry, opening up many new economic opportunities such as hydrogen production, low-carbon ammonia production, enhanced oil recovery (CO₂-EOR) that can help increase oil production in the late stage of the reservoir life cycle, surpassing the ability to achieve by conventional recovery methods besides the important goal of reducing large amounts of CO₂ emissions into the environment.

Table 7.3. Potential Carbon Dioxide Conversion in Viet Nam

Sources	Conversion Method	Expected Products
CO ₂ (from industrial sources)	+ H ₂	Methanol* → DME (dimethyl ether)
	+ H ₂	Methane
	Electrolysis	CNTs (carbon nanotubes)
	Pyrolysis	Liquid Fuel
CO ₂ + CH ₄ (from oil and gas exploitation)	Reforming	Fertiliser*
	Reforming	H ₂ *
	Reforming	Liquid fuel & methanol*
	Pyrolysis	CNTs (carbon nanotubes) *
	Reforming / Other	Petrochemical project*

CO₂ = carbon dioxide, H₂ = hydrogen.

Note: * VPI, PVN researched/continues researching.

Source: Authors based on Petrovietnam (2024).

Viet Nam has many sources of CO₂ emissions, such as coal mines, oil and gas rigs, transport, thermal power plants running on gas and coal, and concentrated industrial zones. These are large sources of CO₂ emissions that can be used to carry out CCUS/CCU projects. Currently, according to some studies by PVN and some partners, the total estimated (theoretical) storage potential for saline aquifers, oil and gas fields and enhanced coalbed methane recovery is about 12 gigatonnes (Gt) of CO₂. Of which, mineralised aquifers have the largest potential with more than 10 Gt. Although mineralised aquifers have a higher CO₂ storage potential than oil and gas fields, there are currently not many studies, assessments, or information about CCUS projects in this subject in the world (Duc et al., 2024). In the chemicals sector, due to the specific geological formation characteristics, the CO₂ volume in natural gas fields in Viet Nam is high. Notably, Viet Nam has two major gas fields with very large natural gas reserves that are currently planned for exploitation: the Block B – Ô Môn gas field and the Blue Whale (Cá Voi Xanh) field, with estimated reserves of approximately 107 billion standard cubic metres (Sm³) and 150 billion Sm³, respectively. However, both of these fields contain high levels of CO₂ with approximately 20% and 30% by volume, respectively. One emerging trend receiving attention is the recycling of CO₂ separated from these gas fields by converting natural gas into high-value-added products such as nanocarbon materials, including CNTs and carbon nanofibres. These materials can also serve as substitutes in several traditional manufacturing sectors, such as lubricants, coatings, asphalt, and fertilisers.

In the field of electricity production and industry, CO₂ emissions from coal-fired thermal power plants account for a large proportion of total emissions from coal-using households. With a coal-fired thermal power capacity of 25.3 gigawatts (GW) in 2022 (MOIT, 2023), and the energy sector emitting approximately 207.5 million tonnes of CO₂ equivalent, making it the largest source of greenhouse gas emissions in Viet Nam (Socialist Republic of Viet Nam, 2022). According to the Power Plan VIII, if 6.2 GW of coal-fired power projects facing difficulties in loans are still built, the coal-fired power capacity is expected to reach 37.4 GW by 2030 (Prime Minister of Viet Nam, 2023b). Thus, CO₂ emissions will be about 208 million tonnes (APEC, 2022). This is a very large source of CO₂ emissions, which needs to be eliminated to achieve the goal of net-zero emissions by 2050. However, Viet Nam currently does not have the technology to reduce CO₂ emissions from coal-fired thermal power plants.

Viet Nam has explored the potential of CCUS/CCU technologies, but these efforts are still in the early stages. Pilot projects and studies have been conducted, especially in energy-intensive industries such as cement and steel. In the future, thermal power plants, industrial parks, chemical plants, petrochemical refineries and offshore platforms with associated gas flares can explore, capture, use, and recycle CO₂ through various technologies. However, the implementation of CCUS/CCU projects in Viet Nam is still facing many challenges, such as high investment costs, the need for support from international partners, issues related to law and environmental management. Therefore, careful consideration and analysis are needed to ensure sustainability and effectiveness in minimising the impact of greenhouse gas emissions on the environment and climate.

4.3. Main Barriers to CCUS Implementation in Viet Nam

In Viet Nam, CCUS and carbon recycling are still considered a new concept, and most projects are implemented in a pilot form. Some of the barriers to implementing CCUS and carbon recycling in Viet Nam are listed as follows:

Policies and legal regulations

One of the biggest barriers today is the lack of a comprehensive and unified legal framework for CCUS or carbon recycling. Viet Nam does not have specific laws or comprehensive regulations to regulate the entire life cycle of CCUS projects, from geological survey, licensing, operational control, and monitoring. Regulations on carbon ownership, carbon credit issuance, transfer mechanisms, and pricing of stored carbon are unclear, causing difficulties in attracting investment and developing the market. Although the Law on Environmental Protection 2020 and a number of decrees related to the carbon market initially mention mechanisms such as carbon credits, measurement, and verification of emissions reduction, they have not specified the application process for CCUS/CCU activities. In addition, the lack of a specific system of documents and direct mention of CCUS and carbon financing, as well as inter-sectoral co-ordination between ministries such as Agriculture and Rural Development, Industry and Trade, Science and Technology, and Finance, also hinders the development of synchronous policies. Therefore, it is necessary to issue a separate guiding decree or include CCUS in the upcoming legalisation plan to create a clear legal corridor and promote the development of CCUS in Viet Nam.

Technological innovation is at the heart of sustainable development. 'Catching up' with industrialised countries requires strong technology policies (United Nations, 2021), and the development and deployment of new green technologies is key to mitigating and adapting to climate change, reducing negative impacts of economic activity on nature, and reducing pollution.² Compared to other clean technologies like electric vehicles (EVs) and hydrogen, it is evident that preferential and supportive policies with specific and well-defined goals play a crucial role in advancing the green transition of the economy. Specifically, EVs and hydrogen have received strong government backing through concrete policies and investment strategies. The government has set clear goals, such as 100% green road transport by 2050 and hydrogen contributing 10% of final energy by mid-century. EVs benefit from tax incentives and are already in use through VinFast (2023) and VinBus

² <https://www.oecd.org/en/topics/policy-issues/green-technology-and-innovation.html> (accessed 30 March 2025).

(2023) projects, whilst green hydrogen projects like the US\$328 million Tra Vinh plant are under development. In contrast, CCUS/CCU remains at an early conceptual stage. Although mentioned in national strategies and the Just Energy Transition Partnership, CCUS lacks a dedicated legal framework or large-scale deployment. Current activities are limited to feasibility studies and international co-operation, with investment below US\$50 million to date. As such, CCUS requires more time for policy development, technical research, and pilot implementation to match the progress seen in EV and hydrogen technologies.

Table 7.4. Carbon Capture, Utilisation, and Storage, Hydrogen, and Electric Vehicles in Viet Nam

Aspect	CCUS (include CCU)	Hydrogen	Electric Vehicles
1. National Policy Support	- Included in the net-zero 2050 target - Energy Master Plan: 1 MtCO₂/year (2040), 3–6 MtCO₂/year (2050) - Mentioned in JETP - No dedicated law yet (Prime Minister of Viet Nam, 2023b)	- National Hydrogen Strategy (2024) - Target: 500,000 tonnes/year (2030), 10–20 million tonnes (2050) - Focus: green hydrogen from renewables (Prime Minister of Viet Nam, 2024)	- Target: 100% green vehicles by 2050 - 0% registration fee until 2027 - Lower excise tax vs petrol cars (Prime Minister of Viet Nam, 2022a)
2. Representative Projects	- Phu My and Ca Mau urea fertiliser production - Pilot CO₂-EOR (Petrovietnam-JOGMEC) - CCUS/CCU studies in the power and chemicals sector (Black & Veatch, 2024; Nguyen et al., 2022) - CNTs research projects by VPI (Nguyen et al., 2022)	- Tra Vinh green H₂ plant: US\$328 million - Quang Tri and Ninh Thuan mega-projects (US\$2 billion+ each) - Ca Mau green ammonia pilot (UNDP, 2023)	- VinFast EV factories (US\$ 1.5 billion+) - VinBus fleet: target 3,000 e-buses in Hanoi, HCMC - EV charging stations expansion (VinFast, 2023; MoT, 2023)
3. Current Status	- Small-scale and separate projects - Mainly R&D and feasibility studies (Black & Veatch, 2024)	- No clean H₂ output yet - Grey H₂ still used - First green plant by ~2025 (MOIT, 2024)	- >8,000 EV cars sold (2022) - >2 million e-scooters - EV buses in operation in two cities (GSO, VinBus, 2023)
4. GHG Emissions Reduction	- 3–6 MtCO₂/year by 2050 - Key for heavy industry, fossil power - Limited impact before 2030 (Energy Plan, 2023)	- 10% of final energy by 2050 - Crucial for industry & power - Minor role before 2030 (Hydrogen Strategy, 2024)	- 12% transport GHG cut by 2030 (~9 MtCO₂) - Full road decarbonisation by 2050 (MoT, 2022; GIZ, 2022)
5. Total Investment to Date (US\$)	- <US\$50 million (Phu My and Ca Mau) - Mostly studies/pilots - JETP may fund pilots	- ~US\$300 million committed (Tra Vinh) - US\$2 billion+ proposed - Pilot support from donors (UNDP, 2023)	- US\$3 billion+ (mainly VinFast) - Public–private funding for e-buses, chargers (VinFast, MoT, 2022)

CCU = carbon capture and utilisation, CCUS = carbon capture, utilisation, and storage, CNT = carbon nanotube, EV = electric vehicle, GHG = greenhouse gas, JETP = Just Energy Transition Partnership, MtCO₂ = metric tonnes of carbon dioxide, VPI = Vietnam Petroleum Institute.

Source: Compiled by authors.

Technology

CCUS and carbon recycling are new and complex technologies that require close integration between many fields such as chemistry, geology, gas engineering, and environmental technology. Viet Nam has not yet mastered the core technology of CCUS, and is largely dependent on imported technology from developed countries. Many advanced technologies, such as CO₂ separation using chemical solvents, and new adsorbent materials, have not been researched and tested in Viet Nam. Technical infrastructure for transporting CO₂ (such as specialised pipeline systems) has not been built and the lack of small-scale CCUS pilot projects also reduces the ability to verify the technology's suitability to Viet Nam's conditions. This poses an urgent need to increase investment in research and development (R&D), international co-operation, and building pilot infrastructure to gradually master technology and localise CCUS equipment.

Currently, CCUS projects in Viet Nam all use foreign technology, for example, the project in Phu My, 'KM-CDR Process' of Mitsubishi Heavy Industries, Ltd. (Japan), JX Nippon Oil & Gas Exploration has deployed CO₂-EOR technology at Rang Dong mine, and plans to co-operate with Black & Veatch (United States) to research carbon reduction technology at three coal-fired power plants (Vung Ang 1 Thermal Power Plant in Ha Tinh province, Song Hau 1 Thermal Power Plant in Hau Giang province, and Thai Binh 2 Thermal Power Plant in Thai Binh province).

Finance

Understanding the economic parameters of CCUS projects is important for policymakers to develop incentives for project implementation. CCUS projects can have large initial capital costs and long-term annual operations and maintenance costs. Information on these costs is essential to quantify the level of incentives at different stages of the project to support large-scale commercial adoption. For example, the initial capital costs and construction costs of a carbon capture plant can range from US\$50 million to US\$1 billion, depending on the source and volume of CO₂ to be captured (IEA, 2022).

The initial investment costs for CCUS projects are very high, especially for large emissions industries such as thermal power, fertiliser production, cement, and steel. It is estimated that the cost of capturing, transporting, and storing 1 tonne of CO₂ can be up to US\$50–US\$100, rely on the technology and location, far exceeding the profit from selling carbon credits at the current level (US\$5–US\$10/tonne in a less advanced market like Viet Nam). In addition, CCUS projects are often projects with long capital recovery periods (15–20 years), with high investment risks, whilst Viet Nam currently does not have preferential credit mechanisms, investment guarantees, or carbon technology development support funds. Commercial banks do not consider CCUS a priority sector, making it difficult to access loans. In addition, the domestic carbon market is still in the experimental stage and has not created a credit price attractive enough to attract private investment. Therefore, there is a need for financial support policies from the State, such as tax exemptions and/or reductions, interest rate support, payment based on emissions reduction results, and mobilising international climate finance to reduce the cost burden for pioneering enterprises.

In Viet Nam, based on the test results from the JOGMEC project at Rang Dong mine, although the technological feasibility has been proven, the results of the test projects show that the investment cost for CCUS is from US\$95–US\$300/tonne CO₂ with an investment cost of US\$1,342 to US\$2,272 million capacity of 1 million tonnes CO₂/year. This cost comes from the cost of collecting and transporting CO₂ from the mainland to the injection well location being too high and the cost of investing in equipment being too large, so the next proposals were not implemented (JOGMEC, 2012; JOGMEC and JVPC, 2012).

In the case of the Phu My Fertiliser Plant, the first CCUS project mentioned above, a US\$27 million investment in the CO₂ recovery technology KM-CDR process was seen as very ambitious and as venture capital for the new technology, as well as an unexpected CO₂ reduction regulation. On the financial side, Phu My generates an annual profit of about US\$1.8 million from increased urea production, but this alone is insufficient to recoup the investment. Without any carbon credit revenue, the project's cash flows produce a negative net present value (NPV) and an internal rate of return (IRR) far below the 8% hurdle rate, indicating an unprofitable venture.

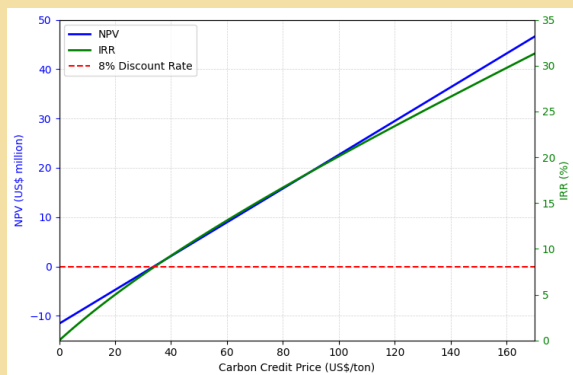
Box 7.1. Financial Analysis of Phu My Carbon Dioxide Recovery Project

The CO₂ recovery project at the Phu My Fertiliser Plant was commissioned to capture and utilise CO₂ emissions from the urea production process. This approach increases urea output whilst reducing greenhouse gas emissions. The project employs CO₂ recovery technology provided by Mitsubishi Heavy Industries (Japan), achieving a CO₂ purity of 99%.

The project's annual net cash flow comprises two main components:

- Profit from additional urea output: US\$1.8 million per year
- Assumption factor: Revenue from carbon credits that varies with the carbon credit price (analysed in a range from US\$0.46 to US\$167 per tonne of CO₂)*

Using these cash flows, the project's financial performance was evaluated. In particular, the net present value (NPV) was calculated at an 8% discount rate, and the project's internal rate of return (IRR) was determined. These metrics are examined under different carbon credit price scenarios to assess the project's sensitivity to carbon pricing.



The blue line represents the NPV in US\$ million (left axis), and the green line represents the IRR in % (right axis). The red dashed line indicates the 8% discount rate (hurdle rate) for IRR. As the carbon credit price increases, NPV rises approximately linearly and IRR increases non-linearly. The project's NPV crosses from negative to positive around the US\$34–US\$35 per tonne level, at which point the IRR likewise reaches the 8% threshold.

Analysis shows that the project essentially breaks even at a carbon credit price of about US\$34.5/tonne. At roughly this price, the NPV $\approx$ 0 (at an 8% discount rate) and the project's IRR $\approx$ 8%, meeting the required rate of return. This price represents the minimum level for financial viability. Above US\$34.5/tonne, the NPV becomes positive and the IRR exceeds the 8% hurdle rate, indicating an attractive investment. Below US\$34.5/tonne, the IRR falls below the 8% discount rate and the NPV turns negative, meaning the project would not be financially attractive to investors. In conclusion, the Phu My CO₂ recovery project achieves a favourable financial outcome only if carbon credit prices remain above approximately US\$34.5 per tonne of CO₂. As shown, at US\$10/tonne (equivalent to the value of some projects being implemented in Viet Nam) the NPV is around US\$8 million and IRR only 2.6%. Thus, if the factory relies solely on additional urea output for revenue, it will be a significant challenge to make a profit from the CO₂ recovery project. There is a need for additional revenue from the sale of carbon credits to achieve profitability.

*Note: This is a hypothetical assumption, as Viet Nam has not officially launched its carbon market until December 2025 and the Phu My project has not yet generated revenue from selling carbon credits.

Source: Authors.

In addition, due to the lack of specific policy guidance on how CCUS projects will be granted green credit and issue green bonds, no project has yet borrowed capital at preferential interest rates for implementation, whilst the initial investment capital required is very large. Despite the increasing importance of industrial decarbonisation technologies such as CCUS, there is currently little to no dedicated financial support through green bonds or credit schemes for such solutions (Climate Bonds Initiative, 2023). This imbalance highlights a significant gap – whilst the energy and waste sectors receive strong financial backing, CCUS remains absent from most green investment portfolios. The lack of tailored taxonomies, verification mechanisms, and carbon credit pricing for CCUS limits its eligibility within current green finance frameworks.

Human resources and capacity

Human resources serving the CCUS sector in Viet Nam are currently lacking in both quantity and quality. CCUS is an interdisciplinary field that requires extensive knowledge of gas processing techniques, exploration drilling, geological simulation, safety assessment, and carbon economics and finance. However, domestic universities and research institutes currently do not have in-depth training programmes on CCUS. The team of engineers, researchers, and state management officials have not been properly trained, and most of them lack practical experience from implemented projects. Access to international documents and courses is also limited due to language and financial barriers. In addition, there is no linkage programme between businesses and training institutions to develop human resources according to market needs. This affects the ability to effectively manage, monitor, and operate CCUS projects. Viet Nam needs to invest in training and fostering officials, establish academic co-operation programmes with foreign countries, and promote the development of domestic experts in this field.

To promote the implementation of CCUS and carbon recycling towards the set goals and in line with the long-term strategy, Viet Nam needs to supplement relevant legal regulations to reduce costs and risks, increase benefits for investors, minimise climate change, and contribute to the country's sustainable development.

5. Proposing a Policy Framework and Roadmap for Implementing Carbon Recycling

With such potential, it is necessary to propose solutions, policy frameworks, and roadmaps for implementing CCUS for Viet Nam and to cover all aspects of the value chain. Currently, Viet Nam does not have specific mechanisms and policies related to the implementation of CCUS/CCU technology. However, CCUS/CCU technology has been included by the government in the list of high technologies prioritised for development as well as in a number of important sectoral strategies and plans (presented in section 3.1).

Some of the above legal issues are scattered in current legal documents for industrial activities such as: the Law on Petroleum, the Law on Environmental Protection, the Law on Resources, Marine and Island Environment, the Law on Water Resources, the Land Law, and Decree No. 42/2020/ND-CP regulating the list of dangerous goods, transportation of dangerous goods by road motor vehicles and transportation of dangerous goods on inland waterways. Regarding the legal framework for CCUS, in 2010, the International Energy Agency (IEA) issued the Model Regulatory Framework (2010 Model Regulatory Framework) to support countries in developing a legal framework for CCUS/CCU and the IEA has proposed six steps that can help guide the

development of a legal framework for CCUS/CCU (IEA, 2010) :

- Step 1: Identify key legal issues
- Step 2: Review international practices, approaches, and standards
- Step 3: Assess current legal frameworks for CCUS/CCU activities
- Step 4: Determine options for regulating CCUS/CCU operations
- Step 5: Determine the most suitable option and build support capacity according to regulations
- Step 6: Periodically review the legal framework and regulations on CCUS/carbon recycling (CR)

5.1. Proposed Policy Framework on CCUS/CCU

To date, CCUS/CCU technology has been included on the government's list of high technologies prioritised for development. Current regulations on 'sea dumping' in the Law on Marine and Island Resources and Environment can be considered for application to CO₂ landfill. The policy framework is built on updating and supplementing existing legal documents, combined with the results of several pilot projects, which will accelerate the promulgation of mechanisms and policies on CCS/CCUS in Viet Nam.

Table 7.5. Proposed Policy Framework for Carbon Capture, Utilisation, and Storage/Carbon Capture and Utilisation in Viet Nam

Principle	- The government leads policy, and the private–public sector takes the lead on investment. - Integrate CCUS with major goals such as energy transition, circular economy, and greenhouse gas emissions reduction. - Take advantage of international support: Climate finance and technology transfer from the European Union, Japan, the Republic of Korea, the World Bank, and the Asian Development Bank.
Legal basis and national strategy	- Issue the National Strategy on CCUS to 2050, in line with the Nationally Determined Contribution and Green Growth Strategy. - Integrate CCUS/CCU into: - Environmental Protection Law - Petroleum Law (to allow CO₂ storage in exploited oil fields and EOR applications) - Investment Law - Energy, industrial, transport and urban planning - Develop a separate legal mechanism to regulate CO₂ capture, utilisation, and recycling.
Technology, research and development	- Establish a list of priority technologies alongside each step of CCUS: Capture and/or utilisation (EOR/fuels/chemicals/materials), storage and common enablers (infrastructure/monitoring and verification) (IEA, 2022) - Support R&D in the fields of: - Optimise CO₂ capture technology at source (cement, electricity, fertiliser, petrochemicals, chemicals production, fossil-fuel-based power...) - Recycle CO₂ into products (building materials, CO₂ for food, chemicals...) - Issue national technical standards on CCUS equipment and procedures.
Human resources and management capacity	- Integrate CCUS/CCU into undergraduate, graduate, and vocational training programmes. - Establish a national centre for innovation and training of CCUS/CCU. - Develop technical manuals and safe operating instructions for businesses and localities. - Public research institutes collaborate with Asian/IEA CCUS networks. Viet Nam's participation in ASEAN Clean Energy Centre's CCUS updates and adoption of the Asia CCS Deployment Roadmap helps align national policies with regional goals.
Finance and investment incentives	- Add CCUS to the list of eligible industries - Preferential income tax, land tax, and preferential loan interest rates - Support access to green credit capital, green bonds - Create a Carbon Technology Development Fund (or use the Environmental Protection Fund, Science and Technology Development Fund) - Encourage the implementation of projects in the form of public–private partnerships and international co-operation to develop CCUS infrastructure

Infrastructure and data	- Plan underground CO₂ storage areas (at sea, depleted oil and gas fields) - Build infrastructure for collecting, transporting, and recycling CO₂ (CO₂ pipelines, storage) - Establish a national data system on CO₂: major emissions sources, usability potential
Market and development mechanism	- Allow CCUS to generate carbon credits to participate in the carbon market (according to the Law on Environmental Protection 2020 and Decree 06/2022) - Develop a domestic CO₂ pricing mechanism, gradually moving towards a carbon tax or emissions trading system - Promote the purchase and sale of reused CO₂ in the food, chemical, and materials processing industries

ASEAN = Association of Southeast Asian Nations, CCS = carbon capture and storage, CCUS = carbon capture, utilisation, and storage, CO₂ = carbon dioxide, EOR = enhanced oil recovery, IEA = International Energy Agency, R&D = research and development.

Source: Authors.

Recognising the potential of CCUS/CR, developed countries have built legal frameworks and issued many policies and incentives to attract businesses to implement projects in this field. In the United States, the Investment in Infrastructure and Jobs Act has been passed into law, providing more than US\$12 billion for CCS and related activities. In Canada, the government has implemented a tax credit worth C\$2.6 billion for CCS projects, whilst the province of Saskatchewan has extended a 20% tax credit under the Oil and Gas Infrastructure Investment Program for CO₂ transport pipelines. In Europe, Denmark has announced a subsidy package worth €5 billion for CCS, whilst Norway has earmarked NOK1 billion (US\$100 million) to support three large-scale green hydrogen projects (Government of Norway, 2021). The United Kingdom has also released a CCUS Investment Roadmap, which sets out plans to develop four low-emissions industrial clusters with CCS by 2030. Whilst North America and Europe have the strongest climate and CCS policies, the Asia-Pacific region is also making significant progress. Japan has adopted its Sixth Strategic Energy Plan, in which CCUS plays a key role in achieving its goal of carbon neutrality by 2050. China has issued more than 10 national policies and guidelines on CCS, including those in its 14th Five-Year Plan (2021–2025) and China's Vision 2035 (People's Republic of China, 2023). In Southeast Asia, both Indonesia and Malaysia have taken steps to legislate on geological CO₂ storage, and the Thai government has also said it is working on legislation (Global CCS Institute, 2022).

Although Viet Nam signed a commitment to implement the Paris Agreement in 2016, there are no legal regulations for CCUS or CCU yet. Based on the experience of a number of countries that have issued CCUS mechanisms and policies, as well as the eco-innovation determinants approach as an important solution to reduce CO₂ emissions towards the net-zero target, the research team proposes a number of solutions to promote the implementation of the policy framework in section 5.1 as follows:

For the policy side

Enabling framework

Clear and streamlined regulations for CCUS should accompany these efforts to avoid excessive red tape and encourage innovation (Prendergast, 2025). To have a legal basis for implementing the project, the government needs to soon direct the Ministry of Agriculture and Environment to preside over and co-ordinate with relevant ministries such as Industry and Trade, and Finance to submit to the government a legal framework, incentives, plans, and roadmap for the CCUS project. Some laws and decrees need to be amended and supplemented accordingly, such as:

- Law on Environmental Protection: supplementing concepts, regulations on environmental impact assessment, standards, and regulations on monitoring during CO₂ storage

- Law on Petroleum No. 12/2022/QH15: Regulations allowing the use of used oil wells to inject CO₂ gas
- Law on Labor Safety and Hygiene: Regulations on ensuring safety for workers in areas where CO₂ is stored, pumped and transported
- Decree No. 42/2020/ND-CP regulating the list of dangerous goods, transportation of dangerous goods by road motor vehicles and transportation of dangerous goods on inland waterways: Regulations on allowing enterprises to build CO₂ transport pipelines on roads and waterways.

In addition, it is necessary to study and promulgate additional regulations requiring businesses, especially groups of businesses that emit large amounts of CO₂ such as thermal power plants, cement, steel, chemical plants, petrochemical refineries, etc. If the legal basis is clear, reasonable incentives will become sanctions, forcing businesses that emit emissions to recover emissions; businesses with capital will invest in technology to perform emissions recovery services and store CO₂ at locations planned and approved by competent authorities. This is also the basis for Viet Nam to form a market for CO₂ emissions recovery, storage, and trading services, helping businesses improve their competitiveness in the international market, meeting Viet Nam's net-zero commitment goal at COP21 (at the United Nations Climate Change Conference in Glasgow in Paris in 2015).

Financial and investment support and incentives

Mobilising investment will require supportive and innovative financing mechanisms. The government should introduce targeted policies to de-risk these investments. In July 2025, a vital decision on green credit and green bonds was issued and enforced with outlined environmental criteria for project eligibility (Prime Minister of Viet Nam, 2025), CCUS was not included in this taxonomy due to the lack of effectively practical projects. Additionally, experiences from the UK show that strong government backing helps unlock private capital (HM Government, 2021). Furthermore, Viet Nam should promote green credit, issue sovereign green bonds, and offer fiscal incentives like interest rate subsidies or guarantees.

The CCUS/CCU project is a long-term investment process because the technology of collecting, transporting, and storing CO₂ requires modern technology, specialised equipment, a large amount of investment capital, and a long payback period, unlike other business sectors. Therefore, it is necessary to classify businesses involving in the manufacturing process to have preferential tax rates and support, such as:

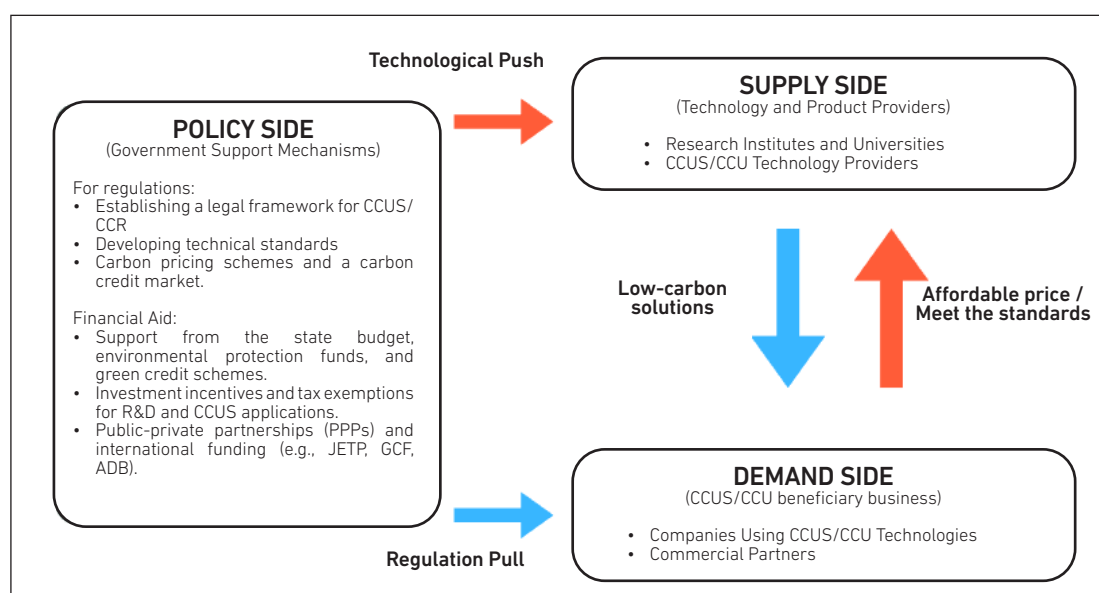
- Businesses applying recovery technologies to reduce CO₂ emissions (steel, thermal power, coal mines, petrochemical refineries, oil and gas)
- Enterprises investing capital and technology to provide services for CO₂ collection, transportation, and recycling.
- Businesses that recover CO₂ and reuse it. For example, oil and gas businesses recover CO₂ and then use it to pump into wells to increase the amount of oil recovered. Or businesses that produce fertilisers and chemicals use recovered CO₂ and reuse it in the production process of fertilisers and chemicals.

Most recently, the Central Executive Committee's Resolution No. 57-NQ/TW has emphasised the need to accelerate breakthroughs in science, technology, innovation, and national digital transformation. The resolution calls for the establishment of a Strategic Program for Technology and Industrial Development, alongside the creation of a Strategic Investment Fund for Industrial Development, with priority given to sectors such as environment and energy. It also mandates the introduction of regulatory sandbox mechanisms to support the research, development, application, and transfer of strategic technologies. Furthermore, it sets a target of allocating at least 15% of

the state science and technology budget to strategic technology research and advocates for the development of public–private partnership (PPP) mechanisms and policies to enhance strategic R&D efforts (Central Executive Committee, 2024). A strategic approach to promote carbon-based innovation in Viet Nam involves supporting enterprises in research, pilot testing, and early adoption of emerging technologies such as CNTs. These materials show high potential in construction, lubricants, and other high-performance applications. Policy mechanisms – such as PPPs, preferential green credit schemes, or direct government funding – can play a critical role in lowering financial barriers and investment risks. Encouraging private sector engagement through these incentives will accelerate commercialisation and foster a low-carbon economy (Nguyen and Dang, 2024).

The interactions and the critical role of the government in promoting R&D and the commercialisation of CCUS/CCU products are illustrated in Figure 7.3.

Figure 7.3. Interactions of Carbon Capture, Utilisation, and Storage/Carbon Capture and Utilisation Determinants



ADB = Asian Development Bank, CCU = carbon capture and utilisation, CCUS = carbon capture, utilisation, and storage, GCF = Global Climate Facility, JETP = Just Energy Transition Partnership, R&D = research and development.

Source: Authors.

For supply side: innovation and technology development

High costs and limited available technology remain major hurdles for CCUS (IEA, 2022). To overcome this, Viet Nam should invest in advanced CCUS technologies and innovation. For example, Australia has designated CCUS as a 'priority technology' in its national roadmap for low-emissions solutions (Australian Government, 2021). Viet Nam's own hydrogen strategy also calls for world-class CCUS technologies by 2030 (MOIT, 2022). By partnering with countries that have operational CCUS/CCU projects and facilitating technology transfer, Viet Nam can facilitate local expertise.

The supply side includes a range of actors involved in developing, piloting, and commercialising CCUS and carbon recycling technologies. Key players include research institutions such as the VPI, the Institute of Chemistry, and leading technical universities like Hanoi University of Science and Technology. These institutions are actively researching the synthesis of carbon-based materials (e.g. CNTs, graphene) from CO₂-rich gases, as well as developing technologies for CO₂ capture and recycling.

In addition to domestic innovation, regional collaboration plays an increasingly strategic role in advancing Viet Nam's supply-side capacity. Viet Nam's supply-side development is further strengthened through technical co-operation with organisations such as Japan Organization for Metals and Energy Security (JOGMEC), which has supported feasibility studies for CO₂-EOR in Viet Nam's offshore oil fields. Similarly, collaboration with regional companies like Petronas enables shared capacity-building, access to reservoir data, and joint ventures in CCUS deployment (PetroVietnam, 2022). These partnerships not only boost Viet Nam's technological capabilities but also provide opportunities to scale up CCUS infrastructure through shared investment and risk mitigation. Besides, participating in CCUS/CCU networks like the Asia CCUS Network can help Viet Nam promote technology transfer, knowledge sharing, and joint development of CCUS infrastructure amongst ASEAN countries and beyond. It also facilitates regional dialogues on legal frameworks and standard harmonisation across borders (ERIA, 2024). Moreover, building a skilled local CCUS/CCU workforce is essential. Viet Nam should launch on-site training programmes and academic partnerships to develop expertise in engineering, geology, and project management for CCUS. On the other hand, Viet Nam can incentivise companies to invest in worker training, integrate CCUS into university curricula, and perhaps establish a PPP for a CCUS centre of excellence. Enhancing local capacity through such programmes will ensure Viet Nam has the human capital to design, operate, and maintain CCUS facilities sustainably.

The government supports this side of the ecosystem through 'technological push' policies, including R&D funding, infrastructure investment, and pilot project facilitation. Regulation-driven innovation is also important: emissions limits and technical standards create market incentives for providers to innovate and scale.

For demand side: industrial adoption and market needs

The demand side comprises businesses and sectors that can adopt CCUS and carbon recycling applications. This includes power generation companies (e.g. EVN, PV Power), cement and steel producers (e.g. Hoa Phat, Formosa), chemical manufacturers, refineries, and transportation providers. These sectors are either high emitters or have processes where captured CO₂ can be reused or stored effectively. For example, CO₂ can be used in EOR, carbon-cured concrete, or chemical synthesis (e.g. methanol, urea) (Nguyen and Dang, 2024).

Private-sector construction firms (e.g. Coteccons, FiCO) and manufacturers of lubricants, paints, and fertilisers are also emerging adopters of recycled carbon materials. These actors generate a 'market pull' that drives the commercialisation of CCUS-based products. At the same time, regulatory pull – in the form of emissions targets, low-carbon product standards, and procurement policies – can accelerate adoption. Government financial aid (e.g. tax credits or green loans) is essential to de-risk early adoption and encourage long-term investment.

Importantly, international climate agreements and regional regulations, such as the Paris Agreement and the European Union's Green Deal and Carbon Border Adjustment Mechanism, are creating strong external pressures for industries to shift towards low-carbon production.

These frameworks promote the use of environmentally friendly products and require exporters to demonstrate embedded carbon reductions (European Commission, 2023; UNFCCC, 2015). As a result, Vietnamese producers seeking to access global markets are being driven to adopt recycled or low-carbon technologies.

A notable domestic example is the initiative by Phu My and Ca Mau fertiliser plants, which have begun recycling CO₂ emitted from ammonia production to manufacture urea fertiliser. This not only reduces the overall CO₂ emissions of the plants but also lowers input costs, improving economic efficiency (Le, Phan, and Nguyen, 2024; Nguyen et al., 2022). Such innovations provide clear incentives for other industries to adopt CO₂-based production technologies. As the cost competitiveness and environmental credentials of these products improve, the demand side is increasingly compelled to source recycled carbon products, reinforcing the supply–demand feedback loop essential for the growth of CCUS and carbon recycling in Viet Nam.

5.2. The Proposed CCUS/CCU Implementation Roadmap

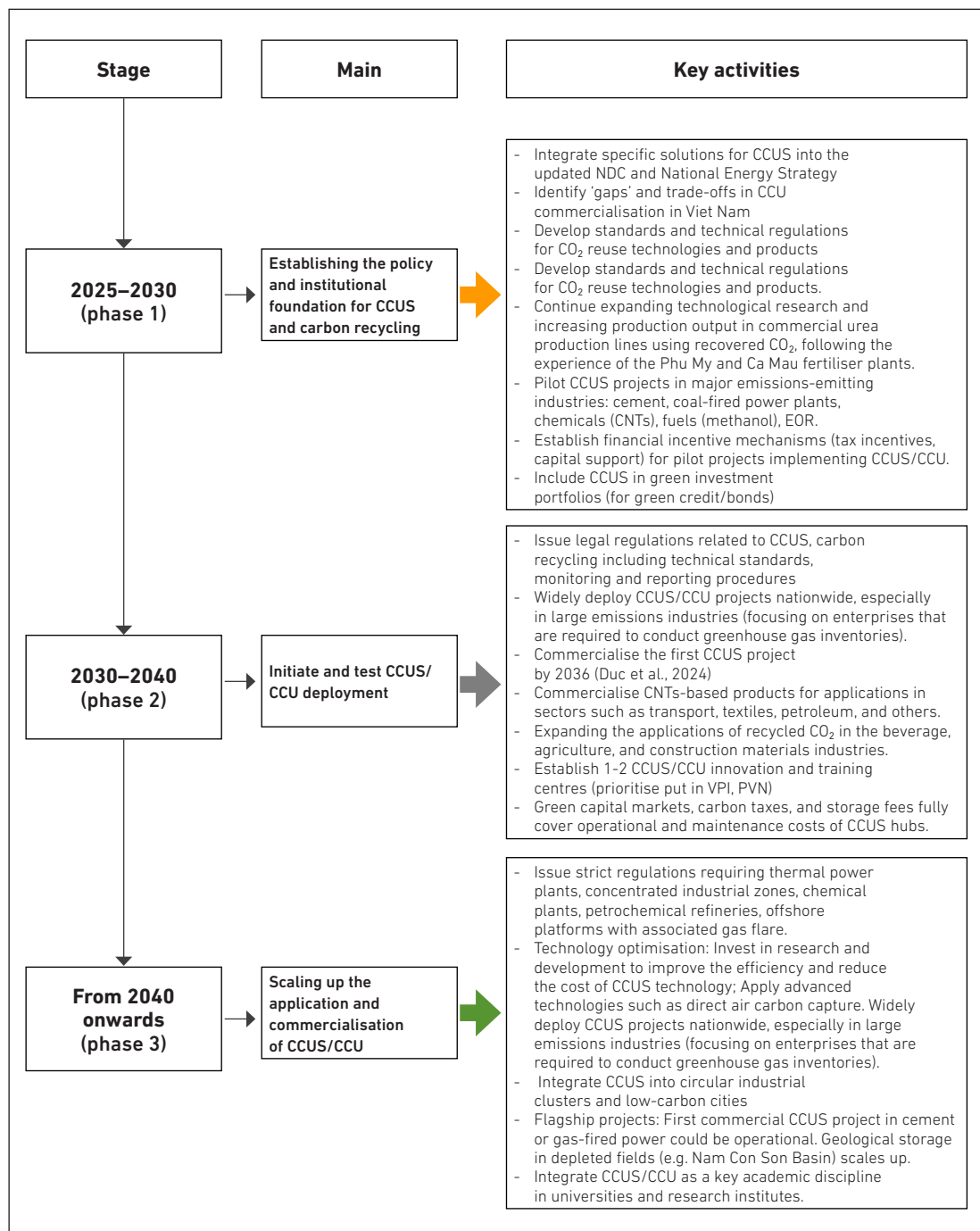
The government assigned the Ministry of Agriculture and Environment to develop and promulgate a plan for CO₂ capture and recycling, as Japan and many other countries have developed plans for 2030 and long-term plans for 2050 in line with the goals of the Paris Agreement. This plan should be divided into small phases to match the investment phases for businesses. For other emissions sources, such as means of transport, enterprises, and small-scale craft villages that emit CO₂ without the conditions to install recovery equipment and technology, the Ministry of Agriculture and Environment will establish emissions fees that must be paid. The collected amount can be set aside for a fund, creating a source of support for enterprises investing in CCUS projects.

CCUS/CCU is a completely new field in Viet Nam. Developing a comprehensive legal and regulatory framework for CCUS/CCU in Viet Nam may take several years and requires close collaboration amongst ministries (Ministry of Industry and Trade, Ministry of Natural Resources and Environment, Ministry of Finance, Ministry of Planning and Investment, Ministry of Science and Technology, Ministry of Justice), businesses, experts, and the community to ensure the safety, sustainability, and effective development of this technology.

The national energy planning has set the goal of promoting the application of carbon capture, use, and storage solutions in industrial production facilities and power plants to achieve the capacity to capture about 1 million tonnes by 2040, with a target of 3 million–6 million tonnes by 2050. The plan also outlines the task of establishing mechanisms and policies for implementing CO₂ capture and utilisation in energy sector activities, consistent with the carbon-neutral roadmap and Viet Nam's net-zero target by 2050 (Prime Minister of Viet Nam, 2023a).

Therefore, to realise this ambitious goal, Viet Nam must begin taking the first preparatory steps now, in parallel with ongoing research and pilot projects as previously discussed. The proposed CCUS/CCU implementation roadmap (Figure 7.4) aligns with Viet Nam's commitments and the orientations of the Party, State, and Government, as well as the development strategies and action plans of relevant sectors, especially reflecting the preliminary roadmap towards the first commercial CCS project in Viet Nam by 2036, jointly developed by Petrovietnam and JOGMEC (Duc et al., 2024), along with current materials research progress conducted by VPI, EVN, FiCO Pan-United, amongst others.

**Figure 7.4. Proposed Carbon Capture, Utilisation and Storage/
Carbon Capture and Utilisation Roadmap**



CCU = carbon capture and utilisation, CCUS = carbon capture, utilisation, and storage, CNT = carbon nanotube, EOR = enhanced oil recovery, NDC = Nationally Determined Contributions, PVN = Vietnam National Oil and Gas Group, VPI = Vietnam Petroleum Institute.

Source: Compiled by authors.

6. Conclusion

In the context of Viet Nam's strong commitment at COP26 to achieve a net-zero emissions target by 2050, carbon capture, utilisation, and storage in general and carbon recycling technology are emerging as important strategic solutions to reduce greenhouse gas emissions in large emitting industries. The report pointed out that Viet Nam has conducted some initial projects in the oil and gas sectors and construction materials, and has significant potential for capturing CO₂ emissions and industrial CO₂ utilisation. However, the implementation of CCUS in Viet Nam is still in its infancy, facing many barriers from the legal framework, technological capacity, finance, and specialised human resources.

To effectively promote CCUS/CCU development, Viet Nam needs to develop a separate policy and legal framework for the entire CCUS value chain, including CO₂ capture, transportation, and utilisation. Current policies, such as the Law on Environmental Protection, the Investment Law, and the Petroleum Law, need to be amended and supplemented to create a clear legal corridor, especially in recognising CO₂ ownership, the carbon credit trading mechanism from CCUS, the pricing of recycled CO₂, and the investment incentive mechanism. In particular, it is necessary to accelerate the promulgation of the National Strategy on CCUS/CCU and integrate this content into the planning of the energy, transport, industry, and environment sectors.

In addition to policies, Viet Nam needs to have specific financial incentive mechanisms for pioneering enterprises investing in CCUS/CCU through tax incentives, access to green credit, green bonds, and low-interest loans from international environmental funds or climate finance. At the same time, it is necessary to invest heavily in R&D, testing technologies suitable for domestic conditions, as well as establishing specialised training centres to develop high-quality human resources in this field.

Finally, a clear implementation roadmap, divided into phases 2025–2040 with specific goals and solutions, is necessary to ensure synchronous and effective deployment of CCUS/CCU technology, whilst contributing to realising the net-zero commitment, protecting the environment and developing a circular economy in Viet Nam.

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Chapter 8

A Global Systematic Review on the Cost of Carbon Recycling Technologies: Towards Sustainable Financing in Indonesia

1. Introduction

1.1. Overview of Carbon Capture Utilisation in the Context of Carbon Management Strategies

The Intergovernmental Panel on Climate Change (IPCC) has determined that the main cause of the increase in the carbon dioxide (CO₂) concentration is fossil fuel burning (mainly from industrial sources such as cement and power plants, iron manufacturing, and the chemical industry). Under the 2015 Paris Agreement, almost all of the world's nations committed to collectively hold 'the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (UNFCCC, 2016). According to the projections, global net anthropogenic CO₂ emissions must be halved by 2030 compared with 2020 levels and reach net zero in 2050 (Rogelj et al., 2018; IEA, 2023). Achieving this net-zero CO₂ target requires deep emissions cuts across all sectors, gradual phase-out of high-emissions technologies, and the deployment of a diverse portfolio of low-carbon solutions (De Kleijne et al., 2022).

To achieve the targeted emissions reduction, carbon capture and utilisation (CCU) has consequently emerged as a promising approach for carbon recycling. By capturing CO₂ from industrial processes or directly from the atmosphere, CCU technologies enable its conversion into valuable products such as fuels, chemicals, and construction materials. This approach not only mitigates CO₂ emissions but also promotes the circular carbon economy by transforming waste carbon into useful resources. This is mainly because the manufacturing processes in the industry sector, such as iron and steel making and chemical product production, which not only emit the substantial amounts of CO₂, but also require large amounts of fossil fuel in their operations (IPCC, 2014).

The reason why CCU contributes as the carbon management strategies is that it replaces fossil feedstocks, avoids upstream emissions, and temporarily keeps CO₂ out of the atmosphere until re-emitted in the use phase of the product. CCU appeals to policymakers and the general public because it is the concept of carbon recycling and seen as part of the circular economy as a form of sustainable waste processing (Cuellar and Azapagic, 2018; IEA, 2019). It also appeals to industry because CCU creates value from waste through CO₂-based products while avoiding the storage costs and concerns of geological storage of captured CO₂, known as carbon (dioxide) capture and storage (CCS) (Lilliestam, Bielicki, and Patt, 2012). In this context, the Carbon Sequestration Leadership Forum changed the term 'CCS' to 'CCUS' (carbon capture, utilisation, and storage) (Rodrigues, Dinis, and Lemos de Sousa, 2015). The main goal of CCU technologies is to integrate the captured CO₂ as a raw material into a range of industrial production processes, either directly or succeeding a chemical transformation. This will produce a twofold benefit, the production of valuable products and the emulation of a natural carbon cycle or at least a partway closing of the industrial carbon cycle. Other beneficial outcomes of CCU technologies are the potential to reduce resource consumption, creating an extension of resource lifetime. Generally, if the economic value of captured CO₂ is high enough to cover its capture and transportation costs, CCUS projects can be profitable (IEA, 2018). Therefore, the key to CCUS projects is now the CO₂ value chain, which requires a feasible business model because it is not only an emission reduction activity but also a business activity (Yao et al., 2018).

According to a report by the International Energy Agency (IEA, 2010), 'utilizing captured carbon dioxide can be a game-changer for the economics of carbon capture, making it more viable for both power and industrial applications'. The report also notes that carbon utilisation has the potential to reduce the cost of CCUS by up to 50%, depending on the technology used and the price of CO₂ emissions. Several carbon utilisation pathways have been proposed and tested, including enhanced oil recovery, mineral carbonation, and the production of chemicals and fuels. Captured CO₂ can be used as a feedstock to produce chemicals and fuels, including methanol, urea, and dimethyl ether.

1.2. CO₂ Utilisation as Carbon Recycling

Carbon utilisation technologies are a set of innovative solutions that aim to transform CO₂ and other carbon-containing waste streams into valuable products, materials, or energy (Godin et al., 2021; Hepburn et al., 2019). These technologies offer a promising approach to mitigating climate change by reducing greenhouse gas emissions and promoting a carbon recycling economy. Carbon utilisation in the production of chemicals and fuels involves the conversion of CO₂ emissions into useful chemical compounds and fuels, creating a sustainable pathway to reduce greenhouse gas emissions (Martens et al., 2017). CO₂ emissions are captured from industrial sources such as power plants, refineries, or cement factories. The captured CO₂ is then converted into chemicals and fuels through a variety of technologies (De Luna et al., 2019). These processes involve the use of catalysts, enzymes, or electricity to convert CO₂ into useful compounds. The produced chemicals and fuels are then commercialised, either by being sold as products or used as feedstocks for other industrial processes.

The main principle behind carbon utilisation in the production of chemicals and fuels is the concept of carbon recycling (Martens et al., 2017). By capturing and utilising CO₂ emissions as a feedstock for chemical and fuel production, carbon utilisation reduces the need for non-renewable resources such as petroleum or natural gas (Tetteh, Amankwa, and Yeboah, 2021). Some common and latest fuels derived from carbon utilisation include synthetic methane, methanol, formic acid, dimethyl ether (DME), and synthetic hydrocarbon fuels.

Synthetic methane, also known as substitute natural gas, can be produced by reacting CO₂ with hydrogen through a process called methanation (Koytsoumpa and Karellas, 2018). This renewable methane can be used as a direct replacement for natural gas in various applications, including power generation and heating. Methanol, produced by hydrogenating CO₂, serves as a fuel for internal combustion engines, fuel cells, and as a feedstock for chemicals such as formaldehyde and biodiesel (Çelebi and Aydın, 2019). Formic acid, synthesised from CO₂, functions as a hydrogen storage material, allowing on-demand hydrogen generation for fuel cells and other applications (Xu and Liu, 2021). DME, produced by reacting CO₂ with hydrogen, is a clean-burning alternative fuel for diesel engines, and is also used as a propellant, refrigerant, or aerosol spray (Kapoor et al., 2020). Furthermore, synthetic hydrocarbon fuels (such as gasoline, diesel, and aviation fuels) can be produced from CO₂ and hydrogen Fischer-Tropsch process (Panzone et al., 2020).

Some valuable chemicals derived from carbon utilisation include urea, ethylene, carbonates, polymers and plastics, and syngas. Generally, urea is produced by syngas and after the separation of carbon dioxide, nitrogen reacts with hydrogen to produce ammonia. In another reactor, ammonia and carbon dioxide react into urea. Urea is produced from CO₂ and ammonia and is widely used as a nitrogen-based fertiliser, as well as in other applications like plastics and resin production

(Liu et al., 2022). Ethylene can be produced from CO₂ through electrochemical reduction processes (Qin et al., 2019) and is an essential building block in the petrochemical industry used to produce plastics, resins, and various chemicals.

Carbon utilisation technologies promote innovation and support the transition to a more sustainable economy. The production of chemicals and fuels for carbon utilisation has promising future prospects. Advances in catalysts, reactors, and separation techniques now enable the efficient conversion of CO₂ into valuable chemicals and fuels (De Luna et al., 2019). Ongoing research and development are expected to further enhance efficiency and reduce cost. Growing demand for sustainable products highlights the importance of carbon utilisation as a renewable carbon source for chemical and fuel production (Yadav, Yadav, and Patankar, 2020). An essential aspect of commercial feasibility for a CCU technology is economic viability and profitability is required, especially compared to conventional production technologies.

1.3. Objectives

The main purpose of this study is to analyse the cost structure of CO₂ utilisation value chain from the carbon capture into valuable products as the value added of CO₂ feedstock. The framework of this study is the assessment of economic feasibility carbon utilisation of CO₂ for useful chemical product such as synthetic fuel, methanol, and its derivatives. Furthermore, more specifically, the objectives of this study are to (i) assessing the capital expenditures (CAPEX) and operational expenditures (OPEX) related to CO₂ utilisation using a systematic review based on the individual studies across the world, particularly in the context of carbon capture and utilisation (CCU); (ii) analysing the costs associated with CO₂ converting it into valuable products or fuels and its value chain for commercialisation technology; and (iii) to assess the relevance and transferability of global cost data for the Indonesian study of carbon recycling, considering the country's industrial landscape, energy mix, and emissions profile.

1.4. Organisation of the Chapter

The organisation of this chapter consists of the following sections. Section 2 discusses carbon capture cost structure of CCU technologies, Section 3 value chain and cost dimensions of CO₂ utilisation and its derivatives into commercial chemical products and fuels, Section 4 discusses the study, and Section 5 concludes with recommendations.

2. Methodology

2.1. Research Design

A global systematic review was conducted using the Scopus web search engine (<https://scopus.com/search>) to identify research papers on CO₂ utilisation and CCU. Scopus is Elsevier's abstract and citation database that covers around 35,000 peer-reviewed journals from over 10,000 publishers. The following keywords were used to search appropriate data with 'OR' function of CCU, CCUS, CO₂ utilisation, cost of CO₂ utilisation, CAPEX of CO₂ Utilisation, OPEX of CO₂ Utilisation, CO₂ to fuel, and CO₂ to chemicals.

The initial search yielded 123 articles, which were then filtered by publication year (2010–2024) to ensure that the studies focused on the latest advancements in the field. Additionally, only articles written in English were considered, resulting in a refined selection of 102 articles. These were further screened for relevance based on their abstracts and categorised into four groups: highly relevant (papers are relevant to the topic and provide a detailed cost structure of CO₂ utilisation and CCU), relevant (papers are relevant to the topic but generally lack a detailed cost structure), partially relevant (papers are relevant to the topic but primarily focus on efficiency, cost reduction, or alternative CCU methods, and irrelevant (papers are related to the topic but do not primarily focus on CCU).

Following a detailed screening process based on the key words (highly screened), 41 highly relevant articles were selected for in-depth assessment of the technology used, cost structures, cost estimation (when available), CO₂ utilisation value chain, technological challenges, business model, benefits, and limitations. Additionally, 23 relevant and partially relevant articles were used to support the discussion by providing insights on cost reduction strategies, efficiency improvements, and alternative CCU technologies. These databases are used exclusively to get a sample of journal articles to examine the feasibility cost of CCUS.

2.2. Meta Data Analysis for Cost Dimension of CO₂ Utilisation

Given the significant contribution of industrial processes to overall global emissions, effective climate change mitigation requires an economic framework focused on CO₂ management. This includes the capture, storage, and transformation of CO₂ into value-added products, supported by the development of technically viable, efficient, and cost-effective CCU and recycling strategies. A total of 64 papers, both high relevant and relevant, were considered into the database for meta-analysis. The focus was placed on CO₂ utilisation and its derivatives for chemical and fuel production, with cost effectiveness assessed through key economic indicators such as CAPEX and OPEX associated with CCU technologies.

3. Findings

3.1. Carbon Capture Cost Structure of CCU Technologies

This section highlights several developments that have affected carbon capture of CCU technologies over the past decades, then summarise current cost estimates for CO₂ capture processes (post-, pre-, and oxy combustion) on our review of recent studies. Table A8 in the Appendix explains the CAPEX and OPEX of the pathways of carbon capture technology (post combustion, pre combustion, and oxy fuel combustion) based on the individual studies of CCU technologies.

3.2. Cost Dimensions of CO₂ Utilisation and its Derivates into Commercial Chemical Products and Fuels

The cost dimensions of CO₂ utilisation, particularly in converting it into commercial chemical products and fuels, involve several factors. These include the cost of capturing CO₂, energy for conversion, catalysts and other materials, and the overall investment needed for scaling up and commercialising these technologies. While CO₂ utilisation offers a potential pathway to reduce emissions and create valuable products, achieving cost-effectiveness and scalability remains a significant challenge.

Indonesia's net-zero 2060 roadmap emphasises the need for scalable emission reduction options aligned with both domestic industrial demand and export potential. Methanol is already on the national priority – not only as a feedstock for biodiesel blending under the B50/B60 policy pathway,¹ but also as a globally traded C1 molecule. Further analysis will also explore additional CCU targets such as DME, blue ammonia, soda ash, and carbon-based polymers that could drive sectoral decarbonisation across fertilisers, household energy, and manufacturing industries.

CO₂ utilisation to methanol

Methanol is a major target product for CCU implementation due to the large global demand; it is predicted that global demand will exceed 95 million metric tonnes by 2021. Furthermore, methanol may be converted to other valuable commodities such as gasoline, olefins, and dimethyl ether. CO₂ utilisation processes are broadly classified into two main categories: physical and chemical utilisation (von der Assen, Jung, and Bardow, 2013). In chemical utilisation processes, CO₂ molecule loses its identity and is transformed into another molecule (as end product), then converted to other product. CO₂ can be utilised chemically to produce fuels and chemicals including methanol, ethanol, DME, dimethyl carbonate (DMC), syngas, methane, and carbonates (Hepburn et al., 2019; Centi and Perathoner, 2014; Syah et al, 2021). Methanol is amongst of the most promising power-to-liquid products due to its versatility and potential to serve as an alternative fuel to gasoline (Koytsoumpa and Karellas, 2018). Methanol is a pivotal volume scale C₁ feedstock in the global

¹ The B50/B60 policy pathway represents Indonesia's aggressive strategy to mandate a blend of 50% to 60% palm oil-based biodiesel (fatty acid methyl ester/FAME) with 50%–40% fossil diesel by 2026. Simultaneously, C1 molecules (such as methanol, derived from gas, or green methanol) are essential in this pathway as they are used in the transesterification process to convert crude palm oil into FAME.

chemical industry, with roughly 42 million tonnes per year used to manufacture formaldehyde (about 70 % of total demand), acetic acid, dimethyl ether, and olefins (via methanol-to-olefins [MTO] or methanol-to-propylene [MTP] processes) and other methylates – making it amongst the most widely used and versatile chemical inputs in sectors from plastics to fuels. Methanol is one of the major feedstocks of the chemical industry and can achieve better overall efficiency through advances in catalyst development, process integration, and the utilisation of renewable raw materials. Methanol can be produced from CO₂ by either one-step or two-steps processes. In one-step process, direct hydrogenation of CO₂ to methanol takes place; while in the two-step process, CO₂ is first converted to CO by reverse water gas shift reaction, which is then hydrogenated to methanol (Laumb et al., 2013). A comparison concluded that both these processes are roughly similar in terms of economic and energy efficiency (Rivarolo et al., 2017). However, cost of electricity was identified to be the major factor effecting the economics of methanol production as water electrolysis (for hydrogen production) requires significant electrical energy input.

According to Su et al. (2022) in Table 8.1, the capital expenditure for renewable methanol production equipment amounts to US\$46,015,712, with a total capital investment of approximately US\$77,673,612. The operational cost of CO₂-to-methanol conversion of renewable methanol production is US\$16.534 million, compared to US\$14.412 million for conventional methanol production from natural gas. Amongst operational costs, the feedstock (natural gas) represents the highest operational costs, with water consumption contributes the least (Su et al., 2022).

Methanol can also be converted to other valuable commodities such as gasoline, olefins, and DME, potentially increasing its market demand. Traditionally, methanol is synthesised using syngas produced from steam methane reforming of fossil fuel sources. The typical approach explored regarding CCU and methanol production is through the indirect thermocatalytic processes, involving the hydrogenation of CO₂ via reforming processes (Ahmed, 2022). The conventional methanol consists of three steps: (i) synthesis gas production, (ii) catalytic conversion of synthesis gas, and (iii) distillation of raw methanol based on the syngas from natural gas.

Table 8.1. Economic Assessment of Carbon Dioxide Utilisation to Methanol Production

Capital Expenditure of Renewable Methanol Production Plant		Operational Expenditure of Renewable Methanol Production		Operational Expenditure of Methanol Production with the Conventional Method (natural gas - syngas)	
Items	Cost (US\$)	Items	Cost (US\$ million)	Items	Cost (US\$ million)
Plant Capacity of Commercial Scale Methanol Production 12,625.37 kg/h and 93,270.96 kg/h of Gas-fired Power Plant Exhausts					
Direct Costs		Electrical energy consumption	0.822	Cost of natural gas	6.168
Purchased equipment	46,015,712	Thermal energy consumption (natural gas feed for methanol production 10 cents per cubic metre)	3.341	Cost of catalyst	0.710
Installation (insulation painting), 10% purchased equipment	4,601,571	Cost of catalyst	0.071	Cost of water	0.200

Capital Expenditure of Renewable Methanol Production Plant		Operational Expenditure of Renewable Methanol Production		Operational Expenditure of Methanol Production with the Conventional Method (natural gas - syngas)	
Items	Cost (US\$)	Items	Cost (US\$ million)	Items	Cost (US\$ million)
Instrumentation & controls, installed	181,020	Cost of water	0.437	Direct wages	1.280
Piping, installed	663,740	Direct wages	1.280	Electrical	0.786
Electrical, installed	110,623	Depreciation	8.848	Depreciation	4.424
Building, process & auxiliary	181,020	O &M cost	1.485	O &M cost	0.549
Service facilities & yard improvement, 3% purchased equipment	1,380,471	Cost of sales and marketing (1% total gross sales)	0.25	Cost of sales and marketing (1% total gross sales)	0.250
Land	60,340	Total Production Cost	16.534	Total Production Cost	14.412
Sum direct costs	53,194,497				
Indirect Costs					
Engineering & supervision	331,870				
Construction expense & contractors feed	211,190				
Contingency fee, 30% purchased equipment	13,804,714				
Sum indirect costs	14,347,774				
Fixed-capital investment	67,542,271				
Working capital, 15% fixed-capital investment	10,131,341				
Total Capital Investment	77,673,612				

kg/h = kilogramme per hour, O&M = operation and maintenance.

Sources: Su et al. (2022), Zhang et al. (2017), Jouny, Luc, and Jiao (2018); Anicic, Trop, and Goricanec (2014), Mondal et al. (2016), Bellotti, Rivarolo, and Magistri (2019), Yousaf et al. (2022).

As shown in Table 8.1, the total construction cost of a conventional methanol production plant is \$46.807 million, with the methanol production process accounting for the biggest share of the equipment purchase cost. The reactor, compressors, and distillation have the biggest share of the cost, while the smallest share of the equipment cost belongs to the pumps (Su et al., 2022). The investment and production cost for renewable methanol are approximately 1.07 and 1.147 times higher than those of the conventional method, respectively. Su et al. (2022) compared the conventional and renewable methanol production methods through a thermos-economic analysis. Synthesis gas is produced from a compound of hydrogen from water electrolysis and CO₂ from a gas power plant and then it is converted into renewable methanol by going through a few stages. Based on the economic indicators in Table 8.1, the internal rate of return differs considerably between both methods (with discount rate 18%–20%), while the payback period varies slightly due to differences in CAPEX. Moreover, the OPEX of the conventional method is higher than renewable methanol, though the CAPEX contrast is more significant.

Methanol production by CO₂ hydrogenation is generally considered as economically infeasible due to huge cost of hydrogen production. Yousaf et al. (2022) examined the integrated process combining methanol production and solid oxide electrolyser hydrogen production, improving overall economic viability of methanol. In the reproduced process, the cost of the hydrogen production was based on alkaline electrolysis estimates, with the methanol cost estimated at US\$1,165/tonne. The study found that hydrogen production was identified to be the major cost burden on methanol economy with contribution of more than 83%, including both operating and capital expenses, indicating that even a small improvement in hydrogen economics could improve the economy of methanol production. Utilities (electricity and cooling water) contributed around 2.4% of total methanol costs, other operating expenses (workforce, contingencies, etc.) around 7.66%, and capital cost only 1.0%. When incorporating the sale of oxygen, methanol production cost per tonne was reduced to US\$1,063 per tonne.

Table 8.1 shows that the conversion of CO₂ into methanol typically happens through one of two main methods: catalytic hydrogenation and electrochemical conversion. In CO₂ utilisation, renewable hydrogen (produced from water electrolysis powered by renewable energy) can be used to achieve a carbon-neutral process: $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$. When using renewable hydrogen, hydrogen production cost becomes a major factor, typically ranges from US\$2–US\$6 per kilogramme, depending on the production method (e.g. steam methane reforming or electrolysis) and the scale of production. Consequently, methanol production via this method can cost US\$300–US\$800 per tonne of CO₂, including both CO₂ capture and hydrogen production.

In electrochemical conversion, CO₂ is reduced into methanol using electricity, often from renewable sources like solar or wind, with the reaction of: $\text{CO}_2 + 6\text{H}^+ + 6\text{e}^- \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$. This is a promising technology for utilising CO₂ directly and may eventually offer a more cost-effective and scalable solution with the process, although its cost depends heavily on electricity price and conversion efficiency, ranging between US\$600–US\$1,500 per tonne of CO₂. The electrochemical hydrogenation reaction ($\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$; molar masses: CO₂ = 44 kg/kmol, CH₃OH = 32 kg/kmol) indicates that producing 1 tonne of methanol requires about 1,375 tonne of CO₂ input, meaning that CO₂ feed-input alone would be US\$825–US\$2,063 per tonne of methanol (MeOH), depending on the CO₂ cost.

A crucial cost factor in methanol production from CO₂ is hydrogen. When produced via electrolysis using renewable energy (green hydrogen), cost typically fall between US\$3–US\$6 per kilogram of H₂, but this varies significantly depending on electricity costs and system efficiency. Since methanol production requires three molecules of hydrogen for every molecule of CO₂, the hydrogen cost can

be a large contributor to the final cost of methanol production. Additionally, the process of capturing CO₂ and converting it to methanol is energy-intensive, especially when using renewable electricity or hydrogen, with renewable energy prices generally from US\$30–US\$50 per megawatts per hour (MWh), depending on the region. Therefore, the efficiency of CO₂ conversion (e.g. in electrochemical cells) and hydrogen production systems also plays a role in the final cost.

In summary, establishing a CO₂-to-methanol production plant involves significant capital expenditure for infrastructure (CO₂ capture systems, reactors, electrolyzers, catalysts, and other necessary equipment). The cost of producing methanol from CO₂ varies widely depending on the chosen method, energy source, and scale. However, rough estimates suggest that catalytic hydrogenation with renewable hydrogen the cost can range from US\$500 to US\$1,000 per tonne of CO₂, depending on the price of hydrogen and CO₂ capture methods. Meanwhile, the electrochemical conversion costs between US\$600 and US\$1,500 per tonne of CO₂.

When converted to methanol (using about 1,375 tonne CO₂ per tonne MeOH), and adding synthesis costs, this results in US\$700–US\$1,400 per tonne MeOH for hydrogenation routes, and US\$900 to over US\$2,000 per tonne MeOH for direct electrochemical routes, depending on hydrogen and capture assumptions.

CO₂ utilisation to ethanol

Schmidt (2016) explored two routes for ethanol synthesis from a CO₂ feedstock: ethanol from a reverse water-gas shift (RWGS) reaction and ethanol synthesis using a DME intermediate. It was found that the DME intermediate process provided a higher thermal efficiency due to the decreased heating demands in comparison to the RWGS system. The DME based ethanol process provided an 18% reduction in ethanol production costs in comparison to the RWGS system.

Table 8.2. Economic Assessment of Ethanol Production of Carbon Dioxide Utilisation Technology

Capital Expenditure (US\$/t product)	Operational Expenditure (US\$/t product)	Production Cost (US\$/t product)	Total by Product Value (US\$/t product)	Profit (US\$/t product)	Profit per tCO ₂ Incorporated (US\$/t product)
1,013.15	1,260.13	2,273.28	1,003.41	-269.98	-144.70
565.64	1,231.17	1,796.81	NA	-796.81	-430.24
36.71	573	609.71	NA	350.29	175.1231

CO₂ = carbon dioxide, NA = not available, t = tonne, tCO₂ = tonne per carbon dioxide.

Sources: Schimdt et al. (2016), Jouny, Luc, and Jiao (2018).

Table 8.2, based on Jouny, Luc, and Jiao (2018), shows that ethanol production from CO₂ utilisation is an emerging field in sustainable energy and carbon capture technologies. Using electricity (often from renewable sources), CO₂ is reduced to ethanol in an electrolyser. This method offers flexibility in terms of using renewable electricity and is gaining attention for being highly efficient in lab-scale experiments. The estimated cost ranges from \$1,000 to \$3,000 per tonne of CO₂. The cost is heavily influenced by the electricity price and the efficiency of the electrochemical reactor.

The cost of setting up a CO₂-to-ethanol plant involves significant capital investment, particularly for the CO₂ capture system and the conversion infrastructure (bioreactors, electrolyzers, etc.),

while operational costs include maintenance, energy consumption, labour, and raw materials. Using high-temperature processes such as Fischer-Tropsch synthesis, CO₂ can also be converted into ethanol, though this method requires significant energy, high temperatures, and expensive equipment and operating costs, with costs around US\$1,500 to US\$2,500 per tonne of CO₂.

Overall, the producing cost of ethanol from CO₂ utilisation varies greatly depending on the specific method and location. However, most estimates put the cost at around US\$2 to US\$4 per litre of ethanol (approximately US\$2,000 to US\$4,000 per tonne). This is still significantly higher than conventional methods such as fermentation from sugarcane or corn, with cost as little as US\$ 0.20–US\$0.30 per litre of sugarcane ethanol and US\$ 0.30–US\$0.53 per litre for corn ethanol. This translates roughly to US\$300–US\$400 per tonne ethanol for sugarcane, and US\$400–US\$600 per tonne for corn-derived fuel ethanol.

Other derivate products of CO₂ utilisation

Indonesia has the potential to be a regional leader in CO₂ utilisation by converting emissions into valuable economic resources. With the right combination of policy support, targeted investment, and public–private collaboration, CO₂-derived products can contribute meaningfully to national decarbonisation, industrial growth, and green job creation. Table 8.3 presents a systematic review summarising individual studies that examine the economic perspectives of CO₂ utilisation derivate product.

Table 8.3. Economic Assessment of other Commercial Derivate Products of Carbon Dioxide Utilisation Technology

CAPEX (US\$/t product)	OPEX (US\$/t product)	Production Cost (US\$/t product)	Total by Product Value (US\$/t product)	Profit (US\$/t product)	Profit per tCO ₂ Incorporated (US\$/t product)	Technology
Ethylene Glycol						
47	567.96	614.96		109.04	534.45	Method CO ₂ to CO via coal gasification
Ethylene						
52.86	781	833.86		426.14	131.13	Method electrolysis
Dimethyl Ether (DME)						
462	1,703	2,130	NA	–1,674.08	–1,000.11	Method CO ₂ to CO through RWGS
Dimethyl Carbonate						
214.88	843.46	1,058.34	828	454.66	933.59 933.59	Method indirect through ethylene carbonate intermediate
123.21	1,284.63	140.84	NA	–722.84	–769.98	Method thermocatalysis
Olefins and Synthesis Fuels						
1.47	6.48	7.95	NA	0.68	0.60	Method
1.50	6.39	7.89	NA	0.74	0.67	Method CO ₂ to CO through dry reforming/steam reforming

CAPEX (US\$/t product)	OPEX (US\$/t product)	Production Cost (US\$/t product)	Total by Product Value (US\$/t product)	Profit (US\$/t product)	Profit per tCO ₂ Incorporated (US\$/t product)	Technology
Formic Acid						
83.28	1,755.24	1,838.52	80.13	-1,018.39	-1,524.54	Method thermocatalysis
14.71	264	278.71	NA	421.29	421.61	Method electrolysis
Urea						
CAPEX			OPEX			
Cost of urea manufacturing unit: US\$137 million			Direct cost (site development, utilities): US\$17 million			
Total direct cost to the organisation: US\$158 million			Civil works and site development: US\$4 million			
Total CAPEX: US\$227 million			Indirect cost (government taxes, engineering, field expenses): US\$69 million			
36.71			36.71			

CO₂ = carbon dioxide, CAPEX = capital expenditure, NA = not available, OPEX = operational expenditure, RWGS = reverse water-gas shift, t = tonne, tCO₂ = tonnes of carbon dioxide

Source: Zhang et al. (2017), Pérez-Fortes (2016), Zhang et al. (2015), Kongpanna et al. (2015), Michailos et al. (2019), Jouny, Luc, and Jiao (2018).

Value chain of ethylene glycol

The production of ethylene glycol from CO₂ utilisation is an emerging field aimed at transforming CO₂ emissions into valuable chemical products. Ethylene glycol, a key ingredient in antifreeze, plastics, and polyester production, is traditionally made from petroleum-derived ethylene, but using CO₂ as a feedstock can provide both an environmental and economic advantage in the long run. The conversion of CO₂ into ethylene glycol requires specialised catalytic or electrochemical processes. The most common route is through CO₂ hydrogenation, where CO₂ reacts with hydrogen to form intermediates that can eventually be converted to ethylene glycol. There are a few primary methods:

Catalytic hydrogenation to ethylene glycol. In this method, CO₂ is hydrogenated to produce ethylene (C₂H₄), which is then converted to ethylene glycol (C₂H₆O₂) via an additional catalytic process (CO₂ + 3H₂ → C₂H₄ + 2H₂O (ethylene); C₂H₄ + O₂ → C₂H₆O₂ (ethylene glycol)). Since hydrogen is required to reduce CO₂ to ethylene, the cost of hydrogen becomes a significant factor in the overall cost of ethylene glycol production. Some studies suggest that the cost of producing ethylene glycol from CO₂ could range between US\$1,000 to US\$3,000 per tonne of CO₂ captured, depending on hydrogen costs, the scale of the operation, and the energy source. Electrochemical conversion is a newer and potentially more sustainable method where CO₂ is directly reduced to ethylene glycol in an electrochemical cell powered by renewable electricity. The cost of electrochemical conversion of CO₂ to ethylene glycol is currently high, with estimated costs ranging from US\$1,500 to US\$3,500 per tonne of CO₂. Key cost factors include the price of electricity, catalyst efficiency, and cell design, but advances in technology could reduce these costs over time.

The conversion of CO₂ to ethylene glycol typically requires high-energy inputs, including electricity for electrolysis or hydrogen production, as well as heat for the reaction processes. The cost of renewable energy (solar, wind, etc.) is a key factor in reducing the overall cost of production. The price of electricity can vary from US\$30 to US\$50 per MWh depending on location and availability, but it is often more expensive than grid electricity. Thus, the efficiency of the CO₂-to-ethylene glycol process will directly affect the cost. In summary, establishing a CO₂-to-ethylene glycol plant involves significant upfront CAPEX, including the purchase and setup of CO₂ capture infrastructure, hydrogen production units, conversion reactors, and renewable energy sources. These costs can run into the tens of millions of dollars, particularly for large-scale operations. OPEX include energy, labour, raw materials (such as hydrogen), and maintenance. The ongoing costs of hydrogen production and energy consumption are key contributors to operational expenses. While the exact cost of producing ethylene glycol from CO₂ is still highly variable depending on the technology and scale, rough estimates suggest that CO₂ hydrogenation with green hydrogen estimated costs of US\$1,000 to US\$3,000 per tonne of CO₂, with hydrogen being a significant contributor to the price. Electrochemical methods might cost between US\$1,500 to US\$3,500 per tonne of CO₂, primarily driven by the cost of electricity and process efficiency. Traditional ethylene glycol production (from petrochemical sources) in comparison, conventional ethylene glycol production from fossil fuels costs around US\$600 to US\$1,000 per tonne.

Value chain of ethylene

The production of ethylene from CO₂ utilisation is an exciting, yet challenging, area of research and industrial application. Ethylene is one of the most important building blocks in the chemical industry, used in the production of plastics (like polyethylene), solvents, and antifreeze. Traditionally, ethylene is produced from petroleum or natural gas via processes like steam cracking. However, converting CO₂ into ethylene not only offers the potential for a more sustainable process, but also helps address the issue of carbon emissions. Catalytic hydrogenation involves reacting CO₂ with hydrogen to produce ethylene. This method is based on the idea of CO₂ hydrogenation ($\text{CO}_2 + 3\text{H}_2 \rightarrow \text{C}_2\text{H}_4 + 2\text{H}_2\text{O}$ (ethylene)), where the carbon dioxide reacts with hydrogen gas under high temperature and pressure, typically in the presence of a catalyst. The reaction produces ethylene (C₂H₄), and it typically requires high-pressure reactors and hydrogen as a key reactant. The conversion process itself (i.e. hydrogenating CO₂ to ethylene) can cost approximately US\$1,000 to US\$3,000 per tonne of CO₂ captured. The main cost drivers are the price of hydrogen and the energy required for hydrogenation.

In electrochemical CO₂ reduction, electricity is used to drive the conversion of CO₂ into ethylene ($\text{CO}_2 + 6\text{H}^+ + 6\text{e}^- \rightarrow \text{C}_2\text{H}_4 + 2\text{H}_2\text{O}$ (ethylene)). This process is similar to CO₂ electrolysis, where CO₂ is reduced at the cathode of an electrolyser using renewable electricity (e.g. from solar or wind). Electrochemical methods for CO₂-to-ethylene conversion are still being refined, but current estimates put the cost between US\$1,500 and US\$4,000 per tonne of CO₂, depending on electricity costs, process efficiency, and catalyst development. The main cost driver is the price of electricity (especially if using renewable sources) and the efficiency of the conversion process. The energy requirements for producing ethylene from CO₂ are significant, especially when hydrogen production or electrochemical. Scaling up CO₂-to-ethylene production is a significant challenge. Small-scale operations can be expensive due to high capital expenditures for equipment, infrastructure, and the setup of CO₂ capture and conversion technologies. However, as technologies mature and larger plants are built, the costs will likely decrease due to the economies of scale.

Value chain of dimethyl ether

The production of dimethyl ether (DME), a versatile chemical used as a fuel, propellant, and feedstock for other chemicals like methanol, typically occurs through methanol dehydration process, though new methods are being explored to directly produce DME from CO₂.

Before CO₂ can be converted into DME, it must be captured from the atmosphere or from industrial sources. Direct air capture (DAC) costs range between US\$50 and US\$200 per tonne of CO₂, depending on the specific technology used (e.g. amine-based, solid sorbent, or direct air scrubbing), while industrial capture (such as power plants, cement production, or chemical plants) tends to be cheaper at US\$30 to US\$100 per tonne of CO₂. Once captured, the CO₂ needs to be purified, compressed, and stored, which adds to the total cost.

The conversion of CO₂ to dimethyl ether can take several different forms, but the general process involves two main steps:

1. CO₂ hydrogenation to produce methanol (CH₃OH): $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$
This step typically requires high temperatures, pressures, and metal catalysts (such as copper-based catalysts). The hydrogen source, especially green hydrogen produced via electrolysis powered by renewable electricity, priced at US\$3 to US\$6 per kilogramme, depending on electricity prices and electrolysis efficiency. Converting CO₂ to methanol typically costs between US\$500 to US\$1,500 per tonne of CO₂, depending on the source of hydrogen and efficiency of the process.
2. Methanol dehydration to produce dimethyl ether (CH₃OCH₃): $2\text{CH}_3\text{OH} \rightarrow \text{CH}_3\text{OCH}_3 + \text{H}_2\text{O}$
This industrialised step requires significant energy input and catalyst regeneration. Costs for this step are usually lower than the first step, but can add US\$100 to US\$300 per tonne of DME.

Both stages are energy-intensive, with the total cost of producing DME from CO₂ can range from US\$600 to US\$1,800 per tonne of CO₂, driven mainly by hydrogen and electricity prices. In comparison, conventional fossil-based DME production tends to cost around US\$500 to US\$1,000 per tonne of DME, highlighting the current economic gap despite the sustainability benefits of CO₂-derived DME.

Value chain of dimethyl carbonate

The production of dimethyl carbonate (DMC) from CO₂ utilisation is a promising but still emerging technology that combines carbon capture with the production of useful chemicals. The production of DMC from CO₂ typically involves a few distinct steps:

1. CO₂ hydrogenation to methanol: $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$ (methanol)
Producing methanol from CO₂ costs between \$500 and \$1,500 per tonne of CO₂, depending on hydrogen costs, energy prices, and the efficiency of the hydrogenation process.
2. Methanol carbonylation to dimethyl carbonate (DMC): $2\text{CH}_3\text{OH} + \text{CO}_2 \rightarrow (\text{CH}_3\text{O})_2\text{CO} + \text{H}_2\text{O}$ (dimethyl carbonate)

The carbonylation of methanol can be done by reacting methanol with CO₂ (or carbon monoxide), typically in the presence of a catalyst. This step is well-established in industry, so its costs are relatively predictable and can range from US\$100 to US\$300 per tonne of DMC produced.

The cost of producing DMC from CO₂ is influenced by several key factors: CO₂ capture, hydrogen production, energy consumption, and catalyst efficiency. Based on current technologies and estimates, the total cost of producing DMC from CO₂ can range between US\$600 to US\$2,000 per tonne, with a breakdown as follows: The cost of converting CO₂ to methanol is estimated at US\$500 to US\$1,500 per tonne of CO₂, converting methanol to DMC through carbonylation at US\$100 to US\$300 per tonne of DMC, and energy consumption for hydrogen production and reactor heating can add an additional US\$100 to US\$300 per tonne of DMC, depending on the energy source and process efficiency. Although the CO₂-based DMC is currently more expensive due to the high costs of CO₂ capture, green hydrogen, and energy-intensive processes, it has significant environmental benefits, particularly in transforming CO₂ into valuable products and contributing to carbon emissions reduction.

Value chain of olefins and synthesis fuels

Olefins value chain

The production of olefins (such as ethylene and propylene) and synthesis fuels (such as synthetic gasoline and diesel) from CO₂ utilisation is a highly attractive prospect for a sustainable and low-carbon chemical industry. Both olefins and synthesis fuels are major building blocks in the chemical and energy industries, and shifting their production from fossil-based sources to CO₂-derived feedstocks could significantly reduce global carbon emissions. The production of olefins from CO₂ typically involves two major steps:

1. CO₂ hydrogenation to methanol ($\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$)

The cost of producing methanol from CO₂ can range from \$500 to \$1,500 per tonne of CO₂, depending on hydrogen costs and energy efficiency.

2. Methanol-to-olefins (MTO) or methanol-to-propylene (MTP) processes

Once methanol is produced, it can be converted into olefins (e.g. ethylene, propylene) through a MTO or MTP process ($2\text{CH}_3\text{OH} \rightarrow \text{C}_2\text{H}_4 + \text{CO} + 2\text{H}_2\text{O}$ (ethylene, for example)). The cost of the MTO and/or MTP process is typically around US\$200 to US\$500 per tonne of olefins produced. Energy consumption for the MTO process is high, with typical energy requirements around 4–6 MWh per tonne of olefins produced. Overall, cost of olefins production from CO₂ are CO₂ hydrogenation to methanol: US\$500 to US\$1,500 per tonne of CO₂.

Thus, the total cost for producing ethylene or propylene from CO₂ is estimated to be in the range of US\$700 to US\$2,000 per tonne of olefins, depending on hydrogen costs, energy efficiency, and scale of production.

Synthesis fuels production from CO₂ (synthetic gasoline, diesel)

Synthesis fuels such as synthetic gasoline and synthetic diesel can be produced from CO₂ using technologies such as the Fischer-Tropsch (FT) synthesis or CO₂ hydrogenation. In these processes, CO₂ can be hydrogenated to form liquid hydrocarbons, which are the building blocks of fuels like gasoline and diesel, via reactions such as $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{C}_8\text{H}_{18}$ (octane), or a similar hydrocarbon chain that can be further refined into gasoline or diesel. The cost depends on the hydrogen costs and the specific process used.

FT synthesis is a well-established process for converting syngas (a mixture of hydrogen and carbon monoxide) into liquid hydrocarbons. When producing synthetic fuels from CO₂, the process typically involves the following steps: a) CO₂ reduction to syngas (CO + H₂): this can be done using CO₂ hydrogenation, and b) the syngas is then converted to liquid hydrocarbons (gasoline, diesel, kerosene) via the FT process ($\text{CO} + 2\text{H}_2 \rightarrow (\text{C}_n\text{H}_{2n+2})$ (liquid hydrocarbons)).

FT synthesis is capital and energy-intensive, typically costing US\$1,000 to US\$3,000 per tonne of CO₂, with energy requirement of approximately 5–10 MWh per tonne of liquid fuel produced. The energy requirements for producing olefins and synthesis fuels from CO₂ are significant. These processes require hydrogen, high temperatures, and pressures. Total breakdown cost estimates for olefins and synthesis fuels from CO₂ are listed in Table 8.4.

Table 8.4 .Cost Estimates of Olefins and Synthesis Fuels

Olefins (ethylene, propylene)	Synthesis Fuels (gasoline, diesel)
CO ₂ hydrogenation to methanol: US\$500–US\$1,500/tonne CO ₂	CO ₂ hydrogenation via Fischer-Tropsch: US\$1,000–US\$3,000/tonne CO ₂
MTO/MTP conversion: US\$200–US\$500/tonne olefins	Energy and catalyst costs: US\$100–US\$300/tonne fuel
Total: US\$700–US\$2,000/tonne olefins	Total: US\$1,200–US\$3,300/tonne synthesis fuels

CO₂ = carbon dioxide, MTO = methanol-to-olefins, MTP = methanol-to-propylene.

Source: Compiled by authors.

Value chain of formic acid

Formic acid (HCOOH) is a key chemical in the production of plastics, textiles, leather, and pharmaceuticals, and it has growing interest as a carbon-neutral chemical when produced from CO₂. Producing formic acid from CO₂ is part of the broader effort to reduce carbon emissions and close the carbon loop by converting captured CO₂ into valuable products.

The production (and thus the cost) of formic acid from CO₂ involves several steps is influenced by factors such as CO₂ capture, hydrogen production, catalysis, and energy inputs. First, CO₂ is converted into formate (HCOO⁻), which can then be further processed into formic acid (CO₂ + H₂ → HCOOH). The process typically involves hydrogenation, where CO₂ reacts with hydrogen in the presence of a catalyst to form formic acid.

The hydrogen used in the reaction can be produced via electrolysis (using green hydrogen) or through natural gas reforming. Electrolysis of water powered by renewable energy (wind, solar, etc.) is the most sustainable method, but it is still relatively expensive. Green hydrogen costs range from US\$3 to US\$6 per kilogramme (kg). Reformed natural gas is cheaper but less sustainable. This can lower the cost of hydrogen to around US\$1 to US\$3 per kg. The amount of hydrogen required is approximately 6.6 kg of hydrogen per tonne of CO₂.

The hydrogenation of CO₂ to formic acid requires a suitable catalyst, and several catalysts are being researched for the process, including copper-based, ruthenium-based, and nickel-based catalysts. Catalyst costs can range from US\$50 to US\$200 per kg of catalyst, and some catalysts may need to be regenerated or replaced periodically. Taking into account the value chain of formic acid, the CO₂ capture costs, hydrogen production costs, catalysis, energy consumption, and economies of scale, the estimated cost of producing formic acid from CO₂ ranges between US\$1,000 to US\$3,500 per tonne of formic acid (depending on hydrogen costs, scale of the operation, and process efficiency), with the following breakdown:

- CO₂ capture: US\$30 to US\$100 per tonne of CO₂

- Hydrogen production (green hydrogen): US\$300 to US\$1,000 per tonne of CO₂ (6.6 kg of hydrogen required)
- Energy cost: US\$50 to US\$200 per tonne of formic acid
- Catalyst and operational costs range between US\$200 to US\$500 per tonne of formic acid.

Green urea value chain

Green urea production involves synthesising urea using CO₂ as a feedstock, which contributes to reducing greenhouse gas emissions. This process is part of a broader effort to utilise captured CO₂ and convert it into valuable products. The primary method for producing urea from CO₂ involves two main steps. The first step is ammonia synthesis, which is typically done via the Haber-Bosch process, where nitrogen (N₂) from the air is combined with hydrogen (H₂). The hydrogen can be generated from renewable sources, such as water electrolysis powered by solar or wind energy. The second step is urea formation, where ammonia is then reacted with CO₂ to produce urea through the following reaction: $2\text{NH}_3 + \text{CO}_2 \rightarrow (\text{NH}_2)_2\text{CO} + \text{H}_2\text{O}$.

Looking ahead, projections indicate that the levelised cost of green urea could decrease to as low as US\$135 per metric tonne by 2030 due to anticipated advances in technology and process efficiencies. Currently, the production cost breakdown indicates that utility costs constitute the highest share of total costs, with some sources citing an approximate US\$0.334 per kg for green urea production. For comparison, traditional methane-based urea production costs around \$550 per metric tonne, highlighting the higher costs associated with green urea processes, primarily due to renewable energy and hydrogen production.

A techno-economic analysis of a renewable urea project indicated a six-year payback period with a return on investment of around 16.7%. This suggests that while the initial costs may be high, there is potential for profitability as technologies advance. The primary production cost components are raw materials, energy consumption, and government taxes. The cost of monoethanolamine solvent is US\$1.31/kg (99% purity), while the utility cost from conventional sources is \$0.06/ kWh. The green hydrogen cost per tonne is US\$2.40, with production cost from conventional and renewable power is US\$409.27 and US\$334.80 per tonne, respectively. The cost of green hydrogen and utility are the key lever price determinations of green urea. Also, the captured CO₂ must be cooled and compressed, increasing the capture cost by 10%.

4. Discussion

Carbon capture and utilisation (CCU) technologies have recently gained significant attention for their ability to transform captured CO₂ into valuable products, positioning it as a renewable carbon resource rather than a waste to be permanently stored underground or in oceans. The outlook for carbon utilisation is promising, with considerable potential across various industries to commercialise CO₂-based processes. With continued research and development in key areas of CO₂ utilisation, many of the emerging technologies are expected to become more cost-effective, opening up opportunities in markets such as fine chemicals, fuels, and even water treatment. However, the adoption of these technologies largely hinges on their economic viability. Currently, only a small portion of captured CO₂ from industrial emissions is being utilised for energy

generation or the production of value-added goods (Su et al., 2024). The primary barriers to wider implementation are the high costs and low efficiency of existing technologies, which have significantly slowed progress in the field.

Integrating CCU presents a promising approach to reducing the high energy demands typically associated with producing chemicals and fuels directly from waste-gas streams. This is particularly effective when both capture and conversion occur at similar temperatures, enabling process intensification that results in more compact, cleaner, and energy-efficient systems. The idea of combining gas separation with chemical reactions – referred to as hybrid processes – has already been explored in various applications. For instance, the direct conversion of industrial flue gases into syngas (a mixture of CO and H₂), which serves as a precursor for methanol production, has been achieved using dual-function materials (Jouny, Luc, and Jiao, 2018). Another example includes the hydrogenation of CO₂, which combines its capture and subsequent reduction. Additionally, the simultaneous capture and mineralisation of CO₂ from coal combustion flue gases has been successfully demonstrated at the pilot scale in the United States (Kongpanna et al., 2015).

This review has examined the existing challenges and future opportunities associated with CCU technologies, emphasising their efficiency and cost. While there has been significant progress in recent years in developing various CCU solutions – with a few achieving industrial-scale deployment – most technologies are still in the early stages of research and development. To enhance the performance of both capture and utilisation processes, the use of next-generation materials that outperform current standards is essential, as they can help lower energy consumption. Additionally, assessments conducted at a small scale should align with the requirements of commercial-scale operations to provide more realistic insights into performance metrics and cost implications. Amongst all influencing factors, cost-effectiveness remains the primary determinant for the widespread adoption of CCU technologies. CCU is also gaining attention for its role in enabling cleaner ammonia production. A notable example is the bilateral collaboration between Japan and Indonesia, formalised through a 2022 memorandum of co-operation.. This agreement fosters joint efforts in hydrogen, ammonia, carbon recycling, and CCU, and stands as a strong example of international collaboration in the pursuit of low-carbon industrial strategies. Signed between Indonesia's Minister of Energy and Mineral Resources and Japan's Ministry of Economy, Trade and Industry under the Asia Energy Transition Initiative framework in Energy Transition Roadmap Development (joint roadmap planning to achieve clean emissions and net-zero targets (Indonesia by 2060; Japan by around 2050), technology collaboration and transfer (focus on real-world deployment of low-carbon hydrogen [green/blue H₂] and fuel ammonia, carbon recycling [CCU] pathways), and policy, human-capacity, and knowledge sharing (Includes support for energy-related policy alignment and standards, training and capacity-building of Indonesian technical institutions, and regulatory and tariff guidance (e.g. renewable energy electricity pricing reforms).

The long-term stability of materials used in various CCU technologies is a critical factor, as it directly influences both system efficiency and overall economic viability. In the utilisation phase, producing fuels and chemicals—particularly when powered by renewable energy – can significantly reduce costs, while supporting the sustainable generation of value-added products. In many cases, integrating systems and intensifying processes enhances separation efficiency and thermodynamic performance, offering a more cost-effective solution. However, such improvements often introduce operational complexity and other technical challenges that must be addressed. Indonesia's current CCUS strategy places strong emphasis on enhanced resource recovery applications, especially enhanced oil recovery, which provides the combined benefits of emissions reduction and increased oil output. Still, there is a growing interest in diversifying CO₂

utilisation pathways, including synthetic fuel production, incorporation into construction materials, and supplying food-grade CO₂ for industrial use (Zhu, 2019). The growth of these emerging markets will largely depend on supportive regulatory frameworks, international technology transfer, and alignment with carbon pricing and trading mechanisms. From an economic perspective, the lack of a robust carbon pricing system continues to undermine project feasibility. The current carbon market fails to adequately incentivise emissions reduction, rendering CCU investments financially unattractive.

Beyond the technical, environmental, and economic benefits, the successful deployment of CO₂-based products also depends on market readiness and the acceptance of key stakeholders – including policymakers, investors, and the general public. CCU consists of two interdependent processes: capturing CO₂ and converting it into useful products. As such, the cost of carbon capture must be factored into the overall economic assessment. While carbon capture is already technologically mature and in use at industrial levels (Technology Readiness Levels 8–9), it remains economically unviable in many cases due to the absence of financial incentives. For developing countries like Indonesia, supportive mechanisms – such as subsidies, tax incentives, or other forms of government intervention – are essential to make CCU economically justifiable and encouraging broader adoption. In summary, the economic value of CO₂ utilisation refers to the potential financial benefits derived from converting captured carbon dioxide into commercially valuable products or services. While the exact value depends on the technology, market, and regional policies. In this context, it refers to the net financial benefit or revenue potential of turning captured CO₂ into marketable products, such as methanol, urea, synthetic fuels building materials (e.g. carbon-cured concrete). This value is shaped by the market price of the CO₂-derived product, production cost (including CO₂ capture, conversion, and energy inputs), and policy incentives (like carbon credits, subsidies, or tax benefits).

5. Conclusion and Policy Recommendations

This global systematic review has examined the cost landscape of CO₂ utilisation and its derivatives – including synthetic fuels, and chemicals – offering key insights for Indonesia's path towards low-carbon development. While the economic viability of these technologies remains constrained by high capital and operational costs, global trends indicate a downward trajectory in costs driven by technological advancements, increased scale, and policy support in more developed economies.

For Indonesia, CO₂ utilisation presents both a challenge and an opportunity. The nation's industrial emissions, growing energy demand, and commitment to climate goals make carbon utilisation a promising solution to reduce greenhouse gas emissions while creating value-added products. However, Indonesia currently lacks the financial mechanisms, regulatory clarity, and infrastructure necessary to bring these technologies to scale.

To unlock the potential of CO₂ utilisation in Indonesia, sustainable and innovative financing avenues are essential. These include mobilising green bonds, blended finance, public–private partnerships, carbon markets, and international climate funds. These mechanisms must be supported by an enabling environment—clear policies, economic incentives, institutional co-ordination, and technical capacity.

In summary, the utilisation of CO₂ and its related products holds significant potential to support both Indonesia's climate goals and industrial development. By aligning investments with supportive policies and securing sustainable financial resources, Indonesia can adopt international best practices to build a robust carbon economy and play a substantial role in global efforts to reduce greenhouse gas emissions.

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Appendix

Table A8. Cost Structure of Carbon Capture and Utilisation Technologies

No.	Post Combustion		Pre Combustion		Oxy Fuel Combustion	
	CAPEX (US\$)	OPEX (US\$)	CAPEX (US\$)	OPEX (US\$)	CAPEX (US\$)	OPEX (US\$)
1.	MEA capture cost 1. Coal-fired power plant (500 MW) - Capital cost (US\$900 million) 2. Iron production flue gas - Capital cost (US\$145 million) 3. Oil refinery exhaust flue gas - Capital cost (US\$176 million) 4. Cement flue gas Capital cost (US\$91 million)	MEA capture cost 1. Coal-fired power plant (500 MW) - Operating cost (US\$ million/year) 2. Iron production flue gas - Operating cost (US\$88 million/year) 3. Oil refinery exhaust flue gas - Operating cost (US\$52 million/year) 4. Cement flue gas - Operating cost (US\$42 million/year)	Investment 331,294,147 Fixed capital 256,000,023	Direct cost 205,336,559 Indirect 51,200,004	Investment 88,444,247 Fixed capital 160,305,051	Direct cost 128,244,160 Indirect 32,061,040
2.	Total CAPEX (US\$) - NGCC plant (550,000,000) - CCSU plant (233,072,402) Annualised CAPEX (US\$) - NGCC plant (60,555,000) - CCSU plant (21,337,843)	Electricity cost (US\$/year) - CCSU plant (35,652,706) Cooling water (US\$/year) - NGCC plant (16,120,590) - CCSU plant (137,453) Solvent makeup (US\$/year) - CCSU plant (19,211) Fuel cost (US\$/year) NGCC plant (79,400,474)	Equipment cost US\$1,752/kW Fixed cost US\$3,385/kW	Maintenance cost US\$2,154/kW Operational cost US\$4,661/kW	Equipment cost US\$2,455/kW Fixed cost US\$3,385/kW	Fuel cost 3,11 HHV (US\$/GJ) Operating cost (US\$2,206/kW)
3	Investment 235,329,147	Direct cost 145,476,200 Indirect 36,369,050 Fixed capital 181,845,250	NA	NA	NA	NA

No.	Post Combustion		Pre Combustion		Oxy Fuel Combustion	
	CAPEX (US\$)	OPEX (US\$)	CAPEX (US\$)	OPEX (US\$)	CAPEX (US\$)	OPEX (US\$)
4.	Natural gas processing - CO₂ volume captured (24,000 tonnes/year) - Unit capital cost 20-year life low–high (US\$7–US\$12/tonne) - Unit total cost 20-year life low–high (US\$23–US\$36/tonne) Cement plants - CO₂ volume captured (842,000 tonnes/year) - Unit capital cost 20-year life low–high (US\$17–US\$29/tonne) - Unit total cost 20-year life low–high (US\$64–US\$95/tonne) Refinery fluidised catalytic cracking plants - CO₂ volume captured (374,000 tonnes/year) - Unit capital cost 20-year life low–high (US\$43–US\$72/tonne) - Unit total cost 20-year life low–high (US\$97–US\$150/tonne) Steel/iron plants - CO₂ volume captured (3,324,000 tonnes/year) - Unit capital cost 20-year life low–high (US\$26–US\$44/tonne) - Unit total cost 20-year life low–high (US\$75–US\$113/tonne) Coal-fired power plants (500 MW)	Natural gas processing - Unit nonenergy cost 20-year life low–high (US\$8–US\$13/tonne) - Unit energy operating cost (US\$9/tonne) Cement plants - Unit nonenergy cost 20-year life low–high (US\$22–US\$37/tonne) - Unit energy operating cost (US\$28/tonne) Refinery fluidised catalytic cracking plants - Unit nonenergy cost 20-year life low–high (US\$28–US\$47/tonne) - Unit energy operating cost (US\$29/tonne) Steel/iron plants - Unit nonenergy cost 20-year life low–high (US\$22–US\$38/tonne) - Unit energy operating cost (US\$29/tonne) Coal-fired power plants (500 MW) - Unit nonenergy cost 20-year life low–high (US\$22–US\$37/tonne) Unit energy operating cost (US\$30/tonne) Industrial furnaces (refining/chemicals) - Unit nonenergy cost 20-year life low–high (US\$33–US\$55/tonne) - Unit energy operating cost (US\$31/tonne) Natural gas power plants (560 MW net)	NA	NA	NA	NA

No.	Post Combustion		Pre Combustion		Oxy Fuel Combustion	
	CAPEX (US\$)	OPEX (US\$)	CAPEX (US\$)	OPEX (US\$)	CAPEX (US\$)	OPEX (US\$)
	- CO₂ volume captured (3,089,000 tonnes/year) - Unit capital cost 20-year life low–high (US\$33–US\$55/tonne) - Unit total cost 20-year life low–high (US\$83–US\$124/tonne)	- Unit nonenergy cost 20-year life low–high (US\$29–US\$49/tonne) - Unit energy operating cost (US\$31/tonne)				
	Industrial furnaces (refining/chemicals)					
	- CO₂ volume captured (220,000 tonnes/year) - Unit capital cost 20-year life low–high (US\$49–US\$83/tonne) - Unit total cost 20-year life low–high (US\$110–US\$171/tonne)					
	Natural gas power plants (560 MW net)					
	- CO₂ volume captured (1,279,000 tonnes/year) - Unit capital cost 20-year life low–high (US\$34–US\$58/tonne)					
	Unit total cost 20-year life low–high (US\$93–US\$140/tonne)					

CAPEX = capital expenditure, CCSU = carbon capture, storage, and utilisation, CO₂ = carbon dioxide, HHV = higher heating value, kW = kilowatt, MEA = monoethanolamine, MW = megawatt, NGCC = natural gas combined cycle, OPEX = operating expenditure.

Sources: Ho, Allinson, and Wiley (2011), Kheirnik, Ahmed, and Rahmanian (2021), Kamolov et al. (2024), USDOE (2013), IEAGHG (2014), National Petroleum Council (2021).

Chapter 9

Catalysing Carbon Circularity: The Role of Green Finance, Trade, and Governance in Reducing Carbon Emissions in the East Asia Summit Countries

1. Introduction

Since the early 2000s, and particularly following the adoption of the Sustainable Development Goals (SDGs) in 2015, countries in the East Asia Summit (EAS) region have faced significant challenges in achieving their carbon emissions reduction targets, mainly due to their high dependence on fossil fuels and rapid industrialisation. Reducing carbon emissions has become a strategic priority amongst the EAS countries amidst intensifying climate commitments and rapid industrial growth. Structural barriers, such as dependence on fossil fuels, urban expansion, and limited low-carbon infrastructure, continue to impede emissions reduction in key sectors like manufacturing, energy, and transport (Shi, 2001; Zhen and Freire, 2023). While renewable energy mandates and emissions trading systems (ETS) have been implemented across the region, their effectiveness remains uneven due to governance challenges and technological constraints (Liu and Zhang, 2023; Nawaz, Hussain, and Hussain, 2021; Otsuki et al., 2024).

China and India exemplify these challenges. Despite China's net-zero commitment by 2060 and large-scale renewable investments, energy transition efforts are hindered by fossil fuel lock-ins and infrastructure bottlenecks (Gao and Qu, 2025; Yang, Xang, and Li, 2024; Y. Zhang, 2024). Similarly, India faces growing energy demands and implementation hurdles despite its National Action Plan on Climate Change (Anderson, 2023; Ordonez et al., 2023). Other countries, such as Viet Nam, have articulated net-zero targets but struggle with transmission and storage limitations (Agarwal et al., 2022). In contrast, Japan's low-carbon innovation and ETS progress are tempered by volatility in carbon pricing and limited industrial participation (Oh, 2023; C. Zhang et al., 2024).

At the same time, transparency in carbon reporting remains a concern. Pham et al. (2024) highlighted underreporting practices driven by regulatory evasion, while Dechezleprêtre, Nachtigall, and Venmans (2023) noted the limited impact of ETS in hard-to-abate sectors like cement and steel. In some cases, companies have even engaged in symbolic environmental, social, and governance (ESG) disclosures without meaningful innovation, further complicating the credibility of carbon reporting mechanisms (Xing et al., 2024; Yu, Liu, and Li, 2024). These challenges point to the need for more integrative strategies that extend beyond traditional linear approaches to carbon management. While Liu and Zhang (2023), and S. Zhang (2024) emphasise the role of policy pressure and emissions regulation, they do not explore how enabling factors like finance, innovation, and trade might work together to support carbon recycling. Similarly, Qing et al. (2024), and L. Zhang et al. (2024) assess green investment and innovation, but fall short of integrating these with long-term circular carbon strategies.

In this context, carbon recycling, the process of reusing carbon dioxide (CO₂) from industrial emissions in productive applications, has gained attention as a conceptual pillar of the circular economy (Izumi, Iizuka, and Hoet, 2021). Although currently unmeasurable as an empirical variable, carbon recycling represents a long-term decarbonisation pathway, particularly for sectors lacking viable low-carbon alternatives. Early-stage applications in Japan and the Republic of Korea via mineral carbon capture and utilisation illustrate its potential, though widespread adoption remains constrained by cost and infrastructure (Felkner et al., 2025; Shobande, Ogbeifun, and Tiwari, 2025). In addition, effective fiscal instruments and institutional capacity play critical roles in accelerating low-carbon transitions. Evidence from regions outside EAS countries, such as Africa and the European Union (EU), suggests that green public procurement and sustainable fiscal planning can reduce emissions without sacrificing economic stability (Halkos and Paizanos, 2013; Onofrei, Vatamanu, and Cigu, 2022; Osinubi, 2024). Similarly, green bonds and sustainable finance instruments have been found to facilitate technological upgrading and innovation in clean industries (Buglea et al., 2025; Caleb, 2024; Čeryová et al., 2020).

Recognising these constraints, this study focuses empirically on carbon emissions reduction (CEI) to assess the enabling role of green financing (GFI), green innovation (GVA), and trade in green technology (TRA), with governance (WGI) as a moderating factor in the GFI–CEI relationship. Specifically, the study applies panel regression using principal component analysis (PCA) to develop composite indicators. It compares outcomes before and after the global adoption of the Sustainable Development Goals (SDGs) in 2015 to observe institutional and policy dynamics changes.

This study differs from prior research in several important respects. First, unlike Liu and Zhang (2023), who emphasise ETS implementation, or Qing et al. (2024), who focus narrowly on green investments, this chapter combines three enabling factors – finance, innovation, and trade –and examines them together. Second, in contrast to Yi et al. (2025) and L. Zhang, Wong et al. (2024), who explore technological or trade dimensions in isolation, this study integrates these domains under a unified framework moderated by governance. Third, While most empirical studies treat carbon emissions reduction as a terminal outcome, this study embeds emissions reduction within a broader conceptual ambition to support carbon recycling and circular carbon systems.

Accordingly, this chapter contributes to the literature in two key respects. First, it provides empirical evidence on the short-term determinants of carbon emissions reduction in the EAS context. Second, it offers conceptual insights into how enabling conditions today, through GFI, GVA, and TRA, can support the eventual transition towards circular carbon practices. This research supports formulating regional policies that promote immediate emissions reduction and long-term decarbonisation strategies by bridging economic, technological, and governance dimensions. The findings are expected to inform policies such as targeted fiscal incentives for carbon recycling, ESG-aligned investments, and green technology transfers, especially in hard-to-abate sectors.

2. Literature Review

In recent years, efforts to reduce carbon emissions have increasingly emphasised the importance of integrating economic instruments, technological advancements, and institutional quality. Within this framework, green financing, green innovation, and trade in green technology are recognised as crucial enablers for promoting sustainable decarbonisation, particularly in economies characterised by high emissions. These three dimensions, financial, technological, and trade-based, offer complementary yet distinct contributions to emissions reduction efforts, mainly within the broader conceptual underpinnings of sustainable development theory and circular economy principles. By linking short-term mitigation goals with long-term carbon recycling strategies, they support linear reductions in emissions and the structural transformation of carbon-intensive systems.

Green finance is a fundamental lever to mobilise capital towards low-carbon development pathways. Green bonds, sustainability-linked loans, and concessional financing have been widely adopted to overcome the initial cost barriers associated with low-carbon technologies. These financial tools also strategically catalyse systemic shifts in carbon-intensive sectors by aligning capital allocation with environmental goals. Empirical evidence highlights the role of green bonds in facilitating investment in clean technologies across the EU (Čeryová et al., 2020) and in enabling fiscal support for the renewable transition in countries such as the Republic of Korea (Oh, 2023).

In the EAS region, green finance has shown potential to stimulate private sector involvement in mitigation efforts, while remaining aligned with national climate strategies (Otsuki et al., 2024). Moreover, green finance directly contributes to circular carbon systems by supporting the development and deployment of technologies such as carbon capture, utilisation, and storage (CCUS), mineral carbonation, and carbon-to-value processes (Izumi, Iizuka, and Ho, 2021; Wang, Cui, and Zhou, 2025).

The circular economy framework provides a conceptual basis for this transformation, emphasising resource efficiency through reuse, recycling, and closed-loop production systems. Within this model, green finance plays a catalytic role by allocating capital to innovations that reduce emissions and close carbon loops. Research in the context of South Asia underscores that government expenditure and fiscal policy can support sustainable and inclusive growth, provided they are directed towards low-carbon development (Pradhan et al., 2017). However, financing alone is insufficient without concurrent advancements in green innovation.

Green innovation complements finance mechanisms by improving the technological readiness and scalability of emissions-reducing solutions. Innovations in industrial processes such as mineral carbon utilisation or CCUS are central to achieving circularity, particularly in hard-to-abate sectors. Empirical evidence from China demonstrates that green technology development significantly reduces emissions, mainly when supported by green investments and policy instruments (Gao and Qu, 2025). Moreover, evidence from developing countries indicates that environmental innovation contributes to a reduction in the carbon footprint, while supporting economic growth (Ali et al., 2023). These findings are consistent with research that links environmental management accounting with enhanced operational efficiency and long-term competitiveness (Buglea et al., 2025). In this way, green innovation supports environmental goals and strengthens the financial case for sustainability by generating bankable projects that attract climate finance.

While innovation is critical for technology development, its deployment at scale often depends on the facilitative role of international trade. In many developing economies, the capacity to produce green technologies domestically is limited by weak research and development (R&D) ecosystems, a lack of skilled technical labour, and fragmented market incentives. Thus, trade in green technology becomes a vital channel for bridging these gaps. It allows countries to access equipment, know-how, and best practices necessary for low-carbon transitions. Evidence shows that the import of green technologies leads to improvements in environmental performance and accelerates emissions reduction trajectories (Van et al., 2023; Yi et al., 2025). Although green technology is crucial in promoting sustainable development, its effective diffusion remains constrained by systemic challenges, particularly in developing countries. Shobande, Ogbeifun, and Tiwari (2025) highlight the need for co-ordinated policy frameworks to support technology adoption, while Li et al. (2025) emphasise the importance of targeted green finance mechanisms, such as government green funds, to accelerate firm-level transitions towards low-carbon operations. In response to these challenges, multilateral trade agreements and co-ordinated policy reforms are needed to ensure the equitable diffusion of green technologies across borders.

The success of these enablers (finance, innovation, and trade) ultimately hinges on the quality of governance. High-quality governance improves policy coherence, enhances transparency in carbon reporting, mitigates the risks of greenwashing, and builds stakeholder trust. Several studies emphasise the role of strong institutions in improving the effectiveness of climate-related financial and policy interventions. For example, Ansari et al. (2024) show that governance quality strengthens the link between financial inclusion, renewable energy, and environmental sustainability. Meanwhile, Nawaz, Hussain, and Hussain (2021) highlight the role of green financial

policies in supporting sustainable economic growth in developing countries, although governance is not examined as a moderating factor. Poor governance, by contrast, leads to the misallocation of climate finance, fragmented innovation efforts, and conflicts over technology transfer and intellectual property rights. The risks of greenwashing are particularly acute in state-owned or large firms, which may exploit symbolic environmental disclosures to gain government subsidies and green credit, without delivering substantive green innovation (Xing et al., 2024). This tendency is exacerbated in contexts where ESG reporting is driven more by financial incentives than regulatory accountability (Yu et al., 2024).

Institutional theory provides a theoretical foundation for understanding these dynamics. According to DiMaggio and Powell (1983), organisations tend to conform to institutional norms and expectations to gain legitimacy. In the context of climate policy, governance structures serve as these institutional norms, guiding the behaviour of firms, financial actors, and governments towards environmentally aligned outcomes. This framework conceptualises governance as a moderating factor that strengthens the relationship between green finance and carbon emissions reduction. Good governance improves regulatory alignment, strengthens accountability mechanisms, and facilitates effective co-ordination amongst actors, all of which are critical for the long-term mobilisation of climate finance and the realisation of carbon recycling goals.

Despite the growing body of literature on the individual roles of green finance, innovation, and trade, few studies have examined their integration within a single framework, particularly concerning governance as a moderating variable. Most prior research has addressed these components in isolation; for instance, Qing et al. (2024) focused on green investment and finance, Yin et al. (2024) on green innovation, and Yi et al. (2025) on the role of foreign direct investments and trade openness in promoting green technology. This study addresses that gap by proposing and empirically testing a model that unites green finance, green innovation, and trade in green technology within the framework of carbon circularity, while also evaluating the moderating effect of governance quality. Such an approach offers insights into the short-term determinants of carbon emissions reduction in the EAS context. It contributes to the long-term vision of a circular carbon economy supported by financial, technological, and institutional convergence.

Hypotheses

H1: Green financing has a significant positive effect on carbon emissions reduction.

H2: Green innovation has a significant positive effect on carbon emissions reduction.

H3: Trade in green technology has a significant positive effect on carbon emissions reduction.

H4: Good governance strengthens the positive effect of green financing on carbon emissions reduction.

3. Methodology

3.1. Research Design

This study aims to assess the impact of government quality interventions on green financing, green innovation, and trade in low-carbon technology within the framework of carbon emissions reduction. The carbon emissions reduction index (CEI) serves as the dependent variable, representing the overall effects of the system. Meanwhile, green financing (GFI), green innovation (GVA), and trade in low-carbon technology (TRA) function as the independent variables influencing carbon recycling dynamics. Additionally, the baseline model accounts for the dynamic effects of CEI by incorporating its lagged value [CEI (Lag) 1], capturing the persistence of carbon recycling over time. The panel regression equation is as follows.

$$CEI_{it} = \gamma_0 + \gamma_1 CRI_{it-1} + \gamma_2 GFI_{it} + \gamma_3 GVA_{it} + \gamma_4 TRA_{it} + \sum \gamma_k CONTROLS_{it} + \varepsilon_{it}$$

where γ_0 represents the constant term, γ_k denotes the coefficient associated with each independent variable, i signifies the research subject (country), t indicates the period under study, and ε represents the error term, capturing unobserved factors influencing CEI.

The model employs the negative inverse of carbon emissions growth to quantify the CEI. The variation in carbon emissions across different years captures the reversal effect of carbon recycling. A greater positive change in carbon emissions indicates a higher level of success in a country's recycling efforts, whereas a negative change suggests lower recycling effectiveness. Mathematically, CEI is formulated as follows:

$$CEI_{it} = - \frac{(CE_{it} - CE_{it-1})}{CE_{it-1}}$$

where CE represents the carbon emissions of each country (i) in a given year (t).

Conversely, the Green Finance Index (GFI) is derived through principal component analysis (PCA), which is applied to multiple financial components. PCA is employed when variables exhibit strong correlations, allowing for dimensionality reduction, while retaining the most relevant information. The optimal PCA transformation is determined by identifying an orthogonal direction that maximises the variance of the original components (Gewers et al., 2021). The components selected for PCA in constructing the GFI include: (i) green credit (GCR); (ii) green insurance (GIS); (iii) green investment (GIV); and (iv) green securities (GSC). The application of PCA facilitates the reduction of these four dimensions into a single composite indicator representing green finance (Kahraman, 2022; Nawaz, Hussain, and Hussain, 2021). The mathematical formulation of GFI is expressed as follows.

$$GFI_{it} = \omega_1 GCR_{it} + \omega_2 GIS_{it} + \omega_3 GIV_{it} + \omega_4 GSC_{it}$$

where ω_k represents the eigenvector weight of each component, indicating its contribution to the GFI for a given country (i) in a specific year (t). To enhance the robustness of the model, several control variables are incorporated: (i) government expenditure (GEX); (ii) economic complexity (ECI); (iii) economic growth (GDP); and (iv) population (POP). The inclusion of GEX is based on its role in reducing carbon emissions, which serves as an indicator of successful carbon recycling (Halkos and Paizanos, 2013; Oh, 2023). Conversely, GDP and POP have consistently demonstrated

a positive correlation with carbon emissions, implying a reduction in the potential for effective carbon emissions reduction (Ali et al., 2023; Lawal, 2019; Onofrei, Vatamanu, and Cigu, 2022; Shi, 2001). Meanwhile, the impact of ECI on the carbon footprint remains ambiguous, with existing literature presenting mixed findings (Osinubi, 2024; Zhen and Freire, 2023). To improve the model's efficiency, the GEX, GDP, and POP variables have been transformed using natural logarithms, thereby minimising fluctuations and normalising data distribution. The mathematical formulation integrating these control variables is structured as follows.

$$\Sigma \gamma_k \text{CONTROLS}_{it} = \gamma_5 \text{GEX}_{it} + \gamma_6 \text{ECI}_{it} + \gamma_7 \text{GDP}_{it} + \gamma_8 \text{POP}_{it}$$

The baseline model is further extended by incorporating the moderating effect of government quality on the relationship between carbon recycling and its independent variables. Government quality is assessed using the Worldwide Governance Indicators (WGI) framework, which is derived from PCA applied to six key governance variables: (i) control of corruption (COC); (ii) government effectiveness (GEF); (iii) political stability and absence of violence/terrorism (PSA); (iv) regulatory quality (REQ); (v) rule of law (RUL); and (vi) voice and accountability (VAC). All these variables constitute the World Bank's WGI dataset. Mathematically, WGI is expressed as follows.

$$\text{WGI}_{it} = \omega_1 \text{COC}_{it} + \omega_2 \text{GEF}_{it} + \omega_3 \text{PSA}_{it} + \omega_4 \text{REQ}_{it} + \omega_5 \text{RUL}_{it} + \omega_6 \text{VAC}_{it}$$

Where ω_k represents the weight of the eigenvector for each governance component, indicating its contribution to the WGI of a given country (i) in a specific year (t). The incorporation of WGI into the baseline model is formally structured as follows.

$$\text{CEI}_{it} = \gamma_0 + \gamma_1 \text{CEI}_{it-1} + \gamma_2 \text{GFI}_{it} + \gamma_3 \text{GVA}_{it} + \gamma_4 \text{TRA}_{it} + \gamma_5 \text{WGI}_{it} + \gamma_6 \text{GFI} \times \text{WGI}_{it} + \gamma_k \text{CONTROLS}_{it} + \varepsilon_{it}$$

The baseline model was evaluated using panel data regression. Before performing the regression analysis, the Chow, Hausman, and Lagrange multiplier tests were conducted to determine the most appropriate panel regression model. The presence of endogeneity within the panel data regression framework necessitated the application of the generalised method of moments (GMM) to address this issue. Specifically, the study employed the difference GMM approach, utilising lagged values [CEI (Lag) 1]. To ensure the robustness of the model, several diagnostic tests were performed. The Sargan test was conducted to assess the validity of the instrumental variables, with a threshold of p-value >0.05 indicating instrument validity. Additionally, the Arellano-Bond test was employed to verify the absence of second-order autocorrelation, with a criterion of p-value AR(2) >0.05 (Roodman, 2009). The GMM method was applied across two distinct periods: the pre-SDGs era (2000–2014) and the post-SDGs era (2015–2022).

3.2. Sample Selection and Descriptives

The study examines the EAS participating countries (18 nations categorised into three regions within Asia, East Asia (China, Japan, and the Republic of Korea), South Asia (India), and Southeast Asia (Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Viet Nam), as well as four non-Asian countries (Australia, New Zealand, Russia, and United States). Given these parameters, the GMM method is appropriately applied, as the number of countries (N) exceeds the research period (T), satisfying the condition $N > T$ (Roodman, 2009).

Most data were sourced from the World Bank Database, complemented by additional reliable sources. Specifically, PCA components of the Global Financial Inclusion (GFI) and Worldwide Governance Indicators (WGI) were incorporated. At the same time, the Economic Complexity Index (ECI) was obtained from The Observatory of Economic Complexity, and trade-related data (TRA) were retrieved from the International Monetary Fund Database. Table 9.1 presents the descriptive statistics of all variables used in the study. Amongst the variables, GVA exhibits the highest level of deviation, highlighting significant disparities amongst countries adopting green innovation.

Table 9.1. Descriptive Statistics

Variable	Observation	Mean	Median	Maximum	Minimum	Std. Dev.
CEI	288	-0.023134	-0.019000	0.122800	-0.329200	0.045933
GFI	288	0.879370	0.618000	4.776.000	0.000000	0.772322
GVA	288	1.866.032	1.734.100	6.234.400	1.446.000	7.868.648
TRA	288	0.668889	0.396000	3.184.000	0.001000	0.669211
GEX	288	7.521.907	2.211.500	15056.84	-13967.60	1.052.323
ECI	288	0.491419	0.260946	2.818.791	-1.356.330	0.999823
GDP	288	1.150.088	1.153.100	1.341.500	9.238.000	0.956771
POP	288	0.597893	0.627150	1.000.000	0.185900	0.248165
WGI	288	1.888.517	2.113.000	3.798.000	0.054000	0.932311

CEI = carbon emissions reduction, GFI = green finance, GVA = green innovation, TRA = trade in low-carbon technology, GEX = government expenditure, ECI = economic complexity, GDP = gross domestic product, POP = total population, WGI = World Governance Indicators.

Source: Authors.

4. Results and Discussion

4.1. Baseline Regression Result

Before conducting the primary test, we performed a preliminary test as a prerequisite to ensure that the data in this study could be analysed using the GMM. To apply this method, the model first needed to be confirmed as fit using the fixed effect model (FEM). Based on the regression results in Table 9.2, the Chow-Test value was 0.007. This result indicated that the model was more suitable for FEM than the common effect model (CEM), as the Chow-Test value was lower than the 5% significance level. Subsequently, the analysis proceeded with the Hausman test to compare FEM with the random effect model (REM). The test results showed that the Hausman-Test value was 0.000, confirming that FEM was more appropriate than REM.

Table 9.2. Generalised Method of Moments Results

Variables	CEM	REM	FEM	Sys-GMM	Sys-GMM Moderating
Dependent Variable: CEI					
CEI (-1)	0.197***	0.197***	0.106	0.139***	0.121***
GFI	-0.003	-0.00293	0.002	-0.0140**	0.0363**
GVA	0.001*	0.000773*	0.001	0.000755**	0.00125***
TRA	-0.002	-0.00163	-0.002	-0.000183	0.0102*
GEX	-0.000	-0.000	0.000	-0.000	-0.000
ECI	-0.003	-0.00250	0.019	-0.00435*	-0.00623
GDP	0.007*	0.00691*	-0.047	0.0111***	0.00391
POP	0.042***	0.0420***	0.217	0.0578***	0.0662***
WGI	0.006*	0.00585*	0.020	0.00946***	0.0385***
GFIxWGI					0.0266***
Constant	-0.108**	-0.108**	0.337	-0.216***	-0.196**
Observations	288	288	288	288	288
AR (1) test p-value				0.015	0.013
AR (1) test p-value				0.922	0.891
Hansen J test				1.000	1.000
Year Effect	Yes	Yes	Yes	Yes	Yes
Country Effect	No	No	No	No	No

AR = Arellano-Bond, CEI = carbon emissions reduction, CEM = common effect model, FEM = fixed-effect model, GFI = green finance, GMM = generalized method of moments, GVA = green innovation, TRA = trade in low-carbon technology, GEX = government expenditure, ECI = economic complexity, GDP = gross domestic product, POP = total population, WGI = World Governance Indicators, REM = random effect model.

Notes: * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

Source: Authors.

After confirming that the model was fit using FEM, the GMM could be employed to address the issues inherent in FEM. One immediate problem in applying ordinary least squares (OLS) to this empirical setting was that $y_{i,t-1}$ it was correlated with the fixed effects in the error term, leading to what is known as dynamic panel bias. If T had been large, the impact of a single year's shock on the country's apparent fixed effect would have diminished, thereby reducing the endogeneity problem. There were two approaches to mitigating this endogeneity issue. The first, which lies at the core of GMM, involved transforming the data to eliminate the fixed effects. The second approach entailed instrumenting $y_{i,t-1}$ and other endogenous variables with instruments assumed to be uncorrelated with the fixed effects (Roodman, 2009).

Table 9.3 indicates that amongst the three green policies, only green finance and green innovation significantly impact carbon emissions reduction. In contrast, trade in low-carbon technology does not exhibit a significant effect. After moderation by good governance, all three green policies demonstrate significant effects on carbon emissions reduction. Furthermore, green finance, initially exhibiting a negative influence, shifts to a positive impact on carbon emissions reduction post-moderation. Moreover, the influence of green innovation strengthens to 0.00125 following the moderating effect of good governance on green finances.

Table 9.3. Generalised Method of Moments Results before and after the Sustainable Development Goals

Variables	Before SDGs		After SDGs	
	(1)	(2)	(3)	(4)
Dependent Variable: CEI				
CEI (-1)	0.087	0.053***	0.178	0.253
GFI	-0.008*	0.039*	-0.014*	0.072**
GVA	0.003*	0.001*	0.001**	0.001***
TRA	-0.001	0.003	0.008*	0.033*
GEX	-0.046***	-0.001***	-0.009**	0.001
ECI	0.004	0.002	-0.008	-0.007
GDP	-0.002	-0.003*	0.018**	0.004***
POP	0.055***	0.074***	0.002	0.014***
WGI	0.019***	0.024***	0.026***	0.0039***
GFIxWGI		0.026**		0.043***
Constant	-0.019	0.215	0.337	-0.216***
Observations	288	288	288	288
AR (1) test p-value	0.015	0.013	0.039	0.019
AR (1) test p-value	0.945	0.921	0.342	0.391
Hansen J test	1.000	1.000	1.000	1.000
Year Effect	Yes	Yes	Yes	Yes
Country Effect	No	No	No	No

AR = Arellano-Bond, SDGs = Sustainable Development Goals, TRA = trade in low-carbon technology, GEX = government expenditure, ECI = economic complexity, GDP = gross domestic product, POP = total population, WGI = World Governance Indicators.

Notes: *p<0.10; ** p<0.05; *** p<0.01.

Table 9.3 presents the results of the GMM estimation, which was conducted separately for two periods, (i) before the adoption of the Sustainable Development Goals (2007–2014), and (ii) after the adoption (2015–2022). This period segmentation was performed to assess the direct impact of the SDG targets on green instruments in achieving these objectives. Columns (1) and (3) represent models prior to the moderation process, whereas columns (2) and (4) depict the models after incorporating moderation. The GMM estimation results for the period before the SDGs indicate that government expenditure (-0.046) had a significant negative effect on carbon recycle ($p < 0.01$), suggesting that higher government spending contributed to a reduction. Population (0.055) exhibited a strong positive effect ($p < 0.01$), implying that population growth was associated with an increase in carbon recycle. Additionally, green innovation (0.003) had a significant positive relationship ($p < 0.10$), indicating a marginal contribution of green innovation to CEI. Green finance (-0.008) showed a significant negative effect ($p < 0.10$), suggesting that higher green finance to a decline in CEI. Last, governance (0.019) demonstrated a strong positive influence ($p < 0.01$), underscoring the importance of governance quality in shaping CEI outcomes before the SDGs era.

The empirical results demonstrate that green finance (GFI), green innovation (GVA), and trade in low-carbon technology (TRA) exhibit distinct effects on carbon emissions reduction (CEI), with notable differences before and after the implementation of the SDGs. Prior to the SDGs, GFI exhibited a negative and statistically significant coefficient (-0.008 , $p < 0.10$) when WGI was not considered. However, when the WGI were introduced as a moderator, the effect of GFI turned significantly positive (0.039 , $p < 0.10$), suggesting that good governance can enhance the effectiveness of green financial policies in reducing carbon emissions. This moderation effect is further reinforced after the SDGs, where GFI initially has a negative effect on CEI (-0.014 , $p < 0.10$) but turns significantly positive (0.072 , $p < 0.05$) in the presence of WGI. This shift indicates that post-SDGs, green finance is more effective in fostering carbon reduction, especially in economies with strong governance frameworks.

Similarly, GVA has shown a consistent but increasing positive effect on CEI across all models. Before the SDGs, GVA had a small but significant impact (0.003 , $p < 0.10$) when governance was not considered, which persisted even with WGI moderation (0.001 , $p < 0.10$). However, after the SDGs, the effect of GVA became stronger, increasing from 0.001 ($p < 0.05$) to 0.001 ($p < 0.01$) in the moderated model. This trend highlights the rising importance of green innovation in carbon reduction efforts, particularly as governance mechanisms improve post-SDG implementation. The stability and growing significance of GVA suggest that innovation-driven green policies are increasingly effective in addressing environmental concerns in a well-governed setting.

A notable transformation is observed in the TRA variable. Before the SDGs, TRA was not statistically significant in either model, suggesting that trade in low-carbon technology had a limited impact on carbon reduction. However, after the SDGs, TRA became significantly positive (0.008 , $p < 0.10$) and even more pronounced in the moderated model (0.033 , $p < 0.10$). This finding implies that after introducing the SDGs, the role of low-carbon technology trade has been reinforced, particularly in countries with strong governance structures. The increasing significance of TRA suggests that policies promoting cross-border exchange of green technology have gained traction post-SDGs, especially in well-governed economies.

Overall, the comparison between the before-and-after SDGs reveals a strengthening of the positive effects of GFI, GVA, and TRA on carbon reduction, particularly in governance-moderated environments. The pre-SDG models show relatively weaker or inconsistent effects, whereas the post-SDG models indicate a more robust and statistically significant influence. The rising coefficients of GFI and TRA and the sustained and increasing role of GVA suggest that the SDGs have reinforced the role of green financial instruments, innovation, and technology trade in carbon mitigation efforts. Additionally, the WGI moderation effect is more pronounced after the SDGs, underscoring the importance of governance in ensuring the effectiveness of green policies. These findings emphasise the necessity of good governance structures to maximise the impact of green finance, innovation, and sustainable technology trade in achieving long-term carbon reduction goals.

4.2. Discussion

Rebound effect of green finance

Table 9.2 indicates that green finance may paradoxically yield effects contrary to its original purpose, contributing negatively to carbon emissions. The surge in green finance initiatives has triggered increased atmospheric carbon emissions. This anomaly highlights a critical issue limiting the effectiveness of green finance, specifically mismanagement and fraudulent practices commonly known as greenwashing. Mismanagement, particularly by governments in developing countries, significantly impedes efforts to address environmental challenges.

Felkner et al. (2025) emphasise the necessity for governments to adopt long-term, bottom-up policy approaches to prevent green finance from resulting in rebound effects and contributing to carbon lock-in. Designing long-term policy frameworks is inherently challenging, which explains why many governments are reluctant to implement abstract or uncertain policies, opting instead to prioritise short-term strategies (Lu, Gulzar, and Lai, 2024; Sognnaes et al., 2021). Additionally, Sun et al. (2025) argue that the institutional quality of a country plays a critical role in shaping how effective green finance instruments are in supporting long-term sustainable development goals.

Green finance rebound effects can be critically linked to the prevalence of greenwashing, a practice where firms or institutions exaggerate or fabricate their environmental credentials. According to Yu et al. (2024), green finance policies, intended to incentivise sustainable behaviour, can unintentionally fuel greenwashing amongst heavily polluting enterprises. These companies often respond to policy-induced financial pressures by inflating their ESG reports, masking actual environmental performance. It found that such behaviour is statistically significant, particularly under policy pressure, leading to misleading capital allocation and undermining the environmental goals of green finance.

This tendency to present symbolic rather than substantive sustainability actions reflects a broader organisational response to institutional pressures. As DiMaggio and Powell (1983) in institutional theory, firms often mimic environmental practices to appear legitimate in the eyes of regulators and stakeholders, even if those practices are decoupled from actual performance. In this sense, under weak institutional governance, green finance may encourage disclosure conformity without necessarily driving behavioural or operational change. Empirical evidence by Liu and Zhang (2023) reinforces this notion, showing that regulatory pressure can drive firms to innovate, but actual environmental impact remains limited if institutional and technological capacities are lacking.

Moreover, Xing et al. (2024) broaden this concern by showing that firms often deploy symbolic environmental disclosures to gain institutional resources like subsidies and loans. These resources are used not necessarily for genuine sustainability transitions but for strategic, superficial green innovation, termed 'innovation-washing'. This behaviour dilutes the efficacy of green finance by creating the illusion of progress, while maintaining unsustainable practices. A complementary finding by Zhang, Wong, et al. (2024) further highlights that green technological innovation becomes truly impactful only when backed by coherent policy frameworks and sustained green financing, suggesting that fragmented or inconsistent policy environments intensify the rebound effect.

Does governance matter?

The effectiveness of green finance in promoting low-carbon transition across EAS countries is heavily conditioned by governance quality. Despite increasing adoption of green financial instruments in the region, their environmental impact remains uneven. This can be attributed to several structural and institutional challenges commonly observed across EAS countries.

A key factor is institutional fragmentation, particularly between national and subnational levels of government. This fragmentation often results in inconsistent policy implementation, limited regulatory oversight, and weak enforcement mechanisms, undermining the integrity of green finance allocation and monitoring. In such contexts, symbolic compliance and greenwashing behaviour become prevalent, where firms exploit sustainability frameworks for reputational advantages without committing to substantive environmental improvements.

This situation aligns with institutional theory as outlined by DiMaggio and Powell (1983), which posits that organisations are less likely to adopt practices that lead to genuine transformation in environments lacking intense coercive and normative institutional pressures. Instead, they may conform superficially to gain legitimacy, particularly in response to external expectations or financial incentives.

Several empirical studies support this theoretical framing. For instance, Buglea et al. (2025) demonstrate that ESG and digital transformation initiatives only deliver measurable sustainability outcomes when embedded within robust governance systems. Without adequate regulatory quality, such reforms risk becoming performative rather than impactful. Similarly, Li et al. (2025) emphasise the role of rigorous oversight and central control in ensuring the effectiveness of green finance mechanisms such as China's Government Green Fund. Their findings suggest that strong governance can mitigate the adverse effects of local institutional weaknesses by enabling more targeted and accountable resource allocation. In the financial sector, Ansari et al. (2024) show that digital financial inclusion contributes to environmental sustainability only in high-institutional-quality settings. In weak governance environments, however, these tools may instead amplify environmental risks through unchecked financial expansion or inadequate due diligence.

Complementing these findings, Lu et al. (2024) reveal that ESG regulatory pressures are only effective when supported by strong corporate governance. This reflects the institutional theory view that normative expectations and regulatory consistency are essential for driving real behavioural change in firms. From a broader development and policy perspective, Nawaz, Hussain, and Hussain (2021) assert that environmental policy success is deeply rooted in institutional capacity, especially in developing countries. Their analysis confirms that governance is not a peripheral consideration but a foundational precondition for the successful deployment of green finance. Lastly, studies by Xing et al. (2024), and Yu et al. (2024) highlight the risks of innovation-washing and ESG misreporting in low-governance contexts. These behaviours flourish in environments with limited regulatory scrutiny, distorting the intended effects of green finance and undermining public trust.

Thus, the governance challenges across EAS countries, ranging from institutional fragmentation and limited transparency to weak enforcement, help explain why green finance may fail to achieve its transformative goals. These structural issues allow symbolic adherence and opportunistic behaviours to proliferate, diluting the environmental benefits of financial interventions. Therefore, strengthening governance remains essential for ensuring that green finance mechanisms produce real, verifiable outcomes across the EAS region.

Collaboration between green finance and SDGs

The comparative analysis of the pre- and post-SDGs periods demonstrates a precise amplification in the effectiveness of green financial instruments – the Green Finance Index (GFI), Green Value Added (GVA), and Green Trade (TRA) – in reducing carbon emissions, especially when moderated by governance. This empirical improvement suggests that adopting the SDGs has triggered a global momentum towards decarbonisation and more structured and accountable institutional mechanisms in the mobilisation of green finance. The interaction terms in the post-SDG model point to enhanced institutional coherence and policy alignment that translate into more impactful environmental outcomes, particularly across the EAS countries where governance capacity is diverse but evolving.

Yadav et al. (2024) support this interpretation by showing that green finance contributes meaningfully to multiple SDGs, specifically SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). For instance, the International Bank for Reconstruction and Development (IEA et al., 2023) documents a 2.6-fold increase in global renewable energy investment since 2010, amounting to US\$15.8 billion. Nonetheless, Čeryová et al. (2020) warn that this growth is insufficient to meet the 1.5°C climate target unless investment is doubled by 2030 and energy efficiency is widely scaled, particularly in emerging economies.

Structured instruments such as green bonds have been critical in channelling capital towards decarbonisation strategies. Bulkot et al. (2023), and Čeryová et al. (2020) emphasise that these instruments reduce investor uncertainty and increase market confidence, particularly in jurisdictions with strong ESG disclosure frameworks. In such environments, ESG practices are not merely symbolic; they represent long-term sustainability commitments that reduce capital costs and improve green investment performance, findings that align with the strengthened GFI and TRA effectiveness in the presence of governance.

Governance also reinforces the synergies between financial inclusion and environmental sustainability. Mehmood et al. (2024) show that in the South Asian context, financial inclusion contributes to lower carbon emissions, but only when institutional quality is high. Although their study does not explicitly address green innovation or digital finance, their findings underline the importance of governance in translating inclusive finance into environmental gains. These results offer insight into the post-SDGs trend observed in EAS countries, where broader policy reforms and institutional modernisation have accompanied the rise in digital platforms.

Gao and Qu (2025) further substantiate that green finance directly stimulates technological innovation, facilitating structural economic transformation. The linkage between GVA and emissions reduction becomes more pronounced when policies, finance, and technology ecosystems align. Caleb (2024) adds that public–private partnerships (PPPs) are vital for mobilising capital and technical expertise, especially in countries with constrained public budgets. These partnerships are instrumental in bridging investment gaps in clean energy infrastructure, aligning well with the empirical observation of improved green finance outcomes in countries strengthening their PPP frameworks.

Effective regulatory design is equally crucial. Idris et al. (2024) argue that comprehensive legislation and monitoring systems, particularly with PPPs, enhance investor protection, increase transparency, and deter greenwashing. Also, Martin (2023) states that green finance must be embedded within broader systemic reforms, including budgetary alignment, legal harmonisation, and institutional co-ordination. Green financial initiatives may remain fragmented or misaligned with long-term sustainability goals without these foundations.

Operational efficiency also determines how well green finance translates into environmental and economic benefits. Zhu, Lin, and Zhu (2025) demonstrate that high-performing green finance systems improve total factor productivity (TFP), alleviate capital constraints, and foster green innovation. TFP growth signifies technological progress and reflects a more efficient use of financial resources to achieve decarbonisation targets.

In the EAS context, strengthening green finance effectiveness after the SDGs is inseparable from improvements in governance. The diversity of institutional capacity across the EAS countries, ranging from relatively advanced systems to more fragmented governance structures, explains the varying baseline performance of green finance prior to 2015. Countries that pursued legal, regulatory, and institutional reforms have better aligned their financial systems with SDG targets, leading to the improved post-SDG model observed in this study.

Thus, the interaction between green finance and governance does not merely reflect a statistical correlation; it signals a foundational shift. Governance acts as the hinge that converts financial flows into environmental transformation. Building robust institutions with clear regulatory mandates, cross-sectoral integration, and transparent accountability mechanisms is essential for EAS countries. Without this, green finance risks becoming a vehicle for symbolic compliance rather than a driver of structural sustainability. The findings underscore that in the SDG era, the success of green finance lies not only in how much capital is mobilised, but also in how well it is governed.

SDGs role on trade in low-carbon and green innovation

Table 9.3 reveals a significant shift in the impact of trade in low-carbon goods and services (TRA) on carbon reduction after adopting the SDGs in 2015. Before the SDGs, trade activities, particularly in maritime transport, were predominantly linked to increased carbon emissions. However, the post-2015 period demonstrates a reversal, with trade becoming a facilitator of emissions reduction, especially when coupled with the GFI. This transition underscores a global policy pivot towards embedding environmental performance in trade flows, aligning economic liberalisation with sustainability goals.

The transformation of maritime trade aligns with international commitments. UNCTAD (2023) emphasises that international shipping contributes approximately 3% of global carbon emissions. To decarbonise this sector, significant investments are required, ranging from US\$8 billion–US\$28 billion per vessel annually to US\$28 billion–US\$90 billion for the modernisation of port infrastructure. Low-carbon fuels such as hydrogen and ammonia are expected to play a central role in this transition. Routroy, Sahu, and Chhetri e (2025) support these projections, suggesting that logistics emissions could be reduced by up to 87% after 2040 if alternative fuels are effectively integrated into trade logistics systems.

Institutional responses to this challenge have gained traction. The International Maritime Organization (IMO) has introduced policy frameworks such as the Energy Efficiency Design Index and the Ship Energy Efficiency Management Plan, which aim to reduce the carbon intensity of vessels (IMO, 2023). In the medium term, the IMO's strategy focuses on market-based mechanisms and strengthening port readiness to support green fuel distribution (IMO, 2023). These measures suggest that decarbonising trade logistics requires more than technological innovation; it hinges on infrastructure investment, policy enforcement, and institutional co-ordination.

Furthermore, implementing the SDGs has magnified the influence of green value-added innovation (GVA) in driving carbon mitigation. The findings reveal that, post-2015, GVA exhibits a more consistent and positive relationship with emissions reduction, signifying a broader global orientation towards green innovation as a vehicle for sustainable development. GVA encompasses efforts to enhance efficiency, reduce pollution, and manage natural resources in ways that align with SDG targets.

Empirical research further substantiates the growing relevance of green innovation. Ullah et al. (2023) emphasise its inclusivity, demonstrating that green innovation is practical across large enterprises and micro, small, and medium-sized enterprises by improving resource efficiency and controlling environmental impacts. Wang et al. (2022) confirm that these innovations are vital for industrial sustainability and play a transformative role in aligning corporate strategies with ecological goals. In a complementary vein, Ahmed et al. (2022) reveal that firms engaging in green innovation are more likely to pursue eco-friendly practices that resonate with public and regulatory expectations, thereby enhancing legitimacy and long-term viability.

Rani et al. (2025) contribute to this narrative by showing that digitalisation amplifies the effects of green innovation, enabling scalable, data-driven solutions for carbon reduction. The integration of digital tools facilitates real-time environmental monitoring, smart logistics, and energy efficiency upgrades. Meanwhile, Wang and Zhang (2025) highlight that online retail firms have adopted green innovation to embed environmental and social accountability into their business models, reflecting the evolution of consumer expectations and regulatory demands. Rizki, Widjaja, and Shanty (2023) also demonstrate that firms adopting green innovation practices are more transparent in their carbon disclosures, reducing emissions and fostering trust amongst investors, customers, and policymakers.

Therefore, the findings suggest that TRA and GVA have evolved from peripheral strategies into central mechanisms for carbon reduction, especially in the post-SDGs era. Their effectiveness is tightly interwoven with technological investments, institutional governance, and international co-operation. For the EAS countries, advancing towards carbon neutrality will require coherent trade and innovation policies, coupled with financial and infrastructural support that reinforces sustainable development pathways.

Anomaly of government spending

Table 9.3 reveals that after the adoption of the SDGs in 2015, the relationship between government expenditure (GEX) and carbon emissions intensity (CEI) significantly weakened. This suggests that while the SDGs were intended to promote sustainability, their broad and multidimensional focus may have diluted the emphasis on carbon reduction. Government spending became more fragmented as fiscal resources were increasingly allocated across diverse objectives beyond environmental concerns.

The SDGs span 17 goals, encompassing economic growth, social inclusion, and environmental sustainability. Consequently, fiscal priorities often shifted towards infrastructure, employment, and access to energy, such as Goals 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), and 9 (Industry, Innovation and Infrastructure), rather than directly targeting emissions mitigation. This trade-off between immediate socioeconomic needs and long-term environmental commitments weakened the potential impact of public spending on carbon reduction. Basic needs like clean water, food security, and healthcare often receive greater attention than investments in low-carbon transitions.

This scenario illustrates a lack of cross-sectoral co-ordination in fiscal planning. Government strategies tend to operate in silos, without fully integrating environmental objectives into national budgetary frameworks. Although the SDGs call for interlinked and integrated planning, many countries still pursue fragmented approaches to public finance. The resulting inefficiencies undermine the role of fiscal instruments in driving environmental outcomes.

From a welfare economics perspective, this situation can be interpreted through Kaldor's compensation criterion, which suggests that resource redistribution is justifiable if the gains outweigh the losses and the beneficiaries can hypothetically compensate the disadvantaged (Martinez-Alier, 2002). However, in the context of climate policy, the most affected groups are often the most vulnerable, those without the institutional power to demand environmental compensation. Martinez-Alier (2002) criticises Kaldor's logic in justifying neoliberal policy prioritising market efficiency over environmental justice.

Furthermore, the unequal allocation of government budgets across sectors highlights the importance of fiscal clarity and prioritisation. As emphasised by Halkos and Paizanos (2023), the carbon impact of government spending depends on the targeted sectors: defence and general consumption tend to increase emissions, whereas education and environmental expenditures can significantly reduce them. These findings underscore the need for deliberate, focused public investments aligning with decarbonisation goals.

Complementary evidence from Onofrei, Vatamanu, and Cigu (2022) also suggests that green public procurement is a strategic tool to reconcile fiscal efficiency with environmental objectives. By embedding sustainability criteria into public spending decisions, governments can optimise their budgets for long-term low-carbon development, though this approach remains underutilised in many developing nations.

The weakening influence of GEX on CEI also resonates with the analysis by Nerini et al. (2018), who emphasise that the short-term pressure to expand access to essential services often overrides investments in clean energy systems. The tension between immediate developmental needs and long-term sustainability objectives contributes to inconsistent environmental policy outcomes.

Thus, the weakening role of government expenditure in reducing emissions is not due to an absence of fiscal policy but rather the fragmentation of priorities, lack of cross-sectoral co-ordination, and insufficient focus on decarbonisation. To ensure that fiscal mechanisms contribute meaningfully to a low-carbon transition, governments must adopt integrated, sectorally aligned, and explicitly green budgeting frameworks that prioritise environmental objectives alongside social and economic goals.

5. Conclusion

This study provides empirical evidence that green finance (GFI), green innovation (GVA), and trade in green technology (TRA) are pivotal drivers of carbon emissions reduction across EAS countries. Green finance plays the most significant role, particularly when moderated by strong governance structures. Governance quality amplifies the environmental efficacy of financial instruments, shifting green finance from a potential source of inefficiency to a catalyst for structural decarbonisation. Similarly, green innovation consistently fosters carbon mitigation by enhancing technological readiness and enabling carbon circularity through solutions such as CCUS and mineral carbon capture and utilisation. Trade in green technology further complements these efforts by facilitating cross-border dissemination of low-carbon technologies. However, its effectiveness is contingent upon institutional trust and policy alignment.

Theoretically, this study contributes to the sustainability discourse by integrating economic, technological, and institutional enablers within a unified framework to address climate mitigation. While the empirical focus lies on carbon emissions reduction as a measurable outcome, the study also provides conceptual insight into the enabling conditions for future carbon recycling adoption. Due to the current limitations in carbon recycling adoption metrics across the EAS countries, a Carbon Recycling Index (CRI) could not be directly utilised. CEI is a meaningful proxy to infer progress towards carbon circularity, especially in industrial economies facing transition challenges.

Several limitations should be acknowledged. First, the CEI indicator reflects carbon mitigation outcomes but may not fully capture carbon recycling systems' scale or technological maturity across different national contexts. Second, data quality and availability disparities, particularly in lower-income EAS countries, may introduce measurement error or estimation bias. Third, the use of the Worldwide Governance Indicators as a governance proxy, while comprehensive, may not reflect sector-specific regulatory characteristics critical to carbon innovation and green finance deployment.

Future research can enhance this framework by employing sectoral or firm-level data to explore more granular dynamics of carbon recycling, including project-level performance of CCUS, industrial carbon reuse initiatives, and policy-induced innovation spillovers. Longitudinal or comparative case studies may also reveal how different governance trajectories affect the scalability and impact of carbon circularity initiatives. Additionally, the intersection between digital technology, such as blockchain for carbon traceability, and carbon recycling presents a promising avenue for future inquiry.

From a policy perspective, differentiated approaches are required across the EAS region. Developed economies such as Australia, Japan, the Republic of Korea, and Singapore should focus on accelerating the commercialisation and integration of carbon recycling technologies within national climate strategies. In contrast, developing EAS countries, including Cambodia, Indonesia, Lao People's Democratic Republic, and Myanmar, must prioritise governance strengthening, build institutional readiness, and establish regulatory incentives to support future adoption. Across all countries, reinforcing environmental disclosure standards, improving transparency in green finance allocation, and enhancing regional collaboration on green technology trade will be essential.

Ultimately, it is about embedding carbon recycling within national decarbonisation pathways. supported by robust governance and targeted economic instruments, will enable a transition from linear mitigation strategies towards a circular carbon economy. By positioning GFI, GVA, TRA, and governance within an integrated sustainability framework, this study advances the theoretical understanding of climate transition enablers and offers actionable insights for policy harmonisation and implementation across the EAS countries.

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Chapter 10

Assessing the Feasibility of Implementing Carbon Recycling Technologies in Indonesia

1. Introduction

Carbon recycling – converting carbon dioxide (CO₂) emissions into higher-value products – has been studied across engineering, earth sciences, and environmental disciplines for decades (Jacquet et al., 2012; Rodygin, Vikenteva, and Ananikov, 2019; Wen et al., 2022; Yang et al., 2014; Ramadhan et al., 2024). This report assesses the technological development and deployment conditions of selected carbon recycling processes to gauge their feasibility in Indonesia. As Asia's third-largest emitter (674.54 metric tonnes of carbon dioxide equivalent (Mt CO₂e) in 2022, largely from power generation) (World Bank, n.d.), Indonesia could substantially reduce its carbon footprint if supportive policies and viable business models are in place.

Japan's 2019 carbon-recycling roadmap sets commercial-scale targets by 2030 and mandates continued development for low-cost, high-impact processes (METI, 2021). By contrast, Indonesia's existing regulations – Presidential Regulation No. 98/2021 and the 2023 Ministry of Energy and Mineral Resources (MEMR) carbon capture, utilisation, and storage (CCUS) rule for enhanced oil recovery – establish a broad emissions reduction agenda but lack dedicated incentives or guidelines to advance carbon-recycling technology.

There are still substantial technological, institutional, and financial barriers that need to be addressed to fully realise its potential. Therefore, this research aims to critically assess the feasibility of carbon recycling implementation in Indonesia with the following objectives:

- To critically assess the existing carbon recycling technologies and evaluate its relevance to Indonesia context.
- To critically evaluate the current situation of the development of specific carbon recycling technology, its prospects for development, and potential hurdles.
- To explore the challenges in developing and implementing the carbon recycling in Indonesia in the context of its policy and markets.
- To critically analyse the governance issues such as life cycle accounting; end-of-life handling of products; and monitoring, reporting, and verification (MRV).

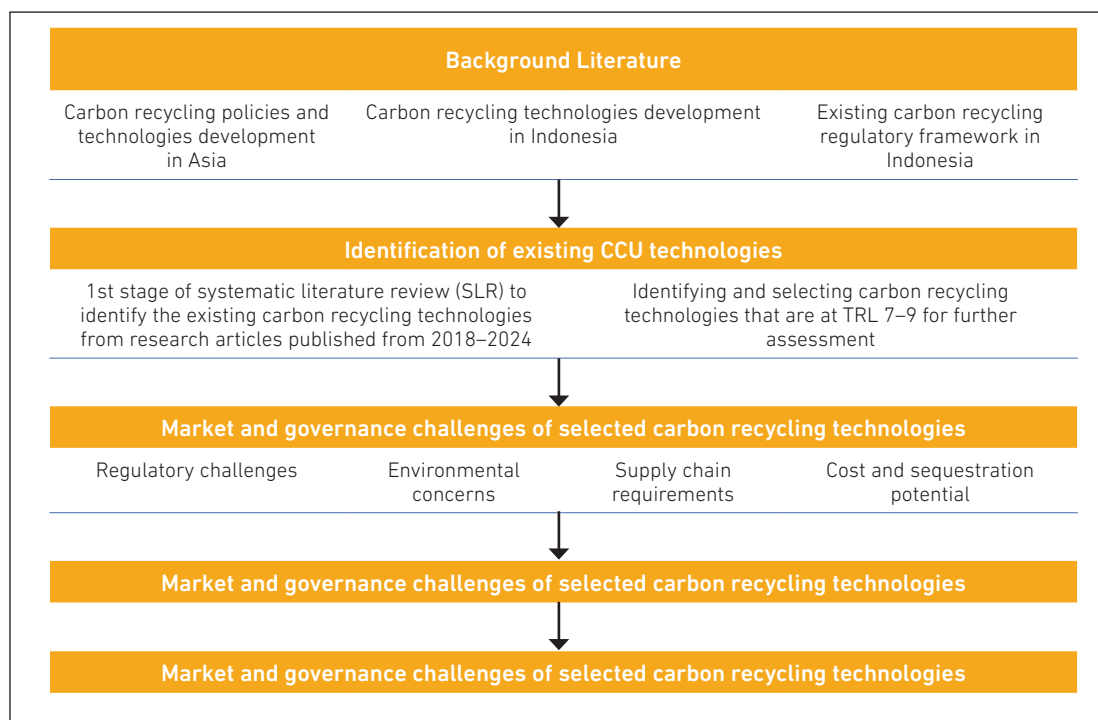
This research covers discussion around the carbon recycling technologies trends in Asia to provide some understanding on the stage of the development. This section will be followed by the methods we applied to achieve the aims and our objectives and discussion on current carbon recycling technologies and the relevant carbon capture and utilisation (CCU) technologies that we analyse. Further, economic analysis will provide insights if any of these relevant technologies are feasible for Indonesia. This discussion will be enriched by having literature reviews on the market and environmental risks as well as the existing regulatory frameworks in Indonesia. Finally, this research provides some insights for the future for Indonesia if it is to develop a carbon recycling roadmap to achieve its National Determined Contributions targets by 2030 and 2040.

2. Methods

This research applied multi-steps methods and a mixed methods approach to assess feasibility of carbon recycling technologies (see Figure 10.1 for our methods framework).

To identify the type of technologies and the technology readiness level (TRL), first, systematic literature reviews were conducted using PRISMA. This process includes identification of the research articles, followed by screening based on the criteria we set, and finally the selection of papers that we used for the literature review. To identify the research articles, first, we selected Scopus papers using the Boolean research with keywords: TITLE-ABS-KEY: Carbon 'AND' Capture 'AND' Utilisation 'OR' integrated 'AND' Carbon 'AND' Capture 'AND' Utilisation 'OR' electrochemical 'OR' thermochemical 'OR' photochemical 'OR' biological 'OR' biochemical. We screened the papers and selected papers that were published in the last 7 years (2018–2024/early 2025). We did not use any paper older than 2018 since there must have been some progress on the carbon recycling technology developments from the previous year. Some technologies might not be commercially feasible in 2010, but in recent years, this type of technology could already be in the TRL 7–9. However, we also includes any cited publications within the selected publications (main publications we selected and analysed) that are relevant to our research. This means, it could also include any publication prior to 2018. The second step is to identify any carbon recycling technologies that are already at the commercial stage. This is captured in the TRL scale, which was originally developed by NASA. For this selection purposes, we adopted the TRL definitions by Chauvy et al. (2019) on the carbon capture technologies (See Appendix, Table A10.1).

Figure 10.1. Methods Framework



CCU = carbon capture and utilisation, TRL = technology readiness level.

Source: Authors.

Once we have identified the carbon recycling technologies that are at TRL 7–9 scale, we then conduct further literature reviews on their environmental aspects. Similar to the first step, we used Boolean research with new keywords: KEY carbon 'AND' capture 'AND' utilisation, 'OR' integrated 'AND' carbon 'AND' capture 'AND' utilisation, 'OR' hydrogenation 'AND' methanation, 'OR' methanation, 'OR' thermochemical, 'AND' environment.

To evaluate its economic feasibility in Indonesia, we conducted quantitative analysis that covers cost analysis, sequestration potential, supply chain analysis, and financing requirements. The parameters and variables are customised to reflect Indonesia's long-term energy landscape and policy goals, ensuring that the findings are relevant and actionable. Understanding these costs will be crucial for determining the economic feasibility of carbon recycling in Indonesia. To evaluate the economic feasibility of carbon recycling technologies, this research compares these technologies to main carbon reduction measures of the power sector as the country's biggest source of centralised carbon emissions. The supply chain analysis includes an examination of the supply chain for carbon, focusing on the availability and logistics of carbon capture and the subsequent utilisation in downstream industries (economics of scale).

3. Carbon Recycling Development in Indonesia

Indonesia has taken a careful and sensible strategy to combat climate change by implementing CCUS or carbon capture and storage (CCS) methods (Ordonez et al., 2021). CCS entails collecting carbon dioxide and moving it to geological storage locations. While there has been much research conducted on CCUS projects in Indonesia and the use of CO₂ for the oil and gas upstream industry, the literature specifically on carbon recycling development and policies in Indonesia is limited. There is more research on CCUS and the use of CO₂ for enhanced oil recovery (EOR) in oil and gas practices, which does not involve CO₂ conversion into other products.

A preliminary study on a carbon capture, utilisation, and storage (CCUS) pilot project in Indonesia was conducted in 2001 in an onshore oil field in East Java (Hedriana et al., 2021). More recently, BP's Tangguh CCUS initiative, centred on the Ubadari gas field in Papua and designed to support enhanced gas recovery through CO₂ injection, has emerged as a major milestone, with operations scheduled to commence in 2028 (BP, n.d.). Collectively, these projects contribute to advancing feasibility assessments and demonstrating pathways for integrating CCUS into Indonesia's oil and gas sector as well as its power-generation infrastructure (Ramadhan et al., 2024). In parallel, research on CCUS deployment within the chemical industry is examining the potential utilisation of captured CO₂ for enhanced oil recovery (EOR) in depleted hydrocarbon fields (Pratiwi et al., 2024).

In the electricity sector, the government has considered CCS technology as part of Perusahaan Listrik Negara's (PLN) energy transition initiatives to lower emissions from coal-fired power plants. This is part of a long-term plan to achieve decarbonisation from 2030 to 2060. Gas fired CCS and coal-fired power plants CCS are the fossil technologies with high overall potential in terms of emissions reduction and its readiness level (Lau, 2023). A recent study by Reza et al. (2024) find that despite this technology being considered feasible technically, with the current condition, this technology is a gimmick.

Despite Indonesia's progress in CCUS and CCS – evidenced by early pilots in East Java's oil fields and planned demonstrations in both oil-and-gas and coal-fired power sectors (Hedriana et al., 2021; Lau, 2023; Ramadhan et al., 2024) – research on converting CO₂ into value-added products remains limited and often hampered by economic and policy uncertainties (Ordonez et al., 2021; Reza, Heksaprilla, and Prakoso, 2024). A clear understanding of sector-specific emissions profiles is therefore critical to guide carbon-recycling deployment. The next section delineates these principal CO₂ streams to inform targeted technology strategies.

4. Carbon Dioxide Sources from Key Indonesian Industries

Indonesia offers strong prospects for carbon recycling across high-emitting sectors (Ramadhan et al., 2024). Power generation, responsible for about 43% of energy-related CO₂ emissions, presents opportunities for mineralisation and synthetic fuel production. While the transport sector contributes around 25%, its relevance lies in consuming CO₂-derived fuels such as methanol and dimethyl ether (Yusuf, Almomani, and Qiblawey, 2023).

The industry sector accounts for about 23% of emissions, with cement (about 37 MtCO₂/year) and steel (10–15 MtCO₂/year) as key contributors. Oil and gas firms are also pursuing CCU, as seen in Chevron and Pertamina's East Kalimantan studies. Additional sources – petrochemicals, pulp and paper, ethanol, and biogas facilities – emit recapturable CO₂ through combustion, chemical processes, and fermentation (Kuparinen, Vakkilainen, and Tynjälä, 2019).

Although CO₂ utilisation potential may reach 50–100 MtCO₂ annually, deployment depends on technological maturity, economic viability, and market conditions (Zhang et al., 2020). Progress requires supportive policies, pilot investments, and private-sector engagement. With regulatory incentives and institutional backing, carbon recycling could become integral to Indonesia's industrial decarbonisation and climate strategy (Ramadhan et al., 2024).

While Indonesia's industrial CO₂ emissions suggest potential for carbon recycling, practical deployment depends on broader considerations, including economic feasibility, infrastructure capacity, environmental trade-offs, and public acceptance. High costs, limited CO₂ handling infrastructure, market uncertainty, and community resistance present key challenges. Thus, a holistic, context-specific assessment is essential to determine viable and sustainable implementation pathways.

5. Legal Framework, Key Regulations, and Policy

Indonesia's regulatory foundation for carbon recycling dates to Law No. 32/2009 on Environmental Protection and Management, which embeds pollution prevention through cleaner-production mandates. Although the statute does not explicitly mention carbon recycling, its emphasis on resource efficiency created fertile ground for later CCUS innovations, signalling an early commitment to integrate environmental sustainability within national development objectives.

A decade later, Presidential Regulation No. 98/2021 formally wove carbon recycling into Indonesia's climate arsenal. By instituting measurement, reporting, verification, and crediting protocols, it enabled companies to monetise captured CO₂ – transforming it into synthetic fuels, construction materials, and chemical intermediates. The regulation thus established a market-based incentive, aligning emissions reduction with industrial competitiveness.

The Long-Term Strategy for Low Carbon and Climate Resilience 2050 further elevates carbon recycling – particularly within the cement, petrochemical, and power sectors where process emissions are unavoidable. Here, CCUS technologies are presented not as optional add-ons but as essential tools that repurpose CO₂ into commercial products, allowing heavy industries to cut emissions without overhauling core operations.

Indonesia's circular economy agenda reinforces and broadens these measures. The 2021 Circular Economy Roadmap for Manufacturing spotlights carbon capture as a linchpin of sustainable industrial transformation, while the National Waste Management Policy (2012) and Marine Debris Regulation No. 83/2018 both encourage energy recovery and cleaner production practices that dovetail with carbon-recycling goals.

Complementary to these policies, Presidential Regulation No. 14/2024 codifies technical standards for CO₂ capture, transport, storage, and cross-border transfer – expanding carbon-storage beyond oil and gas into cement, steel, and fertiliser production, and facilitating Indonesia's engagement in international carbon markets. Finally, Law No. 59/2024 embeds CCUS in the 2025–2045 National Development Plan, mandating sector-wide adoption of carbon-recycling technologies, incentivising public–private partnerships, and prioritizing research and development to drive down costs and accelerate deployment.

This layered regulatory architecture – spanning preventive environmental law, market-based carbon pricing, strategic long-term planning, and targeted technical standards – positions Indonesia to convert CO₂ from a liability into a resource, advancing both its decarbonisation and circular economy ambitions.

5.1. Institutional Co-ordination

The implementation of carbon recycling policies in Indonesia spans several ministries, resulting in a fragmented governance structure. The Ministry of Environment and Forestry leads climate policy development by setting national emissions targets and monitoring systems in line with the Paris Agreement and the National Determined Contributions. Meanwhile, the MEMR manages carbon issues in the energy sector, particularly within fossil fuel and renewable industries, underscoring the sector's significant role in national emissions.

The Ministry of Industry promotes cleaner production in sectors such as cement, petrochemicals, pulp and paper, and steel by encouraging the adoption of innovative technologies, including carbon recycling, to enhance environmental performance and industrial competitiveness. Concurrently, the Coordinating Ministry for Maritime Affairs and Investment leads the development of economic instruments – such as carbon pricing, trading mechanisms, and international climate finance – while facilitating technology transfer and climate investment agreements. However, the absence of a centralised body dedicated solely to carbon recycling results in overlapping institutional roles, regulatory gaps, and unclear lines of responsibility.¹

Indonesia's fragmented institutional framework undermines policy coherence and effective implementation. The Institute for Essential Services Reform (2022) notes that carbon recycling regulations often occupy ambiguous domains with shared yet poorly co-ordinated responsibilities, leading to inconsistent enforcement. For example, an industrial facility may need to secure environmental permits from the Ministry of Environment and Forestry, energy approvals from the MEMR, technology clearances from the Ministry of Industry, and economic incentives from the Coordinating Ministry for Maritime Affairs and Investment. This complexity delays decision-making and discourages private investment, particularly amongst small and medium-sized enterprises. Establishing a centralised co-ordination platform would streamline governance by unifying relevant ministries under a comprehensive framework for carbon capture, utilisation, and recycling.

5.2. Regulations on CO₂ Transportation using Pipeline Infrastructure

Indonesia's pipeline regulations, primarily designed for the oil and gas industry, govern both upstream (GR 35/2004) and downstream (GR 36/2004; MEMR Reg. 29/2017) sectors to ensure the safe and efficient transportation of hydrocarbons. Although these regulations currently concentrate on petroleum pipelines – with SKK Migas and BPH Migas playing key roles – the development of CCUS technologies necessitates an expanded, dedicated CO₂ pipeline infrastructure. Existing regulatory instruments for CO₂ transportation thereby support national policies for CCUS by addressing issues of transport, storage, and utilisation beyond the conventional petroleum framework.

¹ Following President Prabowo's dissolution of the Coordinating Ministry for Maritime and Investment Affairs, the responsibilities related to climate change and carbon recycling policy have been redistributed across multiple newly established or restructured ministries and agencies. This fragmentation of roles has significantly complicated institutional co-ordination, creating challenges in achieving cohesive and integrated policy implementation.

Complementary regulations address CO₂ transport via road under Decree No. SK.725/AJ.302/DRJD/2004, ensuring that this hazardous material is managed with rigorous safety standards – a critical provision for early-stage CCUS projects lacking large-scale pipeline networks. Further, the Ministry of Manpower Regulation No. 37 of 2017 mandates strict technical safety criteria for CO₂ storage containers, mitigating risks associated with high-pressure systems. The Indonesian National Standard No. 3473:2011 offers essential guidance for the design of CO₂ pipelines, emphasising pressure control, corrosion resistance, and emergency response to facilitate safe, continuous, and cost-effective CO₂ transport over long distances.

Collectively, these regulatory measures reduce technical risks, enhance safety, and provide regulatory certainty, thereby aligning with Indonesia's Nationally Determined Contributions and low-emissions development strategies, while promoting international collaboration and investment in CCUS initiatives.

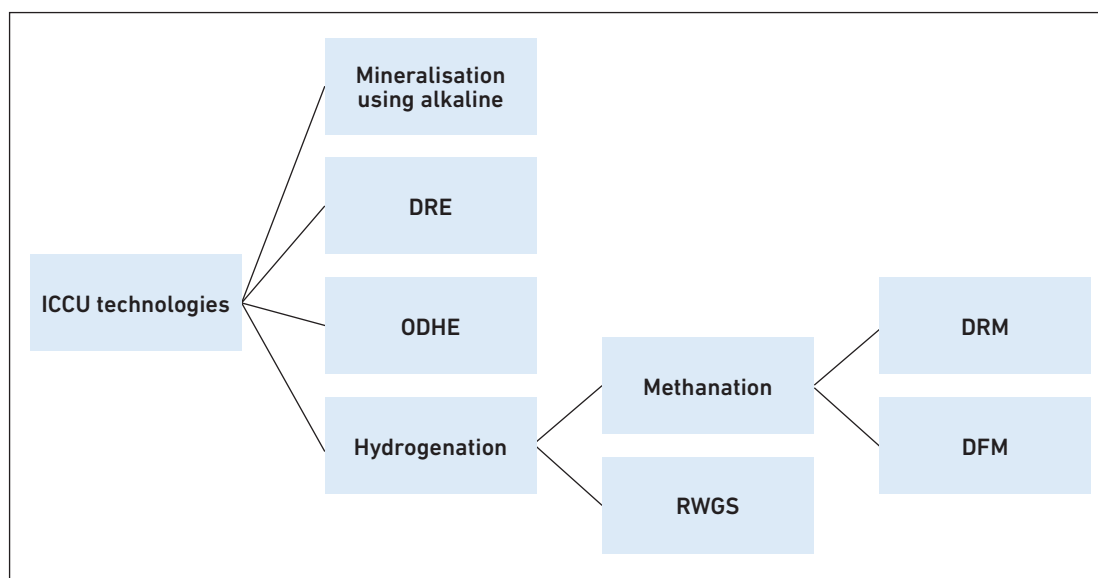
6. Integrated CCU and CCU Technologies

Carbon recycling technologies such as CCU technologies are broadly categorised into conventional utilisation (CU) and integrated carbon capture and utilisation (ICCU) approaches (Al-Mamoori, Rownaghi, and Rezaei, 2018; Podder et al., 2023). While CU involves separate processes for CO₂ capture and subsequent conversion, ICCU integrates these steps, offering potential efficiency gains (Al-Mamoori, Rownaghi, and Rezaei, 2018; Zhao and Itakura, 2023). These technologies hold promise for applications across multiple industries (with the exception of their use in EOR within the oil and gas industry), including energy, chemicals, and materials, contributing to sustainable development and climate change mitigation (Jung et al., 2020; Kätelhön et al., 2019; Zhang et al., 2022). Many studies have shown that both ICCU and CCU are found to be effective to reduce the greenhouse gas emissions and promote circular carbon economy (Gao et al., 2020; Zhang et al., 2022).

Building on this classification, the next section examines the underlying mechanisms, operational integration, and comparative efficiencies of each approach.

6.1. ICCU Technologies

ICCU integrates CO₂ capture and conversion into a single step, eliminating separation, transport, and product-purification costs, while improving energy efficiency (Koytsoumpa, Bergins, and Kakaras, 2018; Sun et al., 2021). Four ICCU pathways are assessed (Figure 10.2): (i) mineralisation with alkaline residues; (ii) direct ethylene synthesis via dry reforming of ethane (DRE); (iii) oxidative dehydrogenation of ethane (ODHE); and (iv) hydrogenation—including methanation (dry reforming of methane [DRM] and dual-function materials [DFM]) and reverse water–gas shift (RWGS) (Guo et al., 2023; Sarmad et al., 2024; Sun et al., 2021).

Figure 10.2. Integrated Carbon Capture and Utilisation Technologies

DFM = dual-function materials, DRE = dry reforming of ethane, DRM = dry reforming of methane, ICCU = integrated carbon capture and utilisation, ODHE = oxidative dehydrogenation of ethane, RWGS = reverse water–gas shift.

Source: Authors, based on Guo et al. (2023), Sarmad et al. (2024), and Sun et al. (2021).

Alkaline mineralisation sequesters CO₂ economically using industrial wastes near emission sources (Bui et al., 2018; Keith et al., 2018). DRE produces syngas (CO/H₂ > 1) at lower temperatures than DRM (Al-Mamoori, Rownaghi, and Rezaei, 2018), while ODHE offers energy-efficient ethylene production with substantially lower CO₂ emissions than steam cracking (Bielicki et al., 2014); however, ODHE's commercial readiness remains limited (Lv et al., 2023). DRM converts CH₄ and CO₂ into syngas but demands high temperatures (> 600°C) and catalysts to reduce activation barriers (Hu et al., 2021a, 2021b; Li, Sun, and Hu, 2021; Sun et al., 2021; Zhao et al., 2022); DFM capture CO₂ before methanation with electrolytic H₂ (Guo et al., 2023), and RWGS yields high-purity syngas under elevated hydrogen (H₂) concentrations (Sun et al., 2021). As renewable H₂ becomes abundant, these routes promise broader ICCU deployment (Falcone, Hiete, and Sapio, 2021).

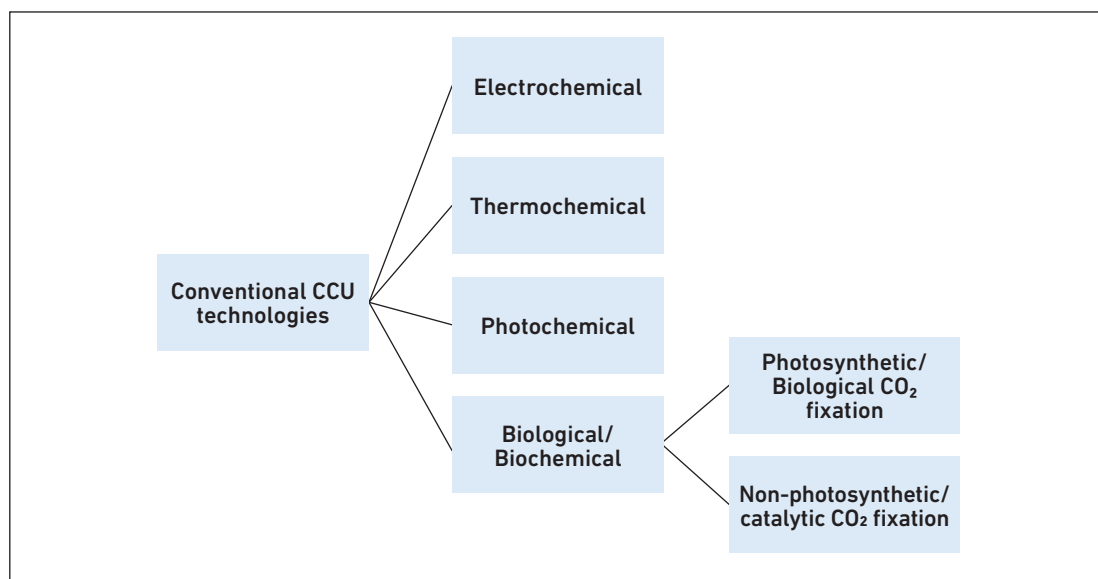
Despite advances – particularly in methanation scale-up (Kamkeng et al., 2021) – most ICCU technologies remain at TRL 2–6, requiring further work to enhance efficiency, selectivity, and cost-effectiveness for commercial viability (Guo et al., 2023; Sarmad et al., 2024; Sun et al., 2021).

6.2. Conventional CCU Technologies

Conventional CCU technologies include electrochemical, thermochemical, photochemical, and biological/biochemical approach (Figure 10.3); each presenting unique opportunities and challenges in enhancing efficiency, scalability, and sustainability (Liu, Lu, and Wang, 2023). Electrochemical conversion uses electricity and catalysts to reduce CO₂ into fuels like methanol, ethanol, and syngas, while high-temperature solid oxide electrolysis cells convert CO₂ into syngas (Wiesberg et al., 2019), while thermochemical methods use high-temperature reactions, such as CO₂ hydrogenation with Cu/ZnO catalysts for methanol and hydrocarbons, and plasma-

assisted conversion, which activates CO₂ with plasma (Valluri, Claremboux, and Kawatra, 2022). Photochemical conversion uses solar energy to reduce CO₂ via photocatalysis and artificial photosynthesis with photoelectrochemical cells (Kalamaras et al., 2018; Li et al., 2022) and biochemical CCU refers to the process of capturing carbon dioxide (CO₂) and converting it into valuable products that use biological catalysts, such as enzymes or microorganisms (biological CCU), to convert CO₂ into useful products (Isah et al., 2024).

Figure 10.3. Conventional Carbon Capture and Utilisation Technologies



CCU = carbon capture and utilisation, CO₂ = carbon dioxide.

Source: Authors, based on Grim et al. (2020), Isah et al. (2024), Luc et al. (2019), Nimmas et al. (2024) (2024), and Yaashikaa et al. (2019).

Conventional CCU technologies offer promising opportunities to convert CO₂ into valuable products such as fuels, chemicals, and stable carbonates, supporting a circular carbon economy. However, challenges remain in improving catalyst efficiency, reducing energy consumption, and scaling up for industrial applications (Saleh, 2022; Veltty and Corma, 2023). Continued research and technological advancements are essential to overcoming these barriers and achieving sustainable, cost-effective carbon utilisation (Gao et al., 2020; Zhang et al., 2020).

Electrochemical conversion

Electrochemical CO₂ reduction (ECR) enables the synthesis of high-value hydrocarbons and oxygenates under mild, voltage- and temperature-controlled conditions, while recycling its electrolyte and integrating renewable power sources (Dindi et al., 2019; Pei, Zhang, and Lu, 2023). By forgoing pressurised H₂, ECR eliminates related production, compression, storage, and transport costs (Grim et al., 2020; Luc et al., 2019). It also tolerates common CO₂ impurities (e.g. sulphur dioxide, water), reducing environmental sensitivity at scale (Luc et al., 2019; Rahimi et al., 2022). Large-scale deployment, however, must address significant electricity demands relative to thermodynamic limits, grid carbon intensity, catalyst kinetics, low energy efficiency from side reactions, solvent decomposition at high overpotentials, and overall cost-effectiveness (Al-Shamari et al., 2024; Kätelhön et al., 2019; Pei, Zhang, and Lu, 2023; Rahimi et al., 2022). Despite these hurdles, ECR's compact, modular, and on-demand design underpins its strong potential for industrial CO₂ conversion.

Thermochemical conversion

Thermochemical conversion processes have rapidly advanced as CO₂-utilisation technologies, with annual publications rising from 9,375 to 15,750 between 2020 and 2023 (Nimmas et al., 2024). Offering commercial feasibility across a broad range of TRLs, they convert CO₂ feedstock into fuels, chemicals, and construction materials via endothermic cycles that demand optimised material selection, oxygen removal, and heat recovery (Chen et al., 2024; IEA, 2019). Yet Carnot-like efficiency² limits and significant heating requirements elevate overall energy consumption (Pashchenko, 2023; Zhong et al., 2020). Mature applications—methanol and methane synthesis, urea production, and mineral carbonation for concrete – operate at TRL 7–9, demonstrating economic competitiveness and prolonged carbon fixation (Chauvy et al., 2019; Kim et al., 2022; Ng et al., 2023; Zhu, 2019). Compared to biochemical routes, thermochemical methods require less purification, enable catalyst recycling, handle diverse feedstocks, and deliver shorter reaction times, thereby supporting circular-economy and sustainable-energy strategies (Shahbaz et al., 2021; Zhang and Brown, 2019).

Photochemical conversion

Photochemical conversion involves transforming CO₂ by utilising excited electrons generated from solar energy. The resulting products vary based on the number of electrons and photons involved in the reactions. This technology is one of the emerging areas in CCU development. This technique is superior to other methods like electrochemical and thermal approaches in terms of energy efficiency and sustainability, as it leverages free solar energy, thereby reducing costs (Brandon et al., 2024). Solar light irradiation is used for CO₂ reduction in photochemical transformation, making it a sustainable and emerging method that has gained significant attention. It requires low temperatures, minimal input energy, and moderate pressure, without negatively impacting the environment (Shehzad et al., 2018; Yaashikaa et al., 2019). Therefore, these advantages could potentially solve energy demands issue and eco-problems (Tahir and Amin, 2013; Tu, Zhou, and Zou, 2014).

Despite its high efficiency, the product selectivity is very low, which then leads to numerous research studies to increase its selectivity (Mustafa et al., 2020; Saravanan et al., 2021; Yaashikaa et al., 2019). Also, this technology is limited by low photoelectric transfer efficiency and a narrow response wavelength range of the photocatalysts, resulting in lower conversion rates compared to electrochemical methods (Huang et al., 2022).

Currently, this technology is still in its early stages, and significant advancements are needed for commercial scaling, as there are no existing commercial projects (Kamkeng et al., 2021). The photochemical CO₂ technologies are still at a low TRL, between 2 to 4 (Brandon et al., 2024).

Biochemical and/or biological conversion

Biological CCU comprises photosynthetic and non-photosynthetic pathways for converting CO₂ into value-added products. In photosynthetic systems – most notably microalgae – sunlight drives CO₂ fixation into biomass, which can be refined into biofuels, nutraceuticals, pharmaceuticals, and specialty chemicals (Liew et al., 2016; Liu et al., 2020; Nocito and Dibenedetto, 2020; Yang, Tang, and Chen, 2024; Zhu, 2019). This approach can capture up to 99 % of CO₂ without separate gas-capture

² The term Carnot-like efficiency refers to the maximum possible efficiency that any heat engine can achieve when operating between two fixed temperatures. This efficiency represents the upper limit that no real engine can exceed, as it depends only on the temperatures of the two reservoirs and not on the working substance or the design of the engine.

or purification steps, thus reducing operational costs (Alami et al., 2021; Gupta et al., 2024). Open-pond cultivation offers a large air–liquid interface and low energy demand but requires extensive land, incurs high cultivation costs, exhibits low biomass density, and faces contamination and seasonal variability (Costa et al., 2019; Isah et al., 2024; Jerney and Spilling, 2018).

Non-photosynthetic (catalytic) CCU uses electrical or chemical energy to drive CO₂ reduction under controlled conditions, yielding higher product rates, shorter reaction times, and tighter selectivity – attributes that favour industrial scale-up (Braga, Vidinga, and Rossi, 2020; Yang, Tang, and Chen, 2024). Yet its reliance on costly catalysts, specialised infrastructure, and geospatially constrained sites limits economic (Isah et al., 2024; Madugu and Collu, 2016). Current research priorities include identifying robust algal strains adaptable to varied conditions, reducing cultivation and process costs, and optimising catalyst systems to reconcile efficiency with scalability in CCU applications (Isah et al., 2024).

6.3. Technology Readiness Level of Carbon Recycling (Conventional CCU/ICCU) Technologies

This report used the TRL scale to shortlist the CCU technologies that are being assessed for its commerciality and feasibility in Indonesia. Table 10.1 is the list of the CCU technologies with its TRL scale based on the literature reviews.

Table 10.1. Carbon Capture and Utilisation Technology Readiness Levels

	CCU Technologies	TRL	Source
ICCU	Mineralisation using alkaline (inorganic carbonates)	2–9	Kamkeng et al. (2021)
	DRE	4–6	Jarvis and Samsatli (2018)
	ODHE	2–6	Du et al. (2024), Geng et al. (2023), Lv et al. (2023)
	Hydrogenation – Methanation DRM	4–6	Jarvis and Samsatli (2018), Kamkeng et al. (2021)
	Hydrogenation – Methanation DFM (methane, methanol and light olefins)	7–9	Jarvis and Samsatli (2018)
	Hydrogenation – RWGS	2–6	(Jarvis and Samsatli (2018), Schmidt et al. (2018)
Conventional CCU	Electrochemical	3–5	Jarvis and Samsatli (2018), Perez-Fortez and Tzimas (2016)
	Thermochemical (urea, polyols, and cyclic carbonates)	7–9	Kim et al. (2022), Zhu (2019)
	Photochemical	2–4	Brandon et al. (2024)
	Biological photosynthetic (algae oil)	4–7	Gupta et al. (2024), Kamkeng et al. (2021)
	Biological non-photosynthetic	2–6	Kamkeng et al. (2021)

CCU = carbon capture and utilisation, DFM = dual-function materials, DRE = dry reforming of ethane, DRM = dry reforming of methane, ICCU = integrated carbon capture and utilisation, ODHE = oxidative dehydrogenation of ethane, RWGS = reverse water–gas shift, TRL = technology readiness level.

Source: Authors, based on literature reviews.

According to Table 10.1, only three technologies have reached commercialisation stage – mineralisation, hydrogenation methanation, and thermochemical. While according to Gupta et al. (2024) and Kamkeng et al. (2021), biological photosynthetic has TRL of 2–7, Isah et al. (2025) have found biological photosynthetic technologies have not yet reached commercial viability, indicating the need of further research and development. Therefore, the following section will focus on these technologies and evaluate its feasibility in Indonesia from the economic perspectives (costs), technology and infrastructure perspective, socio-environmental perspective, and regulatory perspective.

Having assessed the technical readiness of ICCU and conventional CCU, the following section will discuss the market and governance barriers that will determine their adoption in Indonesia. This section evaluates technology costs, supply-chain requirements, economic feasibility, and environmental trade-offs, highlighting the policy and institutional measures necessary to transform technological potential into scalable carbon-recycling practices.

7. Market and Governance Challenges Towards Carbon Recycling Policies in Indonesia

7.1. Selected CCU Technology Costs

Table 10.2 shows the technology costs for each specific technology based on the TRL 7–9 identification. The following section describes the scope of costing and the carbon sequestration potential of each technology in Table 10.2.

Costing and carbon sequestration potential scope

Mineral carbonation – inorganic carbonates (CaCO₃)

The cost of mineral carbonation was calculated based on an assumed new plant in the Netherlands in 2004 (Huijgen, Comans, and Witkamp, 2007) and being adjusted due to inflation in the country (2004 to 2023).³ The equipment needed for this technology mostly used stainless steel (AISI 316) except for the grinder and compressor, which used carbon steel. The costs for carbon sequestration include depreciation, variable, and fixed operating costs. Depreciation is calculated over 10 years (plant lifetime is 10 years). Variable costs cover materials and utilities, while fixed costs include labour, maintenance, and other overheads. The production capacity is 15,000 kilogrammes per hour (kg/hr) – 60,000kg/hr with the price of wollastonite ore is uncertain, but an estimate of US\$18/tonne was used (Huijgen, Comans, and Witkamp, 2007).

³ The inflation rates are taken from the World Bank database for Netherlands inflation from 2004–2023 (World Bank, n.d.).

Hydrogenation DFM – methane production

Methane production has been identified as a preferred method for CO₂ conversion. This preference is due to several factors, primarily the advanced state of the technology and the extensive market potential, which includes applications ranging from fuels to chemicals. In this technology, Sabatier synthesis is used to produce methane by the exothermic reaction of carbon dioxide with hydrogen (Jarvis and Samsatli, 2018). The hydrogen is produced from renewable electrolysis of water with synthetic natural gas (SNG) production capacity of 311 cubic metres per hour (m³/hr) (Götz et al., 2016). The operational lifespan of 20 years is predominantly influenced by the durability of commercial methanation reactors (Jarvis and Samsatli, 2018). It is assumed that the product price for SNG is US\$338.6 per tonne (Jarvis and Samsatli, 2018).

Hydrogenation DFM – methanol production

Apart from methane production, methanol production has also been identified as another preferred method for CO₂ conversion for the same reasons. Methanol (CH₃OH), also known as MeOH, is a vital industrial material in the global energy and chemicals markets, with demand steadily rising globally (Jadhav et al., 2014). The market price of methanol is US\$480/metric tonnes (Mt) with an annual production capacity of 440 kilotonnes (Kt) of methanol and lifespan of 20 years (Pérez-Fortes et al., 2016).

The electricity needed for methanol hydrogenation, excluding hydrogen production, is 0.169 megawatts per hour (MWh) per tonne of methanol (Pérez-Fortes et al., 2016). However, if hydrogen production via electrolysis is included, the requirement can increase to 0.55 MWh per tonne of methanol (Kiss et al., 2016).

Hydrogenation DFM – light olefins production

Do and Kim (2020) conduct research on hydrogenation CCU technology by converting CO₂ directly into light hydrocarbons using Aspen Plus V10 software (Aspentech, n.d.). During the CO₂ hydrogenation phase, the kinetics of the reactions producing C1–C4 hydrocarbons were calculated and optimised using algorithms developed by Meiri et al. (2015). It is assumed that this technology used renewable hydrogen, and electricity was assumed to come from the grid. Meanwhile, heat and refrigeration were expected to be provided by natural gas. The catalyst being used in this hydrogenation is iron-based catalyst.

The cost of the technology includes capital costs (fixed capital investment and working capital, including CO₂ costs). Meanwhile, the costs of replacing the catalyst, absorber, and membrane are variable operating expenses. The lifespan of this technology is 30 years (Kim et al., 2012) with annual production capacity of 1Mt of C2–C4 hydrocarbons (Do and Kim, 2020).

Thermochemical: carboxylation – urea production

In this context, urea is commercially manufactured by reacting carbon dioxide with ammonia at high temperatures and pressures, following the Basaroff reactions (Jarvis and Samsatli, 2018). It is assumed that the operational plant lifetime is 25 years with 1.5 million tonne production capacity (Edrisi, Mansoori, and Dabir, 2016). The market price of urea being used in this study was \$201.9/tonne based on February 2017 market price according to Index Mundi (Jarvis and Samsatli, 2018). It is assumed that this technology utilises petrochemical processing facilities, running 24 hours each day. The CO₂ utilisation per tonne of urea is 0.74tCO₂/tonne, with a conversion rate of 87.5% CO₂ (Eni Saipem, n.d.; Jarvis and Samsatli, 2018).

Thermochemical: carboxylation – polyols production

This technology converts CO₂ into polyols by the use of a catalyst – double metal cyanide, and involves the substitution of propylene oxide with CO₂. The CO₂ used in the polyol synthesis is captured from a hydrogen manufacturing unit at a refinery. The reaction produces polyether carbonate polyol and cyclic propylene carbonate as a by-product. The polyol plant are extensions to an existing facility situated in northwestern Europe. It is constructed within an established industrial zone that already has all necessary utilities and support infrastructure in place (Fernández-Dacosta et al., 2017). The operating expenditures is primarily driven by the cost of chemicals, particularly propylene oxide. The production capacity of this plant is 250 kt per annum with a lifespan of 25 years (Fernández-Dacosta et al., 2017).

Table 10.2. Economic Aspects of Selected Specific Technologies (TRL 7–9)

CCU Technologies	Product	Costs/tonne CO ₂ e (US\$)	Sequestration Potential (MtCO ₂ /year)	Production Capacity	Total Revenue* of Products / tCO ₂ (US\$)	Sources
Mineralisation carbonation	Inorganic carbonates	325.3–378.9	3,600	131,400–525,600 tonnes/year	757.1–883.3	Huijgen, Comans, and Witkamp (2007), Patricio et al. (2017)
Hydrogenation – DFM	Methane	9,248–13,466	3,000–4,000	2,726 million litres/year	438	Chauvy et al. (2019), Godin et al. (2021), Götz et al. (2016), Jarvis and Samsatli (2018)
Hydrogenation – DFM	Methanol	593.3–736	10	440 Kt/year	432.5	Bellotti et al. (2019), Chauvy et al. (2019), Pérez-Fortes et al. (2016)
Hydrogenation	Light olefins	1,935.1	1.85	1 Mt/year	409.7	Do and Kim (2020)
Thermochemical: carboxylation	Urea	249.2	153	1.5 Mt/year	480.4	Edrisi, Mansoori, and Dabir (2016), Godin et al. (2021), Jarvis and Samsatli (2018), Ng et al. (2023)
Thermochemical: carboxylation	Polyols (polymer)	5,371.3	4.5	0.25 Mt/year	7,039.1	Chauvy et al. (2019), Fernández-Dacosta et al. (2017), Godin et al. (2021), Huijgen, Comans, and Witkamp, (2007)

bbl = barrel, CO₂ = carbon dioxide CCU = carbon capture and utilisation, CO₂e = carbon dioxide equivalent, DFM = dual-function materials, Kt = kilotonne, Mt = metric tonne, MtCO₂ = metric tonnes of carbon dioxide, NA = not available, tCO₂ = tonnes of carbon dioxide.

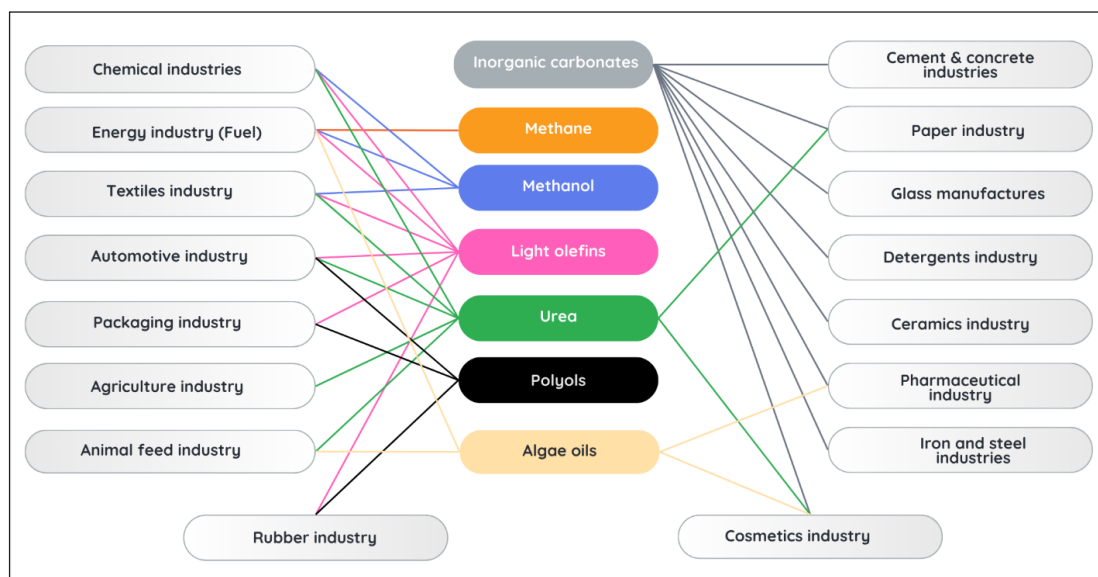
Note: *See Appendix, Table A10.2 for details on selling price.

Source: Authors, based on various literature.

7.2. Key Supply Chain Requirements

This article focuses on economic of scale requirements of the CCU/ICCU products; from the perspective of supply (production capacity) and demand (consumption/demand capacity) in Indonesia. Costs and potential revenues are not the only aspects to assess the feasibility of the mentioned CCU and ICCU products. Evaluating the demand aspect of the products is also key to assess this feasibility. This section will discuss the main users of each of the CCU/ICCU products and the potential demand/consumptions in Indonesia, Figure 10.4 shows how each of these carbon recycling products feed into the industries.

Figure 10.4. Carbon Recycling Products from Selected Technologies and Their Users



Source: Authors.

Inorganic carbonates users

Inorganic carbonates are widely used across various industries due to their versatile properties. There are varieties of inorganic carbonates, such as calcium carbonate (CaCO_3), which is widely used in construction (cement and concrete), paper, and plastic industries; sodium carbonate (Na_2CO_3), also known as soda ash, which is used in glass manufacturing, detergents, and water treatments; potassium carbonate (K_2CO_3), is mainly used in the production of ceramics, glass and drying agent; magnesium carbonate (MgCO_3), is commonly used in pharmaceuticals; iron carbonate (FeCO_3), also known as siderite which is used in iron and steel industries; and finally zinc carbonate (ZnCO_3) which is used in cosmetics and rubber industries (Comes et al., 2024).

Methane users

Methane is widely used as an energy source (fuel) (Wang et al., 2024) in power plants to generate electricity; residential and commercial/industrial use for heating, cooking, operational activities and powering appliances such as water heaters, transportation in the form of compressed natural gas. As a fuel, using methane will not reduce the carbon emissions in the atmosphere, since burning methane contributes to carbon emissions being released.

Methanol users

Methanol is a crucial feedstock and fuel in various industries due to its chemical properties and versatility. Similar to methane, methanol can be used as a fuel and to produce biodiesel and synthetic fuel, and also can be converted to dimethyl ether as alternative to diesel (Simon Araya et al., 2020). Not only as a fuel, methanol is also used in the chemical industry to produce formaldehyde, acetic acid and other chemicals that are essentials in manufacturing plastics, resins, and adhesives. Methanol is also used in the pharmaceuticals industry as a solvent and in the synthesis of various pharmaceuticals products. In the textiles industry, methanol is used to produce synthetic fibres and dyes.

Light olefins users

Light olefins – ethylene, propylene, and butylene – are essential feedstocks with diverse industrial applications (Chernyak et al., 2022; Zhao et al., 2025). Ethylene (C_2H_4) is integral to producing polyethylene, ethylene oxide, and ethylene dichloride, thereby supporting plastics, packaging, textiles, and chemicals. Propylene (C_3H_6) is critical for manufacturing polypropylene, propylene oxide, and acrylonitrile, while butylene (C_4H_8) serves as a precursor for butadiene, isobutylene, and various chemical processes. Collectively, these olefins underpin the synthesis of numerous products and are thus pivotal to modern industrial operations.

Urea users

Urea is a versatile compound with applications across numerous industries. In agriculture, it functions as a nitrogen-rich fertiliser essential for plant growth (Motasim et al., 2024; Swify et al., 2023). In the chemical sector, it is a key precursor for urea-formaldehyde resins used in adhesives, particle boards, and laminates. Urea also serves as a cost-effective protein supplement in animal feed. Notably, in Indonesia, its primary application is as an agricultural fertiliser (Motasim et al., 2024).

Polyols users

Polyols are multifunctional compounds with extensive industrial applications (Batra, 2024). They are employed in the automotive sector to produce polyurethane foams for seating and interior components, thereby enhancing safety and comfort. In construction, polyols facilitate the production of rigid polyurethane foams for insulation, contributing to energy-efficient building design.

The furniture industry utilises polyol-based flexible foams for mattresses and upholstery, and the textile sector applies polyols in coatings and adhesives to improve product performance. Additionally, polyols are integral to protective packaging and the production of polyurethane elastomers in footwear, underscoring their broad industrial significance.

7.3. Economic Feasibility of CCU/ICCU Technologies

According to Table 10.2 in section 7.1, only a few CCU/ICCU technologies are economically viable for development in Indonesia. These include mineralisation carbonation to produce calcium carbonate ($CaCO_3$), which is widely used in manufacturing industries; thermochemical carboxylation to synthesise urea and polyols; and potentially, biological photosynthesis for algae oil production. Each of these technologies transforms carbon dioxide equivalents (CO_2e) into chemically stable, value-added products that can be integrated into existing industrial supply chains (Bobicki et al., 2012; Jacobs and Hitch, 2011; Sanna et al., 2014).

For instance, CaCO_3 is a durable compound commonly used in construction materials such as cement and concrete, where it can remain sequestered for decades or even centuries. Similarly, urea, a key component in fertilisers, and polyols, used in the production of foams and plastics, offers long-term carbon storage in agricultural and manufacturing applications.

These processes not only reduce atmospheric CO_2e but also create economically viable products that meet ongoing industrial demand. The annual consumption of these materials in the country is substantial (Table 10.3), indicating strong market potential and facilitating commercial scalability. Moreover, the inherent stability of the end products ensures that the captured carbon is not easily re-emitted, making these technologies promising candidates for sustainable, long-term climate change mitigation. By aligning environmental goals with industrial utility, these approaches represent a practical pathway towards a circular carbon economy.

Unlike more sustainable carbon utilisation pathways, hydrogenation – DFM technologies, which produce methane and methanol, do not contribute to a net reduction in atmospheric CO_2 levels. While these processes may temporarily convert CO_2 into energy-dense fuels, the carbon is ultimately re-released into the atmosphere when these fuels are combusted or otherwise utilised. This cyclical release undermines their effectiveness as long-term climate mitigation strategies.

Methane, although a potent energy carrier, is also a highly effective greenhouse gas—over 80 times more powerful than CO_2 over a 20-year period (Chung, 2021; Davis, 2002). Any leakage during production, storage, or distribution can significantly offset any perceived climate benefits. Similarly, methanol, when used as a fuel or feedstock, results in CO_2 emissions upon combustion, effectively returning the captured carbon back into the atmosphere.

7.4. Environmental Impacts of CCU and ICCU Technologies

Indonesia's carbon recycling policy governance faces multiple challenges, particularly in the areas of life cycle assessment, (LCA), end of life product management, and monitoring, reporting and verification (MRV) (Wiloso et al., 2019; Woo et al., 2021; Yu et al., 2022). These challenges are fundamental to ensuring an effective carbon management system that supports environmental sustainability.

Indonesia has adopted the ISO 14040 and ISO 14044 standards as national guidelines for conducting LCAs. These standards provide a framework for assessing the environmental impacts of products throughout their life cycles, from raw material extraction to disposal. The adoption of these standards aims to enhance the sustainability of products and align with both national and international quality benchmarks (National Standardization Agency of Indonesia, 2017; Wiloso et al., 2019). Despite these advancements, challenges persist, including limited localised inventory data and a shortage of LCA expertise.

To address these issues, the Indonesian Life Cycle Assessment Network (ILCAN) was established to promote LCA adoption and facilitate the development of national life cycle inventory databases (Wiloso et al., 2019).

Table 10.3. Summary of Carbon Capture and Utilisation/Integrated Carbon Capture and Utilisation Products, Product Capacity, and Demand Capacity in Indonesia

CCU Technologies	Product	Production Capacity	Main Industry Users in Indonesia	Use of Product/tonne Production	Total Production in Indonesia/year	Total Demand for CCU Product (Mt)	Sources
Mineralisation carbonation	Inorganic carbonates	131,400–25,600 tonnes/year	Cement, concrete industries (construction industry)	1.25 tonne/tonne cement ^[1,2]	120 Mt ^[3]	150 Mt CaCO ₃	^[1] Jessa and Ajidahun (2024), ^[2] Febriatna, Darmanto, and Juangsa (2023), ^[3] Portal Informasi Indonesia (2024)
Hydrogenation – DFM	Methane (direct use)	2,726 million litres/year or 17.15 mmbae/year	Energy industry	NA	NA	317 mmbae/year ^[4]	^[4] (Ministry of Energy and Mineral Resources [MoEMR] 2024)
Hydrogenation – DFM	Methanol	440 Kt/year	Energy, chemical, and textiles industries	NA	NA	2 Mt methanol/year ⁵	^[5] Aprobi (2020)
Hydrogenation	Light olefins	1 Mt/year	Energy, chemical, automotive, rubber and textiles industries	NA	NA	1.4 Mt ethylene/year ⁶ 1.2 Mt propylene/year ⁷	^[6] Haryadi et al. (2023) ^[7] Muflih and Prasetya (2018)
Thermochemical: Carboxylation	Urea	1.5 Mt/year	Chemical, textiles, automotive, agriculture, and animal feed industries	NA	NA	23 Mt urea/year ⁸	^[8] Badan Pangan Nasional (2024)
Thermochemical: Carboxylation	Polyols	0.25 Mt/year	Automotive, packaging and rubber industries	NA	NA	0.2 Mt/year ⁹	^[9] Bhandari (2023)
Biological Photosynthetic	Algae oil	330,00 bbl/year	Energy, animal feed, cosmetics, pharmaceutical industry	NA	NA	Data are unavailable. Indonesia currently exports algae plant instead of using it domestically ¹⁰	^[10] Anugrah (2024)

bbl = barrel, CO₂ = carbon dioxide CCU = carbon capture and utilisation, CO₂e = carbon dioxide equivalent, DFM = dual-function materials, Kt = kiloton, Mt = metric tonne, mmbae = million barrels of oil equivalent, MtCO₂ = metric tonnes of carbon dioxide, NA = not available, tCO₂ = tonnes of carbon dioxide.

Source: Authors, based on various literature.

Indonesia has also established comprehensive MRV systems to support its carbon recycling policies, such as MEMR Regulation No. 2 of 2023, outlining the implementation of CCUS in upstream oil and gas activities, National Registry System for Climate Change Control, which was established in 2016.

In assessing the sustainability of CCU and ICCU technologies, it is essential to account for site-specific environmental trade-offs. Many chemical and electrochemical conversion pathways are highly energy-intensive; when powered by fossil-derived electricity or hydrogen – as remains common in Indonesia – they may increase net CO₂ emissions, offsetting intended climate benefits (Garcia-Garcia et al., 2021; Thonemann, 2020). Moreover, the widespread use of amine solvents and metal-based catalysts introduces risks of air and water pollution if storage, handling, or disposal practices are inadequate (Garcia-Garcia et al., 2021). Water demand is also substantial: processes such as CO₂ hydrogenation, algal fixation, and electrochemical reduction require large freshwater inputs, exacerbating scarcity in regions prone to seasonal droughts unless integrated water-management strategies are adopted (Martínez-Huitle et al., 2023).

Land-use pressures further complicate deployment, as large-scale cultivation for biological fixation or the construction of chemical plants may encroach on agricultural and ecologically sensitive areas, driving deforestation, biodiversity loss, and potential food-security conflicts (ADB, 2021; Hasan et al., 2020). Even when capture and conversion succeed, many CO₂-derived products—synthetic fuels, plastics, beverages—re-emit their carbon during use or disposal, limiting net sequestration unless the carbon is mineralised or locked in durable materials (Cheah et al., 2016; Garcia-Garcia et al., 2021). The reliance on cobalt, nickel, and platinum-group metals for catalysts and electrolyzers raises additional concerns over resource depletion and ecological disturbance in mining regions (Arvidsson and Sandén, 2017; Salehi et al., 2023). Finally, spent solvents, deactivated catalysts, and unreacted precursors constitute waste streams that, without robust regulatory frameworks and treatment infrastructure, threaten soil and water quality. Life cycle assessments of several CCU pathways reveal that, depending on feedstock and energy sources, environmental burdens can shift from climate impacts to eutrophication, acidification, or toxicity (Ghamkhar et al., 2021; Khudhur et al., 2022; Xie et al., 2022).

8. Conclusions and Recommendations

8.1. Conclusions

Based on the comprehensive examination of the literature presented in the preceding sections, this study synthesises key insights into the environmental, economic, institutional, and infrastructural dimensions of CCU and ICCU technologies in Indonesia. The review has highlighted both the potential and the limitations of these technologies within the national context, considering factors such as cost-effectiveness, policy coherence, market demand, and technical feasibility. The following sections outline the main conclusions and findings derived from this analysis, offering a critical perspective on the current state and prospects of CCU/ICCU deployment in Indonesia

Economic viability and market limitations

Although Indonesia's large population suggests a strong potential market for CCU/ICCU-derived products, some of these technologies remain financially unfeasible. Table 10.3 presents a detailed overview of the national demand for these products. Nevertheless, despite the evident market demand, the selected CCU/ICCU technologies have not proven to be cost-effective as anticipated. As stipulated in Table 10.2, only a few of them are economically feasible, which are mineralisation carbonation, thermochemical carboxylation (urea and polyols production), and biological photosynthetic.

Meanwhile, the rest of the technologies are too expensive to develop in the country. The high cost of these carbon recycling technologies places them far beyond the reach of current government incentives or other public and non-commercial support mechanisms. These include hydrogenation – DFM technologies which produce methane and methanol. From a policymaking perspective, these technologies may offer short-term economic or energy security benefits, but they do not align with net-zero objectives. In contrast to carbon utilisation methods that result in stable, long-lived products such as mineralised carbonates or durable polymers, methane and methanol production represents a temporary carbon loop rather than a permanent solution. Therefore, while these technologies may have a role in transitional energy systems, they should not be prioritised as core strategies for long-term climate stabilisation.

As part of Indonesia's pathway to net-zero emissions, it is more pragmatic to prioritise cost-effective carbon reduction measures rather than investing heavily in costly and currently nonviable CCU and ICCU technologies. According to Yuwono et al. (2025), the cost per tonne of CO₂ abated through bioenergy with carbon capture and storage (BECCS), renewable energy sources such as solar PV and wind, and nuclear power is significantly lower than that of CCU/ICCU technologies. Specifically, BECCS, solar, and wind range between US\$59–US\$63 per tonne, while nuclear is US\$65–US\$68 per tonne, compared to US\$98 per tonne for CCU and ICCU.

These figures underscore the economic inefficiency of relying on high-cost CCU/ICCU technologies, especially when more affordable and scalable solutions are available. For a developing country like Indonesia, where fiscal resources must be allocated strategically, focusing on proven, lower-cost technologies offers a more viable and impactful route to achieving national climate targets.

Environmental and operational considerations of CCU/ICCU technologies

CCU and ICCU technologies are increasingly recognised as tools to mitigate climate change by reducing atmospheric CO₂ concentrations. However, their environmental performance is highly dependent on local conditions, including energy sources, infrastructure, and regulatory frameworks. If not carefully managed, these technologies can inadvertently contribute to environmental degradation.

For instance, CCU/ICCU processes often require significant energy inputs, which, if derived from fossil fuels can offset the intended climate benefits by reintroducing CO₂ into the atmosphere. Additionally, these technologies may involve increased water consumption and the use of chemicals or materials that pose environmental risks. Therefore, a comprehensive environmental impact assessment and lifecycle analysis are essential before deployment. To ensure sustainability, Indonesia must develop a robust mitigation strategy that includes strict environmental safeguards, monitoring mechanisms, and a clear policy framework.

Institutional and policy fragmentation

CCU deployment in Indonesia is hindered by fragmented mandates across the Ministries of Environment and Forestry, Energy and Mineral Resources, and Industry and was further disrupted by the October 2024 dissolution of the Coordinating Ministry for Maritime Affairs and Investment, which weakened carbon-pricing and climate-finance alignment. These overlaps have produced regulatory gaps, uneven enforcement, and bureaucratic hurdles that deter investment, especially amongst resource-constrained small and medium-sized enterprises (SMEs). Establishing a centralised carbon-management task force to harmonise policies, streamline multi-agency approvals, and liaise with the private sector – supported by targeted training and technical assistance – would strengthen institutional capacity and enable effective CCU implementation.

Infrastructure and logistical challenges

CO₂ pipeline networks are indispensable for CCU/ICCU deployment in Indonesia, yet the archipelagic geography amplifies logistical complexity and capital requirements, demanding co-ordinated onshore–offshore planning and investment. Pipelines must employ corrosion-resistant, high-pressure materials and comply with stringent safety standards to withstand seismic and volcanic hazards, thereby necessitating advanced engineering solutions.

Simultaneously, absent carbon pricing, unclear land-acquisition and transport regulations, and high upfront costs inhibit private-sector participation. Addressing these barriers requires robust regulatory frameworks, targeted incentives for pipeline-integrity innovations, and proactive stakeholder engagement to secure institutional and public support.

8.2. Recommendations

Despite the high costs associated with carbon recycling technologies, this economic barrier does not preclude the formulation of strategic pathways forward. Under current conditions, the economic infeasibility of deploying CCU and ICCU technologies in Indonesia underscores the urgency for targeted interventions. In light of the challenges and insights identified through the preceding literature review, this report offers a set of actionable recommendations to enhance the viability, co-ordination, and long-term sustainability of CCU and/or ICCU development in Indonesia. These recommendations are as follows:

1. The government should prioritise the development and deployment of mineral carbonation, thermochemical carboxylation (for urea and polyols), and photosynthetic biological CCU within an integrated, market-responsive framework that secures reliable carbon feedstocks. They also need to ensure robust inter-agency co-ordination and institutional alignment to facilitate implementation and to nurture CCS and BECCS supply chains. While CCS and BECCS are not yet economically viable in Indonesia's context, advance these technologies in parallel to address potential future needs for emission-overshoot management.
2. The government should mandate comprehensive environmental-impact assessments and full lifecycle analyses for CCU and/or ICCU projects to identify and mitigate trade-offs; establish robust safeguards and monitoring protocols for water use, chemical management, and emissions rebound; and require integration of renewable energy to optimise overall environmental performance.
3. The government should form a centralised carbon-management task force to co-ordinate a CCU and ICCU policy, harmonise regulations, and align sectoral strategies, underpinned by clear interministerial mandates and a unified permitting regime to expedite approvals – particularly for SMEs.

4. Indonesia should develop a national CO₂ transport and storage infrastructure plan focused on key industrial hubs and storage sites, invest in resilient pipeline technologies suited to its geological risks, and establish clear regulations and safety standards to provide legal certainty for investors and developers.
5. Indonesia should foster collaboration between state-owned enterprises and private sector actors, promote international partnerships with countries experienced in carbon management to access technology and finance, and support knowledge sharing through joint research, training, and technical exchanges.

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Appendix

Table A10.1. Technology Readiness Level for Carbon Capture and Utilisation

TRL	Description
TRL 1 – Basic research	Published research that identifies the principles that underlie the technology
TRL 2 – Technology formulation	Publications or other references that outline the application being considered, and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. A major part of the work is analytical or paper studies. Experimental work is designed to corroborate the basic scientific observations made during TRL1 work.
TRL 3 – Research to prove feasibility	Active research and development (R&D) has been initiated. At TRL 3, the work has moved beyond the publication phase to experimental work.
TRL 4 – Technology development of scale (small scale prototype)	TRL4–6 represents the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system.
TRL 5 – Technology development of scale (large scale prototype)	The basic technological components are integrated so that the system configuration is similar to the final application in almost all respects.
TRL 6 – Technology demonstration	This represents a major step up in a technology's demonstrated readiness. TRL 6 begins true engineering development of the technology as an operational system in the intended environment.
TRL 7 – Demonstration scale	TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype. System prototype demonstration in the operational environment (e.g. industrial pilot).
TRL 8 – System commissioning	This TRL represents the end of true system development. System complete and qualified (e.g. commercial scale demonstration of manufacture, construction, and operation). The technology has been proven to work in its final form and under expected conditions.
TRL 9 – full commercial application	The technology is in its final form and operates under the full range of operating mission conditions. Technology fully proven in operational environment and commercially available for customers.

TRL = technology readiness level.

Source: Adopted from Chauvy et al. (2019).

Table A10.2. Carbon Capture and Utilisation/Integrated Carbon Capture and Utilisation Products Selling Price Per Tonne

CCU/ICCU Technologies and Products	Selling Price (per tonne of product, US\$)	Source
Mineralisation carbonation (CaCO ₃)	318	Business Analytiq (2025)
Hydrogenation methane	438	Global Petrol Price (2025)
Hydrogenation methanol	532	Methanex (2025)
Hydrogenation light olefins	758	Echemi (2025)
Carboxylation urea	355	Trading Economics (2025)
Carboxylation polymer	1,619	Imarc (2025)
Photosynthetic – algae oil	1,137	Zhu, Anderson, and Jones (2018)

CCU = carbon capture and utilisation, ICCU = integrated carbon capture and utilisation.

Note: The prices are based on average global prices of each product.

Source: Authors, based on various sources.

